GEOLOGY AND
GROUND-WATER RESOURCES
OF THE ISLAND OF HAWAII

H. T. STEARNS AND G. A. MACDONALD

BULLETIN 9
HAWAII DIVISION OF HYDROGRAPHY
1946

BULLETINS OF THE DIVISION OF HYDROGRAPHY
TERRITORY OF HAWAII

*1. GEOLOGY AND GROUND-WATER RESOURCES OF THE ISLAND OF OAHU, HAWAII. By Harold T. Stearns and Knute N. Vaksvik. 1935.

*2. GEOLOGIC MAP AND GUIDE OF THE ISLAND OF OAHU, HAWAII. By Harold T. Stearns. 1939.

*3. ANNOTATED BIBLIOGRAPHY AND INDEX OF GEOLOGY AND WATER SUPPLY OF THE ISLAND OF OAHU, HAWAII. By Norah D. Stearns. 1935.

4. RECORDS OF THE DRILLED WELLS ON THE ISLAND OF OAHU, HAWAII. By Harold T. Stearns and Knute N. Vaksvik. 1938.

5. SUPPLEMENT TO THE GEOLOGY AND GROUND-WATER RESOURCES OF THE ISLAND OF OAHU, HAWAII. By Harold T. Stearns. Includes chapters on geophysical investigations by Joel H. Swartz, and petrography by Gordon A. Macdonald. 1940.

6. GEOLOGY AND GROUND-WATER RESOURCES OF THE ISLANDS OF LANAI AND KAHOOLAWE, HAWAII. By Harold T. Stearns. Includes chapters on geophysical investigations by Joel H. Swartz, and petrography by Gordon A. Macdonald. 1940.

*7. GEOLOGY AND GROUND-WATER RESOURCES OF THE ISLAND OF MAUI, HAWAII. By Harold T. Stearns and Gordon A. Macdonald. 1942.

8. GEOLOGY OF THE HAWAIIAN ISLANDS. By H. T. Stearns. 1946.

9. GEOLOGY AND GROUND-WATER RESOURCES OF THE ISLAND OF HAWAII. By Harold T. Stearns and Gordon A. Macdonald. 1946.

TOPOGRAPHIC MAP OF THE ISLAND OF HAWAII, scale 1:125,000, contour interval 250 feet, size 44 x 49 inches, price $1.00, for sale by the Survey Department, Territorial Office Building, Honolulu 2, T. H.

---

* Out of print.

Plate 4. Lava fountains and illuminated fume cloud, Mauna Loa, night of May 2, 1942. The fountains rise 150 feet above the cone. Photo by G. A. Macdonald.

TERRITORY OF HAWAII
INGRAM M. STAINBACK, *Governor*
A. LESTER MARKS, *Commissioner of Public Lands*
DIVISION OF HYDROGRAPHY
MAX H. CARSON, *Chief Hydrographer*

BULLETIN 9

GEOLOGY AND GROUND-WATER RESOURCES OF THE ISLAND OF HAWAII

BY

HAROLD T. STEARNS
Former District Geologist, U. S. Geological Survey

AND

GORDON A. MACDONALD
District Geologist, U. S. Geological Survey

Prepared in cooperation with the Geological Survey,
United States Department of the Interior

1900

Printed in the Territory of Hawaii, United States of America, October, 1946
Distributed by the U. S. Geological Survey, 333 Federal Bldg., Honolulu, Hawaii

Printed by
Advertiser Publishing Co., Ltd.
Honolulu, Hawaii, U.S.A.

CONTENTS

CONTENTS

CONTENTS

CONTENTS

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS

ILLUSTRATIONS

ILLUSTRATIONS

ILLUSTRATIONS

GEOLOGY AND GROUND-WATER RESOURCES OF THE ISLAND OF HAWAII

ABSTRACT

Hawaii, the largest island in the Hawaiian group, is 93 miles long, 76 miles wide, and covers 4,030 square miles. Mauna Loa Volcano is 13,680 feet high and Mauna Kea is 13,784 feet high. Plate 1 shows the geology, wells, springs, and water-development tunnels. Plate 2 is a map and description of points of geologic interest along the main highways. Plate 3 (same sheet as plate 2) shows highways and points of geologic interest in Hawaii National Park area. The volcanic terms used in the report are defined.

Hawaii was built by five volcanoes. All the rocks are volcanic, except for minor amounts of sedimentary rock derived from them. Mauna Loa and Kilauea volcanoes erupt often; Hualalai Volcano last erupted in 1801; Mauna Kea has had Recent but no historic eruptions; Kohala Mountain has long been extinct.

Kohala Mountain constitutes the northern end of the island. It is built largely of rocks of the Pololu volcanic series which are dominantly olivine basalt with a few thin intercalated beds of vitric basaltic ash. After the eruption of this series, Kohala Volcano was deeply eroded on the windward (northeastern) side, and a deep soil formed on its other slopes. Later, oligoclase andesite and trachyte lava flows, named the Hawi volcanic series, were erupted. They rest on soil at the top of the Pololu series, and lie in the valleys cut into the Pololu lavas on the windward slope. Both the Pololu and Hawi volcanics were erupted from three rift zones trending N. 35° W., S. 65° E., and S. 50° W. from the summit of the mountain. The rift zones are marked at the surface by rows of cinder cones, and beneath the surface by innumerable dikes. A caldera occupied the summit of the mountain at the beginning of the eruption of the Hawi lavas, and for a time confined the flows. It was gradually filled and the lava escaped northeastward into the large valleys. Some of the caldera faults can still be traced. A shallow graben indents the summit now.

South of Kohala Mountain lies the much larger volcano of Mauna Kea. The early rocks of Mauna Kea constitute the Hamakua volcanic series. The lower member of this series consists chiefly of olivine basalt flows with intercalated thin beds of vitric basaltic ash. The olivine basalt of the lower member changes gradationally into the upper member, in which basalt and olivine basalt are still abundant, but andesite also is present. Lavas of the upper member interfinger with Hawi lavas of Kohala Mountain. The Hamakua volcanic series is mantled with Pahala ash 5 to 20 feet thick, above which lie the rocks of the Laupahoehoe volcanic series. Locally the two series are separated by erosional unconformity. The Laupahoehoe lavas are dominantly andesite. The andesites erupted after the last glacial epoch, are mapped separately on plate 1. The Laupahoehoe volcanic series, and probably also the Hamakua volcanic series, were erupted principally from three rift zones, trending west, northeast and south-southeast from the summit of the mountain. The upper slopes are studded with many large cinder cones, lying principally along the rift zones.

Late in its geologic history, Mauna Kea was capped by a small glacier, presumably contemporaneous with the Wisconsin stage of glaciation in North America, which left conspicuous terminal, lateral, and ground moraines. Deposits exposed in canyons on the southern slope, formerly believed to be of glacial origin, are now believed to be volcanic explosion breccias.

The main bulk of Hualalai Volcano is built of basalts of the Hualalai volcanic series. One flow of andesite has been found. The cinder and spatter cones lie principally along three rift zones which trend northwest, north, and southeast from the summit. On the northern slope of Hualalai Volcano lies the large trachyte pumice cone of Puu Waawaa, and its thick flow of trachyte. These are grouped together as the Waawaa volcanics. They are partly buried by later basalts from both Hualalai and Mauna Loa. The last eruption of Hualalai Volcano, in 1800–1801, produced olivine basalt.

The earliest exposed rocks of Mauna Loa comprise the Ninole volcanic series. Several beds of altered vitric ash are intercalated with the lavas. Following eruption of the Ninole series, a long period of quiescence occurred, during which deep amphitheater-headed valleys were cut. This was followed by the eruption of the Kahuku volcanic series, consisting mostly of lavas with some thin beds of ash. The Kahuku series is overlain by the Pahala ash, which overlies also the Hilina volcanic series on Kilauea, the Hamakua volcanic series on Mauna Kea, and the Hawi volcanic series on Kohala, providing a rough datum for correlation of the lavas of the four mountains. Deposition of the Pahala ash was followed on Mauna Loa by eruption of the Kau volcanic series, which has continued until the present time. The historic and prehistoric flows of the Kau series are mapped separately on plate 1. The historic eruptions and volcanic activity of Mauna Loa are briefly described. The western and southern slopes of Mauna Loa are cut by normal faults along which the lower flanks of the mountain have slipped seaward.

The Kau volcanic series and presumably also the Kahuku and Ninole volcanic series were erupted principally from vents along two rift zones which extend northeast and southwest from the summit caldera. The lavas of all three series are preponderantly olivine basalt. Many of the lavas contain small amounts of hypersthene.

The Pahala ash on the northeastern and eastern slopes of Mauna Loa was derived largely from Mauna Kea. West and south of Kilauea Caldera, however, it was derived principally from Kilauea. Minor amounts were contributed by eruptions of Mauna Loa. It is a vitric basaltic ash, now generally altered to palagonite.

The earliest exposed lavas and thin intercalated ash beds of Kilauea Volcano comprise the Hilina volcanic series. These are capped by the Pahala ash, which in turn is overlain by the lavas and thin ash beds of the Puna volcanic series. The volcanics of both series were erupted along two rift zones, one extending southwestward from Kilauea Caldera, and the other extending southeastward for 5 miles and then bending sharply east by north. The lavas of both series are very largely olivine basalt. A few flows contain hypersthene. Augite phenocrysts are common in Mauna Loa lavas, but rare in those of Kilauea, indicating that crystallization has not progressed as far in the magma chamber of Kilauea Volcano as in that of Mauna Loa. Eruption of the Puna volcanic series has continued until the present time, the historic flows being separated from the prehistoric ones on plate 1. The historic eruptions and volcanic activity of Kilauea are briefly described.

Kilauea Volcano originated on the southern slope of Mauna Loa where faults intersected the Eastern Fundamental Fissure of the Hawaiian Archipelago.

The southern flank of Kilauea is cut by normal faults, along which the southern part is sliding seaward.

The volcanoes of the island of Hawaii are believed to have started their activity in the Tertiary period. The great erosional period which followed deposition of the Pololu and Ninole volcanic series is placed near the end of the Pliocene. The Hilina and Hamakua volcanic series were probably erupted in the late Pliocene and earlier Pleistocene. The Hawi volcanic series and the Waawaa volcanics are probably early or middle Pleistocene in age. The main period of deposition of the Pahala ash was probably late in the middle Pleistocene or early in the upper Pleistocene. The Laupahoehoe volcanic series is late Pleistocene and Recent in age, most of the flows antedating the Wisconsin glaciation. The Hualalai volcanic series probably extends from Tertiary to historic time, and the Kau and Puna volcanic series from late Pleistocene to the present. A chapter is devoted to the petrography of the rocks in which are listed all reliable chemical rock analyses.

The rocks of the island are highly permeable. Most of the rainfall sinks quickly into the ground. Perennial streams are present only on the windward slopes of Kohala Mountain and Mauna Kea. Most of the water sinks rapidly to the basal water table, where it floats on salt water according to the Ghyben-Herzberg principle. Basal water escapes in springs at or near sea level all along the coast. Only a very small proportion of it is recovered in wells. Along the windward coasts the basal water is of good quality and large supplies await development. Along the leeward coasts most of the basal water is brackish.

In Kohala Mountain, much water is perched on ash beds in the Pololu volcanic series and on ash and soil at the base of the Hawi volcanic series. It escapes in perched springs in the big valleys and along the windward sea cliff and is recovered in tunnels. Along the windward slope of Mauna Kea, small amounts of water are perched by ash beds and dense lava flows in the Hamakua volcanic series. Small perched springs issue from these structures and water is recovered by tunnels. In the Kau District ash beds perch considerable water, which is recovered by many tunnels. On the southern slope of Mauna Kea small springs are perched by beds of hill wash.

Dikes in the rift zones are relatively impermeable, but enclose masses of permeable rock. Water is confined at high level in the interdike compartments in Kohala Mountain, and probably in the other volcanoes. It escapes in high-level springs in the deep valleys in Kohala Mountain; some of it is recovered by tunnels.

It is estimated that an average of about 13,085 million gallons of water a day falls as rain over the whole island. Of this only about 2.5 percent is visibly discharged from wells, tunnels, and springs. Large supplies of basal groundwater await development. Projects for development of additional water for the city of Hilo and the Kona District are described.

Chemical analyses of water, water supplies of towns and villages, descriptions of wells, springs, and tunnels, and discharge records of numerous springs and tunnels are given in tabulated form.

INTRODUCTION

Location and area.—The island of Hawaii, county of Hawaii, lies at the southeastern end of the Hawaiian Archipelago between 154°48′ and 156°4′ W. long. and 18°54′ and 20°17′ N. lat. (fig. 1). It is 76 miles wide, 93 miles long, and has an area of 4,030 square miles.[1] It is nearly twice as large as the combined areas of the other Hawaiian islands. Hilo is the principal city. The highest point is the top of Mauna Kea, 13,784 feet above sea level. The island lies about 148 miles southeast of Honolulu and is reached by interisland boats and planes. It has been built by five volcanoes—Kohala,

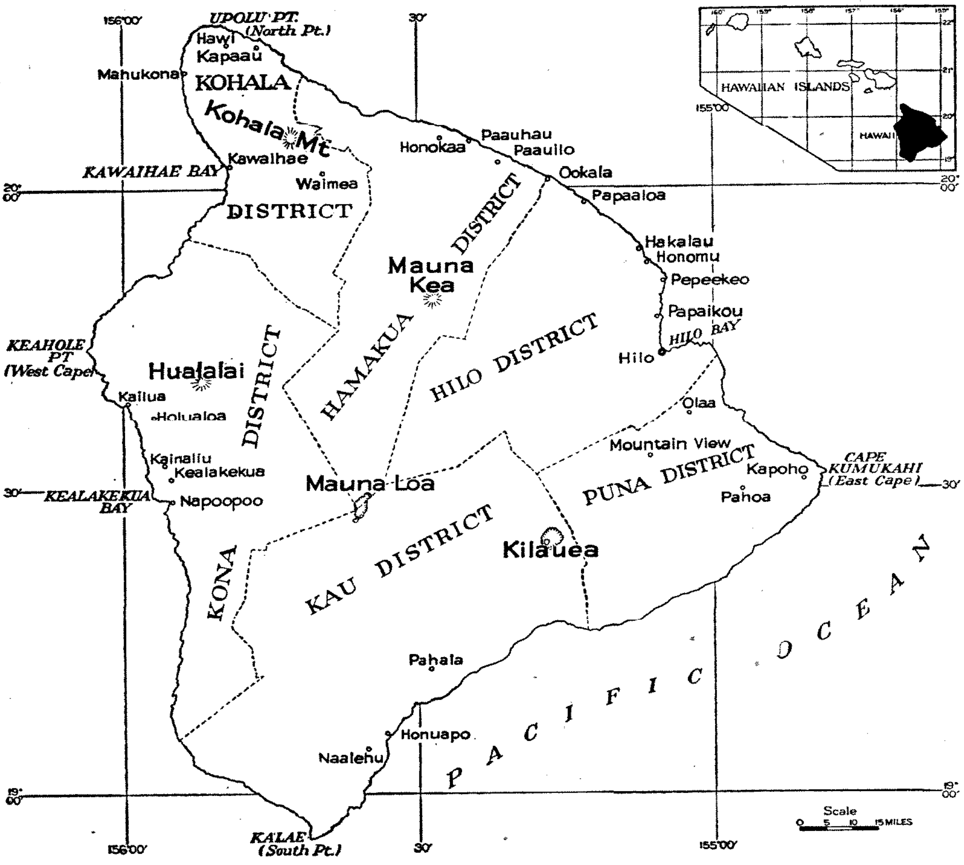


Figure 1. Map of Hawaii showing districts, main towns, harbors, mountains, and inset showing location of Hawaii in the Hawaiian chain.

---

[1] Wentworth, C. K., Physical geography and geology: Hawaii Terr. Plan. Bd., 1st Progress Rept., p. 13, 1939.

Mauna Kea, Hualalai, Mauna Loa, and Kilauea. Its form is shown in the relief map (fig. 2) and by the topography in plate 1. Parts of the active volcanoes of Kilauea and Mauna Loa are included in Hawaii National Park (fig. 3). Maps of the principal roads and points of geologic interest are given in plates 2 and 3.

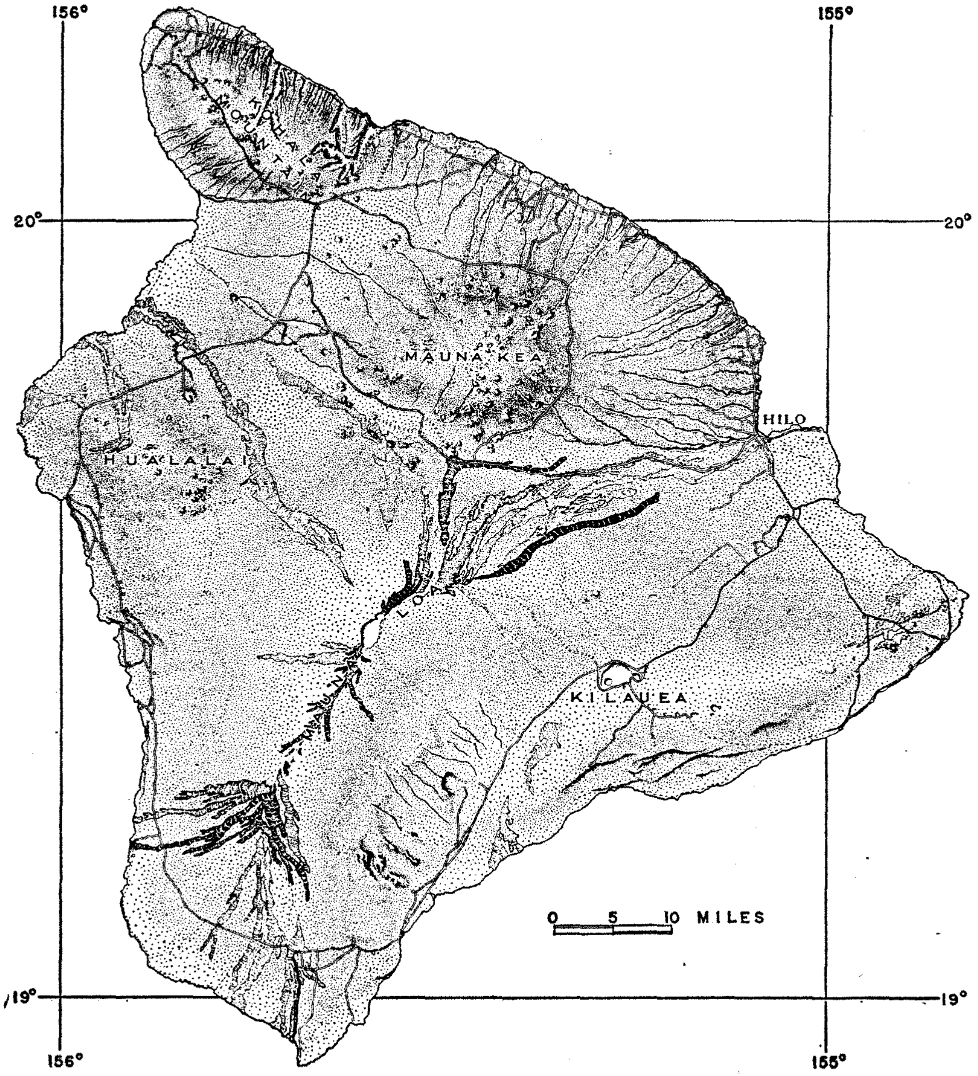


Figure 2. Relief map of Hawaii.

Historical sketch.—The Hawaiian Islands were occupied by people of the Polynesian race about 450 A. D. A second wave of immigration, probably from Tahiti, arrived about the year 1100.[2] The first recorded contact by Europeans with the Hawaiian Islands was in January 1778 when they were visited by Captain James Cook, but it was not until his return from Alaska in November that he

---

[2] Buck, P. H., Vikings of the Sunrise, pp. 249 and 252, New York, 1938.

visited the island of Hawaii. On January 17, 1779, he dropped anchor in Kealakekua Bay. Here he was worshipped by the Hawaiians as the incarnation of the native god Lono. Captain Cook was killed on February 14, 1779, in a fight resulting from the misconduct of some of his sailors. A monument erected by the New Zealand government now marks the place of his death. (pl. 1).

The great Hawaiian warrior and ruler King Kamehameha I was born in Kohala in 1736. He conquered the island of Maui in 1782 and Oahu in 1795. He died in 1819, the year idolatry was abolished.[3] In 1790, an army marching to Kau under the leadership of Chief Keoua, who was then at war with Kamehameha, was partly destroyed by an explosive eruption of Kilauea.

The Hawaiian monarchy was overthrown in 1893, and a republic was set up. It lasted until 1898 when the Hawaiian Islands were annexed by the United States.

The lower lands of Hawaii were thickly settled by the ancient Hawaiians who lived by fishing and agriculture. An excellent description of their life in 1823 is given by Ellis.[4] The ruins of numerous large stone temples (heiaus) and walls of former Hawaiian villages remain. Large temple platforms and enclosures built of local rock are preserved at Kawaihae on the northwestern coast, on the Judd trail in the saddle between Mauna Loa and Hualalai, at Honaunau, at Kealakekua Bay, and in eastern Puna. An extensive system of ancient rock walls on the northwestern slope of Kohala Mountain, now grass covered, are discernable from the air. They were built in parallel rows and probably marked agricultural plots.

The traditions relating to Hawaii contain many references to Pele, the goddess of volcanoes. Formerly, when passing Kilauea Volcano, the natives offered a twig bearing ohelo berries or other offerings to their fiery goddess.

POPULATION.—The island had a population of 73,276 in 1940,[5] distributed by districts as follows: Puna 7,733; South Hilo 32,588; North Hilo 4,468; Hamakua 8,244; North Kohala 5,362; South Kohala 1,352; North Kona 3,924; South Kona 4,024; and Kau 5,581. Hilo, the largest city and the county seat, had a population of 16,576. It is the chief port for importing supplies for the island and for exporting sugar. Interisland boats call at Mahukona, Kawaihae, and Kailua also, chiefly for cattle and coffee. Ocean-going freighters load sugar at several other places.

The low average of 18 persons per square mile is due largely to lack of water and character of the terrain.

---

[3] The historical data are from Alexander, W. D., A brief history of the Hawaiian people, 361 pp., New York, 1899.

[4] Ellis, William, A journal of a tour around Hawaii, the largest of the Sandwich Islands, 264 pp., Boston, 1825.

[5] U. S. census report, Sept. 3, 1940.

INDUSTRIES.—Figure 3 shows the utilization of the land. The chief industry is the production of sugar from cane. Next in importance is cattle raising.

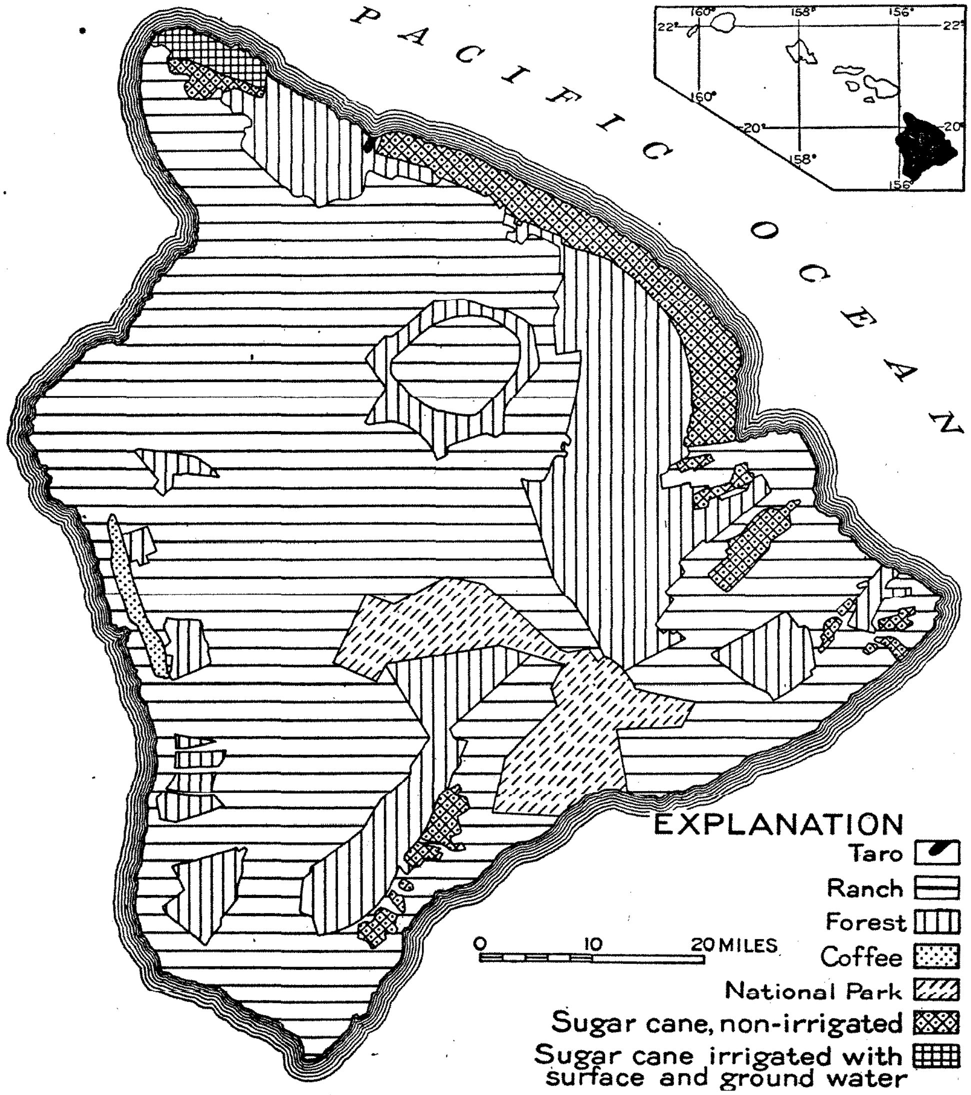


Figure 3. Map of Hawaii showing land utilization in 1937 (after pl. 36, Hawaii Terr. Plan. Bd., 1st Progress Rept., 1939).

Cane is transported to mills by railroads, trucks, and flumes. In recent years, specially designed trucks for hauling cane are displacing flumes and railroads, but large areas remain in which flumes are still used because of the steepness of the slopes. On Hawaii, sugar cane matures in 1½ to 3 years, depending upon altitude. The Hawaiian Agricultural Company grows cane at an altitude of 2,900 feet, the highest it is grown in the islands. Three years is required to mature a cane crop at that level. The accompanying table shows the production of sugar by the various companies in 1943 and its value.

Sugar production for 1943
(Data obtained from annual reports of the companies)

Name	Acreage	Tons of sugar (96°)	Value of sugar and molasses at market
Kohala Sugar Co.	19,515	41,455	$3,158,660
Honokaa Sugar Co.	8,296	15,416	1,227,256
Paauhau Sugar Plantation Co.	4,104	13,775	1,187,325
Hamakua Mill Co., Ltd.	5,256	23,117	1,773,343
Kaiwiki Sugar Co., Ltd.	4,116	15,603	1,164,796
Laupahoehoe Sugar Co.	6,092	18,880	1,463,567
Hakalau Plantation Co.	6,202	20,625	1,646,421
Wailea Milling Co., Ltd.[a]	1,523	4,626	400,088
Honomu Sugar Co.	3,017	10,299	801,521
Pepeekeo Sugar Co.	3,801	13,531	1,022,945
Onomea Sugar Co.	7,838	22,544	1,650,177
Hilo Sugar Co.	3,957	22,417	1,866,013
Waiakea Mill Co.	5,537	14,246	1,097,488
Olaa Sugar Co., Ltd.	14,757	44,219	3,258,318
Hawaiian Agricultural Co., Ltd.	8,326	27,540	2,085,592
Hutchinson Sugar Plantation Co.	4,443	13,793	990,349
Total	106,780	311,365	$24,793,859

[a] Amalgamated with Hakalau Plantation Co., 1944.

The Parker Ranch, one of the largest in the world producing pure-blooded Herefords, has headquarters at Waimea (Kamuela P. O.). The accompanying table gives the significant data regarding the cattle industry:

Principal ranches on Hawaii[a]
(Listed clockwise around the island starting at the north end)

Ranch	Acres[b]	Cattle[c]	Ranch	Acres[b]	Cattle[c]
Kahua	31,886	5,377	Olelomoana	8,000	500
Puu Hue	2,933	3,137	McWayne	15,000	700
Parker	270,320	25,160	Magoon	1,000	200
Honokaa Sugar Co.	2,500	600	McCandless	43,383	1,455
Hanaipoe	6,990	1,000	Arthur Greenwell	2,500	90
Kukaiau	34,304	5,000	Jack Greenwell	19,644	2,944
Puu Oo	20,362	3,519	Gomes	1,000	200
Keaau	77,304	305	Frank Greenwell	14,888	1,513
Ainahou	15,000	821	Huehue	16,326	1,995
Kapapala	45,814	3,000	Puuwaawaa	23,834	3,950
Kiolakaa	3,000	300			
Kaalualu	37,189	4,000	Total	709,046	66,640
Kahuku	15,869	874			

[a] Data from Territory of Hawaii tax office.
[b] Includes leased land, but does not include land unfit for grazing.
[c] At end of 1943.

Eight cows and three bulls, landed on Hawaii by Captain George Vancouver in 1793 and 1794, were the start of the cattle industry.

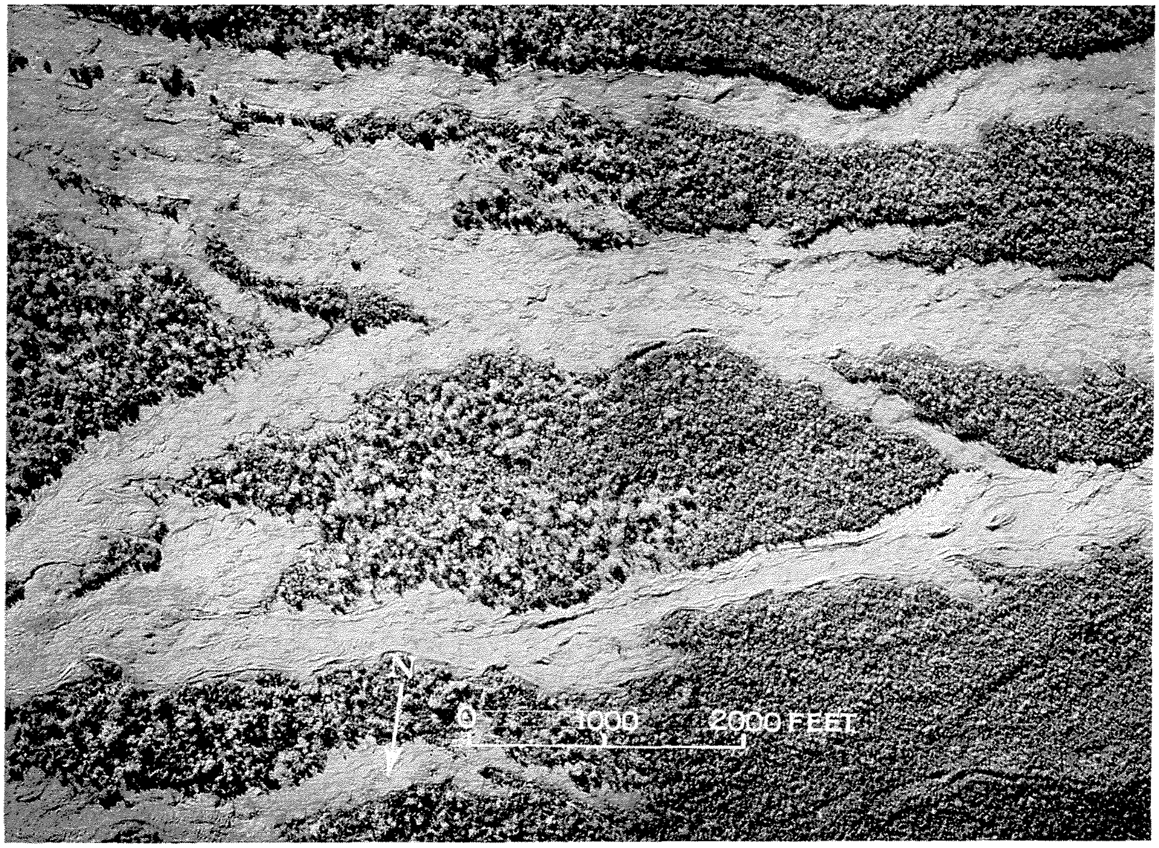
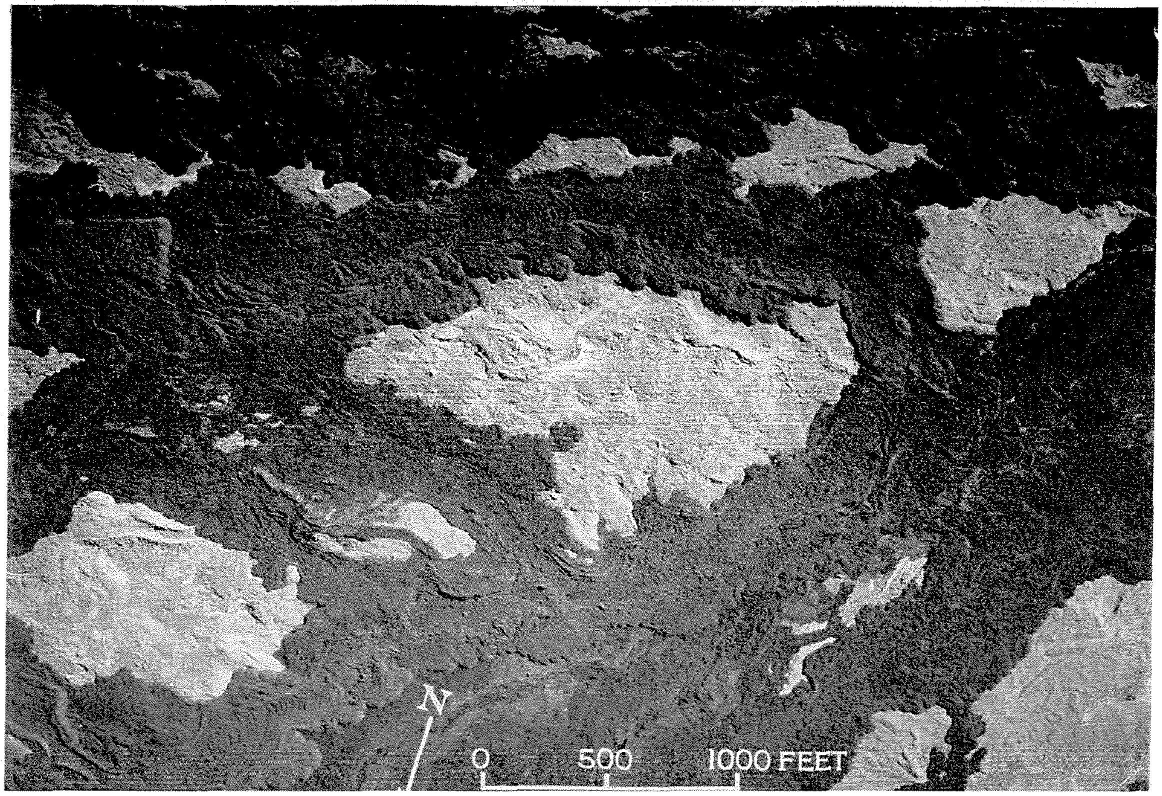


Plate 5. Contrast in appearance of lava flows due to differences in rainfall. Above, A—Vertical air view of aa lava flows of 1916 and 1926, at an altitude of 4,000 feet on the southwest slope of Mauna Loa Volcano, showing appearance in a forest where the rainfall is about 50 inches annually. The gray color is caused by a complete cover of lichens. Photo by USAAF. Below, B—Vertical air view of bare black aa lava flows of 1916 and 1926 at an altitude of 6,500 feet 6 miles northeast of those shown in plate 5A and above the forest. Rainfall is about 30 inches annually. Photo by USAAF.



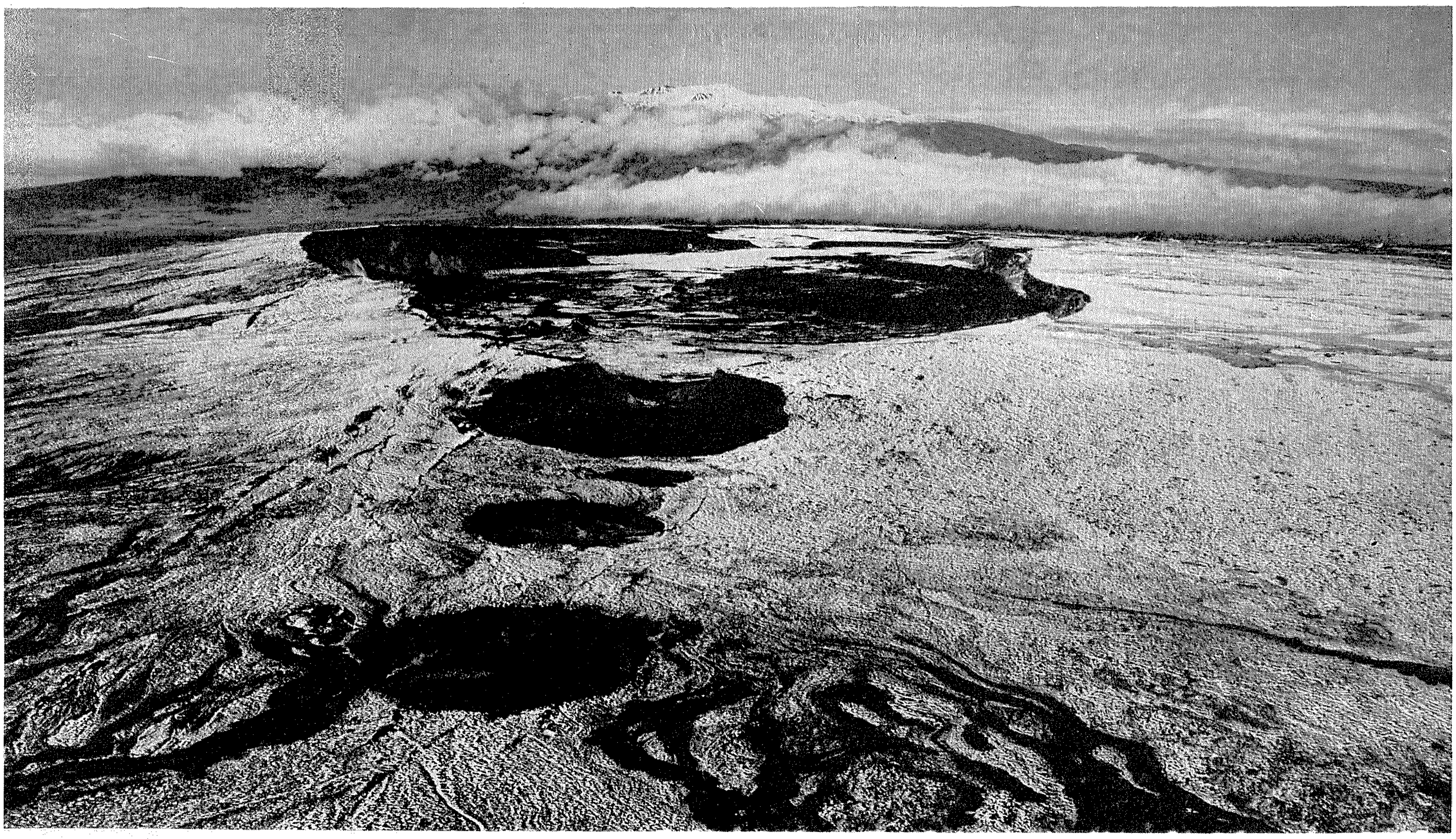


Plate 6. Summit of Mauna Loa Volcano showing Mokuaweoweo Caldera and the pit craters on the southwest rift after a flurry of snow. Mauna Kea in the background. Photo by USAAF.

These animals were placed under a tabu for about 25 years. During that time they became exceedingly numerous. A few wild cattle still roam unfrequented areas.

Vancouver introduced sheep at Kealakekua Bay in February 1793 and landed more in 1794. Goats were introduced by Captain Cook. These animals increased rapidly and ruined much cattle range. They have been eliminated from most of the grazing land, but feral goats and sheep are still common on Hualalai and Mauna Kea. Feral goats are very numerous in the Kau Desert also, in spite of drives to eliminate them. Pigs introduced by the ancient Hawaiians are found wild in large numbers in the forests and brushlands.

From 1919 to 1937 a total of 221,746 destructive wild animals were killed in and near forest reserves, but approximately 30,000 feral sheep are reported in the Mauna Kea forest reserve.[6]

Sheep are raised for the market at Humuula. Hogs are raised chiefly on the smaller ranches. Horses and mules are raised for use on ranches and plantations as riding, draft, and pack animals. Racing and polo horses are raised on the Parker Ranch.

Hawaii ranks next to Oahu in the dairy industry. The agricultural census reports that 55,326 chickens and 519,284 dozen eggs were marketed in 1939. Honey production was 144,460 pounds from 1,621 bee colonies.

Pineapples were raised on Kohala Mountain from 1924 to 1932 but were found to be unprofitable.

Coffee production is the third largest industry on the island. Coffee is grown principally in the Kona District.[7] In 1942–43, 7,193,225 pounds of coffee valued at $737,305.56 were raised. Production has been declining since 1934. About 95 percent of the crop is shipped to the mainland for blending purposes.

Rice production, formerly carried on in the northern valleys, has ceased, chiefly as the result of the accidental introduction of a stem borer from the Orient in 1927. Taro is still being raised in small quantities but its production has declined rapidly since 1900. Bananas and vegetables are raised for the market. Truck crops, especially lettuce, cabbage, and celery from Waimea, and tomatoes from the Kona District, have found a good market in Honolulu because of their high quality. Melons, papaya, and avocados also are grown profitably in some areas. Macadamia nut trees cover about 500 acres.

The forests of Kona are rich in hardwoods. Koa and ohia are shipped to Honolulu. Wallboard made of sugar-cane fiber is manufactured at Hilo.

---

[6] Judd, C. S., Forestry in Hawaii: Hawaii Terr. Plan. Bd., 1st Progress Rept., p. 109, 1939.

[7] A district in Hawaii is a legal subdivision comparable to a township in the eastern part of the mainland.

The tourist trade varies with world conditions and with volcanic activity. Hawaii is known in local parlance as the "Big Island." Prior to 1924, when the lava lake of Kilauea existed most of the time, the Volcano House in Hawaii National Park was a popular resort for both local and distant travelers. Since 1924, volcanic activity has been spasmodic and short-lived. A trip around the island affords the tourist much of interest, however, and air transport has stimulated travel in spite of Kilauea's quiescence.

Fishing is a profitable industry. Tuna is the chief catch. The demand for fresh fish among the large Oriental population keeps prices high. Few mullet ponds exist due to the unsatisfactory configuration of the shore and the lack of fringing coral reef. Kona is famous for swordfishing.

Extent of vegetative cover.—The areas of grazing land shown in figure 3 are covered mostly with grass and shrubs, except for lava flows erupted in the last few hundred years and parts of Mauna Loa above 9,000 feet and Mauna Kea above 11,000 feet, which are bare. However, many of the late lava flows are covered with vegetation where they enter the rain forests. For example, some of the late lava flows from the summit of Mauna Loa are bare down the southwestern slope to an altitude of about 8,000 feet. At this elevation a sparse cover of ohelo bushes, clumps of grass, and other shrubs begins and increases in density until at 6,300 feet a forest completely covers the flows. At an altitude of about 2,000 feet, where they emerge from the rain forest, they have a cover of lantana, guava, and other brush, but a short distance from the coast, where the rainfall is low, they are again bare. This has led some to believe that the flows originated at the lower edge of the forest. The contrast in the appearance of lava flows due to differences in rainfall is shown in plate 5.

The Kau Desert on the southwestern slope of Kilauea is largely drifting sand and bare lava due to aridity and youthful lava flows. The northwestern slope of Mauna Kea is chiefly grassland below an altitude of 6,000 feet.

The forest reserve on the top of Hualalai contains few trees, and rocks are well exposed. A dense forest lies just west of the reserve and is shown in figure 3 as grazing land. Other dense forests lie outside the reserves in privately owned grazing land, such as those east of the Kilauea section of the National Park.

Geologic mapping is exceedingly difficult in the dense forests west and south of Hilo on the slopes of Mauna Loa and Kilauea, on the summit and northeastern slope of Kohala Mountain, and above the cane land on the eastern slope of Mauna Kea. It is also difficult in the dense guava and lantana thickets on the western slope of Mauna Loa and Hualalai. Elsewhere rocks are well exposed.

History and purpose of the investigation.—This report completes another unit in the systematic study of the geology and ground-water resources of the Hawaiian Islands by the Geological Survey, United States Department of the Interior, in cooperation with the Division of Hydrography, Territory of Hawaii. The field work was carried on intermittently by the authors between 1939 and 1944. The Kau District was studied in 1924 but as the report[8] covering that district is out of print, the pertinent parts are summarized herein.

Numerous requests have been received from officials of the county of Hawaii for assistance in locating ground-water supplies. A report by G. A. Macdonald describing places where wells could be sunk to supply Hilo with water was released to the public in February 1942.

The Territorial legislature passed a special bill in 1939 for the investigation of ground-water supplies in the Kona District, and test drilling by the Geological Survey in cooperation with the Territory was started in 1940 but was stopped when drillers became unavailable due to the national emergency. Drilling was resumed in July 1942, in cooperation with the U. S. Engineer Department and again in March 1944 in cooperation with the U. S. Navy. Special surveys have been made in the Kohala, Mauna Kea, and Kau areas to locate ground water for the armed forces.

The areas studied by the two authors respectively are shown in the key map on plate 1. Macdonald did the petrographic work.

ACKNOWLEDGMENTS

The U. S. Army Air Corps cooperated by making aerial photographs of five large areas. These were used as the base for geologic mapping. The boundaries of the lava flows of 1926, 1935, and 1942, and the geology of the rift zones of Mauna Loa were partly determined from the photographs. They also served as a base for mapping the summit of Kohala Mountain.

Field work in the Kohala District was expedited by the following men who furnished animals, guides, and other assistance: Messrs. J. Scott B. Pratt, manager of the Kohala Sugar Co.; Fred Koelling, manager of the Kohala Ditch Co., Ltd.; Ronald von Holt, manager of Kahua Ranch, Ltd.; W. P. Naquin, then manager of Honokaa Sugar Co.; and John Kawamoto, manager of the Kohala division of Parker Ranch. Messrs. Kenneth Bond, representative from North Kohala; William Sproat, division superintendent, Kohala Ditch Co., Ltd.; Masaru Matsunami, superintendent, Hawaiian Irrigation

---

[8] Stearns, H. T., and Clark, W. O., Geology and water resources of the Kau District Hawaii: U. S. Geol. Survey Water-Supply Paper 616, 194 pp., 1930.

Co., Ltd.; and Fred Koelling helped in the field with the tunnel and ground-water survey.

The field work in the Kona district was expedited by Messrs. Leighton Hind, manager of the Puuwaawaa Cattle Ranch, and the late Thomas White who furnished guides, horses, and other assistance. Mr. W. D. Ackerman gave permission for test borings on his land and he, Manuel Gomes, Kona Inn, and American Factors, Ltd., furnished water for drilling. The county of Hawaii furnished a tank truck to haul the water. Mr. Francis Peterson, former supervisor of West Hawaii Schools, furnished quarters. Mr. Jack Greenwell, then county supervisor, and numerous other Kona residents cooperated in various ways. Mr. H. W. Beardin assisted with the drilling.

Permission to use Territorial Forest Service cabins was kindly granted by Messrs. L. W. Bryan and Colin G. Lennox, and rangers Duke Kawai, William Kahele, and John Gouveia cooperated in making the cabins available. Arthur Mitchell of Hawaii National Park assisted in the field in the summit area of Mauna Kea.

Grateful acknowledgment is made of the aid of many persons associated with the plantations and ranches in furnishing data on existing water supplies. Among them may be mentioned W. L. S. Williams, manager, and Gilbert Hay, assistant manager, Olaa Sugar Co., Ltd.; H. H. Padgett, manager of Waiakea Mill Co.; A. T. Spalding, manager of Hilo Sugar Co.; R. Bryan, manager of Onomea Sugar Co.; J. W. Kennedy of Pepeekeo Sugar Co.; D. G. Butchart, assistant manager of Honomu Sugar Co.; E. S. Anderson, A. Yamamoto, and S. H. Lujan, of the Hakalau Plantation Co.; A. S. Costa, manager of Wailea Milling Co., Ltd.; R. A. Hutchison, then manager, Adolf Korte, and D. Pillans, of Laupahoehoe Sugar Co.; A. Walker, then manager, A. N. Walsh, and J. Ignacio, of Kaiwiki Sugar Co., Ltd.; F. Munro, F. Sohlmann, and M. Souza, of Hamakua Mill Co., Ltd.; L. S. McLane, manager, and T. Doi, of Paauhau Sugar Plantation Co.; R. L. Hino of Hawaiian Irrigation Co., Ltd.; A. W. Burt, then manager, and J. Correa, foreman, Kukaiau Ranch Co., Ltd.; A. W. Carter, then trustee, and A. H. Carter, manager, Parker Ranch; J. S. Beatty, manager, and T. Okike, surveyor, Hutchinson Sugar Plantation Co.; William Cushnie, then manager, John Cushnie, assistant manager, and T. Obayashi, surveyor, Hawaiian Agricultural Co., Ltd.; J. S. Rickard, E. L. Wung, Sam Kanau, Jacintho Ventura, W. Oliver, and M. Duarte supplied information regarding county water supplies. S. R. Shiffert supplied measurements of discharge at Waihu Springs. E. G. Wingate, superintendent, and Paul Baldwin, assistant to the superintendent, Hawaii National Park, various members of the ranger staff, and R. H. Finch, volcanologist in charge of the Volcano Observatory, have

Plate 7. View of summit of Mauna Kea (foreground) and Mauna Loa volcanoes, capped with snow. The sub-parallel ridges in the center foreground are lateral moraines of the Makanaka glacier. Photo by USAAF.

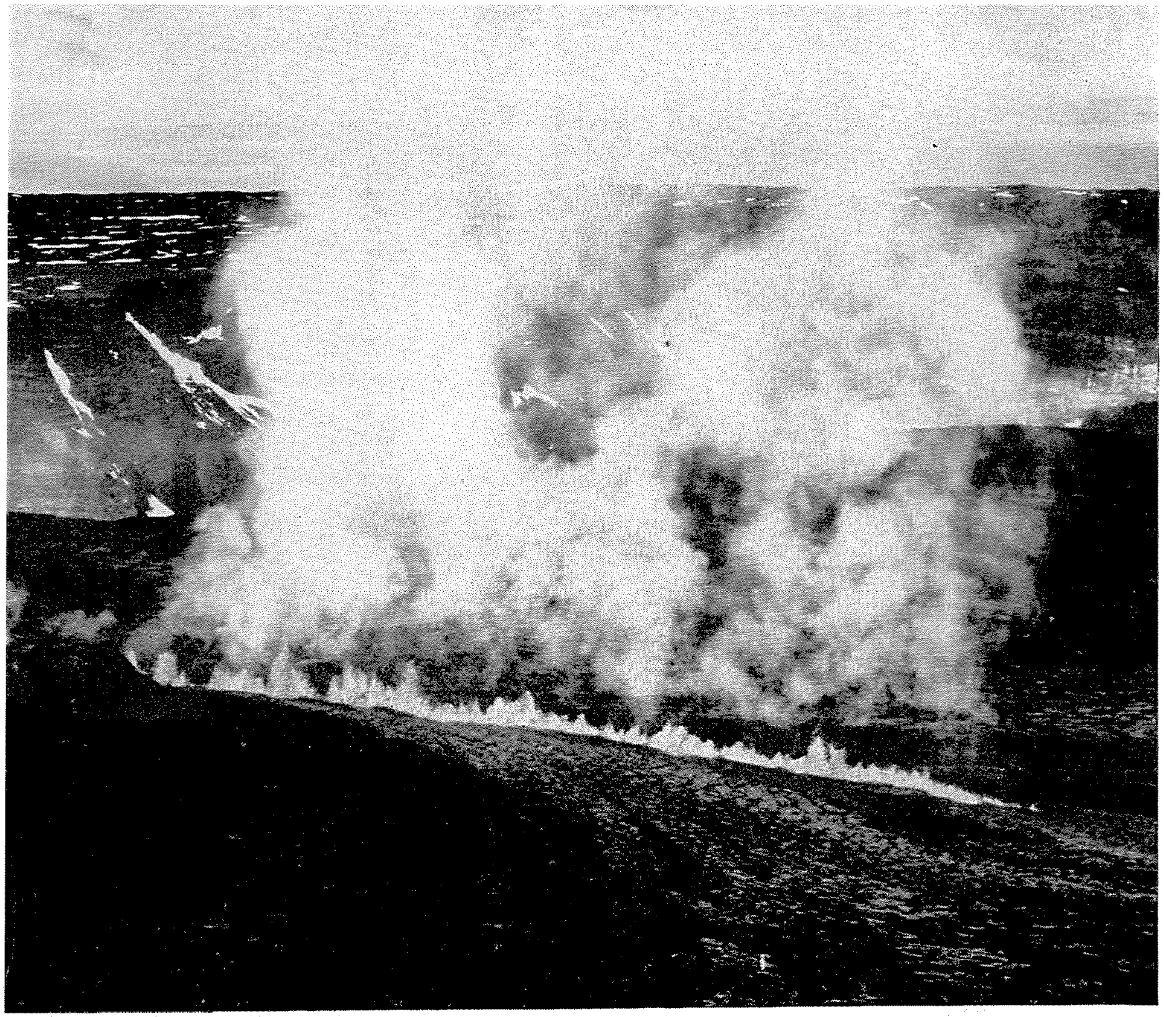


Plate 8A. "Curtain of fire" formed by coalescing lava fountains along a fissure on the floor of Mokuaweoweo Caldera, April 8, 1940. Photo by USAAF.

Plate 8B. "Curtain of fire" on the night of April 8, 1940. Photo by USAAF.

extended many courtesies during the course of the investigation.

Mr. George Duncan, chief engineer of the Olaa Sugar Co., Ltd., has furnished regular measurements of the water level in the Olaa shaft since 1936. Messrs. L. W. Wishard and A. Walker, successive managers of the Kaiwiki Sugar Co., Ltd., have furnished regular measurements of the water level in the Ookala shaft since 1938.

The authors are indebted to Mr. W. O. Clark, geologist for the Hawaiian Sugar Planters' Association, for information regarding tunnels in the Kau District, the dug well near Kawaa Springs, and late developments at the Ookala and Paauilo wells.

Jean Braund edited the report. Mrs. Ethel U. McAfee prepared the index. The illustrations were prepared by J. Y. Nitta and R. B. Norris.

VOCABULARY OF VOLCANIC TERMS

A description of the geology of Hawaii requires the use of many volcanic terms having either vague or inconsistent definitions in most textbooks of geology. Several good classifications have been published, but the terms have not reached common usage, largely because these classifications either restrict the meaning of terms long in general use, or apply them to all types of volcanic action. The following definitions of terms used in this report should be considered as applicable to the Hawaiian type of volcanic products and processes, but not necessarily applicable to all types of volcanoes.[9] *Volcanics* is used herein as a general term covering all the products laid down by a volcano.

COMPOSITION OF THE VOLCANIC ROCKS

The molten rock together with its included gases, as it exists underground, is called *magma.* The volcanic rocks of Hawaii comprise basalts, gabbros, picrite-basalts, andesites, and trachytes, defined as follows:

Basalts are rocks with a fine-grained groundmass containing plagioclase with an average composition at least as calcic as labradorite. *Primitive basalts* are those extruded in the early phase of

---

[9] For more details see: Brigham, W. T., The volcanoes of Kilauea and Mauna Loa on the island of Hawaii: B. P. Bishop Mus. Mem., vol. 2, no. 4, 230 pp., 1909. Dana, J. D., Characteristics of volcanoes, 399 pp., New York, 1890. Hitchcock, C. H., Hawaii and its volcanoes, 314 pp., Honolulu, 1909; 2d ed. with supp., 322 pp., Honolulu, 1911. Jaggar, T. A., Volcanologic investigations at Kilauea: Am. Jour. Sci., 4th ser., vol. 44, no. 261, pp. 161–220, 1917, and other papers by this author. Stearns, H. T., and Clark, W. O., Geology and water resources of the Kau District, Hawaii: U. S. Geol. Survey Water-Supply Paper 616, 194 pp., 1930. Stearns, H. T., and Vaksvik, K. N., Geology and ground-water resources of the island of Oahu, Hawaii: Hawaii Div. Hydrography, Bull. 1, 479 pp., 1935. Wentworth, C. K., Ash formations of the Island Hawaii: Hawaiian Volc. Obs., 3d Spec. Rept., 183 pp., 1938. Wentworth, C. K., and Williams, Howel, The classification and terminology of the pyroclastic rocks: Nat. Research Council, Bull. 89, pp. 19–53, 1932; references listed therein. Williams, Howel, Notes on the characters and classification of pyroclastic rocks: Liverpool Geol. Soc. Proc., vol. 14, pp. 223–248, 1926. Publications of the Hawaiian Volcano Observatory.

a volcano before differentiation occurs in the magma reservoir. They are characterized by olivine crystals, commonly large enough to see with the naked eye. *Differentiated lavas* are those which depart in mineral or chemical composition from primitive lavas, as a result of magmatic differentiation. *Gabbros* are coarse-grained intrusive rocks of basaltic composition. *Picrite-basalts* are basalts rich in ferromagnesian minerals with less than 35 percent feldspar. *Andesites* are rock with a fine-grained groundmass containing plagioclase with an average composition within the range of andesine or oligoclase. *Trachytes* are rocks in which the prevalent feldspar is alkalic; that is, either orthoclase, sanidine, or albite.

DOMES

The mountains of Hawaii fall into two types—broad *shield-shaped domes* consisting chiefly of thin-bedded lava flows dipping away from their respective summit vents and rift zones; and steep domes studded with cinder cones. Mauna Loa, Kilauea, and Kohala are the flat type of dome; Mauna Kea and Hualalai are the steep type (pl. 7 and fig. 4).

The latter are underlain by typical flat shield-shaped domes of primitive lavas and owe their steepness to a cap of differentiated lavas or associated pyroclastics, or both (pl. 48A). Kohala Mountain is capped by cones and flows of differentiated lava, but the cap is too thin to alter the form of the mountain appreciably (pl. 51A). *Rift zones* are the loci of repeated fissure eruptions (pl. 31). They radiate from the summit of a volcano (fig. 6).

CALDERAS AND CRATERS

A *caldera*[10] is a large, more or less circular or amphitheatral basin formed by either engulfment or collapse, usually on the summit of a volcano (pl. 6). A *caldera complex* is the diverse rock assemblage underlying a caldera, and comprises dikes, sills, stocks, vent breccias, crater fills of lava, crack fills of lava or talus, beds of tuff, cinder, and agglomerate, fault gouge, fault breccias, talus fans along fault escarpments, and other products laid down in a caldera. (See sections in figs. 7, 8, and 9.)

A *crater* is a volcanic depression of much smaller dimensions than a caldera. Those on Hawaii range from a few feet to three quarters of a mile across. They fall into three types—negative forms produced by collapse; positive forms that were orifices of either lava fountains or explosions and did not collapse; and orifices of lava fountains later enlarged by collapse.

---

[10] The word has been used loosely in geology. For various classifications of calderas see Williams, Howel, Calderas and their origin: California Univ., Dept. Geol. Sci., Bull., vol. 25, no. 6, pp. 239–246, 1941.

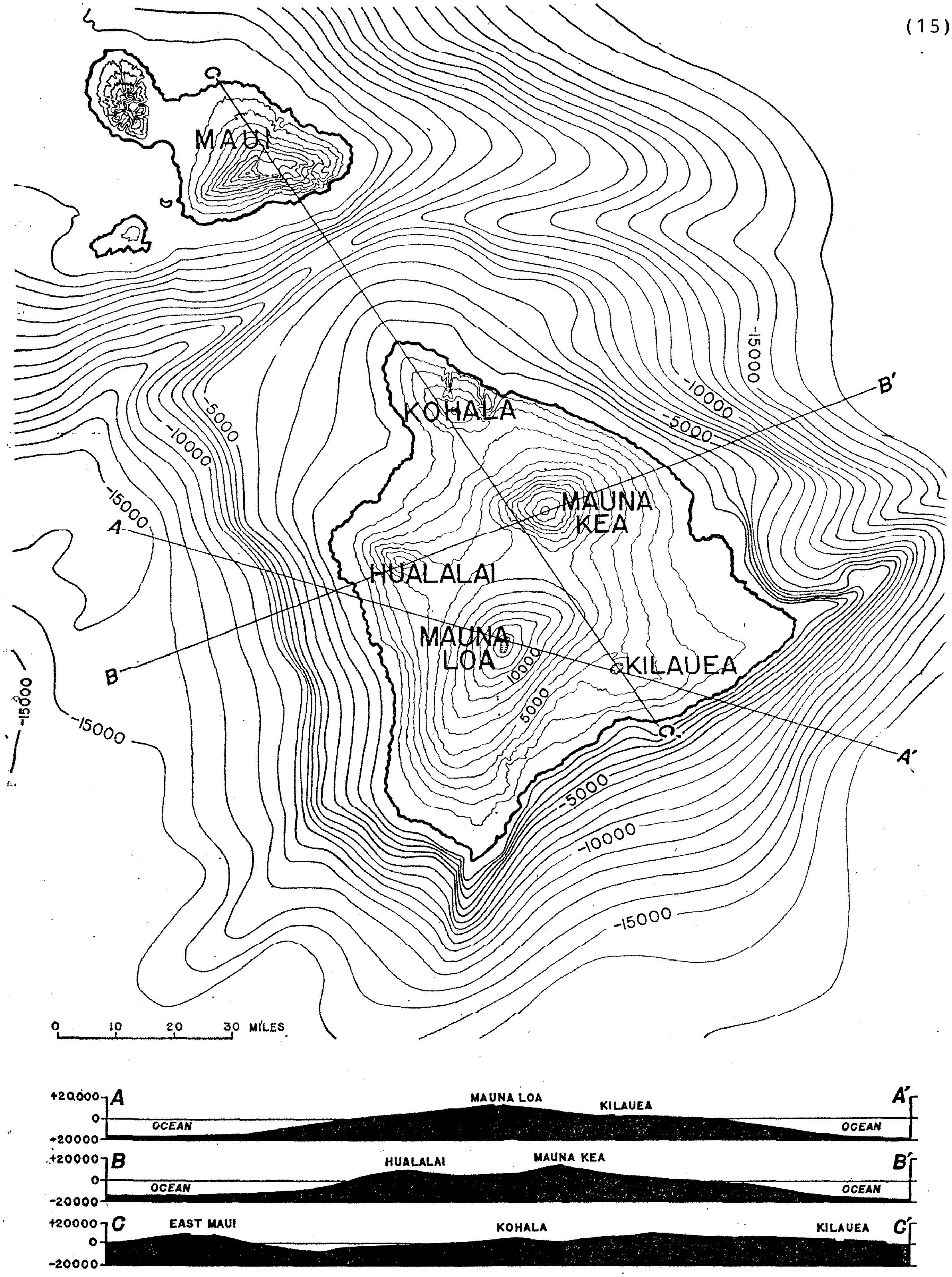


Figure 4. Map of Hawaii showing subaerial and submarine contours and profiles of volcanic domes along the lines AA', BB', and CC'.

Those which were orifices of cinder, lava, and spatter cones will be called *craters*. Those produced by collapse only will be called *pit craters* (pl. 6). Little or no lava flowed from them. Those formed by violent explosions will be called *explosion craters*. Such craters are greatly enlarged by collapse.

Many craters have been enlarged by loose cinders sliding from the rim into the vents after lava fountaining ceased. Some have been enlarged by collapse when the magma column subsided or drained away through tubes in the slopes of the cone. Most craters of spatter cones retain their original form because the walls are sufficiently agglutinated to withstand failure when lava fountaining ceases.

EXPLOSIONS

Explosions deposit *essential* or *magmatic ejecta*—fragments expelled in a fluid state and derived from the magma causing the explosion; *accessory ejecta*—fragments torn from older related volcanic rocks in the walls of the conduit; and *accidental ejecta*—fragments of sedimentary or other rocks of the subvolcanic basement, genetically unrelated to the exploding magma.[11] The whole gamut of fragmental rocks blown out by explosions and deposited from the air is called *pyroclastic rocks*. The large masses are *blocks* or *bombs* (pl. 47A), the small pea- to walnut-sized fragments are *lapilli,* and the fine material is *ash* (pl. 38A).

Several types of explosions have occurred on Hawaii. *Magmatic explosions* are characterized by the presence of plastic incandescent essential ejecta and violently expanding magmatic gases. This type is subdivided into *catastrophic* or *paroxysmal magmatic explosions* —those of sufficient intensity to shatter the wall rock and hurl out accessory and essential ejecta, and if available, accidental ejecta (the explosion of Kilauea in 1790); and *lava fountains*[12]—those of much milder intensity that seldom hurl ejecta more than 1,000 feet into the air and rarely expel accessory ejecta. Lava fountains are the commonest type on Hawaii (frontispiece and pl. 9B). The so-called *curtain of fire,* typical of Mauna Loa eruptions, consists of coalesced lava fountains along a fissure (pl. 8).

Hydro-explosions[13] is a general term for explosions caused by the generation of steam from any body of water. Several varieties have occured on Hawaii. *Phreatic explosions* are primarily the result of conversion of ground water to steam (phreatic refers to ground water). Such steam explosions have a low temperature and do not expel essential ejecta. The explosion of Kilauea in 1924 was

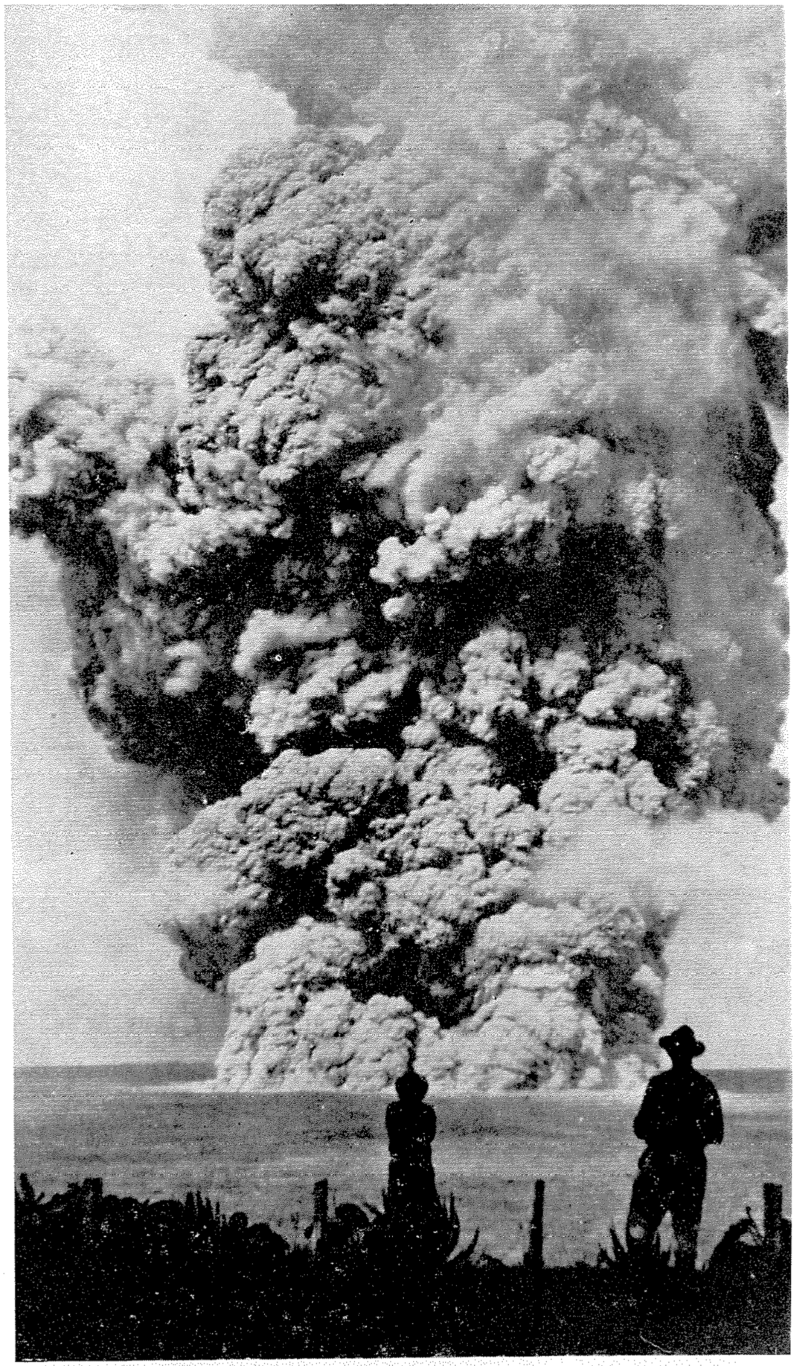
---

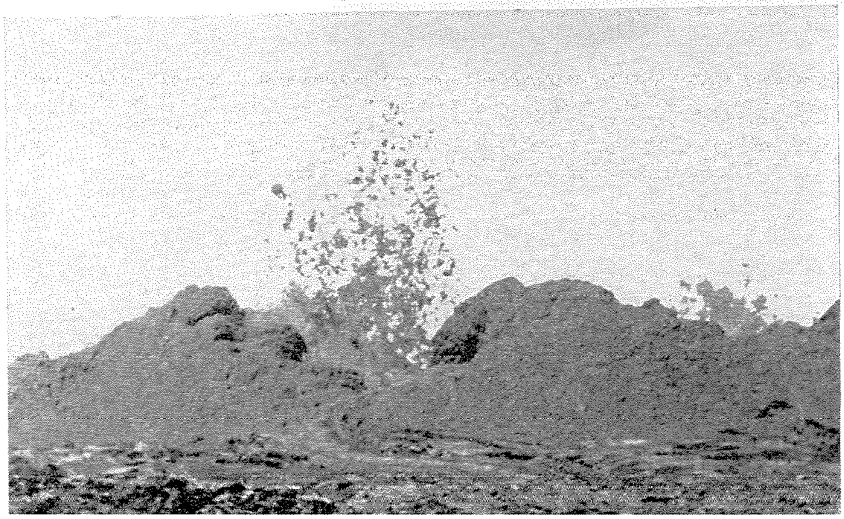
[11] Johnston-Lavis, H. J., On the fragmentary ejectamenta of volcanoes: Geologists' Assoc. London Proc., vol. 9, pp. 421–432, 1885–86.

[12] Also called firefountains and pyro-explosions.

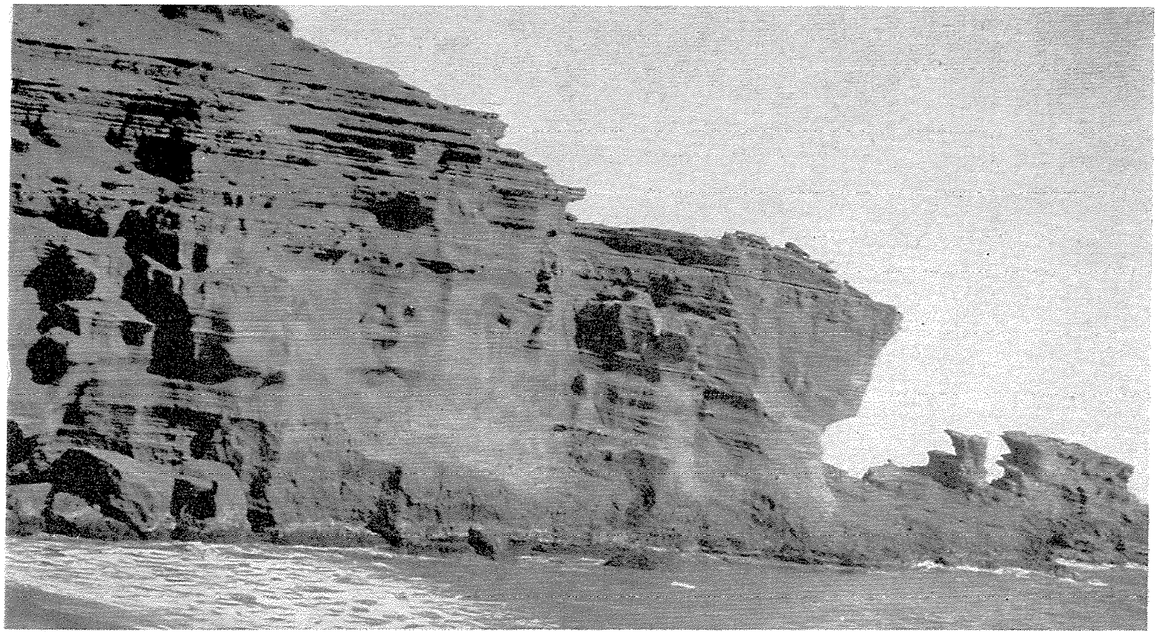
[13] Wentworth, C. K., Ash formations of the Island Hawaii: Hawaiian Volc. Obs., 3d Spec. Rept., p. 22, 1938.

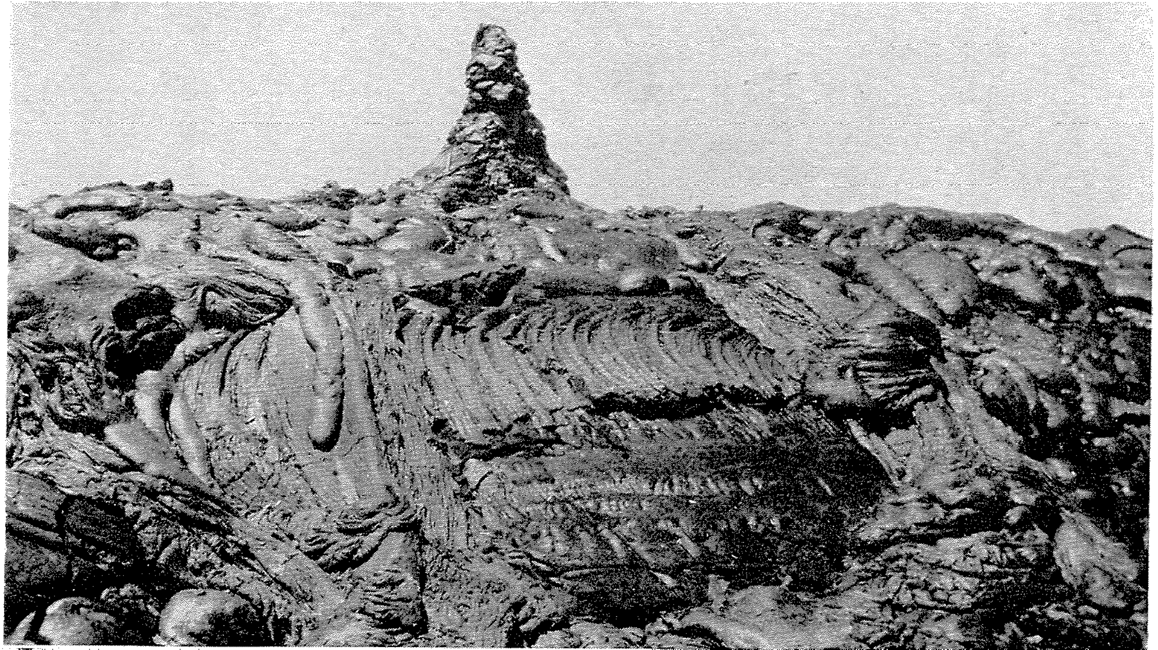
Right: Plate 9A. Phreatic explosion. Halemaumau, Kilauea Volcano, May 22, 1924. The cloud is 11,500 feet high and was rising at the rate of 13 feet per second. Photo by H. T. Stearns.





Left: Plate 9B. D
tailed view of lav
fountains of Maun
Loa Volcano, Novem
ber 24, 1935. Photo b
C. W. Carlsmith.





Opposite page, top: Plate 10A. Bedding in Puu Mahana littoral cone, 3 miles northeast of South Point, Hawaii. Photo by A. E. Jones.

Middle: Plate 10B. Driblet spire about 3 feet high on top of pahoehoe tumulus one mile north of Kamakaia Hills, southwest rift zone of Kilauea Volcano. Photo by H. T. Stearns.

Bottom: Plate 10C. Scaly pahoehoe at the 8,500-foot vent of the lava flow of 1935 on the northern flank of Mauna Loa Volcano. Photo by H. T. Stearns.

phreatic (pl. 9A). *Phreatomagmatic*[14] *explosions* occur when ascending magma contacts ground water. Essential as well as accessory ejecta are violently expelled. These differ from magmatic explosions where the bulk of the gases is derived from the magma. *Submarine explosions* occur when magma rises into the sea, and *littoral explosions*[15] occur where lava flows from the land contact sea water at the coast. Miniature explosions occur when lava covers saturated ground or wet logs, or runs into pools in stream beds. These have no specific names.

SECONDARY CONES

Six types of cognate secondary cones are superimposed on the main domes; in order of decreasing number they are cinder cones, spatter cones, bulbous domes, lava cones, pumice, and ash or tuff cones. The profile of each type is given in figure 5. Adventive or accidental ash or tuff cones formed by the explosion of lava when it runs into the sea are *littoral cones*.[16]

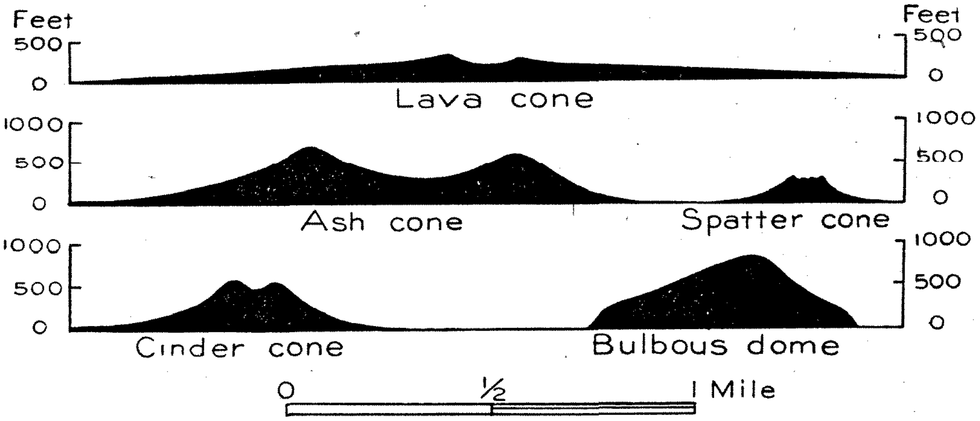


Figure 5. Profiles of cognate secondary cones.

Cinder cones.—The cinder cones range from 50 to 700 feet in height and reach three quarters of a mile in diameter. The largest cones are not primitive olivine basalt but are the product of eruptions of either less or more siliceous types of magma.

Cinder cones are built by lava fountains or the frothing of the erupting magma (pl. 46A). They consist of bedded magmatic ejecta only. The agglutinated clots are *spatter;* the scoriaceous fragments are *cinders;* the small fragments, lighter in weight than cinders and extremely cellular in texture, are *pumice;* and those ellipsoidal, discoidal, or spheroidal forms produced by the action of mechanical forces during their flight through the air are *bombs*.[17]

---

[14] Stearns, H. T., and Vaksvik, K. N., Geology and ground-water resources of the island of Oahu, Hawaii: Hawaii Div. Hydrography, Bull. 1, p. 15, 1935.

[15] Stearns and Clark, op. cit., p. 142.

[16] Wentworth, C. K., op. cit., p. 22.

[17] Reck, Hans, Physiographische Studie über vulkanische Bomben: Zeitschr. Vulkanologie, Ergänzungsband, 124 pp., 1915.

Some of the ejecta contain crystals of olivine, augite, and feldspar, but others are composed of glass commonly blackened with magnetite dust.

During eruptions, *Pele's hair, Pele's tears,* and thin glassy ribbons are made by lava fountains, but they are so fragile they soon weather away. Strong winds during eruptions, especially those on high ridges, cause cones to grow asymmetrically and spread pumiceous material fanwise for several miles leeward. Before consolidation much of this fragile debris commonly breaks into fine dust, and as such is called *ash* or *ashy soil,* depending upon the degree of weathering. In some places it alters to *palagonite,* a waxy yellow silica-gel mineraloid; in others it oxidizes brilliant red. These layers upon consolidation form the commonest type of *vitric* or *glassy tuffs,* or *vitric-crystal tuffs* if they carry crystals[18] (pl. 38A). The terms ash and tuff, if not qualified by descriptive adjectives, refer herein to such lava fountain deposits. Cinder cones are not great ash makers, but deposits as thick as 55 feet have accumulated where conditions were favorable. All degrees of consolidation are present, commonly in the same deposit; hence, the terms ash and tuff are not very specific; but firmly compacted deposits are referred to herein as *tuff.*

A few cinder cones contain fragments of older rock. Such fragments fall into vent cracks when eruptions start and are carried up by the magma; or they may be fragments brought up in the magma from considerable depth. The fragments are commonly coated with vesicular glass and are called *cored bombs.*[19] Cinder cones are not the product of catastrophic blasts that tear wall rock from the volcanic throat, but are the result of relatively mild gas effervescence in magma rising through an open conduit.

SPATTER CONES.—When a lava column froths feebly or the magma is very fluid, spatter 5 to 50 feet deep accumulates around isolated vents as mounds, or along fissure vents as ramparts. Such mounds and ramparts are called *spatter cones.* These agglutinated masses resulting from the splash of lava fountains typify eruptions of early primitive olivine basalts but are less common among later differentiated lavas. Spatter cones on the top or slopes of a cinder cone are the result of dying gasps of the lava fountains. Most bombs are made during this stage.

Where spatter is ejected feebly around a small hole the lava clots accumulate in *driblet spires* a few feet across and up to 16 feet high (pl. 10B). Some form over cracks in lava tubes where the escaping gases carry spatter. This variety is known as a *hornito* or *spiracle.*

LAVA CONES.—Secondary *lava cones* are miniature shield-shaped

---

[18] Pirsson, L. V., The microscopical characters of volcanic tuffs: Am. Jour. Sci., 4th ser., vol. 40, pp. 191–211, 1915.

[19] Brady, L. F., and Webb, R. W., Cored bombs from Arizona and California volcanic cones: Jour. Geology, vol. 51, pp. 398–410, 1943.

lava domes. The lava is emitted in highly fluid condition with little or no gas effervescence. The cones are built of layers of lava a few inches to a few feet thick, commonly highly scoriaceous or spattery in texture near the vent. The flows spread far and wide and build dome-shaped cones with gentle slopes when erupted on nearly level land (fig. 5). They are asymmetrical when built on fairly steep grades, most of the lava flowing downslope. They are composed mostly of primitive olivine basalt.

ASH CONES.—The term *ash cone* is restricted herein to cones built by violent or cataclysmic explosions. Consolidated ash cones are *tuff cones*. Such cones are formed by the explosions of lava erupting under water or water-saturated rocks. They lie near the coast. Ash beds laid down during such explosions are called *vitric-lithic ash*, the word *lithic* referring to the stony fragments present. If consolidated, the deposits are called *vitric-lithic tuff*. The littoral cones typically contain a much larger proportion of ash, and are better bedded than true cinder cones (pl. 10A). Figure 35 illustrates the finer texture of the littoral cones. The contrast is even greater than indicated in the figure, as the cinder sample analyzed contained less coarse material than most.

BRECCIAS

EXPLOSION DEPOSITS.—The coarse compacted deposits of angular blocks lying in a matrix of ash and laid down by cataclysmic explosions are called *explosion breccia* (pls. 11A; 47A, B). They are abundant around Kilauea caldera. The fine-grained deposits of such explosions are *lithic ash*, which when consolidated are termed *lithic tuff*. Some beds carry sufficient crystals and glass to be *vitric-crystal tuffs* but the presence of many accessory ejecta readily differentiates the coarse deposits from the vitric-crystal tuffs laid down by lava fountains.

VENT BRECCIA.—The chaotic assemblage of angular and subangular fragments in a rock-powder matrix that falls into a vent or pit crater as a result of collapse, explosion, or landslide is called *vent breccia*. It may be loosely or firmly consolidated. Some vent breccias contain debris washed into the vent by water; hence, rounded pebbles may be present. In others, cinder and pumice are found, either deposited from near-by lava fountains or subsequently washed into the vents. Vent breccias formed close to the surface usually have poorly developed bedding, dipping toward the center of the vent. Those formed far below ground are not bedded, usually contain many dense fragments of intrusive rock, and are cut by dikes. Vent breccia deposits are roughly cylindrical in outline and generally have nearly vertical contacts. In contrast, beds of explosion breccia laid down outside the vent have nearly horizontal contacts or conform to the underlying lava beds.

EXTRUSIVE ROCKS

PAHOEHOE.—Lava which congeals with a relatively smooth, billowy, entrail-like surface, in places ropy, is called *pahoehoe* (pl. 10C). When extrusion occurs on a fairly flat surface, *tumuli* or *pressure domes* develop (pl. 44B). They may be formed by collapse as well as by pressure. Tumuli and tessellated crusts impart an "elephant hide" texture to the flow when seen from an airplane (pl. 11B). A pahoehoe flow is spread from the vent through a system of ramifying tubes that range from a few inches to more than 25 feet in diameter. If the lava in these conduits drains out at the close of the eruption, as is usual on steep slopes, a cavern called a *lava tube* results (pl. 12B). Lava driping from the roof of such tubes forms *lava stalactites,* and where it accumulates on the floor, *lava stalagmites* are formed (pl. 13). The lava forms *lava cascades* if it pours over cliffs (pl. 12A), and *lava deltas* if it flows into the sea (pl. 46B). Pahoehoe flows are commonly composed of several *flow units,*[20] one above the other (pl. 39B). Each unit or layer represents a different period of spreading, either hours, days, or months apart, during a single eruption. Glass skins a fraction of an inch thick characterize the surface of the units. Upon weathering they turn red or yellow and show as wavy streaks in cross section. Scoriaceous lava, containing closely spaced round vesicles caused by gas bubbles, forms the upper or crusted part of the units. This rock is known in Hawaii as *pukapuka,* meaning full of holes. The crust of some flows, especially near vents high on Mauna Loa, is so vesicular that fragments are indistinguishable from highly cellular ejected pumice. It is sometimes called *thread-lace scoria.*[21] If the unit is thick, the lower part is usually dense with a zone of vesicles close to the bottom and in places lying on slaggy, doughy-looking masses a few inches across. In many units the undrained tubes have concentrically arranged vesicles, giving an ellipsoidal form to the rock in section. These forms have been mistaken by some writers for *pillow lavas,* which are ellipsoidal masses formed only in the presence of steam, snow, or water.[22] No true pillow lava has been found in the island of Hawaii. Small undrained tubes with their concentric structures are sometimes mistaken for fossil logs. *Xenoliths* or fragments of older rock are found enclosed in lava flows. They may come from

---

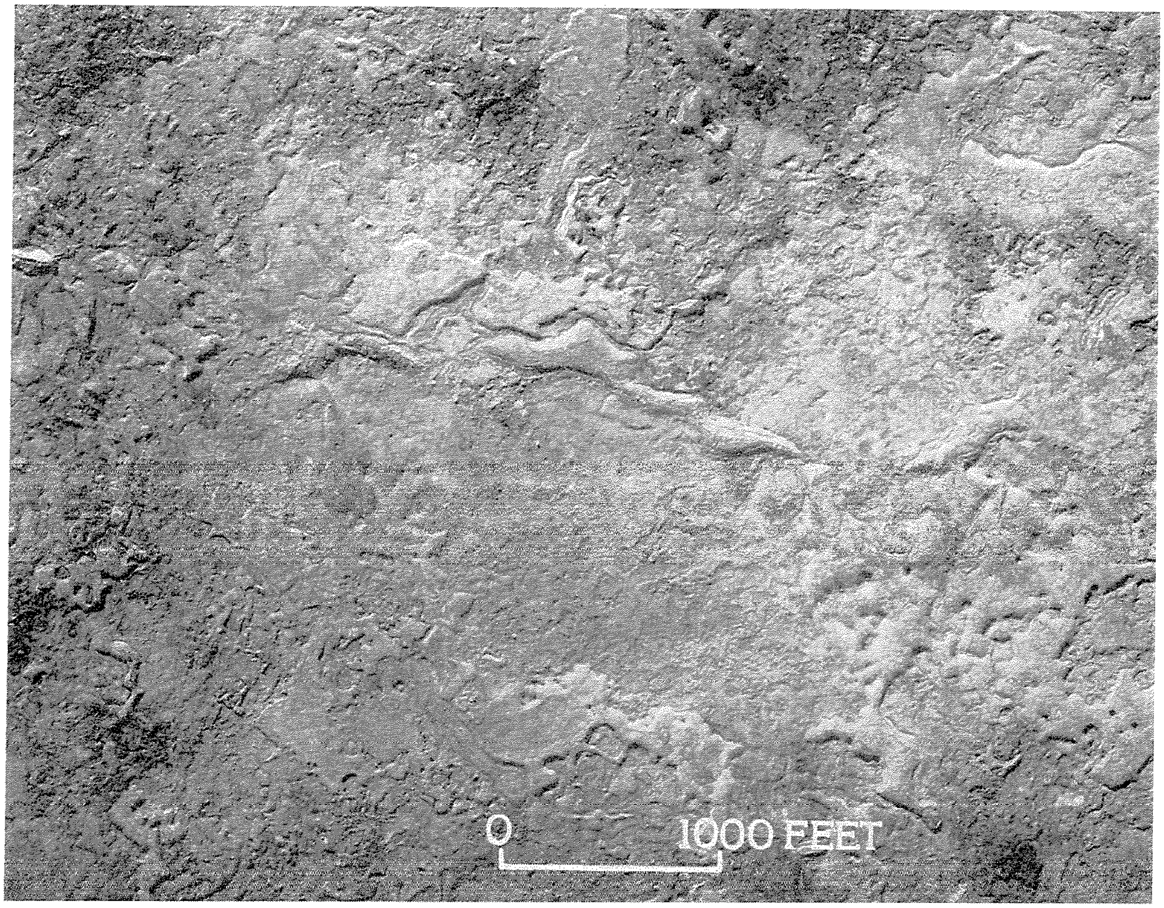
[20] Nichols, R. L., Flow-units in basalt: Jour. Geology, vol. 44, no. 5, p. 617, 1936.

[21] Dana, J. D., Characteristics of volcanoes, p. 163, New York, 1890. Stearns, H. T., and Clark, W. O., Geology and water resources of the Kau District, Hawaii: U. S. Geol. Survey Water-Supply Paper 616, p. 113, 1930. Wentworth, C. K., and Williams, H., The classification and terminology of the pyroclastic rocks: Nat. Research Council, Bull. 89, pp. 40-41, 47-50, 1932.

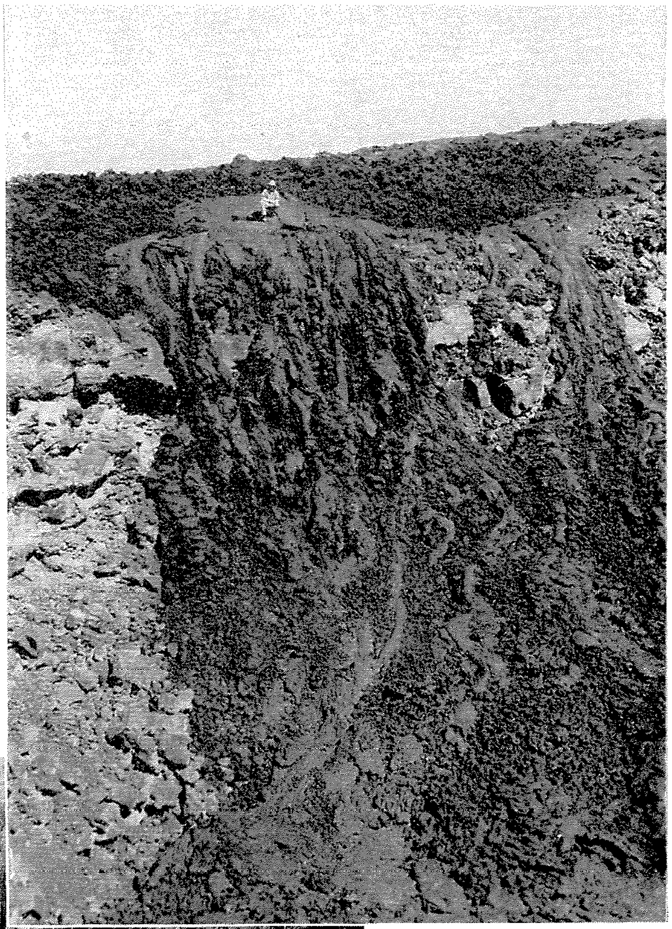
[22] Stearns, H. T., Pillow lavas in Hawaii (abstract): Geol. Soc. America, Proc. for 1937, p. 252, 1938.

Plate 11A. Explosion debris of 1924 on the floor of Kilauea Caldera adjacent to Halemaumau. Photo by G. O. Fagerlund, National Park Service.

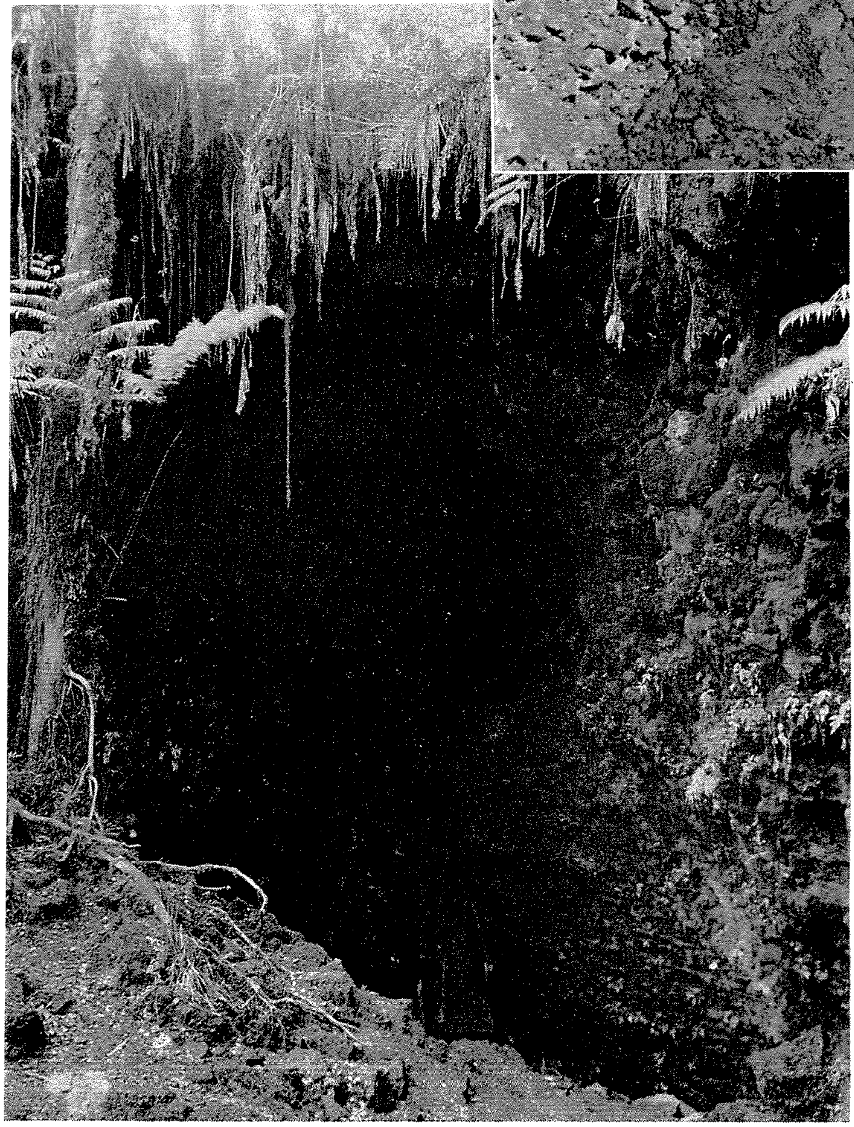
Plate 11B. Vertical air view of a prehistoric lava flow from Hualalai Volcano near Keahuolu Point, 2 miles northwest of Kailua, showing "elephant hide" texture. The lava flowed from left to right. Photo by USAAF.



Right: Plate 12A. Prehistoric lava cascade into an ancient crater at an altitude of 8,123 feet, half a mile northeast of the 8,800-foot vent of the lava flow of 1935 on Mauna Loa Volcano. Photo by H. T. Stearns.



Below: Plate 12B. Entrance to Thurston lava tube, Kilauea Volcano, Hawaii National Park. Photo by Theodore Kelsey.



deep within the earth and may be fragments of the walls of the magma reservoir or conduit.

Pahoehoe which inundates the trunks of trees may form tree molds. The lava is chilled about the tree trunk, often preserving the checks in the charred tree and rarely, details of the bark. The tree burns away, leaving a cylindrical well-like depression (pl. 27B), or if the trunk was recumbent, a trough or tube. If the lava is sufficiently fluid the lower portions may drain away, lowering the flow surface and leaving projecting above it rough columns of lava which were chilled and solidified by contact with the tree trunks. The upper end of the column furnishes a rough indication of the original level of the flow surface. These projecting columns (pl. 28B) are known as lava trees.

AA.—Lava flows composed of dense basalt with stretched and deflated irregular vesicles lying between and in places including beds of spiny clinkers are called aa. The front moves as a wall of livid clinker (pl. 15C). If the flows are massive they have well developed columnar jointing. Tubes are rarely formed. Lava river channels, 5 to 30 feet wide, extend almost to the terminal margins of aa flows. On steep slopes the river channels are bordered by agglutinated splash and veneers of glassy vesicular rock (pl. 45B). These spattery deposits along aa channels are easily confused with spatter ramparts. The aa channel in the 1942 lava flow from Mauna Loa coincides with the fissure vent for half a mile or more. The surfaces of aa flows are indescribably rough and form black dull bands when seen from the air (pl. 14B) in contrast to the shiny pahoehoe. Some flows carry on their surface large numbers of balls from a few inches to 12 feet in diameter. Some balls are masses of clinker subsequently wrapped with lava; others are large masses of the levees or walls of the aa channel undermined and floated downstream by the lava flow. The latter have highly vesicular layered materials inside. All have been called *bombes de roulement* but they are not true bombs, and the name *accretionary lava balls* is preferable[22a] (pl. 13C).

Pahoehoe is emitted with much included gas. If the gas is dissipated rapidly by flowing, cooling, or violent lava fountaining so that crystallization starts, the lava changes to aa. The two types are easily separated except at the point of transition. The conversion of pahoehoe to aa is not yet thoroughly understood. A review of the literature covering this subject is given elsewhere.[23] It is definitely established, however, that aa cannot revert to pahoehoe. It may appear to do so where pahoehoe emerges from a tube beneath

---

[22a] Macdonald, G. A., The 1942 eruption of Mauna Loa, Hawaii: Am. Jour. Sci., vol. 241, pp. 253-254, 1943.

[23] Stearns, H. T., and Clark, W. O., op. cit., pp. 108-112.

aa, or when a new phase of the eruption sends pahoehoe streaming over previously erupted aa.

Most lava flows in Hawaii can be classified as pahoehoe or aa, but in the trachyte flows angular blocks instead of spiny clinker dominate the fragmental part. Such flows are better called *block lavas*[24] (pl. 45A).

KIPUKAS.—Island-like areas of older land ranging in size from a few square feet to several square miles surrounded by later lava flows are called *kipukas*. Kipukas result from either topographic irregularities or the viscosity of the lava. The surface of a kipuka may be lower or higher than the surface of the lava surrounding it. Commonly, it lies below the level of the lava although prior to the eruption it may have been a knoll.

CRATER FILLS.—Lava in pit craters and in the craters of cinder cones generally congeals as a dense lenticular mass with pronounced columnar jointing. These masses are called *crater fills* (pl. 14A). Some fills are coarse grained and except when well exposed, are difficult to distinguish from an intrusive body. The tops of crater fills have the usual crustal features of lava flows—valuable criteria for recognizing their origin if they have not been destroyed by erosion. Such features do not form in intrusives. The fact that crater fills become narrower downward is not always diagnostic. If dikelets or offshoots from the body intrude the adjacent walls, it may be assumed, with rare exceptions, that the body is not a crater fill. Cinders, talus, and weathered rock usually border a crater fill and where present are the best diagnostic criteria.

INTRUSIVE ROCKS

DIKES AND SILLS.—In general, flows are fed by magma that rises through fairly straight, vertical, narrow cracks. The solidified magma in such a crack is called a *dike* (pl. 15B). Dikes formed close to the surface of extrusion are usually vesicular, with the vesicles arranged in parallel vertical zones commonly separated by vertical joint planes. Vesicles and vertical jointing disappear with depth and the rock becomes dense and cross jointed. Most dikes have borders of black glass a fraction of an inch thick. In places glassy *dikelets*, offshoots from the dikes, fill cavities and joint planes in the country rock. A few dikes fill pre-existing tubes.

Groups of parallel closely spaced dikes are referred to as *dike swarms*. Underlying the rift zones are dike swarms 1 to 3 miles wide comprising hundreds of dikes; they are called *dike complexes* (sections, pl. 1).

Relatively few intrusions follow the bedding planes. Those which do, form vertical-jointed nearly horizontal *sills* (pl. 15B). Sills are

---

[24] Finch, R. H., Block lava: Jour. Geology, vol. 41, pp. 769–770, 1933.

relatively scarce in comparison to dikes, but they are fairly abundant around the main vents. Sills more than 300 feet long are scarce in Hawaii.

STOCKS, BOSSES, AND PLUGS.—A relatively small subjacent intrusive body is called a *stock*.[25] If roughly cylindrical in form it is called a *boss*. If it can be established that this body fills a volcanic throat it is called a *neck* or *plug*. Bosses and plugs are found in or close to the main vents, but few flows were fed through circular holes. Bosses and plugs are dense rocks. The larger bodies are coarse grained in the center and fine grained near the margin.

---

[25] Daly, R. A., Igneous rocks and the depths of the earth, p. 113, New York, 1933.

See page 17, top: Plate 10A. Bedding in Puu Mahana littoral cone, 3 miles northeast of South Point, Hawaii. Photo by A. E. Jones.

Middle: Plate 10B. Driblet spire about 3 feet high on top of pahoehoe tumulus one mile north of Kamakaia Hills, southwest rift zone of Kilauea Volcano. Photo by H. T. Stearns.

Bottom: Plate 10C. Scaly pahoehoe at the 8,500-foot vent of the lava flow of 1935 on the northern flank of Mauna Loa Volcano. Photo by H. T. Stearns.

GEOMORPHOLOGY

VOLCANIC FORMS OF ACCUMULATION

Major cones.—Hawaii has been built by lavas poured from five volcanoes, each with independent rift zones and individual geologic history. Their areas and the principal geomorphic features are shown in figure 6. Significant data regarding their forms are given in the following table:

Table of dimensions and form of the domes of Hawaii[a]

Name	Length (miles)	Width (miles)	Area (Square miles)	Percent of island	Summit elevation
Mauna Loa	75	64	2,035	50.5	13.680
Kilauea	51	14	552	13.7	4,090
Hualalai	24	20	290	7.2	8,251
Mauna Kea	51	25	919	22.8	13,784
Kohala	22	15	234	5.8	5,505

[a] Wentworth, C. K., Ash formations of the Island Hawaii: Hawaiian Volc. Obs., 3d Spec. Rept., p. 13, 1938.

The area of each dome is partly dependent upon its age. The southern slope of Kohala Mountain has been buried beneath Mauna Kea lavas. The western and southern slopes of Mauna Kea, the eastern and southern slopes of Hualalai, and the northwestern slopes of Kilauea have been buried by Mauna Loa lavas. The areas listed are present dimensions and make no allowance for buried slopes.

The fundamental concept of Hawaiian volcanism gained from a systematic study of all the islands is that the lavas are almost entirely erupted from narrow fissures confined to rift zones intersecting at the summit of each dome where a central vent may or may not be present depending upon the phase of its development. The principal phases[26] are:

The first or youthful phase is characterized by the rapid outpouring of highly fluid primitive basalts after the cone has built above sea level. A shield-shaped dome of thin sheets is built over two major rifts and one minor rift with a small crater at their intersection. Olivine basalts predominate; small feldspar phenocrysts are common, and pyroxene phenocrysts are scarce. True cinder cones rarely form, the usual vent being either a fissure

---

[26] Stearns, H. T., Geology of the Hawaiian Islands: Hawaii Div. of Hydrography, Bull. 8, p. 17, 1946; Four phase volcanism in Hawaii: Geol. Soc. America Bull., vol. 51, no. 12, pp. 1947–48, 1940.

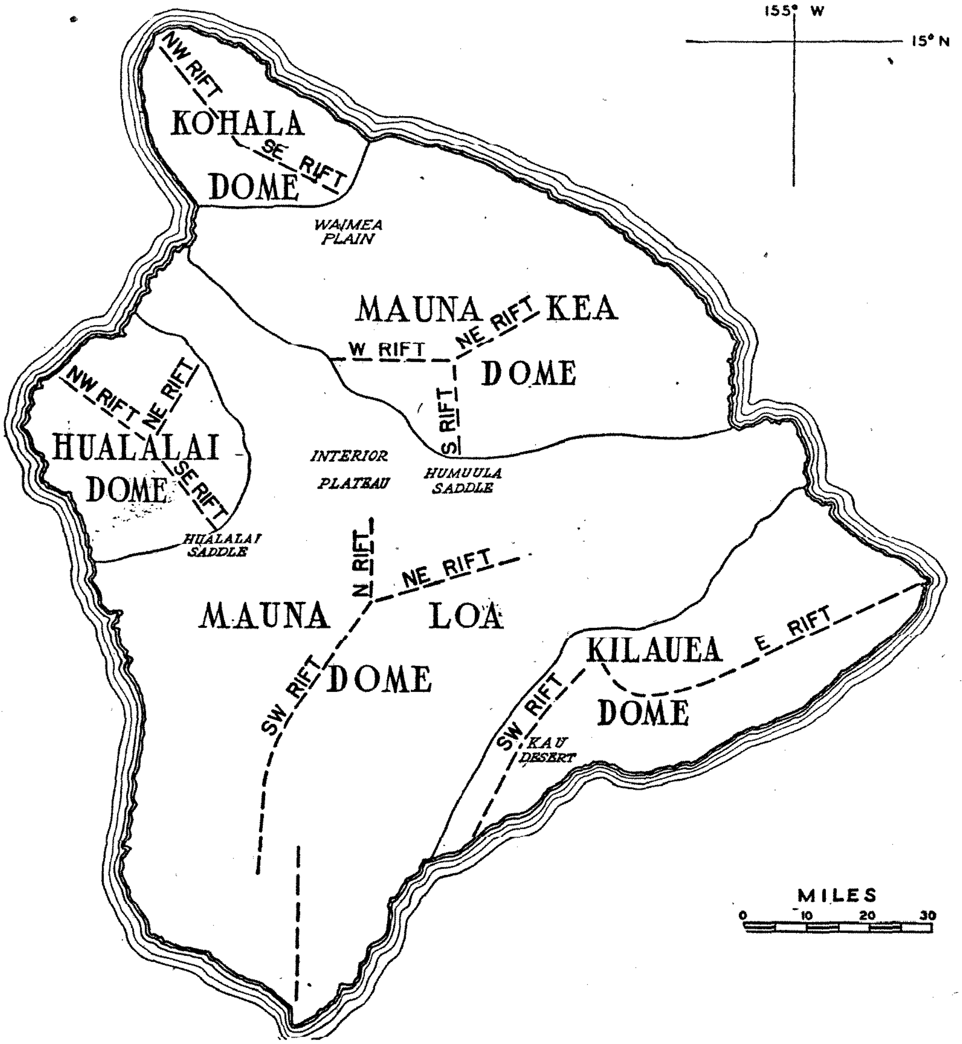


Figure 6. Map of Hawaii showing principal geomorphic features.

bordered by low spatter ramparts or a vent concealed by a flat mound of pahoehoe. A few thin beds of lithic and vitric tuff may be deposited. Stream erosion does not occur as the surface is highly porous and the time interval between eruptions is short. All Hawaiian volcanoes have passed through this stage.

The second or mature phase is characterized by continued volcanism and the gradual collapse of the volcano over the vent areas forming a caldera on the summit and sometimes shallow grabens along the major rifts. The composition of the lavas does not change appreciably, nor does the time interval between eruptions lengthen. However, lavas ponded in closed fault basins are very massive and in physical appearance differ greatly from the pre-caldera lavas. When eroded they form sheer cliffs commonly exhibiting columnar structure. Lithic and vitric tuff beds may be more numerous than in the first phase. The highest part of the caldera wall usually bounds the segment between the two rift zones intersecting at an obtuse angle. Generally this segment is no longer flooded with lavas, with the result that streams carve canyons into it while the other slopes continue to be veneered with flows. Likewise the coast of this segment is cliffed by the sea. Thus two distinct physiographic stages may be present on the same volcano.

Probably most Hawaiian volcanoes are in, or have passed through, this second phase, but there are some in which there is no evidence that it ever existed. Kilauea and Mauna Loa are in the second phase.

The third or old-age phase is characterized by the obliteration in part or in whole of the caldera and grabens because the volume of lava poured out exceeds the amount of collapse. The time interval between eruptions grows progressively longer and the composition of the lavas may change gradually to andesine andesites and picrite-basalts, or it may change abruptly to oligoclase andesites and trachytes. Trachytes, andesites, and closely related rocks are laid down in thick sheets chiefly as aa flows. Most of these eruptions are characterized by high lava fountains which build bulky cinder cones. Vitric tuff beds increase in number and in thickness and plug domes may be formed. The more basic lavas (picrite-basalts) in this phase usually carry large phenocrysts of one or all of the following minerals: pyroxene, olivine, and feldspar. The profile of the dome steepens and becomes studded with cones. Some of the vents lie outside of the rift zones. Local erosional unconformities are found between some of the flows and commonly at the base of the differentiated lavas, especially if only oligoclase andesites and trachytes are erupted. Peridotite and gabbro inclusions are common. Mauna Kea and Kohala are in the third phase, and Hualalai has barely entered it.

The fourth or rejuvenated phase is characterized by the extrusion of lavas following a long erosion interval. These are unconformable upon all lavas of the three preceding phases. The lavas are usually nepheline basalts, with or without melilite, and olivine basalts with or without pyroxene, feldspar, and olivine phenocrysts. Periodotitic and gabbroic cognate inclusions are common. Widespread vitric or crystal-lithic-vitric tuffs may be common also, the latter resulting from phreatomagmatic explosions. Many of the vents of this phase are not closely related to the ancient rift systems of the volcanoes on which they form. No volcano on Hawaii has reached the fourth phase, but many of those on other islands in the archipelago are in it.

The steepness of a volcanic mountain is chiefly a function of its phase. Eruptions solely of primitive olivine basalt build a smooth shield-shaped dome (first phase) which usually is indented with a summit caldera by the end of the second phase, resulting in a pro-

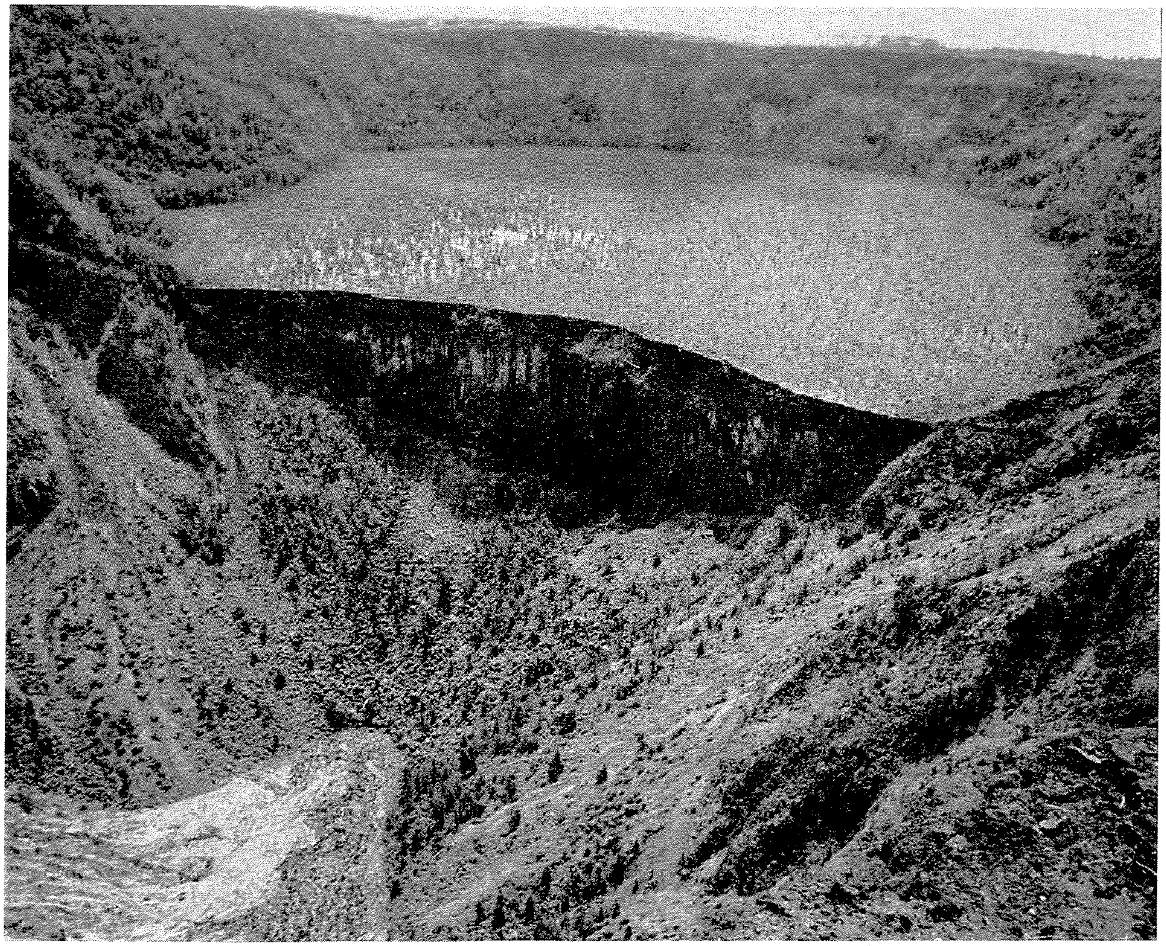
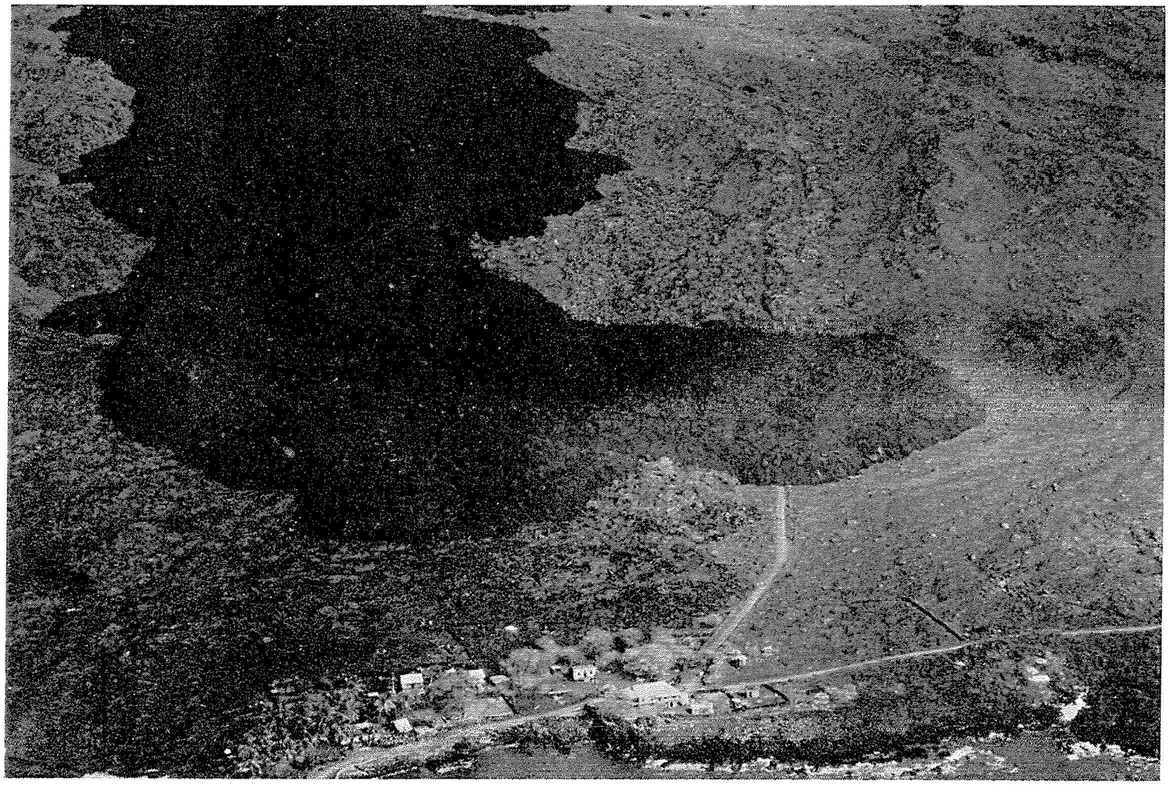
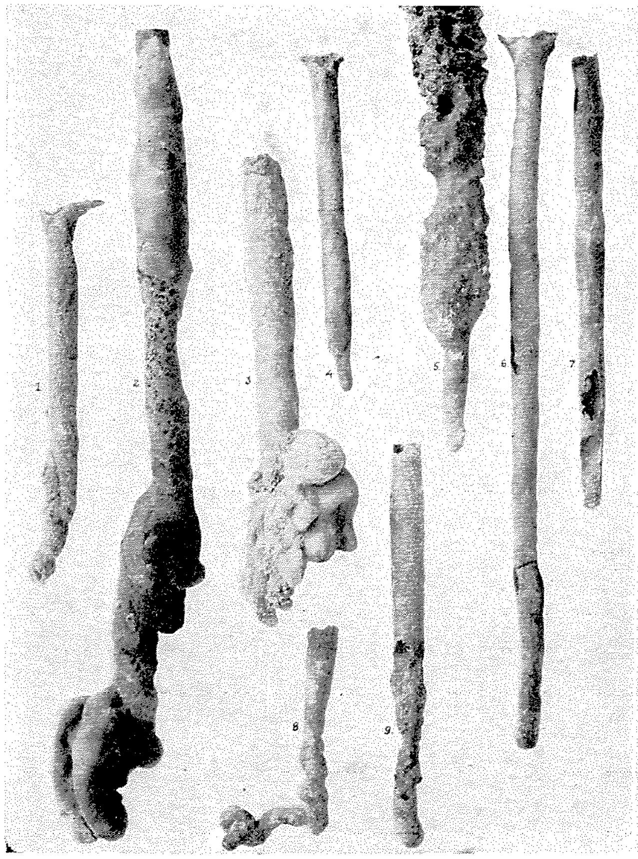
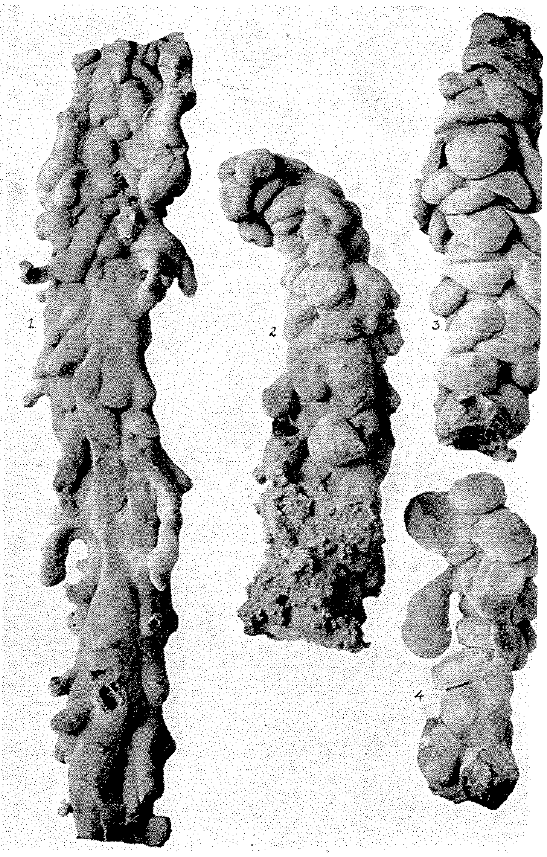


Plate 14A. Makaopuhi Crater, Kilauea Volcano, showing columnar-jointed congealed lava lake and the lava flow of 1922 in the foreground in the bottom of the pit. Photo by R. J. Baker.

Plate 14B. Lava flow of 1926 from Mauna Loa Volcano just before it buried the village of Hoopuloa in the Kona District. Photo by USAAF.



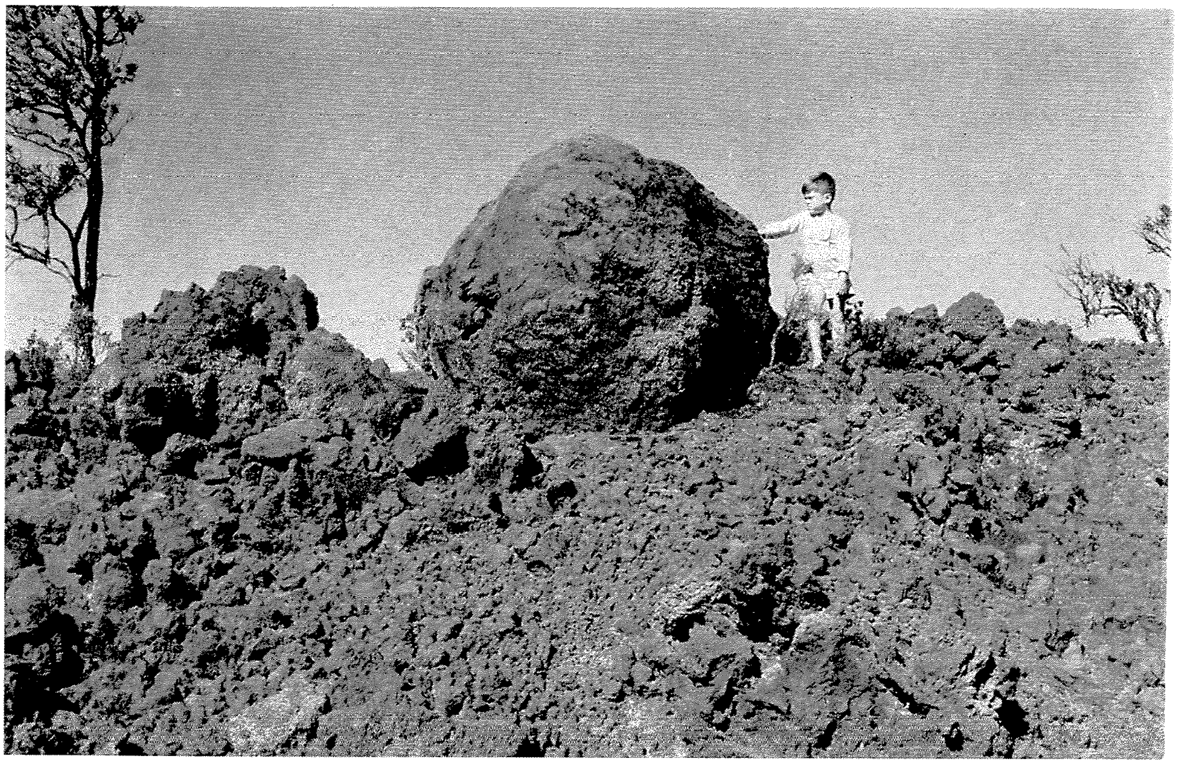




Above, left: Plate 13A. Lava stalagmites from the same tube as stalactites nos. 1 to 3, plate 13B. About one half natural size.

Above, right: Plate 13B. Lava stalactites from Kilauea Volcano. 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 one half natural size.

Below: Plate 13C. Accretionary lava ball on the Keamoku lava flow from Mauna Loa Volcano, two miles west of Kilauea Caldera. Photo by G. O. Fagerlund, National Park Service.



file like that of Mauna Loa (pl. 7). Slight differentiation of the magma and the consequent increase in viscosity lead to bulkier cinder cones and short thicker flows which steepen the upper part of the mountain during the third phase. The caldera, if present, is filled and a mountain with a profile like that of Hualalai results (fig. 4). Further differentiation and prolonged eruptivity in this phase lead to a profile like that of Mauna Kea (pl. 7). A small number of eruptions accompanying extensive differentiation results in a form like that of Kohala Mountain (pl. 51A). Its shield-shaped dome of primitive olivine basalt is thinly capped with differentiated lavas, and outlines of the summit caldera are still discernible. Thus the form of Hawaiian domes in the third phase is determined by the degree of differentiation and by the volume of various kinds of lavas extruded. Faulting and erosion alter the form locally as described later in this chapter. During the fourth phase, the form becomes corrugated with canyons and valleys, some of which are floored with late lava flows.

Prior to differentiation, the highly fluid primitive basalts pour from cracks that extend far down the slopes. These basalts may flow for 30 miles before congealing. As the loci of outbreaks are restricted to narrow strips or zones of land intersecting at the summit, and as more spatter, cinder, and lava congeal per unit area in these rift zones, the zones become ridges that rise toward their point of convergence. Asymmetry of the domes is caused usually by one rift zone pouring out more lava than the others, although erosion or faulting, or both, have caused asymmetry of Mauna Loa, Kilauea, and Kohala.

Primitive basalt eruptions are characterized by many short flows of lava that issue chiefly from the upper part of the source crack, and a few long flows which extend far down the slope from the lower end of the crack. The lava flows lie like shingles of different length upon the slopes. The usual eruption adds half a dozen or more to the upper slopes and one or two that extend nearly or completely to the edge of the dome. The flows commonly thicken toward their extremities and the long flows are generally thicker than the short flows. This condition makes the peripheral area grow a little faster than it would if all flows were of equal thickness.

A conspicuous change in the building process occurs when differentiation sets in, especially when oligoclase andesites and soda trachytes are erupted. These lavas are too viscous to flow far and their cinder cones are bulky. Thus a steep cap is built on top of the shield of primitive lavas.

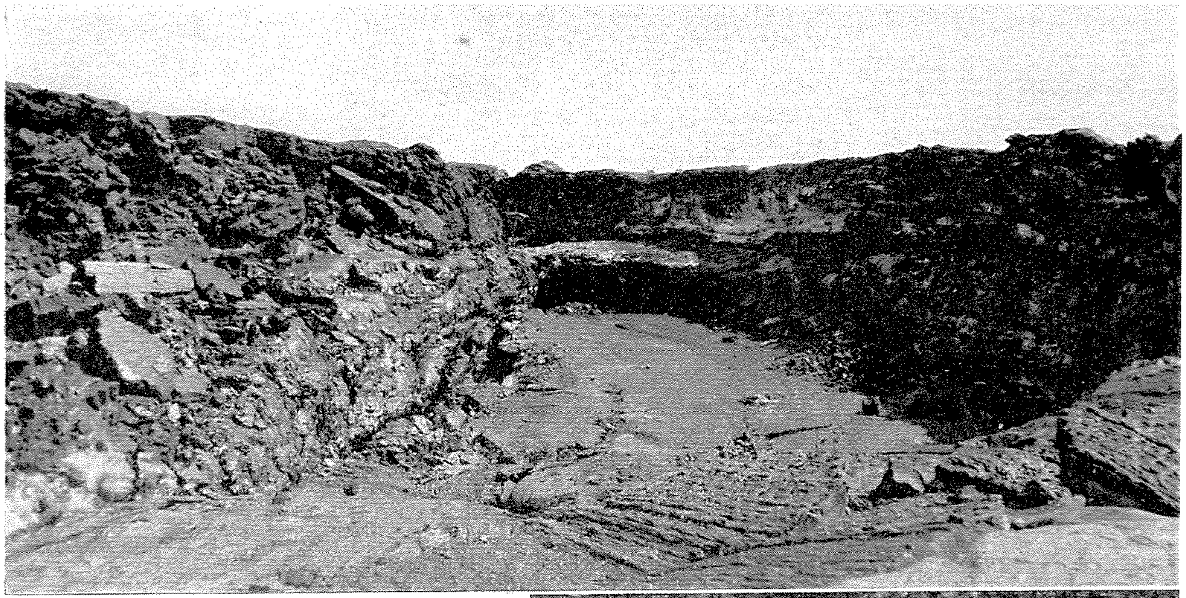
Fissuring of the dome slowly ceases as the time between eruptions increases, probably because sufficient time elapses for the magma to solidify in the dikes under the rift zone and beneath the caldera. When completely solidified for several miles below the surface, these closely spaced dense dikes apparently become the strongest part of the dome. The highly differentiated lavas tend to erupt near the summit beneath which the magma remains liquid longest and where faults associated with the caldera are most numerous. The great strength of the solidified dike complex probably explains why secondary eruptions, following a long erosional period on a volcano, tend to occur in the inter-rift areas.

SECONDARY CONES.—Studding the rift zones of the major domes are the cognate secondary spatter, cinder, pumice, and ash cones connected to the magma reservoir by dike feeders. Their forms are shown in figure 5. Along the shores and a short distance inland of the southern half of the island are littoral ash cones that are not connected to the magma reservoir and are unrelated to the rift zones of the volcanoes. They are built chiefly by the explosion of aa lava where it runs into the sea. Pahoehoe flows, upon entering the sea, tend to produce pillow lavas or to flow undersea without violent explosions, by extending their feeding tubes. Many littoral cones are doublets, one forming on each side of the lava river, the explosion debris falling on the river being carried away as it falls. Such cones are distinguished by the texture of their glassy fragments, the usual highly vesicular pumice and shards typical of cognate cones being absent (see Petrography).

Kapoho tuff cone, in Puna, is a cognate cone and owes its form and composition either to the eruption of magma through highly saturated rocks where ground water was sufficiently abundant to cause the magma to explode and become comminuted, or to magma rising in the sea close to shore. Such cones are probably abundant on the submarine slopes of the volcanoes.

LAVA FLOWS.—The forms lava flows assume upon cooling vary with the temperature during extrusion, chemical composition, degree of crystallization, gas content, distance from source, and character of the terrane over which they flow. If pahoehoe, they are smooth and billowy (pls. 11B and 15A); if aa, they are jagged and bristling (pls. 15C, 49A). The primitive basalts range in thickness from a few inches to about 40 feet depending chiefly upon the distance from the top of the mountain. They average about 5 feet in thickness near the summit and 20 feet near the periphery. They are commonly composed of flow units 6 inches to 10 feet thick. If pooled in craters or on flat slopes they may have a thickness of 200 feet or more. These fills are massive and columnar-jointed (pl. 14A). Innumerable minor forms such as accretionary lava balls, channels, tubes, tree molds, etc., are found in the flows.

Pahoehoe decreases in quantity as the magma differentiates until in the highly differentiated types it is absent. The lavas thicken



Above: Plate 15A. The congealed pahoehoe lava river of 1935 at 8,350 feet between bombing targets A and B on the north flank of Mauna Loa near Humuula. Photo by H. T. Stearns.

Right: Plate 15B. Lenticular sill 26 feet thick and feeding dike in west wall of Mokuaweoweo Caldera, Mauna Loa. Photo by G. A. Macdonald.

Below: Plate 15C. Front of the aa lava of 1935 from Mauna Loa moving through a forest three miles south of Puu Oo Ranch, December 27, 1935. Photo by H. T. Stearns.

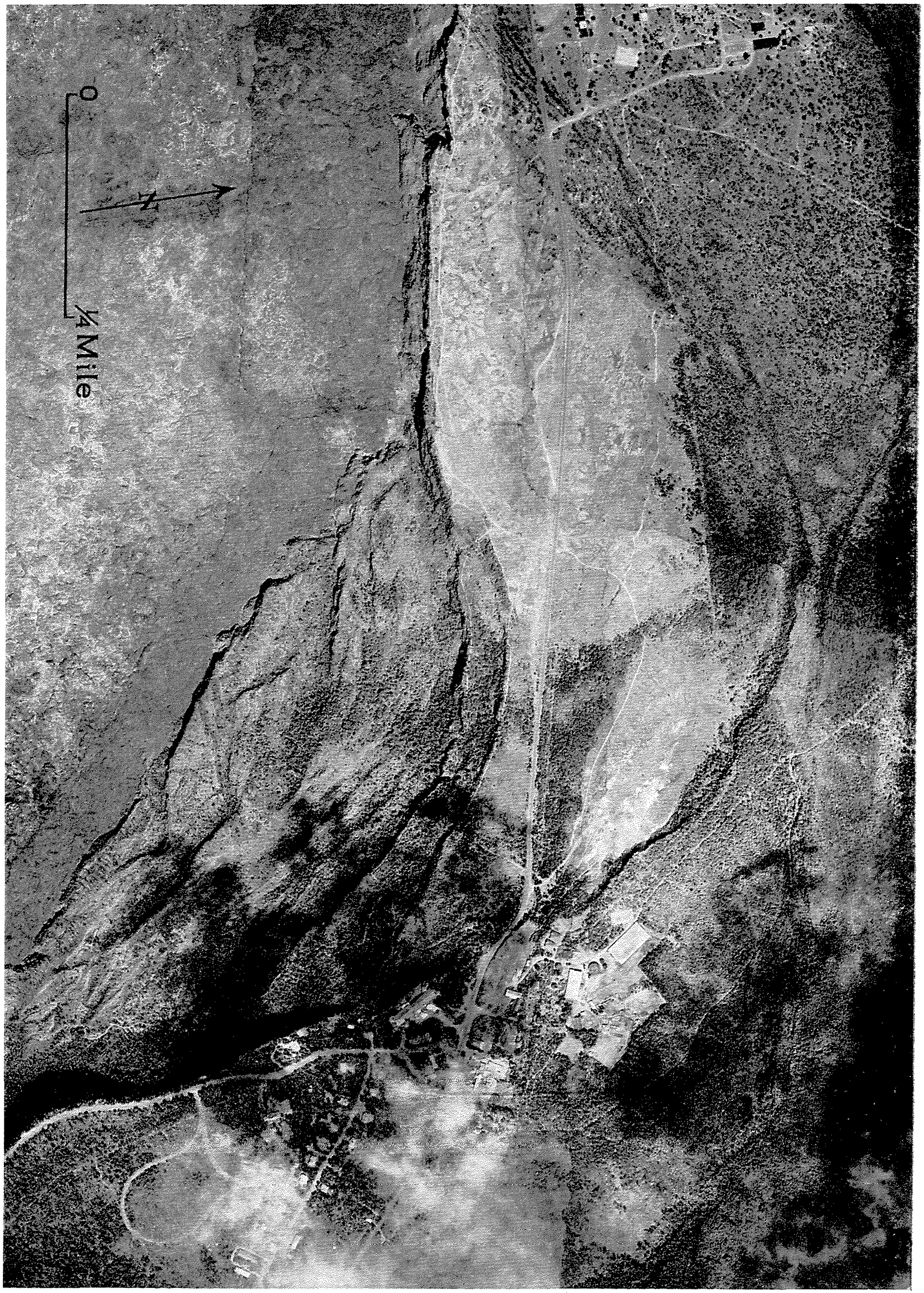


Plate 16. Vertical air view of fault terraces at the northern edge of Kilauea Caldera. Photo by USAAF.

progressively with differentiation, the more basic andesite flows averaging about 20 feet in thickness and the less basic ones about 40 feet. The trachyte flow from Puu Waawaa is more than 900 feet thick.

VOLCANIC FORMS OF SUBSIDENCE

Calderas.—Calderas indent the summits of Mauna Loa and Kilauea. The calderas are essentially the result of collapse, although explosions in both calderas have blown out a small amount of material. Mokuaweoweo, the summit caldera of Mauna Loa, has a circumference of 9.5 miles and an area of 3.6 square miles. In 1925, its deepest point was 652 feet below the rim. In 1841 it was 784 feet deep; thus 132 feet of lava has accumulated on its floor in excess of subsidence since that time. Between 1925 and 1942 filling has amounted to about 60 feet. Plans and sections of Mokuaweoweo Caldera in 1841 and 1944 are given in figures 7 and 8.

The caldera of Kilauea is 7.85 miles in circumference and has an area of 4.14 square miles. The floor near the northern end is about 400 feet below the rim, and the bottom of Halemaumau, the active fire pit, is 1,100 feet below the northern rim of the caldera. Plans and sections of Kilauea Caldera in 1825 and 1944 are given in figure 9. Curved concentric faults bound both calderas and some are actively moving. The calderas have increased their areas by engulfment of blocks which separated them from pit craters and by burying partly sunken blocks with lava flows. The north bay of Mokuaweoweo Caldera was originally separated from the caldera by a cliff which has been buried since 1885; hence, the floor of the caldera extends half a mile farther north now than it did then (figs. 7 and 8). Thus Kilauea Iki and Keanakakoi pit craters are likely to become a part of Kilauea Caldera, and Lua Hou and Lua Hohonu a part of Mokuaweoweo Caldera. Differential movement of the fault blocks bounding a caldera results in terraces (pl. 16).

The fault escarpments bounding the calderas slope toward the calderas indicating that the rock is subsiding through a hole smaller in diameter than the calderas. Calderas on Oahu dissected to about 3,000 feet below their floors expose two types of rock—highly brecciated rock filling pipes which taper downward, and massive lava flows with synclinal structure. It is believed that the synclinal structure is due to sagging after extrusion as a result of the movement downward of the underlying material. It appears from deeply eroded volcanic vents elsewhere that the magma beneath the caldera stopes and fluxes its roof. This process must be fairly rapid during the extrusion of primitive lavas because the depression deepens and enlarges in spite of large volumes of basalt being poured out on the floor of the caldera every few years. It is probable that at a depth of a mile or more under Mokuaweoweo and Kilauea calderas

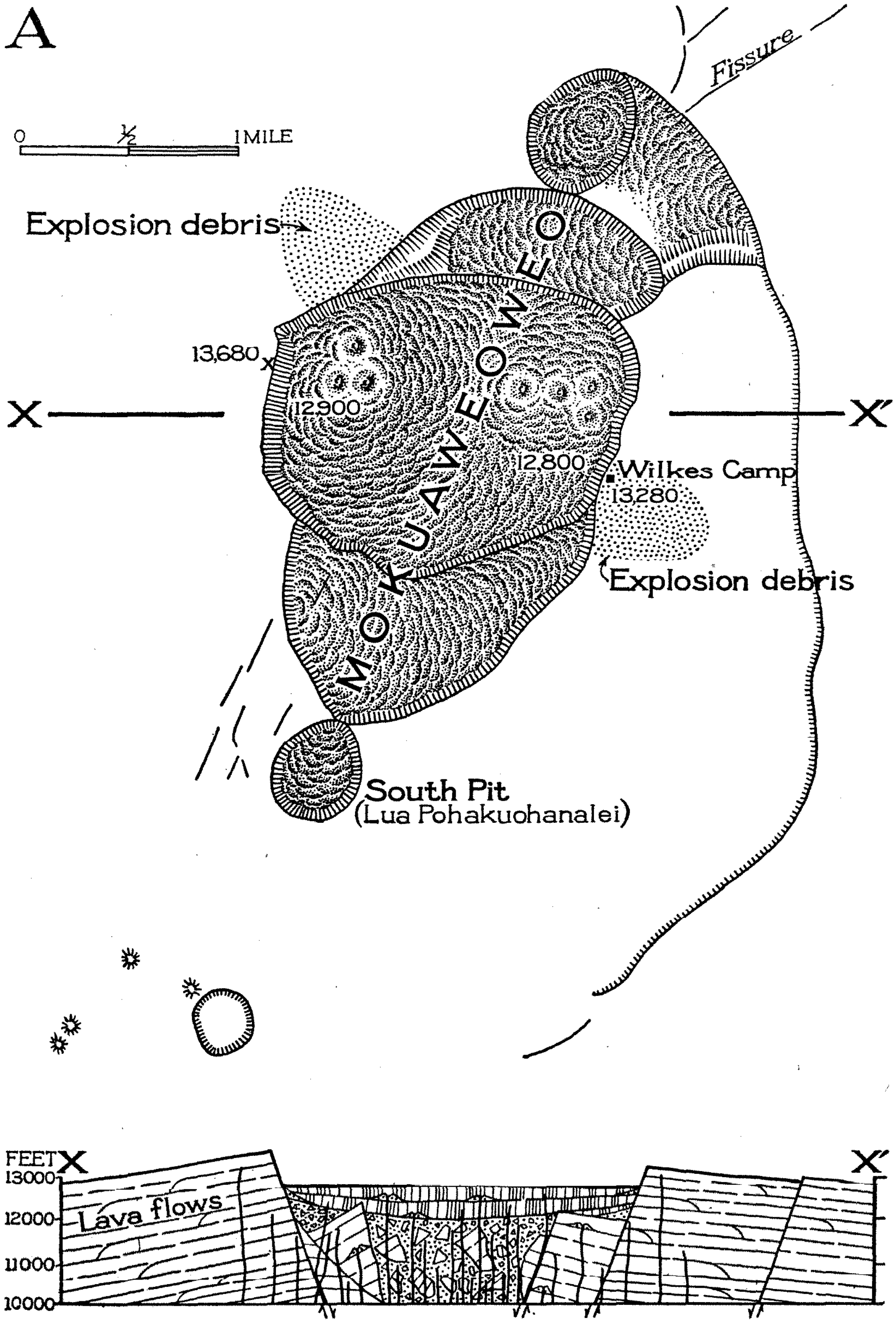


Figure 7. Plan and section of Mokuaweoweo Caldera in 1841 (plan is after Wilkes). Area of explosion debris added. Approximate altitudes in feet. The structure beneath the caldera is hypothetical.

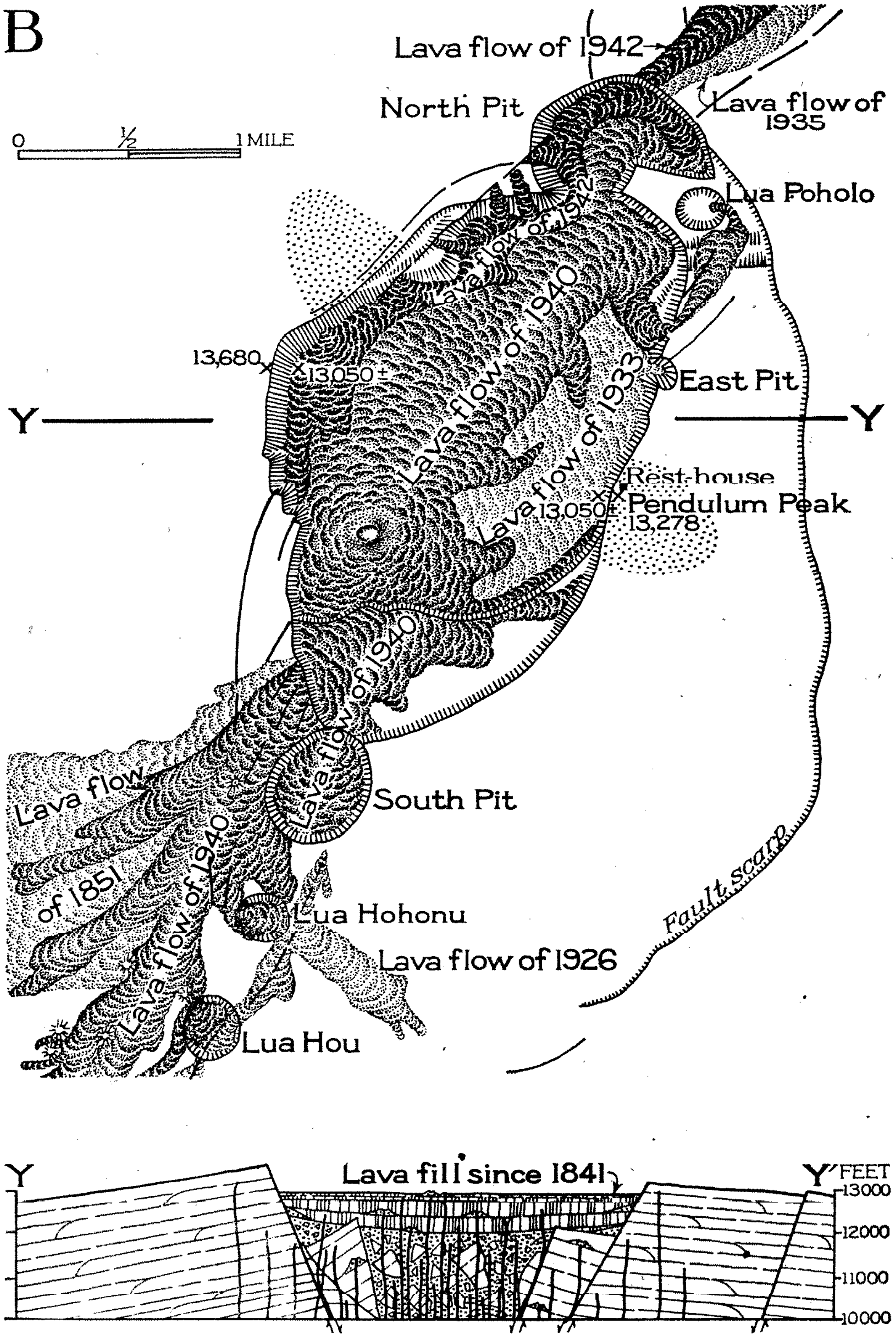


Figure 8. Plan and section of Mokuaweoweo Caldera in 1944. Altitudes on the floor of the caldera are approximate. Lua Poholo, East Pit, and Lua Hohonu have been formed since 1841.

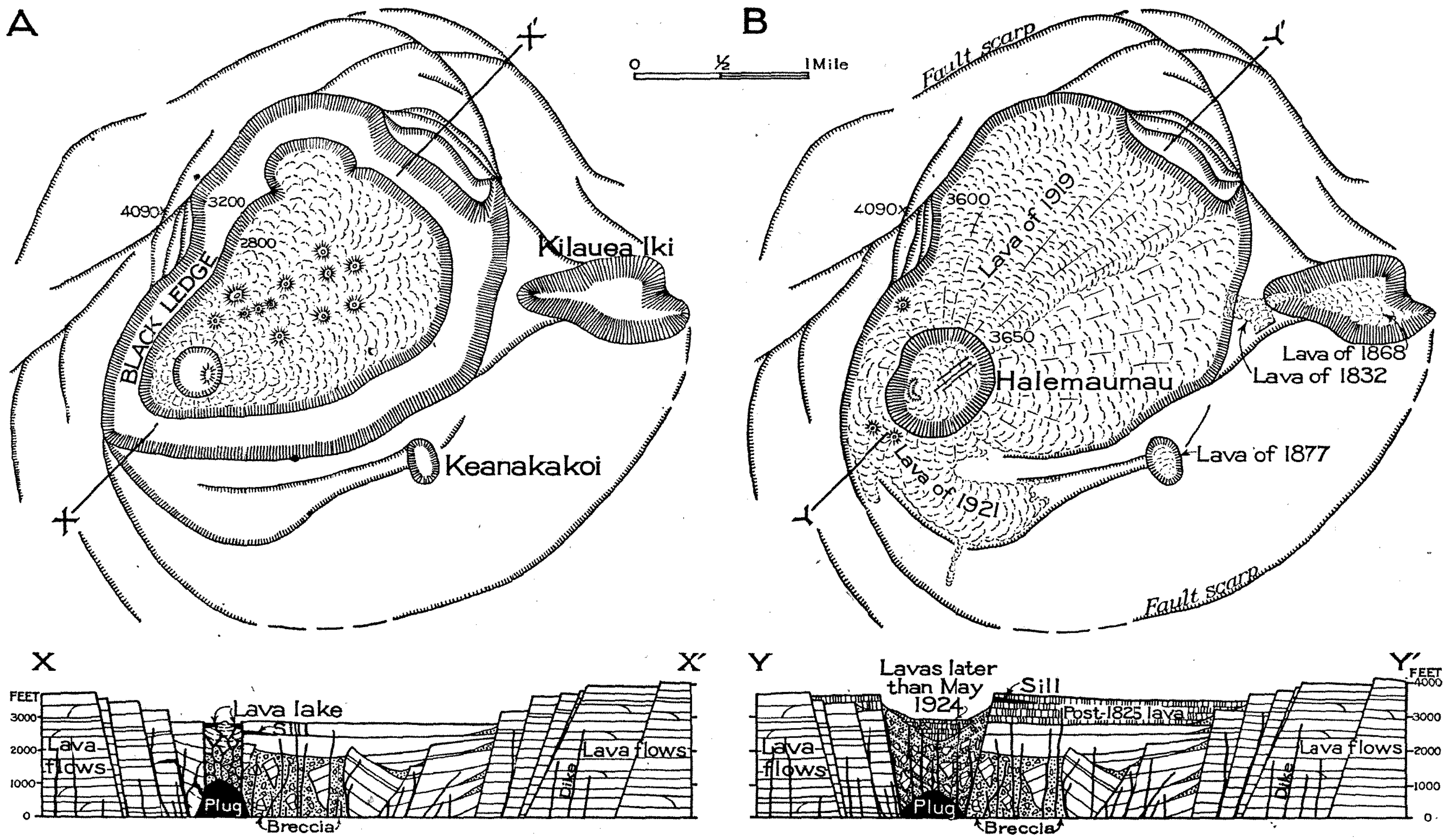


Figure 9. Generalized plans and sections of Kilauea Caldera in 1825 (after Malden) (A), and 1944 (B). Approximate altitudes in feet. Ash beds omitted. The structure beneath the caldera is hypothetical.

many dikes are plastic or liquid, and large segments of rock between these dikes are slowly moving downward en masse into the magma reservoir. Such a process would greatly accelerate engulfment. At depths of 3,000 feet below the floor of former calderas on Oahu, no evidence has been found of dikes that were sheared when plastic or semiplastic, but such evidence might be difficult to find or might be at greater depths. Numerous sheared dikes have been found with and without associated fault breccia and rubble, indicating that faulting of solid rocks takes place in the upper part of the crust. Also, some rubble is carried out in the lava flows erupted in the calderas but as most of the flows do not escape, the rock floated upward in this manner does not materially contribute to the net collapse.

Williams[27] believes that the Hawaiian calderas result from collapse due to lowering of the magma column by dike injection at depth and drainage through fissures in the flanks. Lava is erupted more frequently in the caldera than on the flanks of Mauna Loa. Also flank eruptions occur throughout the entire history of a shield-type volcano and not just during the caldera phase. The intense gas pressure and highly buoyant type of eruption typical of Mokuaweoweo imply no lack of magma below the caldera. The dikes do not have time to cool between the frequent eruptions which are only 2 to 4 years apart. Also the rocks at the bottom are in contact with the magma column and all are in the path of ascending hot gases. Heated gases, fluxing and stoping at the top of the lava column, and the liquid state of the dikes in the caldera complex combine in weakening the summit area until failure of the edifice takes place. The rock sinking into the magma is remelted and poured out again. Thus, the Hawaiian calderas are of the Glen Coe type[28] and result from the collapse of the roof of the magma chamber along ring fractures.

Craters.—Pit craters, deep nearly circular depressions perforating the shield-shaped lava domes from which little or no lava has been extruded, are striking features of the landscape (pls. 6, 18, 37A). From exposures of dissected pit craters elsewhere in the islands, it is known that they are funnel-shaped and filled with breccia. The breccia is usually talus derived from the crater walls. The original land surface bounded by circular faults has moved downward en masse in some pit craters (pl. 18 and fig. 10). Apparently magma, stoping and fluxing at shallow depth over a period of time, usually along a fissure, forms a vertical pipe. Recession of the magma causes the surface to collapse and the shattered rock to

---

[27] Williams, Howel, Calderas and their origin: California Univ., Dept. Geol. Sci., Bull., vol. 25, no. 6, p. 287, 1941.

[28] Idem, p. 246. Williams' "Kilauea type" of caldera appears probably to be merely a variety of the broader Glen Coe type.

tumble downward. Large pit craters are generally formed by repetition of the process. Small explosions followed by collapse occurred at two of the pit craters—Alae on Kilauea, and Lua Poai on Mauna Loa. Halemaumau has been enlarged in this manner.

The pit craters range in diameter from a few feet to about 1 mile and in depth from 50 to 800 feet. Devil's Throat in Kilauea is 250 feet deep and 50 feet in diameter. Its walls overhang slightly. Twenty pit craters indent Kilauea and twelve indent Mauna Loa. They do not occur on Mauna Kea or Kohala as they are made chiefly during eruption of primitive lavas and are filled during later phases.

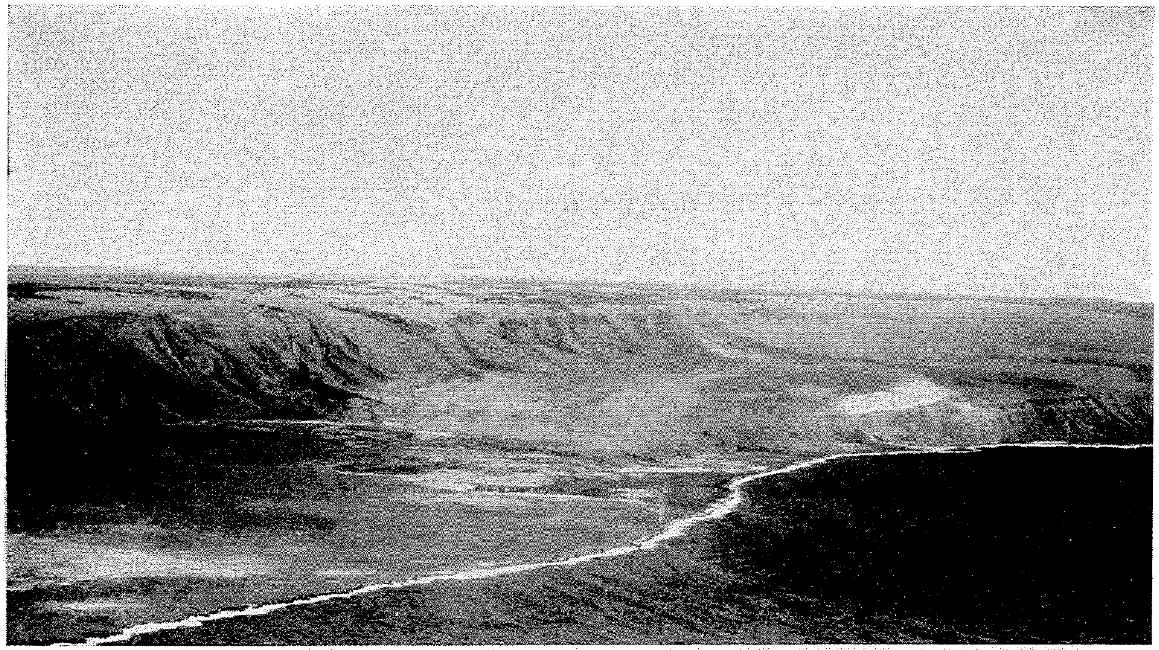
In addition to the pit craters are the orifices of lava fountains in secondary cones. Sometimes these craters are enlarged by collapse at the end of an eruption.

OTHER DEPRESSIONS.—Numerous small depressions, not craters, ranging from 5 to 50 feet across and 5 to 50 feet deep are common except on Mauna Kea. They are symmetrical, smooth, and funnel-shaped in an ash or soil covered area, but are bordered by abrupt ledges in rocky land. They are generally the result of collapse along fissures, faults and tubes. The smaller ones may be molds of large trees which were surrounded by lava, the wood and charcoal subsequently disappearing. None are sinkholes as they are not the result of collapse over a solution cavern. Hundreds of the type due to fissuring and faulting indent the summit of Kohala Mountain and the rift zones of Kilauea and Mauna Loa volcanoes. They usually fall in straighter lines than the holes in the roofs of lava tubes. Some in wet regions contain water and at the summit of Mauna Loa some contain ice.

RIFT-ZONE GRABENS.—Trench-shaped depressions or grabens, formed by blocks sinking between roughly parallel faults, are common in the rift zones of Kilauea, Mauna Loa, and Kohala. The collapse is a volcanic process similar to that which forms calderas except that it results in longitudinal instead of circular depressions. Repeated outflows of lava in the rift zones tend to compensate for the collapse; hence, the depth of the grabens is only a fraction of the total collapse that has taken place. The grabens range from a few feet to 250 feet in depth, from a few feet to half a mile in width, and from 600 feet to 3 miles in length.

FAULT SCARPS

Fault scarps are geomorphic features of Kilauea, Mauna Loa, and Kohala Mountain (fig. 11). It is believed that the eruptions under the sea were commonly explosive and that the submarine foundation of the volcanoes contains much more pyroclastic debris than the parts above sea level. These relatively unstable materials



Above: Plate 17A. Hilina (left) and Kapukapu (right) fault escarpments veneered in places by later lavas on the south shore of Kilauea Volcano. Photo by USAAF.

Below: Plate 17B. Kealakekua Bay and fault escarpment. Deltas of late lava that have spilled over the cliff form the sides of the bay. The small white spire on the far shore marks the place where Captain Cook was killed. Photo by USAAF.

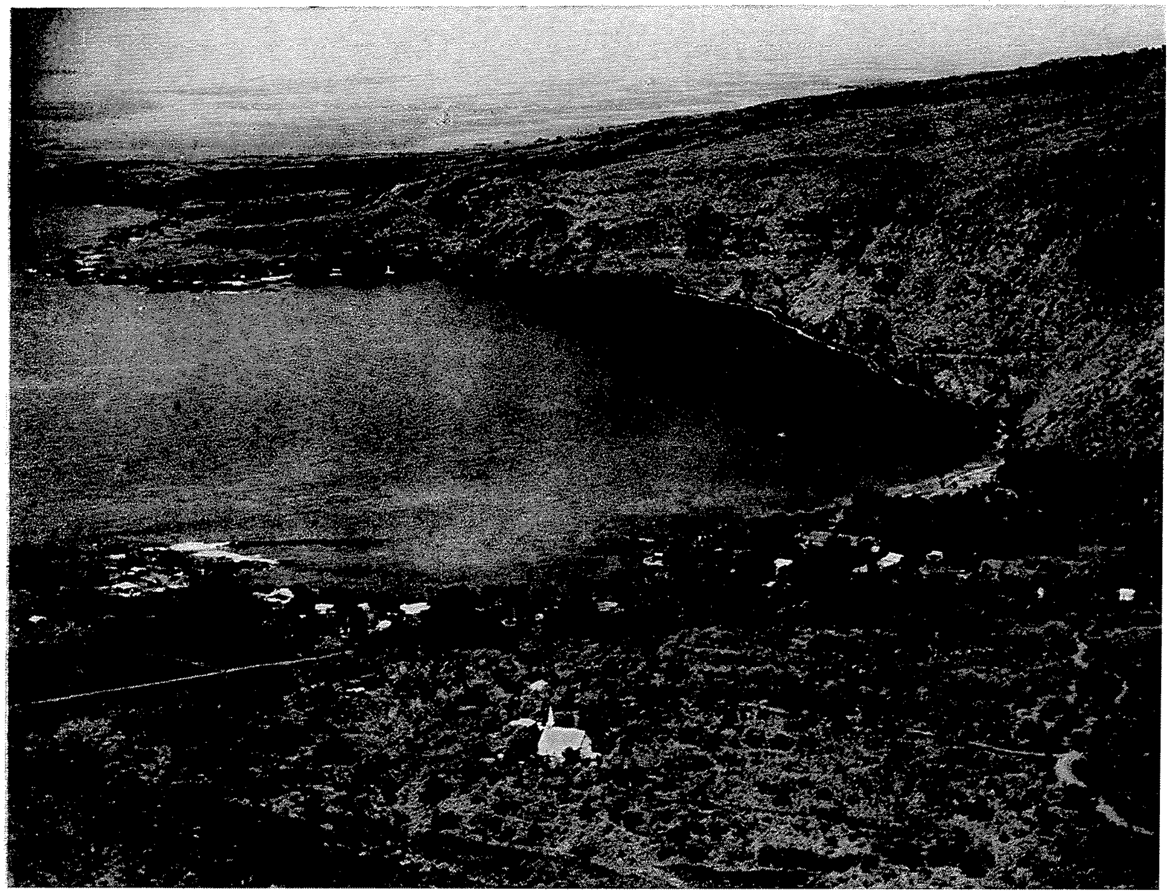


Plate 18. Vertical air view of Lua Poholo crater near the summit of Mauna Loa Volcano. The geology is explained in the facing figure. Photo by USAAF.

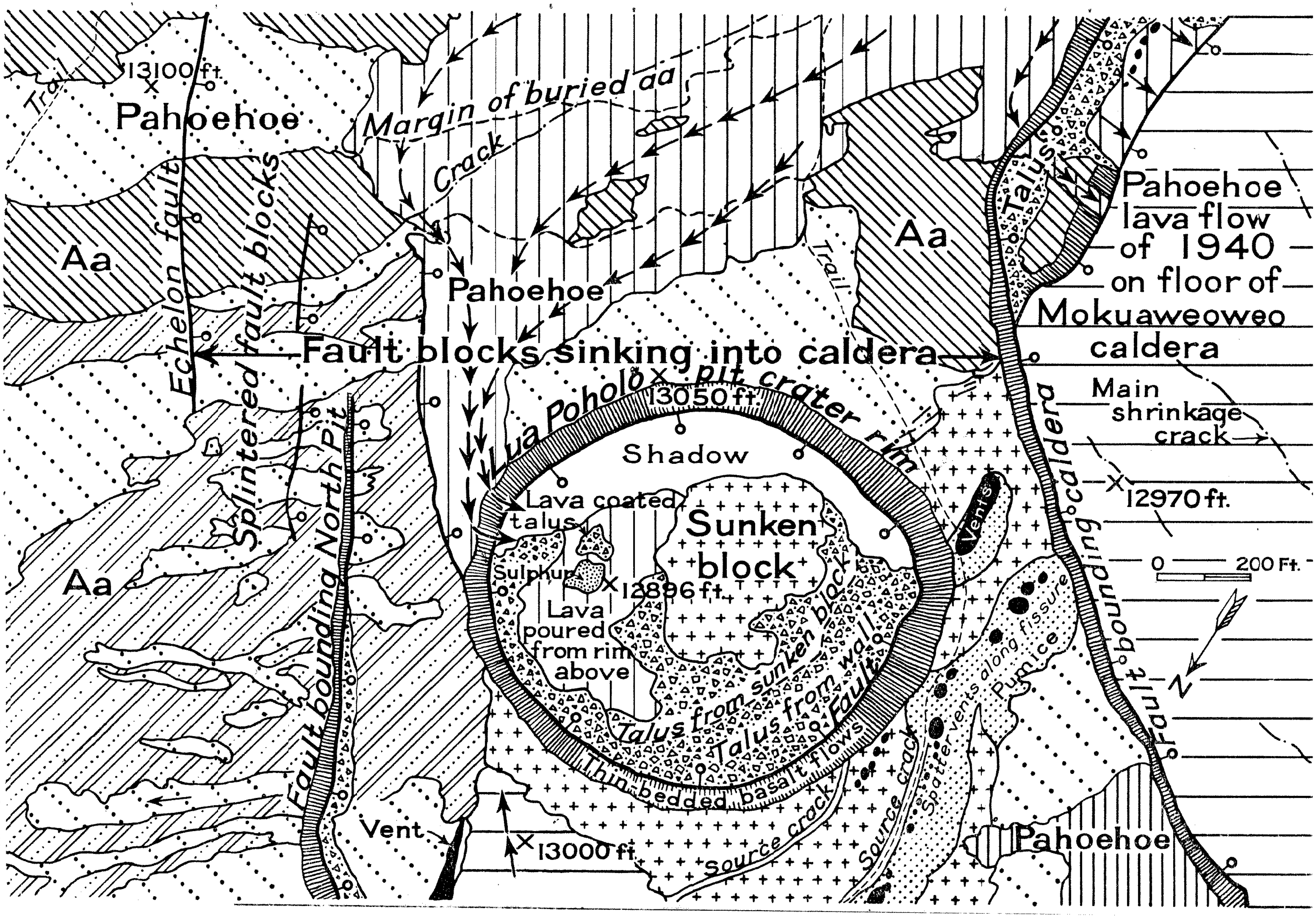
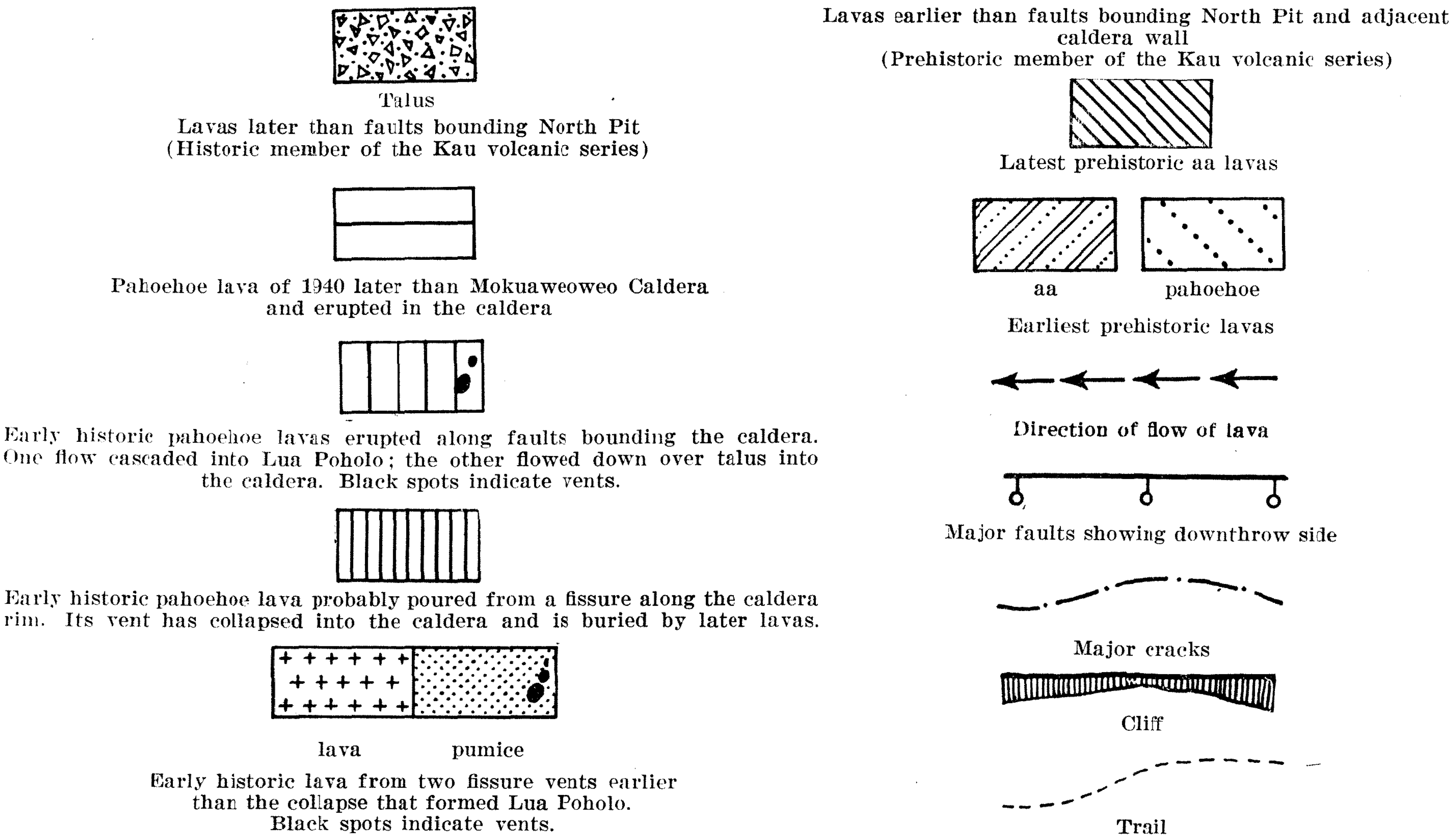


Figure 10. Geologic map of Lua Poholo crater, Mauna Loa Volcano. (See page 36 for explanation.)



Talus

Lavas later than faults bounding North Pit
(Historic member of the Kau volcanic series)

Pahoehoe lava of 1940 later than Mokuaweoweo Caldera and erupted in the caldera

Early historic pahoehoe lavas erupted along faults bounding the caldera. One flow cascaded into Lua Poholo; the other flowed down over talus into the caldera. Black spots indicate vents.

Early historic pahoehoe lava probably poured from a fissure along the caldera rim. Its vent has collapsed into the caldera and is buried by later lavas.

lava — pumice

Early historic lava from two fissure vents earlier than the collapse that formed Lua Poholo. Black spots indicate vents.

Lavas earlier than faults bounding North Pit and adjacent caldera wall
(Prehistoric member of the Kau volcanic series)

Latest prehistoric aa lavas

aa — pahoehoe

Earliest prehistoric lavas

Direction of flow of lava

Major faults showing downthrow side

Major cracks

Cliff

Trail

Explanation of figure 10, page 35 (Geologic map of Lua Poholo area, Mauna Loa Volcano).

in the base of the island may account for the great number of faults dipping seaward along the shores of the island.

Mauna Loa fault scarps.—The Kealakekua fault scarp[29] in Kona is about 6 miles long and 1,250 feet high (pl. 17B). It trends southeastward for 5 miles, then turns southward, and disappears under a mantle of late Mauna Loa flows. It was probably formed by several echelon faults rather than a single fault (fig. 11). Its northwestern end curves and merges with the sea cliff forming Kealakekua Bay. A low cliff, mantled in most places by later lavas, is traceable from this bay for 6 miles northward to Keauhou Bay.

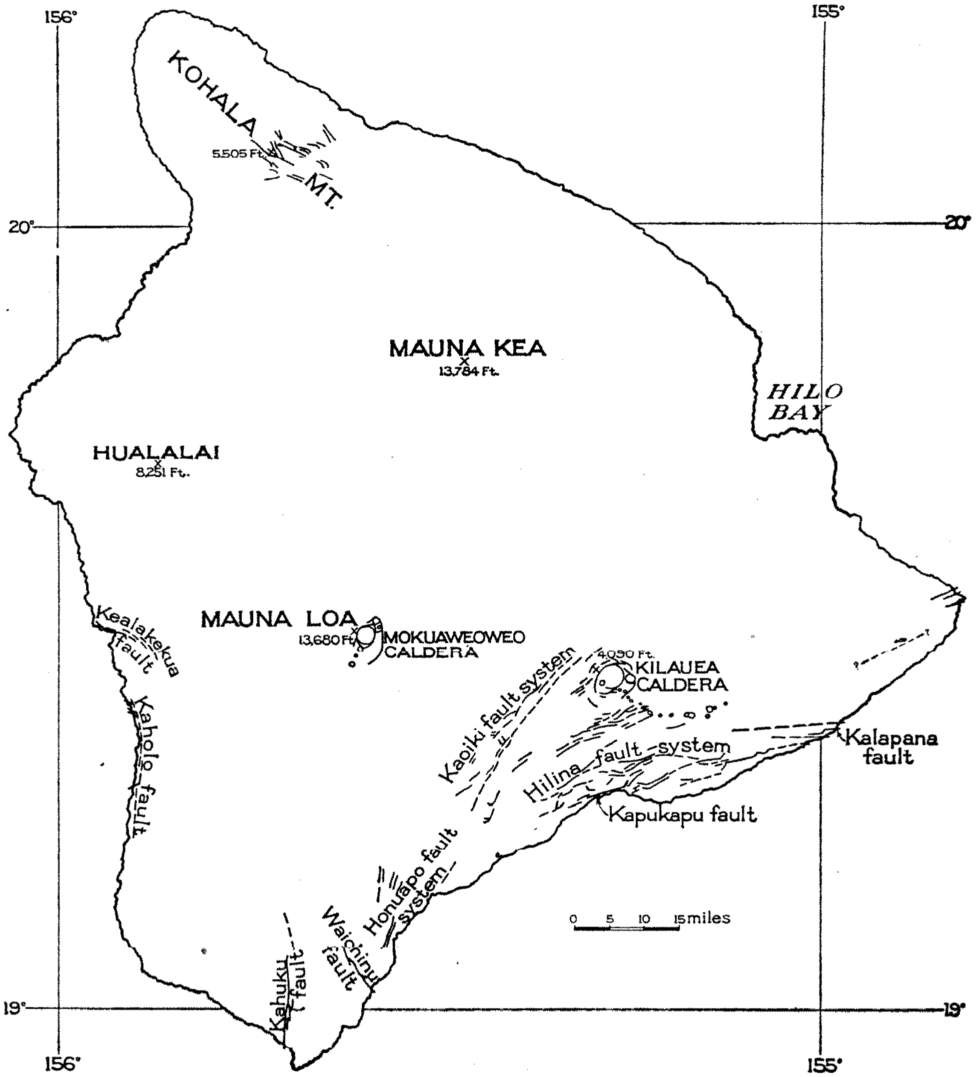


Figure 11. Map of Hawaii showing visible faults (solid lines), concealed faults (broken lines), and names of the fault systems.

---

[29] Dana, J. D., Characteristics of volcanoes, p. 30, New York, 1890.

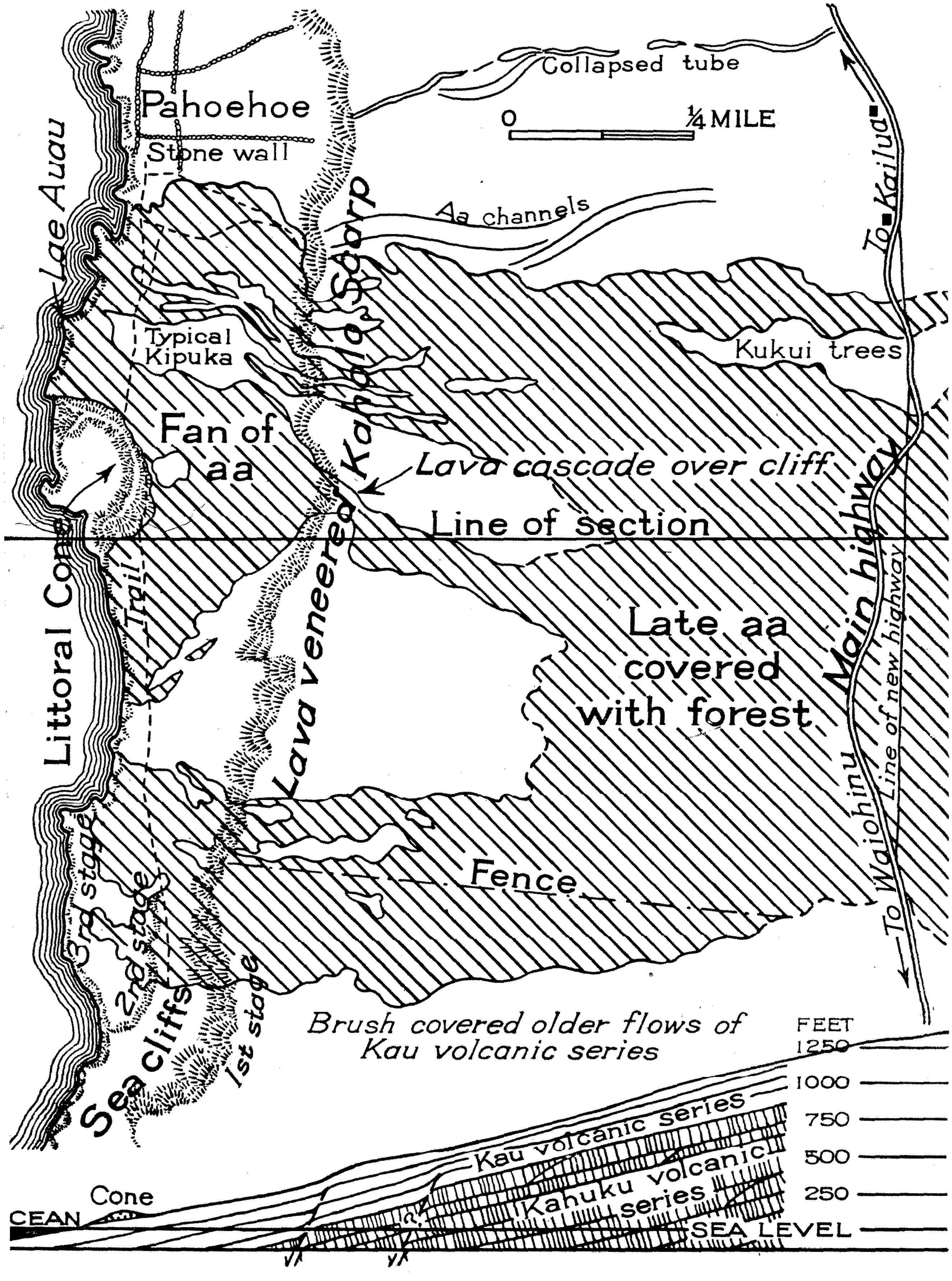


Figure 12. Photointerpretation of the area in the Kona District shown in plate 19. Three stages of sea cliffs are shown in the lower left of the plan.

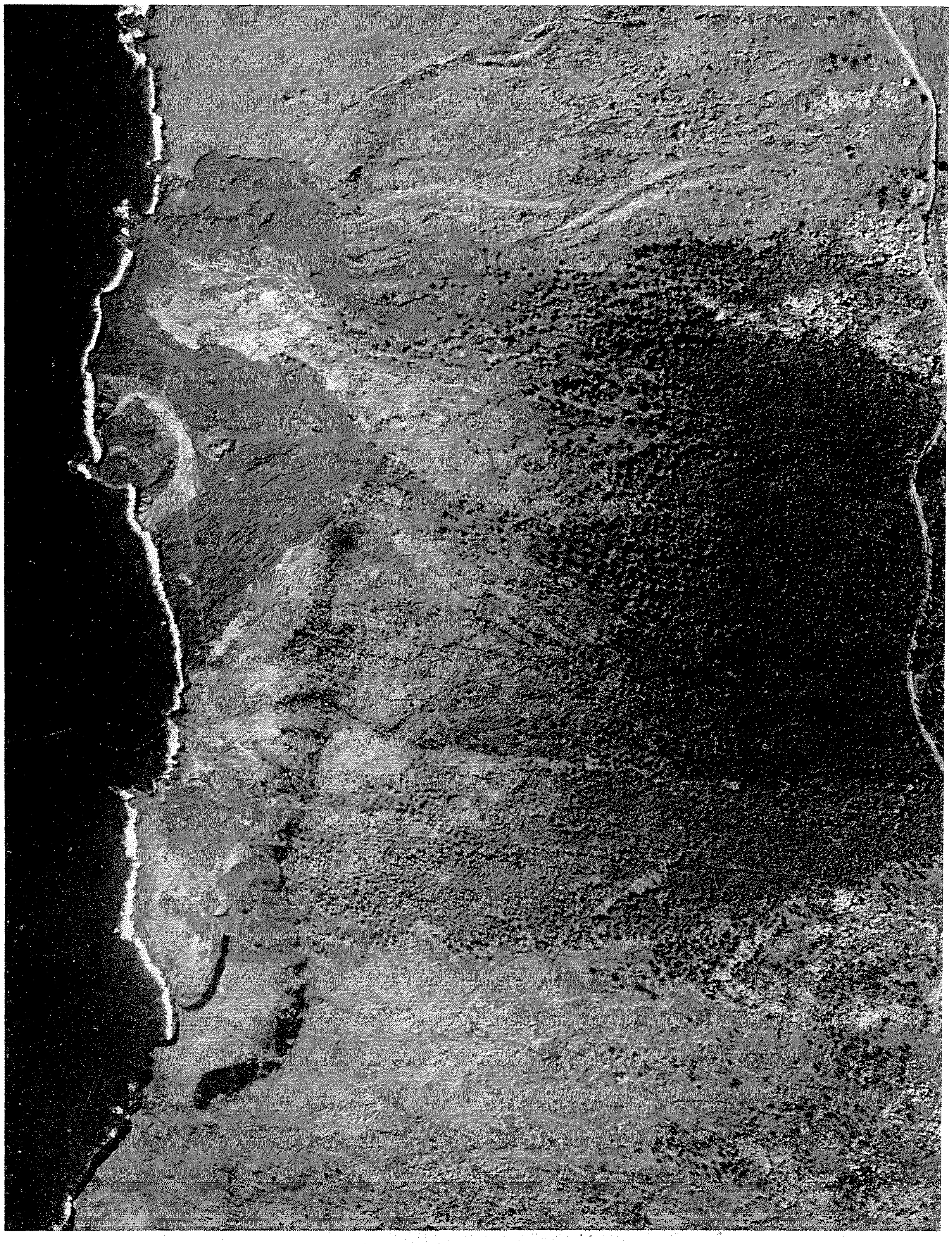


Plate 19. Vertical air view of Pali Kaholo, Kona District. The geology is explained in the facing figure. Photo by USAAF.

Plate 20A. Kapukapu fault escarpment 1,000 feet high showing thin ash beds (light colored thin layers) in the Hilina volcanic series on the south shore of Kilauea Volcano. Photo by National Park Service.

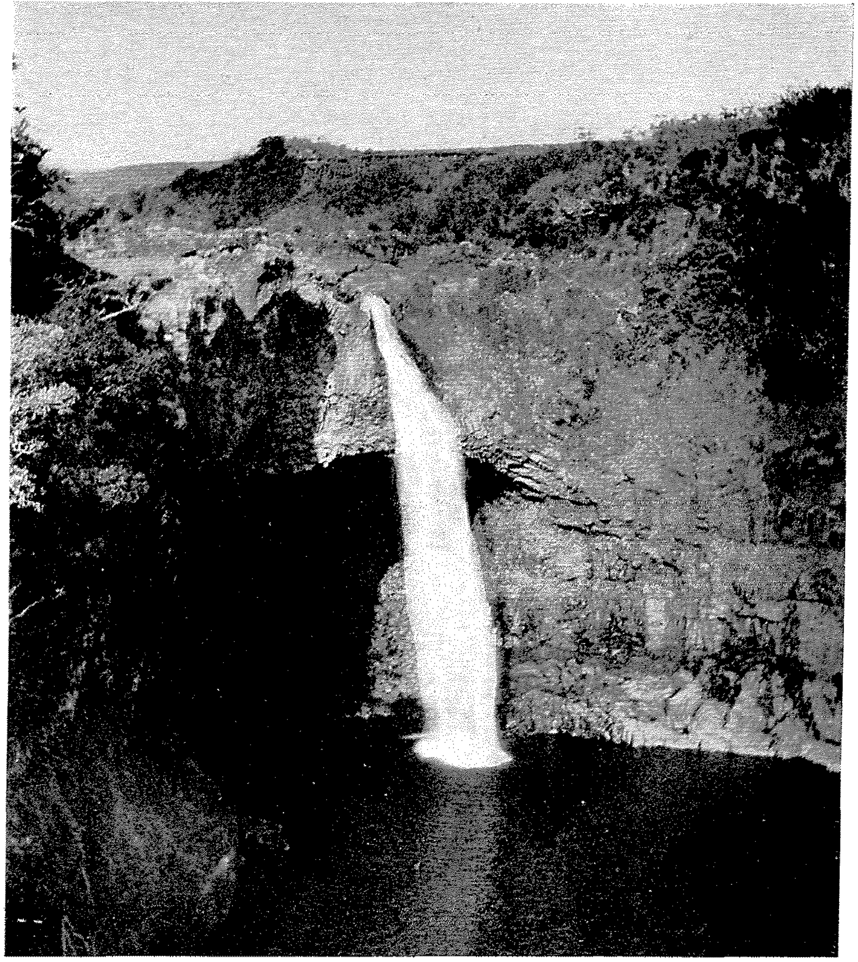


Plate 20B. Rainbow Falls near Hilo. The lavas on the right bank are from Mauna Kea. The lava under the falls is a late valley-filling flow from Mauna Loa Volcano. Photo by C. H. Merriam.

In places the cliff passes inland an eighth to a quarter of a mile but in other places it forms the present sea cliff. It appears to be a sea cliff formed during a repose period late in the history of Mauna Loa, or at least during a time when this sector of the mountain was not overflowed by lava. Ash ½ to 1 foot thick underlies the lavas that spilled over the cliff.

The Kaholo scarp extends from Milolii northward for 16 miles to Honaunau. It is 500 feet high at Pali Kaholo but is less than 250 feet high for most of its length. Subsequent lava flows have spilled over its entire length building fans and plains of lava at its foot (pl. 19 and fig. 12). At Hookena the scarp reaches the coast, and from this point northward decreases rapidly in height and in places is obscured by later flows. It appears to be an echelon fault scarp associated with the Kealakekua fault, for as the Kealakekua scarp dies out southward, the Kaholo scarp increases in height as though the displacement had offset to the west. A similar relation exists in the Hilina fault system along the southern coast of Kilauea. The Kaholo scarp dies out south of Milolii. In spite of the heavy mantle of later lavas along the entire scarp, definite scallops can be discerned in its buried face suggestive of modification by marine erosion.

The possibility exists that the Kaholo scarp, because of the way it parallels the coast, is not due to faulting but to marine erosion only. If so, it indicates a relatively long period in which this sector of Mauna Loa was free from lava flows. No buried soil or lava-filled stream channels have been found in the area to support the hypothesis that a repose period lasted long enough for a sea cliff 500 feet high to have been cut, but such features may not be exposed.

Much of the slope between Kaholo scarp and the highway is steeper than the average slope of Mauna Loa above the highway, which suggests that older parallel fault scarps lie buried in the stretch seaward of the highway (section fig. 12). Also, this slope is shorter than the opposite or southeastern slope. Although other factors may have caused asymmetry, faulting is the preferred hypothesis, especially as the longer southeastern slope of Mauna Loa is known to have been shortened by faulting.

The Kahuku scarp extends north 10 miles from Kalae and reaches a height of 600 feet. It can be traced for 18 miles undersea (fig. 47). Pali o Ka Eo appears to be an echelon extension northward of the Kahuku fault. It is 3 miles long and 250 feet high.

The Waiohinu scarp extends 4½ miles inland from Waikapuna Bay to Waiohinu. It is less than 50 feet high for most of its length. It has not moved since 1868.

The Kaoiki scarp starts 2 miles northeast of Kilauea and extends southwestward for 18 miles where it disappears under late lava flows. The foot of the cliff is the boundary between Kilauea and Mauna Loa. The scarp rises in places 500 feet and is terraced due to movement along a series of parallel fault planes. It is somewhat smoothed in places by subsequent flows and its base is deeply buried.

A series of nearly parallel ancient fault scarps modified by erosion and ash lie inland from Hilea (fig. 11). They appear to extend southward to Honuapo, greatly smoothed by a heavy mantle of late lavas. There, recent movement has displaced the late lavas slightly, but between Naalehu and Waiohinu the latest lavas are undisturbed. These faults will be called the Honuapo fault system.

The Kaoiki fault system is probably an extension of the Honuapo set of faults, as the abnormally steep seaward-facing slopes inland of Pahala have the form of fault scarps deeply buried by subsequent lava flows.

The fault scarps bounding Mokuaweoweo are circular and reach a maximum height of 650 feet on the west side. Splintered echelon fault blocks typify the early stages of the collapse (pl. 18 and fig. 10).

KILAUEA FAULT SCARPS.—The Hilina fault scarp on the southern slope of Kilauea reaches a maximum height of 1,500 feet and is about 12 miles long (pl. 17A). It dies out westward in numerous smaller faults that spread fanwise and are veneered by late flows. It shows recent movement. Its eastern extension is known as Pohiokeawe Pali. The middle part of the scarp has been smoothed somewhat by late flows that spilled over it and formed a voluminous fan-shaped mass at its foot. Several stages in the development of a fault scarp being buried intermittently by lava flows are shown in figure 13.

The Kapukapu fault scarp forms the coast south of Hilina Pali (pl. 20A). It reaches a maximum height of 1,050 feet and extends northeastward for 8 miles where it joins the Hilina fault scarp.

The Hilina-Kapukapu scarp extends eastward 7 miles before it dies out. It reaches a height of 750 feet 4 miles east of the Kau-Puna District boundary. For brevity this group of faults will be called the Hilina fault system.

The slope inland from the Hilina fault system increases in steepness eastward at about the same rate the fault scarp decreases in height. This slope apparently owes its steepness to late lavas mantling a series of high echelon fault scarps that entered the sea at Kalapana. This buried fault scarp system will be called the Kalapana scarp. It is about 7 miles long.

An echelon series of fault scarps a few to 100 feet high bound the southwest rift-zone graben of Kilauea and scarps reaching 400 feet high bound Kilauea Caldera.

KOHALA FAULT SCARPS.—The Kohala scarps reach heights of 250

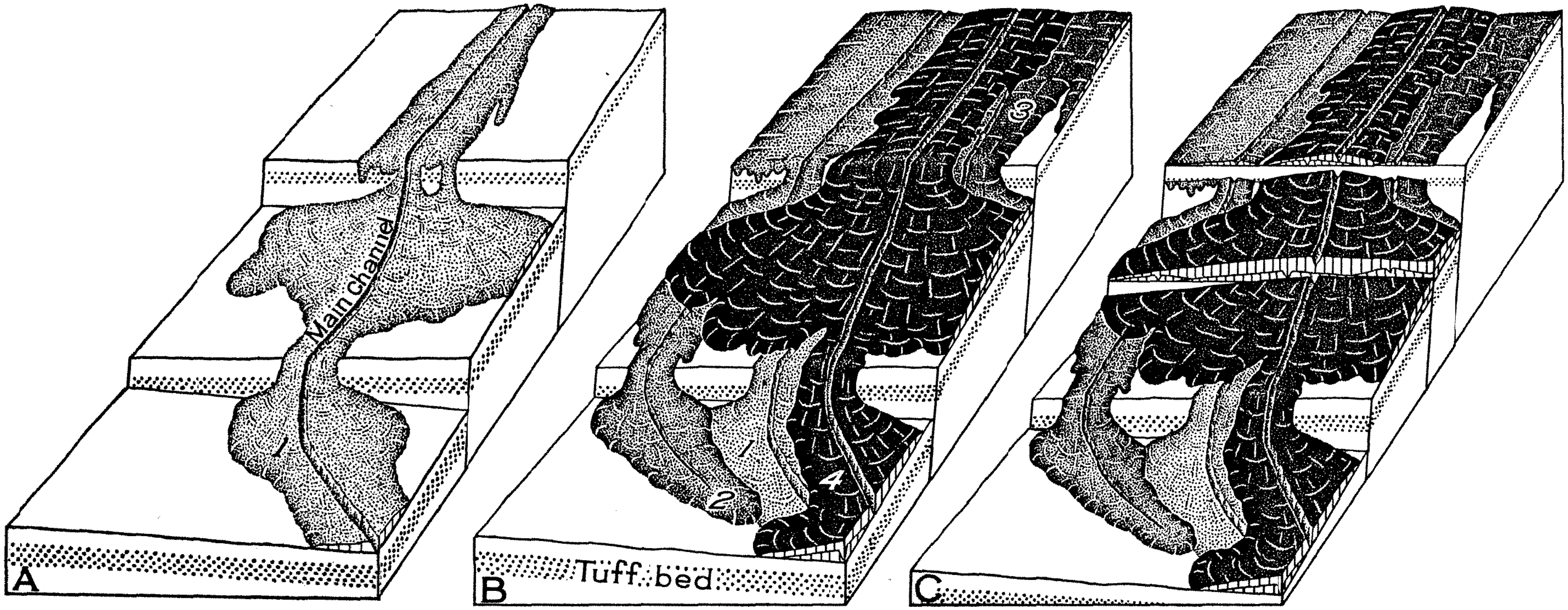


Figure 13. Diagram illustrating the relation of faulting to successive lava flows. **A**. Lava flow spills over two fault scarps forming narrow cascades on the scarps and fans at their bases. The front block is tilted down to the right which deflects the lava in that direction. **B**. Four lava flows have cascaded over the scarps. The inner scarp has been nearly buried. **C**. A new fault has split the middle block in two, the innermost fault has moved while the outermost fault has remained stationary. The two epochs of faulting are distinguished by the hanging plasters and cascades of lava on the innermost scarp and their absence on the newly formed scarp.

feet but average about 50 feet. They trend NW-SE across the summit of Kohala Mountain (fig. 11). Those on the northeastern side are in part slightly concave toward the southwest. They appear to be relict faults of a former caldera 3 miles long and 2 miles wide now partly obliterated by subsequent bulky cinder cones and lava flows.

VALLEYS AND CAUSE OF STREAM PATTERN

Stream erosion is a measure of age on a volcanic island, but it must be used with a knowledge of other factors involved. They are (1) steepness of slope; (2) amount and intensity of rainfall; (3) porosity of the land; (4) strength and structure of the rocks; (5) discharge and permanence of streams; (6) frequency and volume of lava flows interrupting stream erosion; (7) shape, structure, and intake of ground-water body drained by streams, if any; and (8) effect of faulting.

Stream erosion has greatly modified three areas of Hawaii—the northeastern slope of Kohala Mountain, the northeastern slope of Mauna Kea, and the southeastern slope of Mauna Loa (fig. 38). These areas stand in strong physiographic contrast to the rest of the island. The stream pattern is more or less radial and was determined chiefly by the configuration of the constructional form of the dome. However, faults determined the position of the headwaters of Waipio and Honokane Nui streams on Kohala Mountain, as pointed out by Jaggar[30] (fig. 14). Dana[31] and Powers,[32] on similar evidence, thought that Waipio and Waimanu streams followed fault lines. Jaggar inferred, from physiographic evidence, that the faults dipped eastward and bounded a block which had slipped northeastward. In the field they were found to dip westward, bounding one side of a graben on the summit. Locally, stream courses show the influence of lava flows and cones; for example, the Wailuku River follows the edge of late lava flows from Mauna Loa (pl. 20B).

Kohala valleys.—Four deep canyons, Waipio, Waimanu, Honokane Nui, and Pololu, ranging from 1,000 to 2,500 feet in depth, notch the northeastern slope of Kohala Mountain (pl. 22). The factors causing amphitheater-headed valleys in tropical islands are discussed elsewhere.[33] Annual rainfall reaches 200 inches at their heads. Their flat floors are due to alluviation concurrent with submergence of the island. A few of the southern tributaries of Waipio Valley have been buried by lava flows from Mauna Kea. A lava

---

[30] Jaggar, T. A., Seismometric investigation of the Hawaiian lava column: Seismol. Soc. America Bull., vol. 10, p. 182, 1920.

[31] Dana, J. D., op. cit., p. 28.

[32] Powers, Sidney, Tectonic lines in the Hawaiian Islands; Geol. Soc. America Bull., vol. 28, p. 511, 1917.

[33] Stearns, H. T., and Vaksvik, K. N., Geology and ground-water resources of the island of Oahu, Hawaii: Hawaii Div. Hydrography, Bull. 1, p. 24, 1935.

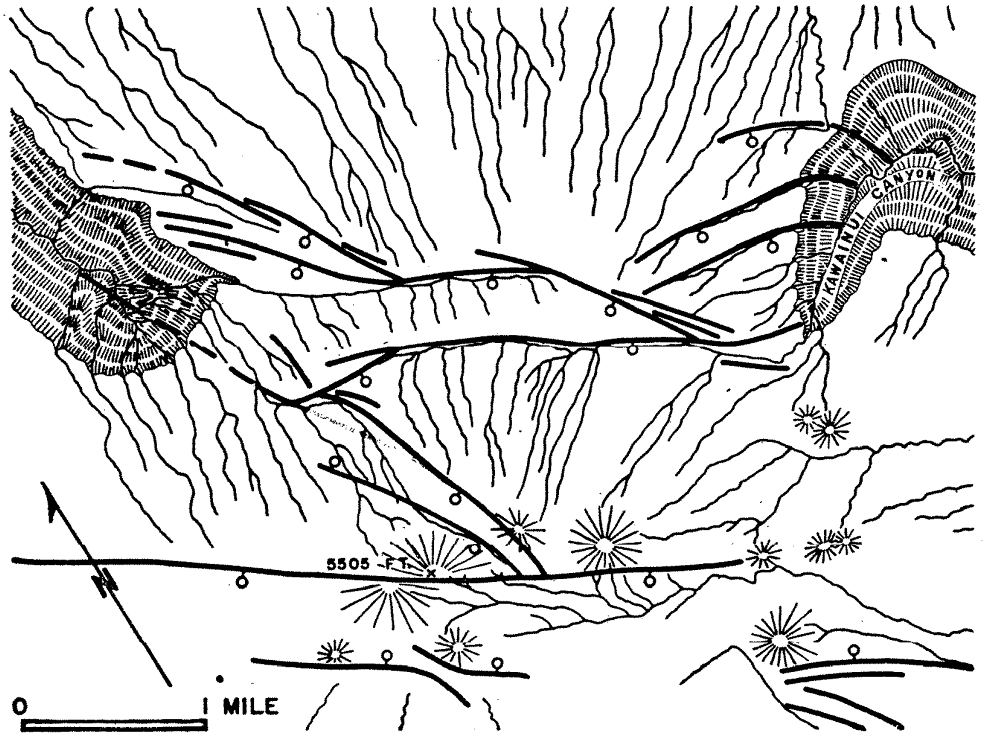


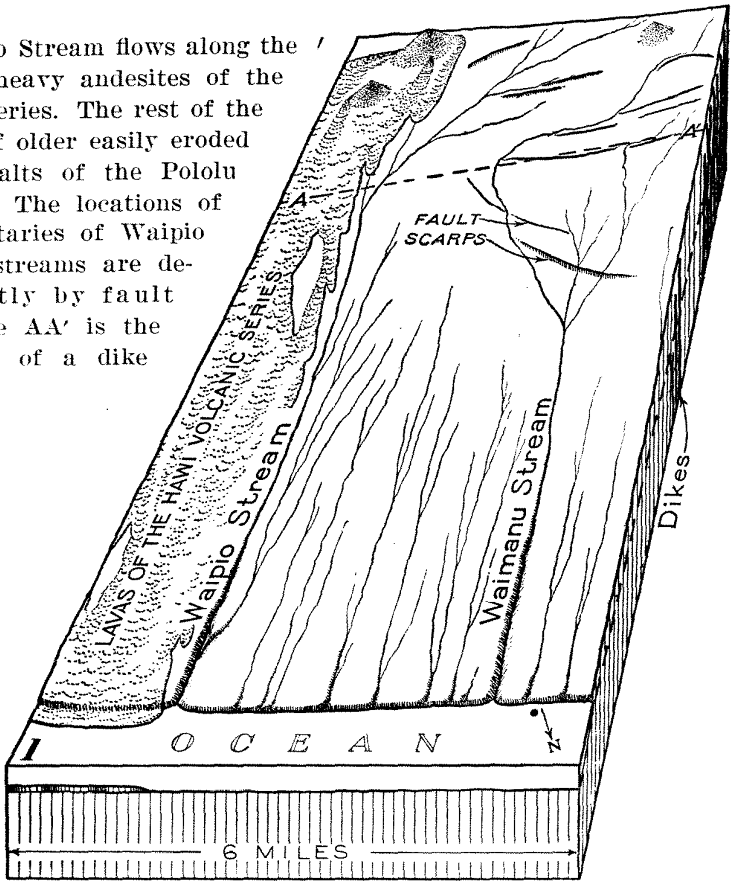
Figure 14. Map of the summit of Kohala Mountain showing how the drainage has been influenced by faulting. The downthrown side of the faults is indicated by small circles.

flow from Mauna Kea spilled into Hiilawe Canyon and reached the floor of Waipio Valley in the late Pleistocene.

The spectacular canyons of Waimanu and Waipio, cut deep into the carapace of Kohala dome, are separated by a very thin divide and have a complicated history. One would suppose from their topographic relations (pl. 1) that Waimanu Stream is about to pirate the Kawainui Branch of Waipio Stream. A field examination of these streams shows instead that Waipio Stream has captured most of the former drainage of Waimanu Stream. The head of Waimanu Canyon is choked with large landslides which the stream, with its present reduced water supply, is unable to remove. Waimanu Spring, 1 mile from the head of the canyon, at an altitude of 425 feet, discharges about 5,000,000 gallons a day in dry weather. The spring issues from behind a 12-foot dike. Above the spring the flow of the stream is only about 500,000 gallons a day. It is obvious that this small stream with about 1 square mile of drainage area did not cut a canyon 3,250 feet deep and a mile wide. Waimanu Canyon was cut at a time when high-level ground water gushed forth in large quantities from springs all the way to its present head.

Four stages in the geomorphic history of this area are shown in figure 15. Stage 1 shows the stream pattern at the close of the vol-

Stage 1. Waipio Stream flows along the margin of the heavy andesites of the Hawi volcanic series. The rest of the block consists of older easily eroded thin-bedded basalts of the Pololu volcanic series. The locations of the upper tributaries of Waipio and Waimanu streams are determined partly by fault scarps. The line AA′ is the north boundary of a dike swarm.



Stage 2. Waipio and Waimanu streams have cut deep canyons in the carapace of the mountain. Hiilawe, Waimanu, and Waihilau streams tap water confined between a few stray dikes whereas the headwaters of Waipio Stream have tapped water confined in the main dike swarm which trends parallel to the line AA′. The sea has cut high cliffs along the shore. The spur on the left side of Waipio Canyon, being armored by thick andesites, has resisted wave erosion better than the rest of the block consisting of basalt.

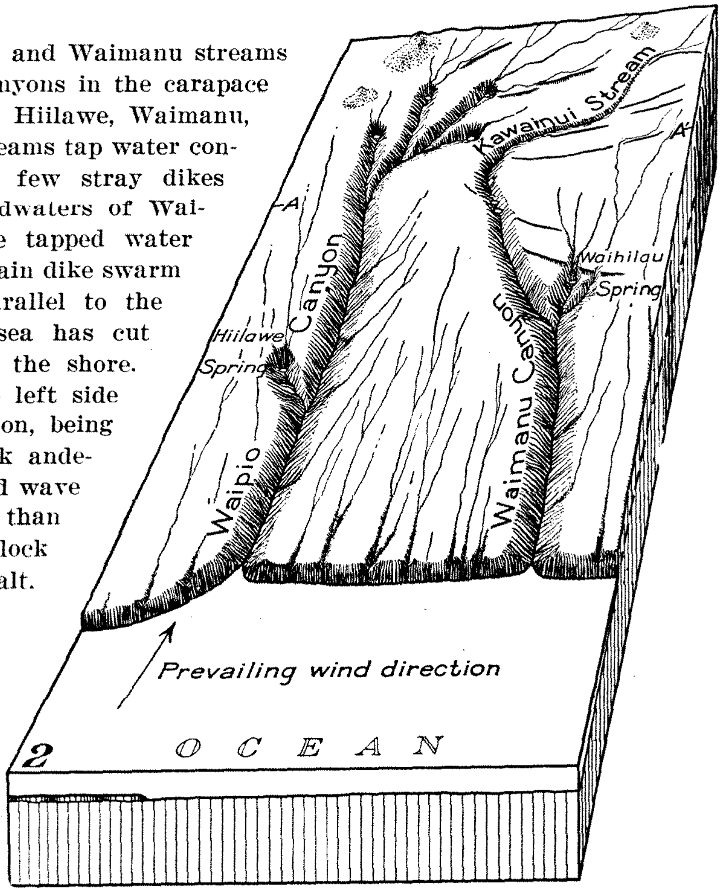
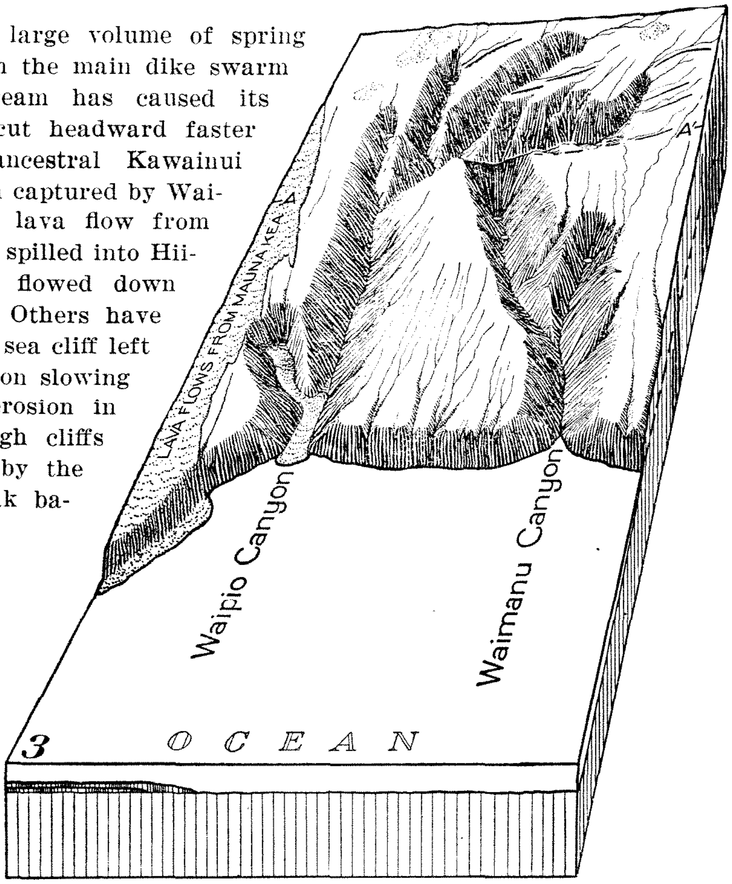
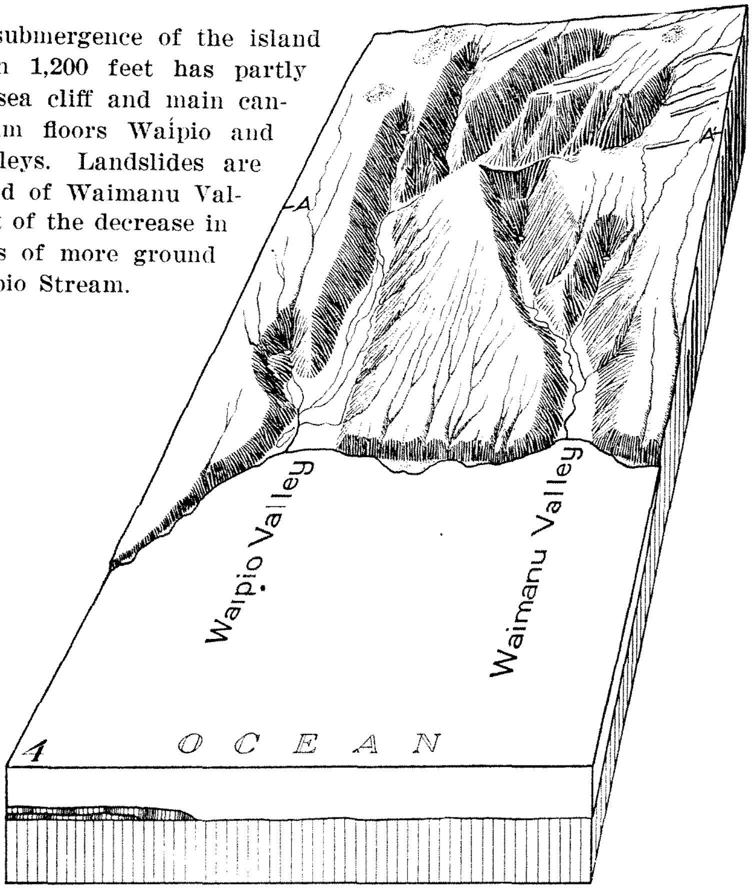


Figure 15. Four stages showing the development



Stage 3. The large volume of spring water tapped in the main dike swarm by Waipio stream has caused its tributaries to cut headward faster so that the ancestral Kawainui stream has been captured by Waipio Stream. A lava flow from Mauna Kea has spilled into Hiilawe cove and flowed down Waipio Valley. Others have spilled over the sea cliff left of Waipio Canyon slowing down marine erosion in this sector. High cliffs have been cut by the sea on the weak basalts.



Stage 4. A submergence of the island by more than 1,200 feet has partly drowned the sea cliff and main canyons. Alluvium floors Waipio and Waimanu valleys. Landslides are filling the head of Waimanu Valley as a result of the decrease in flow from loss of more ground water to Waipio Stream.

of Waipio and Waimanu valleys, Hawaii

canism as affected by low fault scarps 10 to 100 feet high, and the margin of the last thick lavas of the Hawi volcanic series. It is conjectured that the ancestral Kawainui branch of Waipio Stream was tributary to Waimanu Stream, from analogy with the next long stream to the east which even today makes a right angle turn on the rim of Kawainui Canyon and finds its way to Waihilau Canyon (pl. 23B). Also, Waimanu Stream without the large Kawainui drainage probably would not have become a master stream and tapped high-level ground water.

Stage 2 shows both Waipio and Waimanu streams cutting deep canyons as the result of tapping water confined at high levels between dikes. Waihilau, Waimanu, and Hiilawe streams tap water confined between a few stray dikes. Only five dikes are exposed in Waihilau, seven in Waimanu, and four in Hiilawe canyons. It is probable that more cut across Waimanu and are hidden by the thick landslides at its head, as a heavy swarm cuts across the northern wall of Kawainui Canyon just over the divide. Two hundred dikes are exposed in the tributaries of Waipio (pl. 1). They trend chiefly N. 50°-80°W. and lie south of the boundary shown in stage 2, and above the head of Waimanu Canyon. It is also known that they increase in number southward toward the axis of the southeast rift zone of Kohala Mountain and that the main body of high-level ground water and its recharge area lie south of the boundary. Thus, the spring coves at the head of Waipio Canyon progressively cut more dikes and tapped more water as they cut headward. One cove advanced westward toward Waimanu following the strike of a dike swarm. The same dike swarm supplied most of the water for the Waimanu Springs. The perennial flow of Waipio Stream with its spring-fed tributaries was greater than Waimanu Stream; hence, it cut a deeper canyon farther inland than Waimanu. This steeper gradient caused the western spring cove as it migrated westward to drain more and more ground water from Waimanu.

Stage 3 shows the piracy of the main tributary of Waimanu by the western spring cove of Waipio. The sea had cut cliffs more than 2,500 feet high in the weak rocks concurrent with the streams cutting the deep canyons. A lava flow from Mauna Kea has spilled into Hiilawe cove in the east side of Waipio Canyon.

Stage 4 shows the canyons after deep submergence and partial emergence. The lower stretches of the canyons have been deeply filled with alluvium to form flat floors. Piracy of Waimanu water has been nearly stopped as a result of the decrease in grade of Waipio Stream.

The numerous parallel streams between Waimanu and Honokane Nui canyons are typical of a basaltic dome. The smaller ones have hanging valleys at the coast (pl. 24A). Many of the tributaries of the large canyons fall from one plunge pool to another (pl. 21B).

Honokane Nui Canyon heads in two spring coves. It became a master canyon because low fault scarps diverted a large part of the drainage of the mountain into it and it soon tapped high-level ground water confined by dikes. The East and West branches cut the same wide dike near the Kohala ditch and originally both were probably fed by large springs at this point. The cove of the East Branch was closer to the recharge area of the high-level water; hence, as it receded it robbed more and more water from the West Branch cove.

Pololu Valley, the last deep canyon to the northwest, cuts only one dike and has its southeast branch partly filled with later lavas. It goes nearly dry during droughts indicating that the ground water which formerly drained into it has been pirated by the deeper Honokane Nui Canyon which cuts the same dike at a lower level.

In the chapter, "Geology of Kohala Mountain", it is shown that the canyons on the northeastern slope owe their great depth to the following factors: (1) They were cut in a kipuka segment of the dome that lay sheltered from subsequent lava flows by a caldera rim; hence, they are older than the other gulches of the dome. (2) The lava beds are weak primitive basalts in contrast with the strong andesites and trachytes veneering the rest of the dome. (3) They drain the slope with the greatest rainfall. (4) The streams tap the saturated dike complex of Kohala Mountain and ground water reaches them from beyond the crest.

The segment has a history closely parallel to that of the canyon country of Lanai.[34]

The only deep gulch on the leeward side of Kohala Mountain is Honokoa Gulch. Its upper part is shallow where the stream flows on strong andesites, but farther down where the stream flows on weak primitive basalts it has cut a narrow deep gorge.

MAUNA KEA VALLEYS.—The valleys draining the rainy windward slope of Mauna Kea are much smaller than those on Kohala Mountain. They seldom exceed 250 feet in depth, although a few attain depths of more than 500 feet. This difference in size results from the greater youth of the valleys on Mauna Kea. The dry western slope of Mauna Kea is largely undissected by stream erosion, and although the wet eastern slope is traversed by innumerable shallow gulches the area between the gulches is almost untouched by erosion. The topography is still in a youthful stage of the erosion cycle. Certain streams have cut deeper than others, and will in time cut master amphitheater-headed canyons. From north to south they are Kaawalii, Laupahoehoe, Maulua, Hakalau, Kolekole, Kawainui,

---

[34] Stearns, H. T., Geology and ground-water resources of the islands of Lanai and Kahoolawe, Hawaii: Hawaii Div. Hydrography, Bull. 6, p. 10, 1940.

and Honolii streams and the Wailuku River. These streams have cut deeper because they have intersected structures yielding perched perennial springs, and also because cones and thick lava flows have deflected drainage to them from neighboring streams. Erosion of the valleys may have been aided also by the absence or lesser abundance of resistant beds of andesite, as compared with neighboring areas. Laupahoehoe, Kawainui, and possibly some of the other streams have been interrupted in their downcutting by later lava flows. Even the largest canyons are cut back only 1 to 5 miles, heading in amphitheaters beyond which the gulches are generally less than 100 feet deep.

The prominent gulches on the upper slopes of Mauna Kea bear a direct relationship to the glacier which covered the top of the mountain during late Pleistocene time. The outlines of the glacier are shown on plate 1. It will be seen that each of the large gulches is situated directly downslope from a projecting lobe of the ancient glacier, and that the deepest parts of the gulches lie within a mile or two of the former ice margin. Irregularities of topography undoubtedly guided the movement of the ice and determined the position of the most active and farthest advancing lobes, but the generally small size of the gulches within the area covered by the glacier suggests that prior to glaciation the gulches were shallow. The presence of glacial outwash gravel in a shallow gulch which cuts across the present Pohakuloa Gulch indicates that this deep gulch was cut during late glacial or post-glacial time. The close relationship of the short deep segments of the gulches to former glacial lobes shows that the great local deepening of the gulches was the result of erosion by large volumes of glacial melt-water escaping at the ends of the lobes.

Few places exist in Hawaii where the effect of rainfall on the rate of stream erosion is so clearly shown as on Mauna Kea. The leeward and windward slopes are of approximately the same age, yet stream erosion is relatively negligible on the northwestern, western, and southern slopes where the rainfall is less than 40 inches annually. Over large areas on these slopes no drainage pattern has developed as yet, in spite of the fact that the rocks are pre-Wisconsin in age and have a fair cover of ash soil. Nearly all the rainfall is absorbed or transpired. As time passes, the physiographic contrast will become even greater, the wet windward slope becoming rugged and deeply dissected while the leeward slope remains little eroded.

The asymmetry of the Wailuku River system, with tributaries from the northern side only, is caused by the youthful lava flows from Mauna Loa progressively burying the southern tributaries.

MAUNA LOA VALLEYS.—Shallow gulches drain the southwestern slope of Mauna Loa below an altitude of 6,500 feet. The rainfall reaches more than 60 inches annually on this slope as a result of trade winds impinging against it after passing over Kilauea (fig. 36).

The shallow streams flow through subdued canyon-like topography (pl. 21A). It has been shown that five deep canyons were carved in this slope and were partly filled subsequently with hundreds of feet of lava[35] (fig. 16). Erosion continued between lava flows which accounts for the widening of the valleys and the nearly complete destruction of the former sector-shaped interstream divides. From northeast to southwest, the canyons were the ancestral Wood, Punaluu, Ninole, Hilea, and Waiohinu valleys. Prior to burial they ranged from 2 to 6 miles in length, 1 to 1½ miles in width, and 1,000 to probably as much as 5,000 feet in depth. They were comparable to the present great canyons in Kohala Mountain. They indicate either a period of quiescence in the building of Mauna Loa in late Tertiary or earliest Quaternary time, or protection from lava flows by a fault escarpment above this area. As no evidence of such an escarpment exists, the hypothesis of quiescence is favored.

PLAINS

The Waimea Plain and the Interior Plateau are alike in origin and form, but usage has named one a plain and the other a plateau (fig. 6).

The Waimea Plain is the flat land at 2,500 to 3,000 feet above sea level between Mauna Kea and Kohala Mountain. It has an area of about 25 square miles. It is named from the village of Waimea that lies on it. The plain is covered with ashy soil which is underlain with lavas from Mauna Kea. It resulted from these lavas ponding against the older dome of Kohala. It is similar in origin to the Isthmus of Maui, Schofield Plateau on Oahu, and Hoolehua Plain on Molokai.

The Interior Plateau is the relatively flat land lying between 4,500 and 7,000 feet above sea level in the center of the island. It has an area of about 150 square miles. The eastern part has been named the Humuula Saddle, and the western part the Hualalai Saddle.[36] The plateau is covered with fresh lavas chiefly derived from Mauna Loa and has been formed by the lavas of Mauna Kea, Hualalai, and Mauna Loa banking against each other.

Smaller plains or aprons formed by late lava flowing into the sea are numerous along the coast of Hualalai, Mauna Loa, and Kilauea. The aprons range in area from 1 to 4 square miles. The Waiakea flat, on which Hilo lies, is typical of these plains. It may be underlain by a coral reef. The late andesite flow, which partly filled Laupa-

---

[35] Stearns, H. T., and Clark, W. O., Geology and water resources of the Kau District, Hawaii: U. S. Geol. Survey Water-Supply Paper 616, pp. 52–54, 1930.

[36] Wentworth, C. K., Geographic background, in Hawaii Terr. Plan. Bd., 1st Progress Rept., pl. 8, 1939.

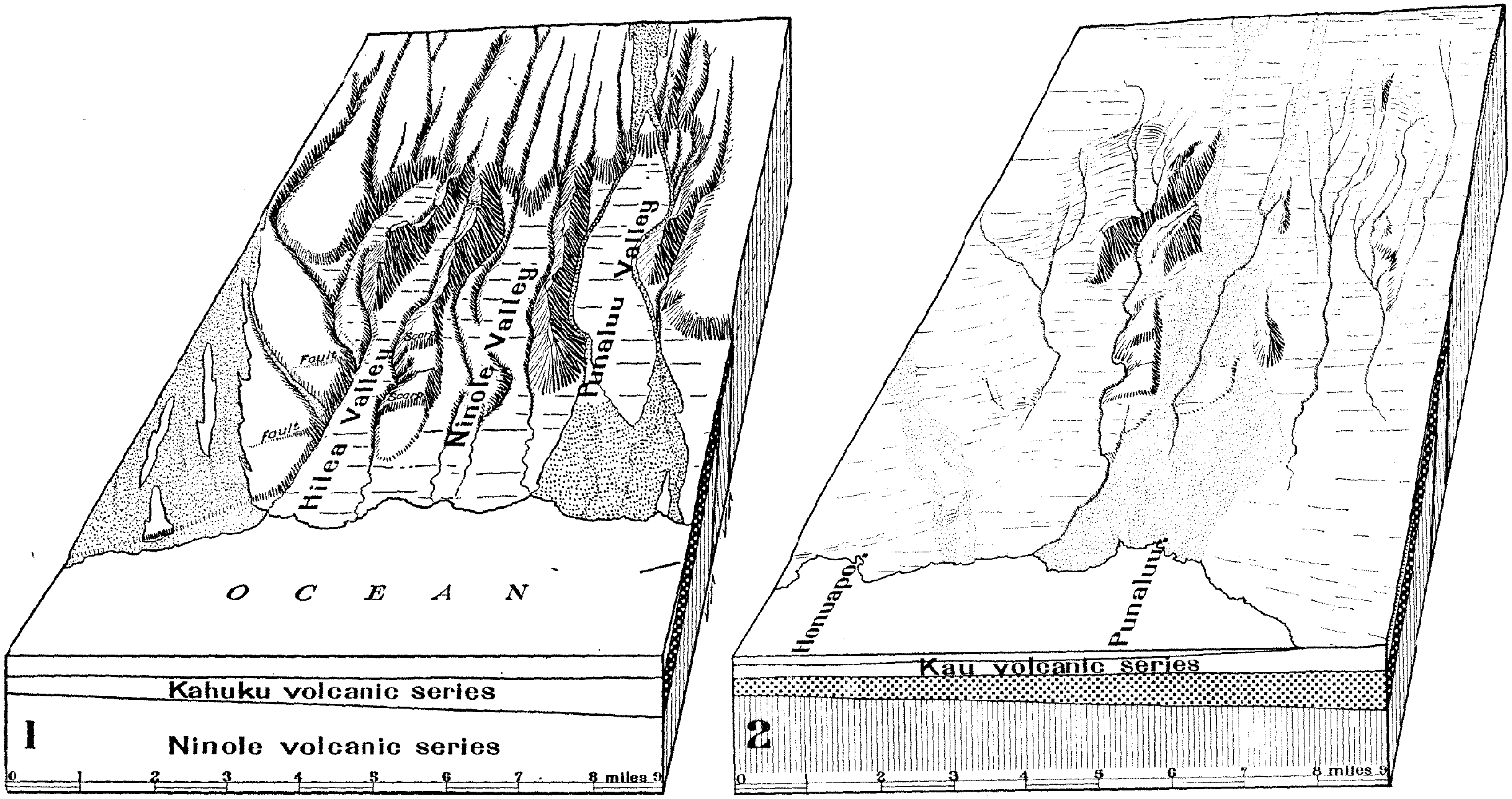


Figure 16. Diagrams showing the origin of the ridges composed of the Ninole volcanic series in the Kau District. Stage 1 shows the ancient canyons cut in the Ninole volcanic series partly filled with lavas of the Kahuku volcanic series. Stage 2 shows the present form after the valleys had been further filled with the lavas of the Kahuku and Kau volcanic series.

hoehoe Canyon on the northeastern slope of Mauna Kea, built a small flat-topped lava delta where it entered the sea. The floors of Mokuaweoweo and Kilauea calderas are constructional lava plains also.

LANDSLIDES

Following the earthquake of April 2, 1868, a destructive landslide occurred in Wood Valley, 5 miles north of Pahala (pl. 1). It was caused by lava rock sliding on a wet ash bed from an altitude of 3,500 feet to an altitude of 1,620 feet, over a distance of 2½ miles. The water and ash acted as a lubricant, and the whole mass moved rapidly down the valley burying a village with 31 persons and more than 500 horses, cattle, and goats.[37]

Another great landslide fell at the same time from the sea cliff 1 mile northwest of Waimanu Canyon in the Kohala District. It was about 1 mile long and half a mile wide and has not yet been cut away by the sea.

There were large landslides in Honokane Nui Valley during the earthquakes of 1929. These earthquakes shattered and upset blocks of crust in the black pahoehoe near Honaunau in Kona, also. A large landslide fell from the sea cliff just east of the mouth of Honopue Valley during heavy rains in January 1941 and built a fan similar to that of the Laupahoehoe landslide of 1868, 2 miles to the southeast. About half of the slide has been removed by the waves since 1941. The cliff along this stretch of the coast is subject to slides because of thin saturated ash beds. In 1942 a landslide fell into the West Branch of Honokane Nui Stream at an altitude of 1,500 feet. A pond 100 yards long, still in existence in 1944, was formed.

Other landslides have occurred in the past. One blocked the East Branch of Honokane Nui Canyon near its head and formed a temporary dam behind which 30 feet of horizontally bedded silts and clays were deposited.

MARINE FEATURES

Marine cliffs.—High cliffs cut by the sea extend from Hilo northwestward to the northern tip of the island along the entire windward coasts of Mauna Kea and Kohala Mountain. The Hamakua cliffs, as those along the windward side of Mauna Kea are called, range from 50 to 350 feet in height (pl. 24B). The amount of rock removed is commensurate with the length of time indicated by the depth of canyons inland from this coast; hence, there is little doubt that the cliffs have been cut by the sea.

---

[37] Alexander, W. D., A brief history of the Hawaiian people; pp. 292–293, New York, 1899.

The scenic coastal cliffs between Waipio and Pololu valleys on Kohala Mountain range from 400 to 1,400 feet in height (pl. 24A). Their great height has led some to ascribe them to faulting[38] but Branner[39] states that the cliffs are wave-cut, as the deep canyons indicate that a great amount of time has elapsed. The present writers favor this view.

Cliffs higher than 50 feet are found at Kealakekua Bay, South Point (Kalae), Maniania Pali, Honuapo, and Puu Kapukapu. Maniania and Honuapo cliffs in the Kau District expose ancient lavas. Sufficient time has elapsed for the sea to cut such cliffs since these lavas were extruded. The other cliffs named are fault scarps little modified by the sea. Elsewhere the coast is made up of cliffs less than 50 feet high either composed of very young lavas or else lying on leeward sheltered coasts where wave action is weak. Ancient sea cliffs 10 to 50 feet high, apparently cut in Recent time and veneered by later lavas, form low escarpments a short distance inland along parts of the Kona coast.

Some of the sea cliffs, especially along the Hamakua and Kona coasts are older than the lavas forming the rim of the cliff. They were cut to nearly their present height, then overflowed with lava and subsequently exhumed by wave action, as shown in figure 18. Thus all lava flows that terminate in a sea cliff may not be older than the cliff.

BAYS.—Good bays are scarce. Hilo Bay, the largest, was formed by late lavas from Mauna Loa flowing northeastward over the wave-cut platform in the Mauna Kea lavas and possibly over coral reefs. An unusual volume of lavas was deflected to this point by the slopes of Kilauea and Mauna Kea. Waipio Bay is due largely to the partial drowning of the mouth of Waipio Canyon and to a lesser extent to Mauna Kea lavas having extended the coast northward in a manner similar to the more recent building of Hilo Bay by Mauna Loa lavas. Kawaihae Bay is a re-entrant in the coast between the slopes of Kohala and Mauna Kea. Kiholo Bay is a re-entrant between the lavas of Hualalai and Mauna Loa. It was partly filled by the lava flow of 1859 from Mauna Loa. Kealakekua Bay is a re-entrant formed by faulting and a fan of late lava from Mauna Loa (pl. 17B). The remaining coves are too small to justify individual descriptions.

BEACHES.—Sand beaches are scarce and places suitable for swimming are rare. Kalapana Beach, the most highly advertised, is composed of fine grains of black glass, undoubtedly derived from the comminution of a pre-historic lava flow which exploded upon reach-

---

[38] Jaggar, T. A., Seismometric investigation of the Hawaiian lava column: Seismol. Soc. America Bull., vol. 10, no. 4, p. 182, 1920. Bryan, W. A., Natural history of Hawaii: p. 149, Honolulu, 1915. Powers, Sidney, Tectonic lines in the Hawaiian Islands: Geol. Soc. America Bull., vol. 28, p. 511, 1917.

[39] Branner, J. C., Notes on the geology of the Hawaiian Islands: Am. Jour. Sci., 4th ser., vol. 16, pp. 301–303, 1903.

ing the sea. Punaluu Beach and many of the unnamed beaches along the Kona coast, have a similar origin. Some exist where waves are now cutting into littoral cones, such as Puu Hou near South Point, but they are mostly inaccessible by road. The remarkable green beach 3 miles northeast of South Point is the result of partial destruction of the littoral cone, Puu Mahana, which was made by the explosion of a lava flow rich in olivine phenocrysts.[40] The olivine crystals cause the green color.

Some of the beaches along the Kona coast are composed of a mixture of black sand derived from lava rock and white sand derived from coral. In a few re-entrants lava cobble beaches are found. They reach heights of 10 to 15 feet along the windward coast, especially at the mouths of the larger partly drowned valleys.

Benches.—The waves of the present sea have stripped flat-lying aa flows of their clinker in many places, thereby forming broad hard rock benches 5 to 10 feet above sea level and as much as 300 feet wide. Where ancient lava flows reached the sea, especially along the Hamakua coast, benches 5 to 15 feet above the sea are common. They were cut when the sea was 5 feet higher than at present, although they are still awash during storms. A still higher bench 20 to 30 feet above sea level is preserved in a few places. It is a relic of the 25-foot stand of the sea and is found only along the shores of Kohala Mountain and Mauna Kea.

Minor shore features.—The clinkery beds, tubes, and other internal structures of lava flows, where subjected to wave attack, give rise to spectacular spouting horns, sea caves, natural bridges, and stacks. Onomea Arch (pl. 23A), a widely advertised scenic point, is a natural bridge cut in an ancient cinder cone during the 25-foot stand of the sea. Much of the shore is too young to support coral reefs but the shore of Kohala Mountain, and parts of the shores of Mauna Loa and Mauna Kea are pre-Wisconsin in age. The absence of reefs on these shores is believed to be due to their steepness and the rapid rate at which the sea rose after Wisconsin time. A small patch of living coral reef lies in Kawaihae Bay.

Effect of seismic sea waves.—Great tsunamis or seismic sea waves sweep the coast of Hawaii at intervals. Most of them originate from earthquakes along the west coast of South America, in the Aleutian Islands, and in Japan; occasionally they result from local tremors. The seismic sea waves of May 1819, November 7, 1837, May 17, 1841, August 13, 1868, August 27, 1872, May 10, 1877, and February 3, 1923, caused loss of life and property.[41] All had foreign origins. That of 1877 originated in Peru and did great damage. The wave of April 2, 1868, accompanying the Waiohinu earthquake,

---

[40] Stearns, H. T., and Clark, W. O., op. cit., p. 59.

[41] Volcano Letter, no. 321, p. 2, Feb. 19, 1931.

wrought the greatest damage. It was 40 to 50 feet high and swept away all the villages along the Kau coast from Kaalualu to Keauhou Landing. More than 80 persons perished within a few minutes.[42] Heavy deposits of unconsolidated beach cobbles and huge angular blocks of rock which lie 5 to 10 feet above sea level along the shore northeast of Kaalualu are due partly to uplift of the coast in 1868 and partly to the accompanying wave. At other places along the flat-lying parts of the Kau and Puna coasts large blocks and waterworn boulders have been deposited several hundred feet inland by such waves.[42a]

EMERGED AND SUBMERGED SHORE LINES.—The following shore lines listed with the youngest at the top have been determined to date in the Hawaiian Islands.[43]

Pleistocene shore lines in the Hawaiian Islands

Approximate altitude (feet)	Name	Evidence on the island of Hawaii	Type locality (island)
0	....	Present shore line	
+5	Kapapa	Wave-cut bench at this level	Oahu
+25	Waimanalo	Wave-cut platforms and terraces..........	do.
+45	Waialae	None	do.
—60±	Waipio	Dunes of this age	do.
+70	Laie	Not identified	do.
+100	Kaena	Terraces	do.
—300±	Kahipa	Submarine shelves	do.
+250±	Olowalu	Deposits of fossiliferous marine conglomerate and stripping of soil.................	Maui
+325±	....	Not identified	Lanai
+375±	....	do.	do.
+560	Manele	Terraces and stripping of soil.............	do.
+625±	....	Not identified	do.
+1,200±	Mahana	Traces of soil stripping to this level.......	do.
—1,200 to —1,800	Lualualei	Deeply submerged valley mouths	Oahu

Most of the coast of Mauna Loa, Hualalai, and Kilauea is younger than the shore lines listed. The remaining part, where rocks of pre-Wisconsin age form the coast, has been lowered recently by faulting. No evidence was found of the 25-foot shore line on these volcanoes but traces of the 5-foot stand exist. Benches and sea caves made by the 5- and 25-foot stands of the sea are common along the Hamakua and Kohala coasts. Gravel deposits graded to these stands form small terraces at the mouths of some of the gulches.

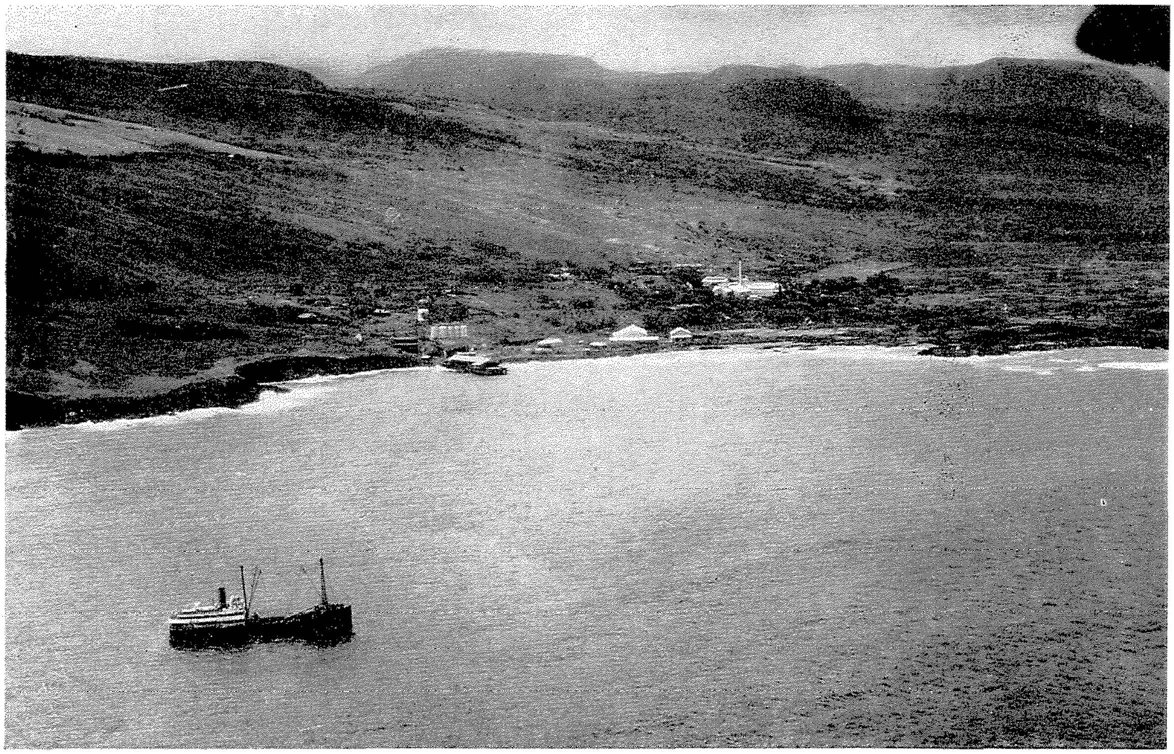
Several small patches of fossiliferous marine conglomerate belonging to the 5- and 25-foot shore lines lie along the coast between Mahukona and Kawaihae, especially on the point north of Keawanui

---

[42] Alexander, W. D., op. cit., p. 293, New York, 1899.

[42a] The seismic sea wave of April 1, 1946, did great damage along the northeastern coast of Hawaii. Originating in the Aleutian deep, the waves swept on shore to heights up to 55 feet at Pololu Valley and 32 feet near Hilo.

[43] Stearns, H. T., op. cit., p. 21.



Above: Plate 21A. Air view of Honuapo. The hills behind are composed of the Ninole volcanic series and are remnants of interstream divides between ancient canyons now partly filled with later lavas. Photo by Hawaiian Airlines, Ltd.

Below: Plate 21B. Waiilikahi Stream on the west wall of Waimanu Valley, Kohala Mountain, showing multiple water falls and plunge pools. Photo by Lt. McNaughton.

Plate 22. Looking into Waipio Valley showing the flat alluvial floor and the spring coves at its head. The cove on the left is Hiilawe into which spilled a lava flow from Mauna Kea. In the background are andesite cinder cones of the Hawi volcanic series. Photo by USAAF.

Bay (pl. 25B). Similar conglomerate lies about 40 feet above sea level half a mile south of Mahukona and at 260 feet (barometer) 2½ miles south of Mahukona in a gully on the north side of an andesite flow. The latter conglomerate was apparently laid down by the sea during the Olowalu stand. The west coast of Kohala Mountain was formerly thickly populated by Hawaiians who made their house floors of small coral and lava pebbles. This marine debris is now widely scattered, but some of the coral pebbles in the area are deeply weathered and appear too ancient to have been carried from modern beaches. It is probably lag gravel left when the sea receded from a higher stand. The basalts in this area originally carried several inches to several feet of residual lateritic soil which graded downward into spheroidally weathered rock. The sea has swept most of the soil away and washed the spheroids free. They are now deeply pitted by subsequent weathering and form a scabland similar to the wave-swept areas of Lanai and Kahoolawe.[44] Where the later aa andesites have been awash, the clinker is slightly rounded and washed from the high ridges into the swales. Thin fans of gravel covering several acres lie along the gulches. They were deposited at the various shore lines as the sea receded. Jaggar[45] reports wave-cut benches extending 275 feet up the west slope of Kohala Mountain. Numerous benches occur but most if not all above 45 feet appear to be due chiefly to dense layers of lava rather than abrasion. No fossiliferous marine sediments have been found above 260 feet but careful search may reveal them at higher levels. At an altitude of 550 feet along a gulch on the trail from Puu Hue Ranch to Keawanui Bay, occurs a lime cemented conglomerate 10 feet thick and much lime-cemented laterite similar to that which forms where an overlying deposit of calcareous sand is dissolved by rain. It is possible that the conglomerate marks the Manele 560-foot shore line. Three miles northeast of Puu Ulaula good evidence exists of waves having stripped away soil and partly decomposed rock up to 800 feet, and some possible traces exist up to 1,000 feet. Kohala Mountain may have been submerged to the level of the Mahana stand of the sea.

Terraces of boulder conglomerate graded to the 100-foot stand of the sea are prominent features in upper Waipio Valley. Still older nearly horizontally bedded conglomerate forms narrow terraces in the large canyons of Kohala Mountain. A conspicuous deposit lies along the lower Hamakua ditch trail between Alakahi and Kawainui intakes. The top of the terrace on the north wall of Waipio Canyon at the mouth of Alakahi Stream is 1,100 feet above sea level. This point is 5 miles from the coast; hence, the gravel was probably graded to the Manele shore line. The streams have not yet cut down

---

[44] Stearns, H. T., op. cit., p. 147 and pl. 6B.

[45] Jaggar, T. A., op. cit., p. 183.

to their preconglomerate bedrock channels except in their headwaters. A similar condition was found in the canyons of West Maui.[46] One gains the impression that West Maui and Kohala Mountain have had a similar history of submergence and emergence.

The great canyons in Kohala Mountain have flat floors composed of younger alluvium. Projection of the side walls below the alluvium indicates that these valleys are drowned a minimum of 750 feet and probably much more. At the mouth of Waipio Valley, the projection gives 1,700 feet. However, lateral erosion by Hiilawe Stream may have widened the valley mouth. Soundings offshore are inadequate to determine how far the valleys extend below sea level but a re-entrant is outlined by the contours to a depth of about 2,500 feet. This re-entrant is partly due to younger lava flows from Mauna Kea and Kohala building out the coast beyond the kipuka occupied by the valleys. From analogy with other deep canyons in the Hawaiian Islands it is probable that the Kohala canyons were cut prior to the Lualualei submergence of 1,200+ feet. The submarine contours (fig. 4) north of Hawaii indicate that the lavas of Kohala Volcano banked against Haleakala, evidence that East Maui is older than Kohala.

The ancient lava-filled valleys in the Kau District were probably cut during the Lualualei stand. Soundings are insufficient to determine whether or not the late lavas discharged through them have buried their submarine extension.

SUBMARINE FEATURES

The subaerial and submarine form of Hawaii is shown by contours in figure 4 and the accompanying silhouettes. The island rises 29,000 feet above the adjacent ocean floor. The submarine trough 5,000 feet deep between Hawaii and Maui resembles the saddles above sea level that have been built by the lavas of one volcano banking against another older one. The broad shelf 30 miles wide extending westward to a depth of 5,000 feet from Kohala Mountain is an anomalous geomorphic feature, as everywhere else the submarine contours closely parallel the shore. This shelf is probably an independent volcanic dome which did not reach sea level and has been buried by lavas from Kohala and Hualalai volcanoes. The southern end of the Hawaiian Archipelago consists of two parallel mountain ranges, which have been named the Loa Range and Kea Range.[47] They are underlain by fundamental fissures along which the volcanoes Kilauea-Mauna Loa, Mauna Kea-Hualalai, and Kohala Mountain and the submarine dome are arranged in doublets. The fundamental fissure passing through Mauna Loa, Hualalai, and the

---

[46] Stearns, H. T. and Macdonald, G. A., Geology and ground-water resources of the island of Maui, Hawaii: Hawaii Div. Hydrography, Bull. 7, p. 182, 1942.

[47] Dana, J. D., Characteristics of volcanoes, p. 262, New York, 1890.

submarine dome will be called the Western Fundamental Fissure; and that passing through Kilauea, Mauna Kea, and Kohala Mountain will be called the Eastern Fundamental Fissure.

The Kahuku fault escarpment that forms the south point of Hawaii can be traced to a depth of 13,000 feet or 18 miles from shore.

The east rift zone of Kilauea which forms the Puna Ridge extends more than 30 miles northeastward and to a depth of 15,000 feet. The east rift of Mauna Kea can also be traced to the same depth. The trough between these two rifts shows filling by Mauna Loa lavas only to the 1,000-foot submarine contour a few miles from shore. This indicates that lavas from the northeast rift of Mauna Loa have only in late geologic time been poured into the trough in sufficient volume to fill it. How much this condition resulted from the extinction of the east rift of Mauna Kea and how much from an increase in volcanic activity in the northeast rift of Mauna Loa is unknown.

The 1,000-foot submarine contour off the deep Kohala canyons shows the same re-entrant as the coast, as a result of submergence of the island by this amount after erosion of the canyons. Soundings farther seaward are insufficient to determine whether these drowned canyons go deeper.

GLACIAL FEATURES

During the Pleistocene epoch the summit of Mauna Kea was occupied by a small glacier, probably correlative in age with the Wisconsin glacier of North America and the Würm glacier of Europe.

Evidence of the former glacier was first recognized by Daly,[48] and the physiographic features caused by the glacier have been described by Gregory and Wentworth.[49] Deposits believed to represent three earlier stages of glaciation have been described by Wentworth and Powers,[50] but have been differently interpreted by Stearns.[51] They are described on pages 155 and 166. There is no question, however, of the existence of the last stage of glaciation.

Erosional features caused by the Makanaka glacier include many areas of rock scraped bare of ash and clinker. Many ledges have been sculptured into roughly oval whale-backed forms (known as roches moutonnées). The tops and ends of these toward the direction from which the ice moved have been smoothed and rounded by ice abrasion, but the lower or lee ends are steep and irregular as a result of glacial plucking. Erosion was nowhere great, and the original irregularities of the lava flows are generally still recogniz-

---

[48] Daly, R. A., Pleistocene glaciation and the coral reef problem: Am. Jour. Sci., 4th ser., vol. 30, pp. 297–308, 1910.

[49] Gregory, H. E., and Wentworth, C. K., General features and glacial geology of Mauna Kea, Hawaii: Geol. Soc. America Bull., vol. 48, pp. 1719–1742, 1937.

[50] Wentworth, C. K., and Powers, W. E., Multiple glaciation of Mauna Kea, Hawaii: Geol. Soc. America Bull., vol. 52, pp. 1193–1218, 1941.

[51] Stearns, H. T., Glaciation of Mauna Kea, Hawaii: Geol. Soc. America Bull., vol. 56, pp. 267–274, 1945.

able. Locally, small areas are well striated and polished (plate 25A), but such evidences of ice work are not common. The lower slopes of the cinder cones within the glaciated area have been slightly eroded by the ice, resulting in slopes which are steeper and less regular than those of normal cones, and in the removal of the thin surficial layer of red cinder, exposing the fresh black cinder beneath. The beds of certain stream courses appear to have been slightly rounded and deepened by ice abrasion.[52]

Depositional features of glacial origin include broad areas of ground moraine, and narrow belts of terminal and lateral moraines. The ground moraine is a thin discontinuous layer of angular lava blocks covering much of the surface within the boundaries of the glaciated area. It represents material dropped by the ice during the final wastage of the glacier. Fine material is generally absent, although in places the blocks are admixed with finer rock debris and with cinders. The terminal and lateral moraines formed, as a result of marginal melting, by deposition of material transported in and on the ice. They are described on page 166. Very few of the blocks in the moraines show polishing, striation, or well developed glacial facets.

The glacier covered an area of about 28 square miles, mostly within the area enclosed by the 11,000-foot coutour line. The margins of the former ice cap, in its most extended development, are shown on plate 1. Within this area many cinder cones protruded through the ice. Gregory and Wentworth estimate the average thickness of the ice to have been about 150 feet, although the maximum thickness may have been as much as 350 feet.[53] The thinness of the ice is in harmony with the comparatively weak erosion which it accomplished.

EFFECTS OF WIND WORK

The work of the wind plays a minor role on Hawaii due to the rocky surface. Black dunes of basaltic beach sand attain heights of 50 feet at the mouths of Pololu and Waipio valleys. Small deposits of wind-blown sand have drifted inland at several places on the Kau and Kona coasts. The most extensive are found northeast of South Point. A strip of drifted sand extends 2 miles inland from Waikapuna Bay, also. The South Point dunes seldom exceed 5 feet in height. The sand is chiefly basaltic but contains a sufficient amout of calcareous sand derived from the attrition of marine limy skeletons to make calcareous molds and casts of the roots and plant stems buried by the dunes. As the dunes migrate these casts are left behind. They are commonly mistaken for fossil bones. These dunes may have been formed chiefly when the sea stood 60± feet lower than

---

[52] Gregory, H. E., and Wentworth, C. K., op. cit., pp. 1733–1734.
[53] Op. cit., p. 1733.

at present, as most other extensive dunes in the Hawaiian Islands were formed at that time. Their lack of the consolidation typical of dunes of that age could be due to the low lime content and reworking by the wind.

Wind work is apparent in most of the Kau Desert. Winds passing over Kilauea lose their moisture and on their way down the southwest slope become adiabatically heated, thereby causing the desert conditions. Dunes 10 to 30 feet high, composed of sand derived chiefly from ash, drift southwestward before the prevailing winds. Near the Kamakaia Hills these dunes have left dead trees and fragments of wood in their wake. A small area of dunes, derived mainly from alluvium, lies south of Hilina Pali.

Sand and dust storms are frequent in the Kau Desert and were especially common after the explosion of Kilauea in 1924.[54] Some of these storms carry dust to an altitude of 6,000 feet and transport it for many miles. An appreciable part of the ash cover on the southeastern slopes of Mauna Loa, especially in the South Point area, is a dust deposit.[55]

Large areas of wind-drifted volcanic sand lie on the leeward slopes and above 9,000 feet on Mauna Kea.

High winds during eruptions distribute pumice far to the leeward. The asymmetrical form of many cinder cones reflects the direction and intensity of the wind at the time of the eruption. An extensive field of pumice lies southwest of Puu o Keokeo on the southwestern rift of Mauna Loa. Such deposits are thin on Mauna Loa due to repeated burial by lava flows. Black vitric ash 5 to 10 feet thick forms extensive deposits to the lee of Mauna Kea cones (pl. 1). The widespread Pahala ash (pl. 26B and fig. 19) owes its distribution partly to the wind.

Benches several yards wide formed by the wind stripping the soil down to bedrock lie along the coast of Hawi and Kapaau. They are similar to those on Maui.[56]

GENERAL CHARACTER AND AGE OF THE ROCKS

Except for minor amounts of gravel, sand and coral reef, the rocks are all igneous. The extrusive rocks consist of beds of basalt, andesite, and small amounts of trachyte and the associated ejecta. Some are porphyritic and carry one or more of the following types of phenocrysts—olivine, augite, and feldspar. Xenoliths of dunite and gabbro are common in some flows. The intrusive rocks are sills and dikes formed concurrently with the extrusive rocks and

---

[54] Stearns, H. T., The explosive phase of Kilauea Volcano, Hawaii, in 1924: Bull. Volcanologique, nos. 5 and 6, pp. 193–208, 1925.

[55] Palmer, H. S., Soil making processes, in Handbook of Hawaiian Soils, p. 30, Honolulu, 1935.

[56] Stearns, H. T., and Macdonald, G. A., op. cit., pl. 31.

have a similar composition. The lava beds range in thickness from a few inches to more than 900 feet and average about 15 feet. In general the beds dip 2° to 15° away from their respective sources. The ejecta make up less than 5 percent of the island. The ash beds range in thickness from a fraction of an inch to 55 feet. The dikes are mostly vertical. They range from a few inches to 40 feet and average about 1½ feet. Sills are scarce and none exceeds 100 feet in thickness. Those exposed lie close to the central vents.

The sedimentary rocks comprise stream- and wave-rounded gravels, dune and beach sand, tiny patches of calcareous marine conglomerate, and glacial deposits. The glacial deposits lie only in the summit area of Mauna Kea. The other sediments cover small areas chiefly along the coast, in the valleys on Kohala Mountain, and on the southwest slope of Mauna Kea (pl. 1). Small areas of living coral reef occur near Kawaihae, and possibly near Hilo. The general stratigraphy of Hawaii is given in the table on page 62.

Fossil plants and bones of a goose[57] were found on ash deposits under lava flows in the Kau District but have not been correlated with geologic formations elsewhere. Evidence of glaciation on the top of Mauna Kea during Wisconsin time definitely dates the major part of this mountain as pre-Wisconsin.[58] Wentworth and Powers described four drifts which they correlated with the four principal glacial stages of North America.[59] The two oldest glacial drifts have since been shown to be explosion deposits and the next to the youngest is fanglomerate, possibly deposited by floods caused by lava flows melting the ice cap in Wisconsin time.[60]

As part of the Pahala ash is derived from cones on Mauna Kea older than the glaciation, that part must have been laid down in pre-Wisconsin time. The ash overlies the Hawi, Kahuku, Hilina, and Hamakua volcanic series and the Waawaa volcanics. Thus, these rocks may be classified as pre-Wisconsin. The age of the older rocks is uncertain.

The great valleys on Kohala Mountain were apparently carved prior to the Lualualei submergence. This submergence took place in early Pleistocene or late Pliocene time, as Pleistocene sedimentary deposits lie unconformably in valleys submerged at that time.[61] On this basis the Pololu volcanic series is referred to the Tertiary period and its upper exposed part to the Pliocene epoch. The Ninole

---

[57] Stearns, H. T., and Clark, W. O., op. cit., p. 60.

[58] Daly, R. A., op. cit., p. 297. Gregory, H. E., and Wentworth, C. K., op. cit. pp. 1719–1742.

[59] Wentworth, C. K., and Powers, W. E., op. cit., p. 1211.

[60] Stearns, H. T., Glaciation of Mauna Kea, Hawaii: Geol. Soc. America Bull., vol. 56, pp. 267–274, 1945.

[61] Stearns, H. T., Pleistocene shore lines on the islands of Oahu and Maui, Hawaii: Geol. Soc. America Bull., vol. 46, p. 1932, 1935.

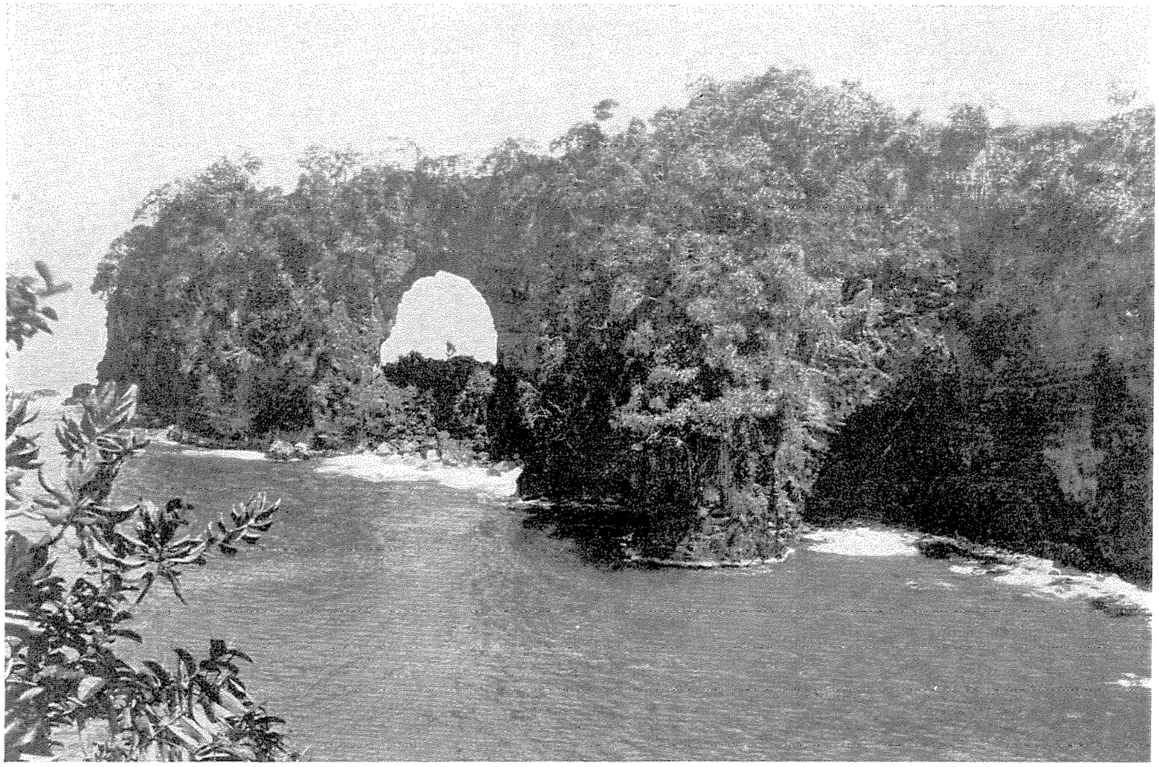
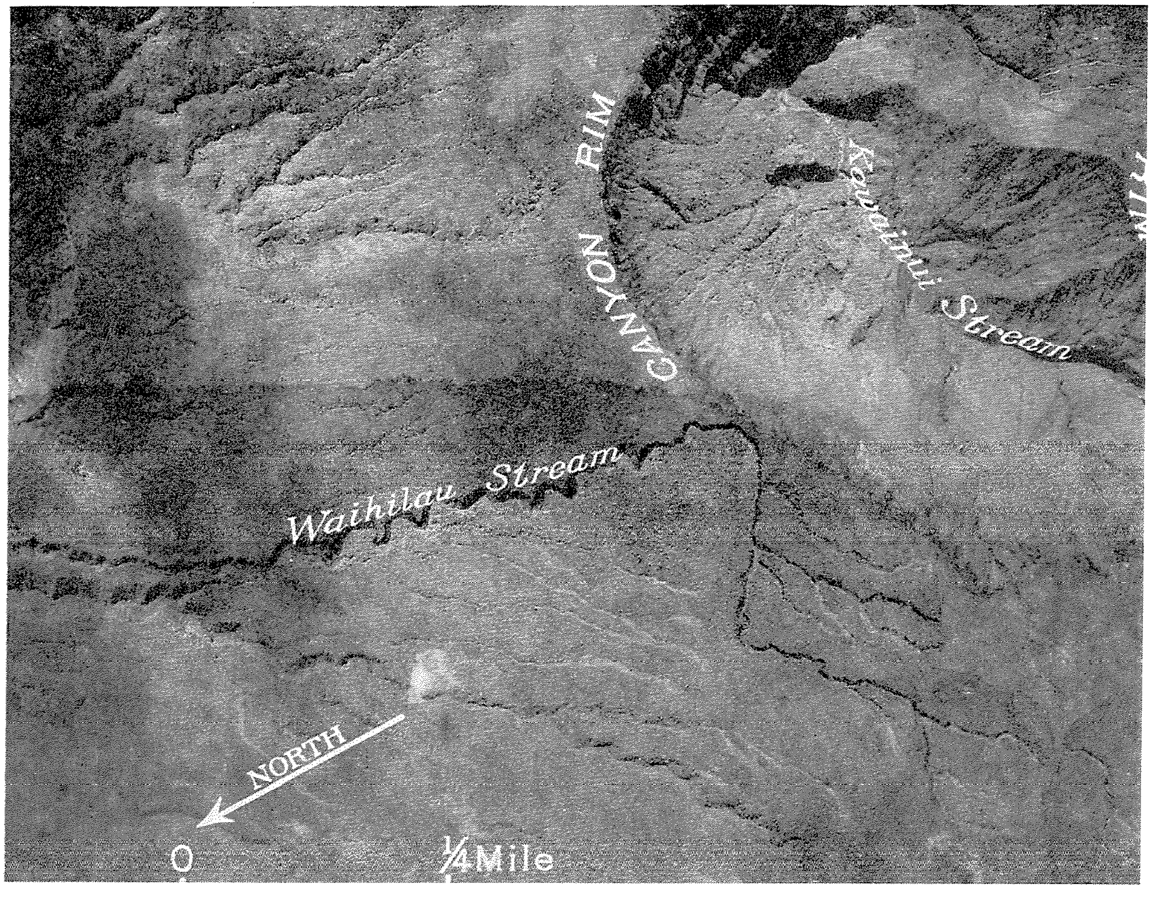


Plate 23A. Onomea Arch, a natural bridge cut by the waves during the 25-foot stand of the sea in an ancient cinder cone of the Hamakua volcanic series of Mauna Kea. Photo by R. J. Baker.

Plate 23B. Vertical air view showing the effect of faulting on drainage near the summit of Kohala Mountain. Waihilau Stream turns abruptly southeastward along a fault line, but instead of tumbling into Kawainui Canyon, turns abruptly again and empties into Waimanu Canyon. Photo by U. S. Navy.



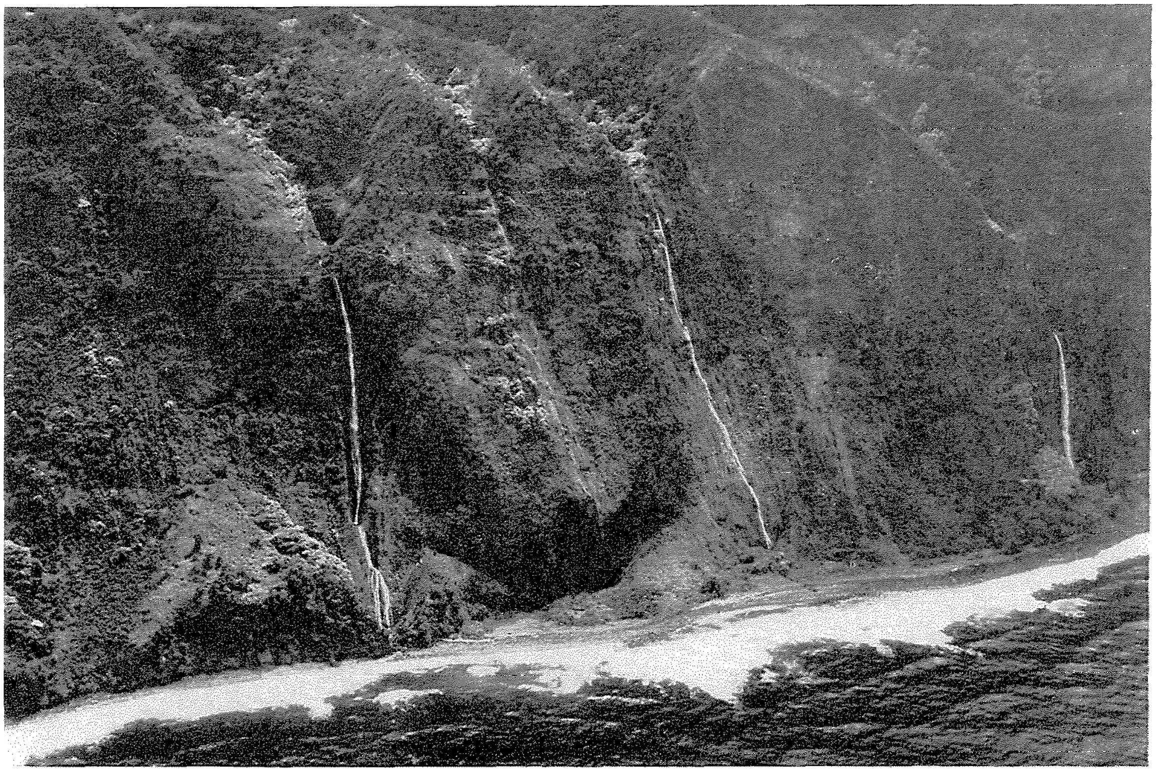


Plate 24A. Cliff on the windward coast of Kohala Mountain showing hanging valleys in the Pololu volcanic series. Photo by USAAF.

Plate 24B. Sea cliff in lavas of the Hamakua volcanic series on the windward coast of Mauna Kea skirted by a marine bench five feet above sea level. The sugar cane grows on the deeply weathered surface of the lavas. Photo by USAAF.

volcanic series, of correlative age or older, is likewise tentatively assigned to the Pliocene. The eruption of the lower member of the Laupahoehoe volcanic series ended in Wisconsin time. The upper member is later than the glacial drift on Mauna Kea, hence is Recent. The lack of erosion in the Hualalai volcanic series and the fact that the later flows in this series buried the Pahala ash, places the exposed volcanics of Hualalai in the late Pleistocene and Recent time. The Kau and Puna volcanic series likewise are later than the Pahala ash, and are regarded as of late Pleistocene and Recent age.

Rocks of all the older series extend downward indefinitely and differ greatly in volume. The cores of all the volcanoes above sea level with the exception of Kilauea (which is questionable) may be confidently assigned to an age not younger than the Pliocene. Nothing is known regarding the age of the great mass of rocks that forms the foundation of these volcanoes below sea level, but this epoch of volcanism may have started in the Pacific in Miocene time.[62]

The most apparent fact gained from the detailed study of the five volcanoes of Hawaii is that volcanism is waning in common with volcanism elsewhere on earth. Rapid and voluminous outpourings of basalt built up the shield-shaped domes of primitive basalt that form the major part of each of the five volcanic edifices. The absence of soils and erosional unconformities in these underlying domes proves that they were built rapidly, probably even faster than the present Mauna Loa which in historic time has erupted on the average of every 3.6 years.[63] This decline of volcanism should be kept constantly in mind while utilizing the time periods assigned. Thus the Laupahoehoe volcanic series, which forms about 10 percent of the bulk of Mauna Kea above sea level, may have required for its extrusion 25 percent of the time since that volcano rose above sea level.

A tabular summary of the general stratigraphy of the island is given in the accompanying table. More detailed stratigraphic sections are given in the chapters describing the geology of separate volcanoes. Plate 1 shows the detailed mapping of the rocks. A simplified geologic map is given in figure 17.

---

[62] Stearns, H. T., Late geologic history of the Pacific basin: Am. Jour. Sci., vol. 243, pp. 614-626, 1945.

[63] Macdonald, G. A., The 1942 eruption of Mauna Loa, Hawaii: Am. Jour. Sci., vol. 241, pp. 241–242, 1943.

Stratigraphic rock units in the island of Hawaii

(The volcanic rocks of Mauna Loa, Mauna Kea, and Hualalai, those of Mauna Kea and Kohala, and those of Mauna Loa and Kilauea interfinger)

Age	Hualalai	Kohala Mountain	Mauna Loa	Kilauea	Mauna Kea
Historic	Historic member of Hualalai volcanic series (volcanics of 1801)	Unconsolidated alluvium, dunes and landslides	Historic member of Kau volcanic series (volcanics of 1832–1942) Mud flow of 1868	Historic rocks of Puna volcanic series (volcanics of 1790–1934)	Ribbons of gravel and small alluvial fans
Recent	Exposed part of prehistoric member of the Hualalai volcanic series		Dunes	Dunes	Upper member of Laupahoehoe volcanic series
Late Pleistocene		Fluvial conglomerates	Prehistoric member of Kau volcanic series	Prehistoric member of Puna volcanic series	Glacial debris and fluvial conglomerates Lower member of Laupahoehoe volcanic series
	Pahala ash (exposed on Waawaa volcanics only)	Pahala ash (not differentiated)	Pahala ash	Pahala ash	Pahala ash
Early and middle Pleistocene	Waawaa volcanics and lower unexposed part of Hualalai volcanic series	Fluvial conglomerates Hawi volcanic series	Kahuku volcanic series	Hilina volcanic series	Hamakua volcanic series
		Great erosional unconformity	Great erosional unconformity		
Pliocene		Pololu volcanic series	Ninole volcanic series		

GEOLOGY OF MAUNA LOA VOLCANO

PREVIOUS INVESTIGATIONS

Archibald Menzies of the Vancouver Expedition was the first white man to ascend Mauna Loa. He reached the top in February 1794 and determined the altitude by barometer. The spectacular and frequent eruptions of Mauna Loa have attracted the attention of geologists ever since 1841 when it was visited by the Wilkes Expedition. A voluminous literature deals with its volcanic history and petrology.[64] It has been under constant observation by the Hawaiian Volcano Observatory since 1911. Systematic structural, stratigraphic, and ground-water study was begun in the Kau District in 1920 by L. F. Noble and W. O. Clark, of the Ground-Water Division of the U. S. Geological Survey.[65] An unpublished memorandum by Noble, who spent six weeks there at that time, is quoted by Washington.[66] Noble recognized the profound erosional unconformity between the younger and older lavas and divided the rocks into the three units used in subsequent mapping. Clark's studies were confined largely to the occurrence of high-level ground water, and methods of prospecting for it. Mr. Clark resigned from the Survey in December 1921 to direct ground-water development for the sugar plantations in the islands. The geologic map of the Kau District was made by Stearns in 1924.[67] The rest of Mauna Loa was mapped by the writers between 1939 and 1943. (See key map, pl. 1.)

ROCKS OF MAUNA LOA AND THEIR WATER-BEARING PROPERTIES

The volcanic rocks comprise all the lava flows, intrusive rocks, pyroclastic rocks, and intercalated soils of Mauna Loa Volcano. They have been subdivided into three series whose general character and water-bearing properties are summarized in the accompanying table. The second table gives the nomenclature of the rock units as used herein in comparison with earlier usages. The sedimentary rocks consist of small deposits of loose gravels in stream beds and unconsolidated sand dunes in the South Point area.

---

[64] See bibliography in U. S. Geol. Survey Water-Supply Paper 616, pp. 36–41, 1930; also Macdonald, G. A., Bibliography of the geology and water resources of the island of Hawaii: in preparation.

[65] Meinzer, O. E., Ground water in the Hawaiian Islands: U. S. Geol. Survey Water-Supply Paper 616, pp. 1–3, 1930.

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

[67] Stearns, H. T., and Clark, W. O., Geology and water resources of the Kau District, Hawaii: U. S. Geol. Survey Water-Supply Paper 616, pl. 1, 1930.

Correlation of nomenclature of rock units in Mauna Loa Volcano

Age	Used herein (Bull. 9)	Wentworth, 3d Spec. Rept. H.V.O. (1938)	Stearns, G.S.A. Abst. (1926) and U.S.G.S. W.S.P. 616 (1930)		Stone, Bishop Mus. Bull. 33 (1926)	Noble and Clark mss. rept. (1920)
Historic	Historic member of the Kau volcanic series	Kamehame basalt	Kamehame basalt	Upper member	Post-Pahala series	Post-Pahala series
Recent and latest Pleistocene	Prehistoric member of the Kau volcanic series			Lower member		
Late Pleistocene	Pahala ash	Pahala basalt (includes capping Pahala ash)	Pahala basalt	Ash member	Pahala series (includes capping Pahala ash)	Pahala series (includes capping Pahala ash)
Pleistocene	Kahuku volcanic series (does not include capping ash)			Basalt member (with interbedded ash)		
Great unconformity						
Pliocene	Ninole volcanic series	Ninole basalt (with interbedded tuff)	Ninole basalt (with interbedded tuff)		Pre-Pahala series (with interbedded tuff)	Pre-Pahala series

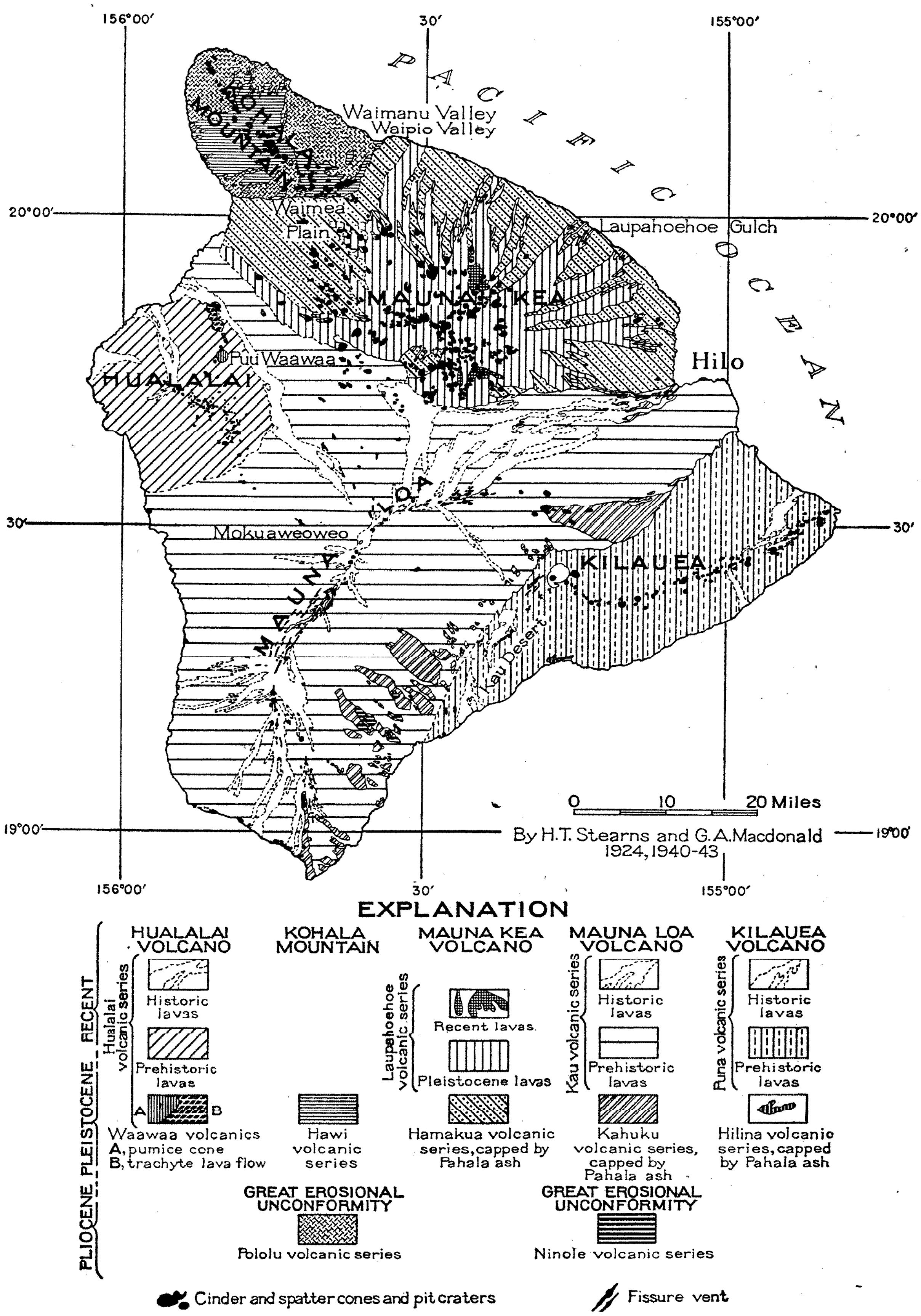


Figure 17. Simplified geologic map of Hawaii.

NINOLE VOLCANIC SERIES[68]

The oldest exposed rocks of Mauna Loa are named the Ninole volcanic series, from Ninole Gulch north of Hilea in the Kau District. The type section is exposed in the walls of the valley at Puu Enuhe, where the formation consists of 1,000 feet of basalt with a 12-foot bed of vitric tuff 500 feet below the top. Some of the upper beds of the series are probably missing as the top of Puu Enuhe is an erosional remnant. The lava beds are dominantly massive, gray, and in places 75 feet thick. A few beds of aa are interstratified with the massive beds of pahoehoe. Some of the beds are partly altered by weathering. The inter-stratified tuff is 2 to 12 feet thick and crops out at nearly the same horizon wherever exposed. It is a compact fine-grained dark red to brown palagonitic tuff, consisting of altered small fragments of glassy pumice typical of lava fountain deposits (pl. 25C). The tuff was cut by small gullies in a few places before burial. Only at Noguchi tunnel (no. 75) has a lava flow been found interstratified with it. There the lower bed of tuff contains near its top coarse pumice reaching 2 inches across. The overlying aa in one place contains spatter, some of which lies on the ash. The spatter probably is splash from a lava river rather than from a spatter cone.

Pakua Hill, 2 miles inland of Kilea, has a landslide scar on its northeast side 100 feet below the top. Twenty-five feet below the top of the scar is a red layer 1 to 2 feet thick containing round cobbles up to 4 inches across. The mixed types of rock indicate that the conglomerate is probably stream-laid. It is underlain by 30 feet of basalt and then 15 feet of tuff. The tuff rests on slightly decomposed pahoehoe. The lower 3 feet of the tuff bed is fine grained brown clay-like sediment that appears to be transported soil. It grades upward into a gritty lateritic tuff.

The Ninole volcanic series crops out in prominent steep hills between Waiohinu and Wood Valley for a distance of 15 miles on the southeastern slope of Mauna Loa. These hills are high remnants of former intercanyon divides, inliers in the later lava flows (pl. 21A). The series has an exposed thickness of 2,100 feet in Makaalia peak at the head of Hilea Gulch, but even there its base is deeply buried by later flows. The Ninole lava beds have a uniformly gentle dip of about 4° that ranges from S. 15° to 70° E. They dip away from a point in the southwestern rift of Mauna Loa about 8 miles from the summit. This is the normal point of dispersal for lava flows reaching this part of the Kau District. The Ninole volcanic series

---

[68] The description of the Ninole volcanic series is abstracted from U. S. Geol. Survey Water-Supply Paper 616, 61–62, 1930 [referred to in that paper as the Ninole basalt]; little additional field work was done in this area during the present investigation.

Stratigraphic section of Mauna Loa Volcano

(Littoral cones formed by lava flows exploding at the shore are specially designated on plate 1 to distinguish them from vents)

Major geologic unit	Rock assemblage	Average thickness (feet)	Symbol on map (pl. 1)	General character	Water-bearing properties
Historic volcanics	Lava flows and cones of 1832 to 1942, the historic member of the Kau volcanic series	15±	Hml	Nonporphyritic and porphyritic aa and pahoehoe basalts. On the flanks of the mountain they are thin black narrow flows; in Mokuaweoweo Caldera they are massive and columnar-jointed	Extremely permeable but carry no water except at the coast where it is brackish
		50±	Hmc	Cinder and spatter cones and fissure vents at source of flows	Extremely permeable but carry no water
			Hmcl	Littoral cones formed where lava enters the sea	Extremely permeable but carry brackish or salt water
			Hmp	Pit craters containing historic lava	Contain no water
Recent sedimentary rocks	Unconsolidated dunes	5±		Cross-bedded dunes composed of uniform grains of black basaltic beach sand mixed with a small quantity of cream colored calcareous beach sand	Highly permeable but carry no water
Recent and latest Pleistocene volcanic rocks	Prehistoric member of the Kau volcanic series	50±	Qkl	Porphyritic and nonporphyritic aa and pahoehoe basalts forming a nearly complete veneer over Mauna Loa. In bare areas they are distinguished from the historic lavas by their brown color. They are more than 600 feet thick in the walls of Mokuaweoweo Caldera	Extremely permeable. The largest springs in the island discharge from these rocks but along the arid coasts the water is commonly brackish. In the uplands these rocks do not contain water unless they lie on Pahala ash, and then only in wet areas. They contain ice in a few cracks at the top of Mauna Loa
		50±	Qkc	Cinder and spatter cones and fissure vents at source of flows	Extremely permeable but carry no water
			Qkcl	Littoral cones formed where lava enters the sea	Extremely permeable but carry brackish or salt water
			Qkp	Pit craters.	Contain no water
		1±		Ash deposits, chiefly vitric, leeward of cones and on the rim of Mokuaweoweo Caldera	Highly permeable but do not carry water
Pleistocene volcanic rocks	Pahala ash	20±		Red to yellow, friable ash, 12 to 50 feet thick, in places separated into two or more beds by intercalated lava flows. The ash is commonly laminated, is composed chiefly of dust- and sand-sized particles of palagonitized basic glass shards and pumice with lithic particles and coarser textured layers near Kilauea Caldera. It everywhere caps the underlying basalt except on the face of cliffs. It also covers the flat-topped hills of Ninole basalt but these outcrops are omitted on plate 1	Relatively impermeable in its finer textured phases. In the wet uplands of the Kau and Hilo districts, the ash perches water in the overlying lava and gives rise to valuable high-level springs and bodies of perched water, some of which have been tapped by tunnels
	Kahuku volcanic series	1,000±	Pkl	Porphyritic and nonporphyritic aa and pahoehoe basalt flows ranging from 5 to 100 feet in thickness and averaging 15 feet	Highly permeable, carrying brackish water near the coast but fresh water near sea level farther inland. In places in the wet uplands these basalts carry water perched by intercalated ash beds
		200±	Pkc	Cinder cones at the source of lava flows	Highly permeable but carry no water
		100±	Pkcl	Littoral cones	Extremely permeable but carry brackish or salt water
		....	Pkp	Pit craters	Contain no water
Great erosional unconformity					
Pliocene or older volcanic rocks	Ninole volcanic series	2,100±	Tn	Porphyritic and nonporphyritic aa and pahoehoe lava flows ranging from 10 to 75 feet in thickness, partly altered by weathering. A bed of reddish-brown, blocky, well consolidated, fine-grained, palagonitized vitric tuff 2 to 15 feet thick is interstratified with the lavas about 550 feet below the top of the series	The basalt member is highly permeable and carries fresh water at sea level and perched bodies of water above the tuff member which is nearly impermeable
			Tnp	Basaltic lava flows covered with Pahala ash	

appears to form an ancient shield-shaped volcanic dome about 10,000 feet high under Mauna Loa.

The basalt is highly permeable and carries fresh water at sea level. Perched bodies of water lie on the tuff, which is nearly impermeable.

EROSIONAL UNCONFORMITY

The rocks overlying the Ninole series are separated from it by a profound erosional unconformity. The unconformity indicates a period of erosion long enough for the carving of canyons about 4,000 feet deep and more than 5 miles long. (See Geomorphology.) One of two hypotheses will account for the canyon-cutting stage—either the volcano became dormant for the entire period or the canyon area was a kipuka for a long time. Such kipukas are found downslope from high fault cliffs and rows of cones on volcanoes. Both conditions have resulted in great canyons in the Hawaiian Islands but the widespread diminution of volcanism in the Pacific about the end of the Pliocene, followed by intense erosion on rainy slopes, supports the first hypothesis. Great seaward-facing fault cliffs presumably truncated the Ninole rocks in Kau, judging from the numerous faults crossing this area. Such cliffs would have steepened the stream gradients and greatly accelerated erosion. It is also probable that Kilauea Volcano did not exist to intercept the trade winds, a condition that would greatly increase the precipitation in the canyon area.

If great canyons had not been carved in Kau, the Ninole series would have been buried by later flows as elsewhere on Mauna Loa where the rainfall is now, and probably was then, too low to form streams powerful enough to cut canyons in the time available.

KAHUKU VOLCANIC SERIES

The Kahuku volcanic series comprises all the basalt flows and interbedded ash beds that are unconformable on the Ninole volcanic series and that were laid down before the end of the deposition of the ash member at its top. It is the Pahala basalt[69] renamed, the name Pahala being here restricted to the top ash member.

The type locality of the Kahuku volcanic series is in the Kahuku Pali, a fault escarpment running north from South Point. 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. The rest of the flows average about 15 feet in thickness. The overlying

---

[69] Stearns, H. T., Origin of the volcanoes of Mauna Loa and Kilauea (abst): Geol. Soc. America Bull., vol. 37, pp. 150–151, 1926.

Pahala ash is fine grained and in places fairly well compacted, but can everywhere be easily dug with a shovel.

Five and one-half miles north of South Point, 3 inches of red soil caps the Kahuku lavas at the rim of the fault cliff. The soil is overlain by 4 feet of gray lithified dune sand and 4 to 8 feet of Pahala ash. The dune deposit contains both lava and coral sand and is similar to the sand in the drifting dunes in this area. The unusual thinness of the Pahala ash probably means that a large part has been removed, probably by the wind, prior to the deposition of the sand. The sand proves that dunes drifted across this area during Pleistocene time, probably correlative with the Waipio low stand of the sea when extensive dunes were formed on most of the other Hawaiian Islands. This dates the Kahuku series as being probably middle Pleistocene in age. The southern end of the Kahuku fault cliff has been cut back half a mile since it displaced the Kahuku rocks.

The Kahuku volcanic series is exposed intermittently in windows in the Kau and Puna volcanic series from Hilo to South Point, where it is truncated by the Kahuku fault (pl. 1). It must extend northwestward in the downthrown block under a veneer of lavas of the Kau volcanic series. A solitary inlier of rocks of similar appearance and mapped with the Kahuku rocks crops out in the escarpment on the north side of Kealakekua Bay 54 miles to the north in the Kona District (pl. 1). The lava beds in this cliff dip about 12° in a westerly direction and are 600 feet thick. A vitric tuff bed ½ to 1½ feet thick lies on top of the basal lava flow in the section. Two thin beds lie between flows higher in the section, and 25 feet below the top is a prominent yellow ash bed several feet thick. The lava at the top, although truncated by the cliff, is later and belongs to the Kau volcanic series. The lava cascaded over the cliff and marine erosion subsequently removed the part that spilled over

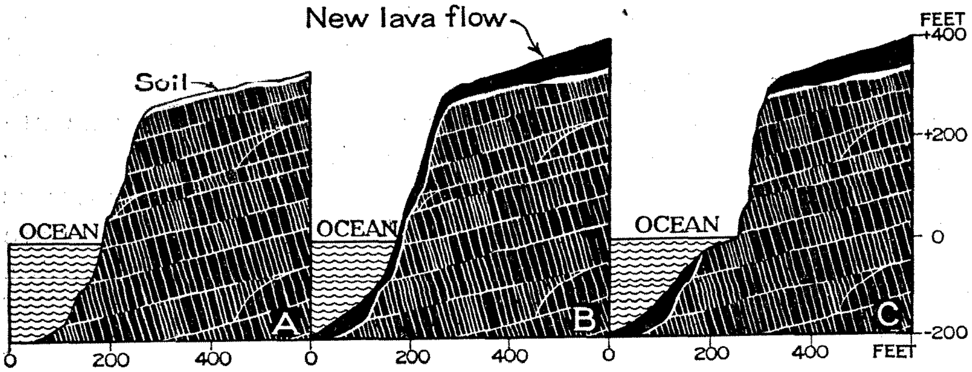


Figure 18. Three stages showing the history of a sea cliff veneered with lava. Before veneering, A; immediately after emplacement of lava flow, B; and veneer removed by subsequent wave erosion, C.

(fig. 18). Small remnants of such plasters cling to the cliff farther west. The cliff composed of rocks of the Kahuku volcanic series can be traced for 6 miles to the southeast although it is heavily manteled with lavas of the Kau volcanic series. It then appears to offset and run southward as Kaholo scarp toward South Point under a relatively thin mantle of later lavas. If this inference is correct, the west slope of Mauna Loa has been extended less than a mile in most places since the close of the deposition of Pahala ash. Some of the kipukas covered with 1 to 2 feet of ashy soil that lie amid later flows on the slopes between Hookena and Kainaliu may be underlain by Kahuku lavas. They are mapped with the Kau lavas because of the lack of distinguishing criteria.

The lavas of the Kahuku volcanic series in the Kau District dip 2° to 10° S. and SE. The normal dips indicate that the lava flows poured from the southwest rift of Mauna Loa. In some places the dip steepens to as much as 30° where the lavas have cascaded over former canyon walls cut in the Ninole volcanic series or steep fault cliffs. The lavas thicken appreciably within these ancient canyons. The Kahuku lavas dip 3° to 5° E. and SE. in the Hilo District. These lavas flowed from the east and northeast rift zones of Mauna Loa. The Kahuku lavas have relatively small exposures as the ash covers them except in gulch banks and fault cliffs. Nowhere are the exposures large enough to be shown separately from the ash on plate 1.

The lavas are highly permeable, carrying brackish water near the coast but fresh water near sea level farther inland. In wet areas bodies of perched water lie on the intercalated ash beds.

Most of the vents of the Kahuku lavas are buried except near Hilo and north of Kilauea Caldera. Halai hill, Puu Hono, and an unnamed cone between these two, lie in the residential section of Hilo. Wentworth included them with the cones of Mauna Kea,[70] but their northeast-southwest alignment on the prolongation of the northeastern rift zone of Mauna Loa makes them appear to be Mauna Loa cones. Halai hill is composed of cinder and spatter with small flows on the east side. The cone is deeply weathered and partly covered with Pahala ash. Puu Hono and the unnamed cone are covered with a thicker layer of Pahala ash and are probably older than Halai. The middle cone has been mostly removed for use as cinder. The cones deflected the later flows from Mauna Loa and are responsible for the ash-covered kipuka on which much of Hilo lies.

The cinder cones north of Kilauea Caldera in the vicinity of Kulani cone are deeply weathered and covered with a layer of Pahala ash. Three deep depressions occur near-by, probably pit craters.

---

[70] Wentworth, C. K., Ash formations of the island Hawaii: Hawaiian Volc. Obs., 3d Spec. Rept., p. 60, 1938.

Exposures are poor but the pit craters appear to be as old as the adjacent cones and are assigned with them tentatively to the Kahuku volcanic series. The cones deflected the later flows of the Kau volcanic series, thereby preventing a large area of Kahuku lavas and Pahala ash to the east from being buried.

It is possible that the bulk of Puu o Keokeo cinder cone on the southwest rift belongs to the Kahuku volcanic series, although it has been the site of later eruptions.

The cones are highly permeable but are too far above the zone of saturation to carry water.

PAHALA ASH ON MAUNA LOA

ORIGIN.—Dutton[71] believed the ash near Pahala to be alluvium deposited during former higher stands of the sea, but all subsequent workers have agreed that it is not an alluvial deposit. Emerson[72] attributed the ash near Pahala to explosions in Mohokea Caldera, but it has since been shown that this caldera never existed.[73] Hitchcock[74] suggested Mokuaweoweo and Puu o Keokeo on Mauna Loa as the sources of the ash in the Kau District. Baldwin[75] thought the ash near Pahala might have come from cones along the southern slope of Kilauea. Stone,[76] however, pointed out that these cones did not produce ash and concluded that the source of some, if not all, of the Pahala ash in the Kau District was from explosions in Kilauea Caldera. Stearns[77] stated that cones on Mauna Kea and Kohala were probably the chief source. Wentworth[78] concluded that Mauna Kea was the chief source.

Now that the island has been studied as a whole, the origin of the Pahala ash is better understood. The dominantly vitric character of the ash proves that it originated chiefly from very light pumice and Pele's hair carried by the wind from lava fountains during eruptions. Duration, frequency, and intensity of lava fountains determine the quantity of these ejecta, and direction and velocity of the wind at the time of eruption and the altitude of the vent determine where and how far away the ash will fall. If it falls on dry windswept land it may be picked up again and blown farther to the lee.

The problem of origin of the Pahala ash resolves into four main sources—Mauna Kea, Mauna Loa, Kilauea, and Kohala volcanoes. Mauna Kea was the source of the bulk of the ash, especially on

---

[71] Dutton, C. E., Hawaiian volcanoes: U. S. Geol. Survey 4th Ann. Rept., p. 97, 1884.

[72] Emerson, J. S., Some characteristics of Kau: Am. Jour. Sci., 4th ser., vol. 14, p. 435, 1902.

[73] Stearns, H. T., and Clark, W. O., op. cit., pp. 56–57.

[74] Hitchcock, C. H., Hawaii and its volcanoes, pp. 148 and 155, Honolulu, 1909.

[75] Baldwin, E. D., quoted by Hitchcock, C. H., Idem, pp. 169–171.

[76] Stone, J. B., The products and structure of Kilauea: B. P. Bishop Mus., Bull. 33, p. 27, 1926.

[77] Stearns, H. T., and Clark, W. O., op. cit., p. 68.

[78] Wentworth, C. K., op. cit., p. 165.

Mauna Kea and the eastern slopes of Mauna Loa inland from Hilo, as shown by the thinning of the ash from 20 feet near the Wailuku River to 8 feet at Glenwood. Great quantities of this ash must be buried by Mauna Loa flows west, southwest, and south of Mauna Kea. The deposits on the southern slope of Kilauea must have been derived chiefly from Kilauea, as evidenced by the sudden increase in thickness of the ash to the lee of Kilauea Caldera. Small quantities in this area probably were derived from eruptions on Mauna Kea and the northeast rift of Mauna Loa. The deposits on the southeastern slope of Mauna Loa were derived from eruptions of Kilauea, Mauna Loa, and Mauna Kea, plus appreciable quantities of dust from the Kau Desert. The southern slope of Kohala Mountain is mantled with Pahala ash from near-by cones and from cones on Mauna Kea. Some of the ash on Waimea Plain must have been derived from late Kohala cones.

The deposit is chiefly Pleistocene but contains in its upper part a small but variable amount of Recent ash depending on the nearness of the outcrops to Recent vents.

Distribution and character.—The distribution of the Pahala ash is shown in figure 19 and plate 1. It crops out over approximately 450 square miles, chiefly on Mauna Kea and Mauna Loa. As it is a composite subaerial ash deposit from four volcanoes, it overlies and its lower part is interstratified with several volcanic series. It is named from the village of Pahala which lies at the edge of extensive fields of yellow ash soil.[79] It includes the Waiau tuff described by Wentworth.[80] The ash is so friable, especially at the top, that the deposit is on the borderline between a tuff and an ash. Following the established usage in the literature on this region, it will be called ash. It fell like snow and mantles the entire terrane regardless of height or irregularities. The dip of the ash is controlled by the slope of the rocks on which it fell. Thus, on the top of a ridge may lie 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 an adjacent valley. Other complexities arise from prevailing wind directions, the fact that ash originated from and fell on simultaneously active volcanoes, and the fact that in many areas deposition has continued up to the present time.

Despite the fact that accumulation of the Pahala ash continued over a long period, the lower part, constituting the bulk of the deposit, appears to be essentially contemporaneous all over the island. It can be traced directly across Mauna Loa to Mauna Kea, and from Mauna Kea to Kohala Mountain. The lower part of the Pahala ash

---

[79] Stearns, H. T., and Clark, W. O., op. cit., p. 65.
[80] Wentworth, C. K., op. cit., p. 57.

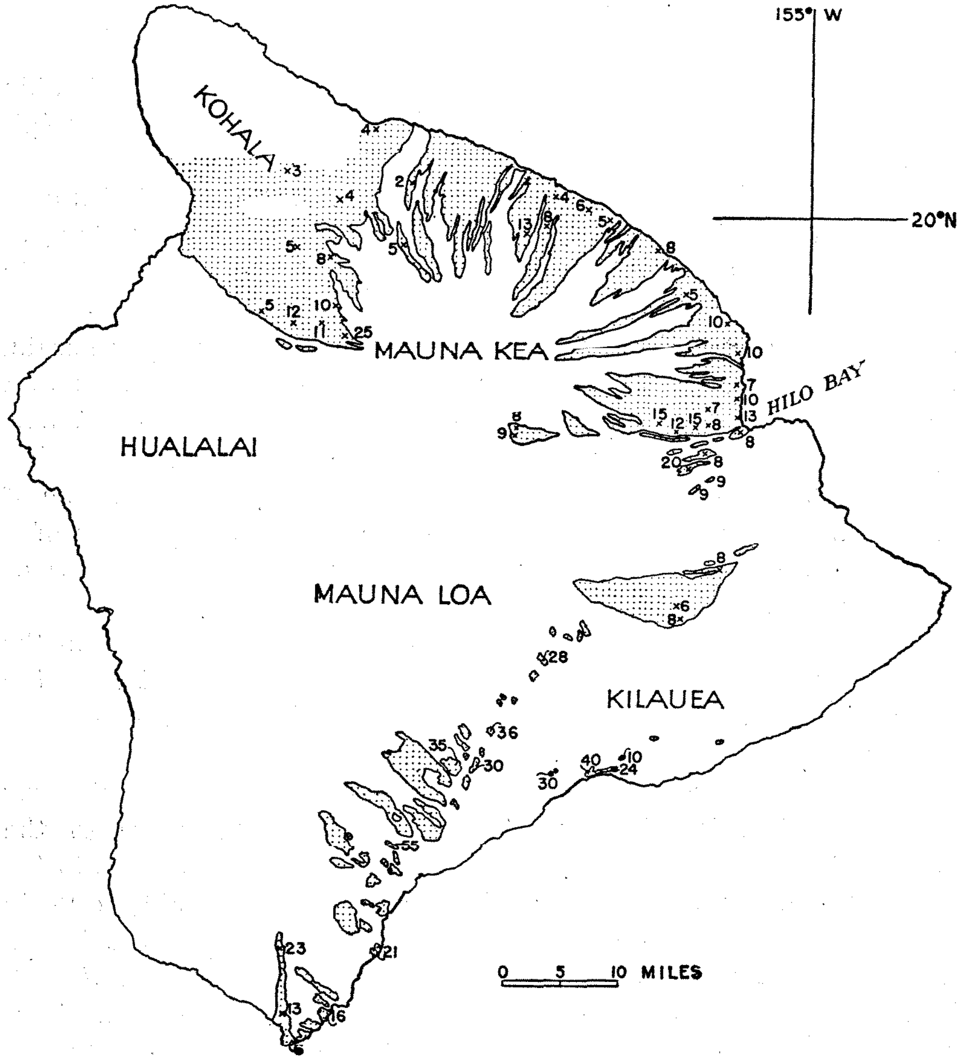


Figure 19. Map of Hawaii showing distribution and thickness in feet of Pahala ash.

serves as a widespread horizon marker, and the separation of several of the stratigraphic units depends on the relation of the rocks of the units to the Pahala ash.

The Pahala ash ranges from a single bed 55 feet thick in the vicinity of Pahala to several beds totaling about 15 feet interstratified with and overlying lavas in the Hilo District. Its character and distribution on Kilauea and Mauna Kea are described in chapters dealing with the geology of these volcanoes.

The Pahala ash on Mauna Loa ranges in color from light buff through dark yellow to brownish red with interstratified gray layers in a few places, chiefly near Kilauea. The color depends upon the amount of alteration, which in turn is largely due to the amount of vegetation and rainfall. The light colored ash is found mostly in areas where the rainfall is less than 40 inches. It is always friable but in some places it is well compacted and breaks into blocks (pl. 26B). In other places it is loose and dusty.

It is a subaerial ash deposit of sand and silt-sized particles containing small scattered pumice fragments. It was originally largely composed of basic volcanic glass. Near Kilauea it contains lithic lapilli. (See Section, p. 200.) In most areas weathering has altered the ash to a fine-grained aggregate of palagonitic clay minerals. The originally sandy texture has been largely lost in wet areas and clay-like properties dominate. Black humus layers, ancient surfaces formerly supporting vegetation, are fairly common. A few of them carry plant fossils.[81] In the vicinity of Kapapala a zone of red decomposed ash 6 to 10 inches thick lies near the middle of a 30-foot section of buff and gray ash, and persists over an area of several square miles. It represents a period of weathering.

The Pahala ash thins progressively away from Mauna Kea on the Mauna Loa slopes inland from Hilo. It thickens abruptly on the slopes of Mauna Loa leeward (southwest) of Kilauea and thins again west of Waiohinu.

Kipukas to the southeast on Mauna Loa carry 6 to 20 feet of vitric ash. The ash thins from 20 feet near Kaumana, close to the border of Mauna Kea, to 8 feet in the Glenwood area 15 miles to the south. Thinning must always be regarded as possibly due to erosion or burial by contemporaneous lava flows. A shaft to sea level and borings have shown that in the Olaa area and near Mountain View no thick buried ash beds exist. On the same radius of arc as Glenwood but due south of Mauna Kea one would expect to find more ash, perhaps half as much again; instead, nearly 5 times as much is found in the kipukas near Kapapala. This great thickening near Kilauea is interpreted to mean that Mauna Kea's lava fountains are not the major source of the ash between Kilauea and Kapapala. From Kapapala to South Point the ash has a fairly uniform thickness except where some has been removed by erosion.

A bed of ash 17 feet thick,[82] interstratified with the lavas at the base of the southern part of Uwekahuna Bluff, in the rim of Kilauea Caldera, has been buried in recent years. A lens of vitric tuff with a maximum thickness of 4 feet, possibly a northward continuation of the same bed, is still exposed in the cliff north of the Uwekahuna fault blocks.

Cinder cones are scarce on Kilauea and even though several have formed in Halemaumau since 1924, the total production of vitric ash has been small in post-Pahala time. Thirty feet of coarse ejecta

---

[81] Finch, R. H., Unconformity in the ash deposits near Glenwood: Volcano Letter, no. 21, p. 1, May 21, 1925.

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

lie on the southern rim of the caldera. The correlative ash is only 3 feet thick 1 mile away from the rim and thins to less than half a foot 3 miles away. How much ash was produced during Pahala time is not known. The observations on the fall of ash in Kau during the explosions in 1924[83] indicate that Kilauea has contributed lithic ash to the Pahala ash in that area. More significant, however, were the great quantities of dust and sand swept from the Kau Desert and carried southwestward over Pahala, Naalehu, and South Point, by the high winds which followed the explosions for many months. Some of the dust banners reached heights of 2,800 feet over Pahala. This process materially contributed to the Pahala ash deposits in the Kau District. In many places the Pahala ash resembles loess.[84] However, the eolian origin of loess is now disputed;[85] hence, these deposits are not here called loess. The term secondary eolian tuff[86] is more appropriate for the South Point deposit.

During eruptions on the northeast rift of Mauna Loa, accompanied by trade-wind weather, Pele's hair and small fragments of pumice, sufficient to give the sky a straw color, drift toward the Pahala area. Pele's hair with droplets of glass attached are common in Kau at such times. Similar material settles in Kau from summit and southwest rift-zone eruptions when the wind is in the right direction. Although such deposits during any one eruption are too small to measure, the 30,000 years of Recent time, with several eruptions each decade, must have produced an accretion of ash measurable in feet in the leeward kipukas.

The fact that so few flows were erupted on the southwestern, southern, and western slopes of Mauna Loa during the accumulation of the Pahala ash indicates either that the rate of extrusion of lava from Mauna Loa decreased decidedly during the epoch of ash accumulation or that the southwest rift became inactive.

The cones on Hualalai are most if not entirely post-Pahala and the prevailing wind blows in the wrong direction for them to have contributed to the Pahala ash. They did, however, lay down deposits of similar vitric ash in the Kona District.[87] The cones on Kohala Mountain are bulky and contain much pumice. The ash formed by these cones fell chiefly west of Waimea on Mauna Kea, on the western slopes of Kohala Mountain, and into the sea. Thus they did not con-

---

[83] Stearns, H. T., The explosive phase of Kilauea Volcano, Hawaii, in 1924: Bull. volcanologique, nos. 5 and 6, p. 201, 1925.

[84] Stearns, H. T., and Clark, W O., op. cit., p. 66. Palmer, H. S., Loess at Kalae, Hawaii: Volcano Letter, no. 350, Sept. 10, 1931.

[85] Russell, R. J., Lower Mississippi Valley loess: Geol. Soc. America Bull., vol. 55, pp. 1–34, 1944.

[86] Wentworth, C. K., op. cit., p. 43.

[87] Powers, H. A., Ripperton, J. C., and Goto, Y. B., Survey of the physical features that affect the agriculture of the Kona District of Hawaii: Hawaii Agr. Expt. Sta., Bull. 66, p. 7, 1932.

tribute to the Pahala ash on the southern slope of Mauna Loa. A small phreatic explosion occurred during Pahala time at Lua Poai, a pit crater 1,000 feet across and 290 feet deep, 1 mile south of Kahuku Ranch in the Kau District. It produced 5 feet of coarse debris on the rim of the crater which is interbedded with 32 feet of Pahala ash.[88] Such explosions locally contributed minor amounts of ash to the Pahala ash deposit.

The Pahala ash, where weathered and fine grained, has relatively low permeability compared with the flows of basalt. It perches valuable water in wet areas where overlain by lavas and not too deeply channelled prior to burial.

KAU VOLCANIC SERIES

General statement.—The major part of Mauna Loa is covered with rocks of the Kau volcanic series (pl. 1). The series is named from the Kau District, where the rocks are well exposed. The type locality is in the wall of Mokuaweoweo Caldera, where the section on page 190 was measured. The Kau volcanic series is the assemblage of Recent and latest Pleistocene volcanic rocks laid down by Mauna Loa Volcano. It is separated into a lower or prehistoric member and an upper or historic member. The Puna volcanic series is the assemblage of Recent and latest Pleistocene volcanic rocks laid down by Kilauea Volcano and is described in the chapter on the geology of Kilauea. Both the Kau and Puna volcanic series were formerly included in one stratigraphic unit, the Kamehame basalt.[89]

Some of the Kau lavas interfinger with and overlie Recent lavas of Hualalai and Kilauea volcanoes and are distinguished with difficulty. For this reason the contact between the Kau volcanic series and the rocks of these two volcanoes is shown in places with a broken line on plate 1. Between Kilauea Caldera and Keaau, the Kau lavas are overlapped by the latest Puna lavas from Kilauea, but below the surface the lavas of the two series probably interfinger.

The Kau lavas form a thin veneer, commonly one flow thick, on the lower slopes of Mauna Loa, but they thicken toward the summit, and in the walls of Mokuaweoweo they exceed 600 feet. Part of the thickening results from the convergence of radial flows and part results from an increase in the number of flows.

---

[88] Stearns, H. T., and Clark, W. O., Geology and water resources of the Kau District, Hawaii: U. S. Geol. Survey Water-Supply Paper 616, p. 154, 1930.

[89] Idem, p. 69.

PREHISTORIC MEMBER OF THE KAU VOLCANIC SERIES

The lavas are chiefly porphyritic or nonporphyritic aa and pahoehoe basalts. Olivine basalts are abundant. The flows average about 15 feet in thickness. The rocks of the Ninole and the Kahuku volcanic series form kipukas in the Kau lavas. The surface of prehistoric lava flows of the Kau volcanic series is usually brown in contrast to the black of the historic lava flows. Most are too recent to carry sufficient soil for tilling, although the older ones carry sufficient soil to support vegetation and coffee plantations. Tubes and minor structures typical of recent lava flows are common in the Kau lavas.

Evidence of erosion between the flows of the prehistoric member of the Kau volcanic series is scanty except near Hilo, where an early Kau lava flow filled an ancient gorge of the Wailuku River. The former valley is exposed in section at Rainbow Falls (pl. 20B). At the Boiling Pots on the Wailuku River, 2.5 miles west of Hilo (pl. 27A), the top of the lava is 20 to 30 feet below the rim of the ancient gorge. Most of the lava within the gorge is dense, columnar-jointed, and 75 to 100 feet thick.

In some places near Olaa the clinker of the aa flows formed mounds 50 feet high. The mounds may have resulted from aa flows being dammed by dense wet forests. Another very hummocky aa lies 1 mile southeast of Keauhou in the North Kona District. It is a dry area; hence, hummocky aa may develop from topographic influences and sluggishness as well as from damming in dense forests.

One of the latest of the prehistoric Kau lavas issued from a fissure on the northern slope of Mauna Loa at a cone called Kokoolau at an altitude of 8,000 feet. The flow extends northward for 20 miles and is thick pahoehoe with large domes on its surface. It is called the Keamuku Lava Flow. It should not be confused with the late prehistoric thick aa flow called the Keamoku flow that issued from the northeast rift and nearly reached Kilauea Caldera. The Keamoku flow extends southwestward along the contact of Kilauea and Mauna Loa for 7½ miles and is crossed by the main highway.

The lavas of the Kau volcanic series are highly permeable and carry brackish water along all coasts except near Hilo, where they yield potable water. They carry perched water bodies where they overlie Pahala ash in wet areas.

The vents of the Kau lavas range from fissures several miles long and 1 to 10 feet wide, bordered by low spatter heaps and ramparts 2 to 50 feet high, to typical cinder cones 100 feet high. They lie chiefly in the three rift zones of Mauna Loa. They outnumber the vents of any other volcanic series on the island of Hawaii, more than 160 fissures and distinct cinder cones being mapped on plate 1.

Most of the pit craters on Mauna Loa were formed during the accumulation of the Kau volcanic series.

Small crateriform depressions have in many places resulted from collapse of the roofs of lava tubes. Several of these lie just north of the road to the Kulani prison camp, near 2,750 feet altitude. One is about 100 feet long, 75 feet wide, and 70 feet deep.

The ash deposits of the prehistoric member of the Kau volcanic series are insignificant in volume. Deposits of pumice a few inches to 2 feet thick lie just leeward of the large cinder cones but they cover too small an area to be shown on plate 1. The largest area of pumice lies leeward of the southwest rift near Puu o Keokeo. A deposit of lithic ash, lapilli, and blocks, too thin to cover completely the underlying lavas, lies on the rim of Mokuaweoweo (fig. 7); another lies 1 mile to the south on the Ainapo Trail. They resulted from two separate phreatic explosions.[90]

The cones and ash deposits are highly permeable but do not carry water because they lie above the zone of saturation.

HISTORIC MEMBER OF THE KAU VOLCANIC SERIES

General features.—The historic volcanics on Mauna Loa date from 1832 when the first lava flow was recorded. The location of this flow is uncertain but it is probably the one above Waiohinu.[91] Hitchcock[92] reports an eruption in 1780 north of Pohaku Hanalei and one on January 21, 1803, on the west or north side of Mokuaweoweo, but cites no authority for these statements. A table giving the significant data regarding the historic flows follows:

---

[90] Op. cit. pp. 153–154.

[91] Op. cit., p. 71.

[92] Hitchcock, C. H., Hawaii and its volcanoes, p. 80, Honolulu, 1909.

Eruptions of Mauna Loa[a]

Date of commencement		Approximate duration (days)		Location of principal outflow	Altitude of main vent (feet)	Approximate repose period since last eruption (months)	Area of lava flow (square miles)	Approximate volume of lava (cubic yards)
Year	Month and day	Summit eruption	Flank eruption					
1832	June 20	21	(?)	SW. rift	8,200(?)	.....	6.8(?)	90,000,000(?)
1843	Jan. 9	5	90	N. flank	9,800	126	20.2	250,000,000
1849	May	15	.....	Caldera	[d]13,000	73	....	....
1851	Aug. 8	21	(?)	Caldera & SW. rift	13,300	26	6.9	90,000,000
1852	Feb. 17	1	20	NE. rift	8,400	6	11.0	140,000,000
1855	Aug. 11	.....	450	do.	10,500(?)	41	[b]12.2	150,000,000
1859	Jan. 23	<1	300	N. flank	9,200	26	[c]32.7	[c]600,000,000
1865	Dec. 30	120	.....	Caldera	13,000	73	....	....
1868	Mar. 27	1	[e]15	SW. rift	3,300	23	[c]9.1	[c]190,000,000
1872	Aug. 10	[f]60	.....	do.	13,000	52	....	....
1873	Jan. 6	2(?)	.....	do.	13,300	3	....	....
1873	Apr. 20	547	.....	do.	13,000	3	....	....
1875	Jan. 10	30	.....	do.	13,000	2	....	....
1875	Aug. 11	7	.....	do.	13,000	6	....	....
1876	Feb. 13	Short	.....	do.	13,000	6	....	....
1877	Feb. 14	10	[g]1	W. flank	−180±	12	....	....
1880	May 1	6	.....	Caldera	13,000	38	....	....
1880	Nov. 1	.....	280	NE. rift	10,400	6	24.0	300,000,000
1887	Jan. 16	.....	10	SW. rift	5,700	65	[c]11.3	[c]300,000,000
1892	Nov. 30	3	.....	do.	13,000	68	....	....
1896	Apr. 21	16	.....	do.	13,000	41	....	....
1899	July 4	4	19	NE. rift	10,700	38	16.2	200,000,000
1903	Oct. 6	60	.....	Caldera	13,000	50	....	....
1907	Jan. 9	<1	15	SW. rift	6,200	37	8.1	100,000,000
1914	Nov. 25	48	.....	Caldera	13,000	94	....	....
1916	May 19	.....	14	SW. rift	7,400	16	6.6	80,000,000
1919	Sept. 29	Short	42	do.	7,700	40	[c]9.2	[c]350,000,000
1926	Apr. 10	Short	14	SW. rift	7,600	77	[h]13.4	[c]150,000,000
1933	Dec. 2	17	<1	Caldera & SW. rift	13,000	91	2.0	100,000,000
1935	Nov. 21	<1	42	NE. rift	12,100	23	[i]13.8	160,000,000
1940	Apr. 7	133	<1	Caldera & SW. rift	13,000	51	[j]3.9	100,000,000
1942	Apr. 26	2	13	NE. rift	9,200	20	[k]10.6	100,000,000
Total		1,136	1,314				211.2+	3,450,000,000

[a] The duration for most of the eruptions previous to 1899 is only approximate. Heavy columns of fume at Mokuaweoweo, apparently representing copious gas release accompanied by little or no lava discharge, were observed in January 1870, December 1887, March 1921, November 1943, and August 1944. They are not indicated in the table.

[b] Upper end of the flow cannot be identified with certainty.

[c] Area above sea level. The volume below sea level is unknown, but estimates give the following orders of magnitude: 1859—300,000,000 cubic yards; 1868—100,000,000 cubic yards; 1887—200,000,000 cubic yards; 1919—200,000,000 cubic yards; 1926—1,500,000 cubic yards. These are included in the volumes given in the table.

[d] All eruptions in the caldera are listed at 13,000 feet altitude, although many of them were a little lower.

[e] Flank eruption started April 7.

[f] Activity in the summit caldera may have been essentially continuous from August 1872 to February 1877, only the most violent activity being visible from Hilo.

[g] Submarine eruption off Kealakekua, on the west coast of Hawaii.

[h] 2.5 square miles of this is the area of the thin flow near the summit. An unknown area lies below sea level.

[i] About 0.5 square mile of this is covered by the thin flank flow above the main cone and 0.8 square mile is in Mokuaweoweo Caldera.

[j] 2.8 square miles is in Mokuaweoweo Caldera and 1.1 square miles outside the caldera.

[k] 2.8 square miles of this is covered by the thin flank flow near the summit, and 0.5 square mile is in the caldera.

The historic flows range from nonporphyritic to porphyritic aa and pahoehoe basalts. Many contain phenocrysts of olivine. Those ponded in Mokuaweoweo are massive and columnar-jointed. Many branches of the historic lava flows were not mapped or recorded during their eruption and cannot now be separated with certainty. Doubtful ones have been mapped with the prehistoric lavas on plate 1.

The historic flows differ only slightly in freshness from the prehistoric lavas and are separated from them on plate 1 only because they are dated. Most are black narrow flows on the flanks of the mountain ranging from 1 to 30 feet thick. They contain many interesting minor features characteristic of basalt flows, such as tubes, stalactites, stalagmites, lily-blossom forms where pahoehoe lava has welled up through holes in lava tubes (pl. 26A), accretionary lava balls (pl. 13C), lava-river channels (pl. 15A), and tree molds.

Dendritic-type lava, similar to that shown in plate 26C, was found along cracks at the 8,800-foot outlet of the lava flow of 1935. The dendritic type develops in pahoehoe along the walls of cracks that form after the surface hardens but while the lava is still viscous a few inches below. It forms where the crust sags, leaving one side of the crack higher than the other. Its rare occurrence indicates that the lava must have just the right consistency in order to develop the arborescence. The dendritic lava described earlier[93] as aa was a transitionary phase between pahoehoe and aa and the conditions under which it formed were similar to those observed in the lava of 1935.

HISTORIC PIT CRATERS.—The pit crater of Lua Poholo, on the northeast side of Mokuaweoweo Caldera, is more than 1,000 feet across and apparently originated between 1874 and 1885 (pl. 18). It is not shown on the map of the caldera made by the Wilkes Expedition in 1841 (fig. 7), nor on the one by J. M. Lydgate in 1874,[94] but it is plainly indicated on Alexander's map of 1885.[95] The area was so thoroughly covered by earlier surveyors, particularly by the Wilkes party, that there is little likelihood of its having been overlooked. Moreover, much of its character indicates recent origin. The pattern of the lava flows in plate 18 shows clearly that this pit has been stoped in the lavas poured from Mokuaweoweo Caldera and that no lava has flowed from it. A geologic map of the area shown on plate 18 is given in figure 10. Lua Hohonu, a pit crater a mile southwest of Mokuaweoweo, appears to have formed between 1841 and 1924 (figs. 7 and 8).

---

[93] Stearns, H. T., and Clark, W. O., op. cit., p. 81.

[94] Brigham, W. T., The volcanoes of Kilauea and Mauna Loa: B. P. Bishop Mus. Mem., vol. 2, no. 4, p. 123, 1909.

[95] Alexander, J. M., On the summit crater of Mt. Loa in October, 1885: Am. Jour. Sci., 3d ser., vol. 36, pp. 35–39, 1888.

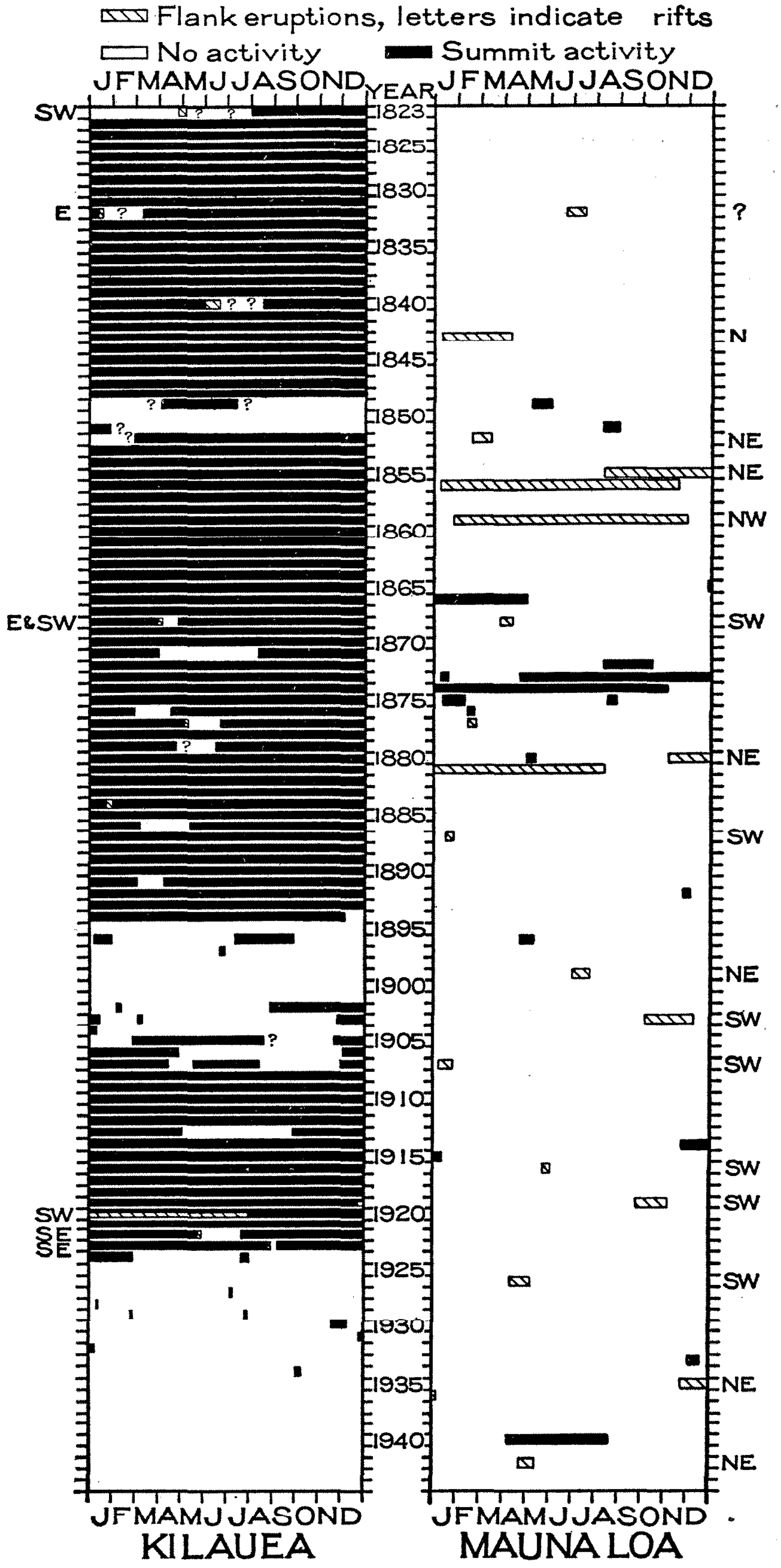


Figure 20. Graph showing periods of activity of Kilauea and Mauna Loa volcanoes.

HISTORIC ERUPTIONS OF MAUNA LOA VOLCANO

General statement.—The eruptions of Mauna Loa Volcano from 1832 to 1943 are listed in the table on page 79, and are shown graphically in figure 20. Mauna Loa has been active about 5.9 percent of the time in the last 113 years. The duration of the flank eruptions was about 54 percent of the time the mountain was active.

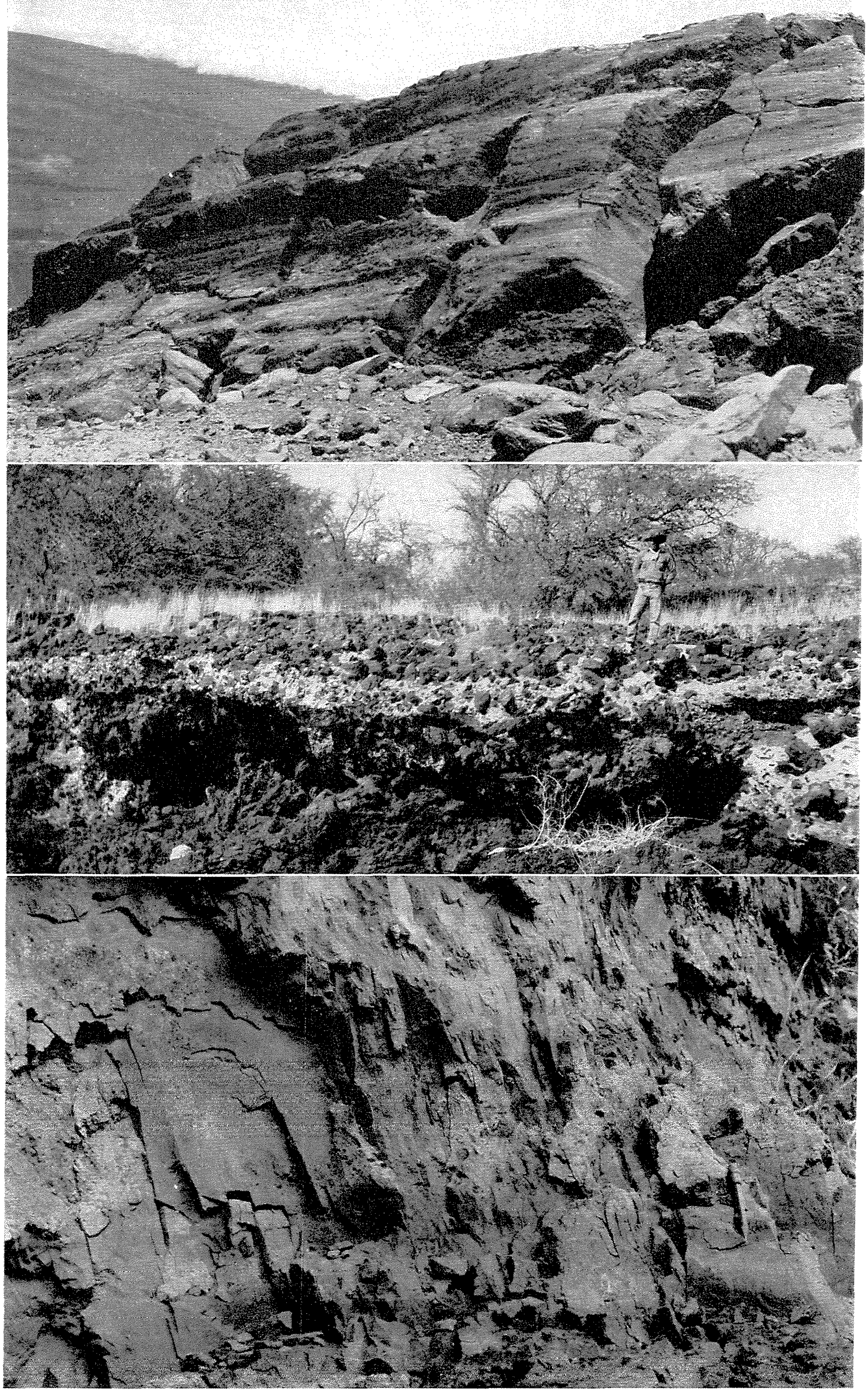
Types.—Most eruptions readily fall into two types: (1) Summit eruptions without accompanying flank flows; and (2) flank flows accompanied by short-lived flows of small volume in the caldera a few minutes to a few days before the flank flow. A few flows appear as borderline types, namely, the eruptions in 1851, 1933, and 1940. Detailed observations of the 1851 flow are lacking but excellent data are available for the others. If eruptions are to be classified on the basis of lava being poured down the slope outside the caldera, such eruptions should be listed as flank flows. Summit eruptions are characterized by lava erupting along fissures which cross the caldera floor. The activity, after a few days, becomes concentrated at one or more cones on the floor. The fissure vents of 1933 and 1940 cross the caldera floor and extend a short distance down the southwest rift (pls. 30, 31, 32). For a few hours lava poured down the southwest flank from these fissures simultaneously with lava erupting on the crater floor. During 1933, activity on the southwest rift lasted less than a day, whereas that in the caldera continued for 17 days. Again in 1940, flank activity lasted only 18 hours, but eruption continued in the caldera for more than four months. These two eruptions are therefore shown in figure 20 as summit eruptions. The 1851 eruption poured a good sized flow from a fissure just downslope from the southern rim of the caldera. No record exists of what happened in the caldera. Judging from its course, however, the source fis-

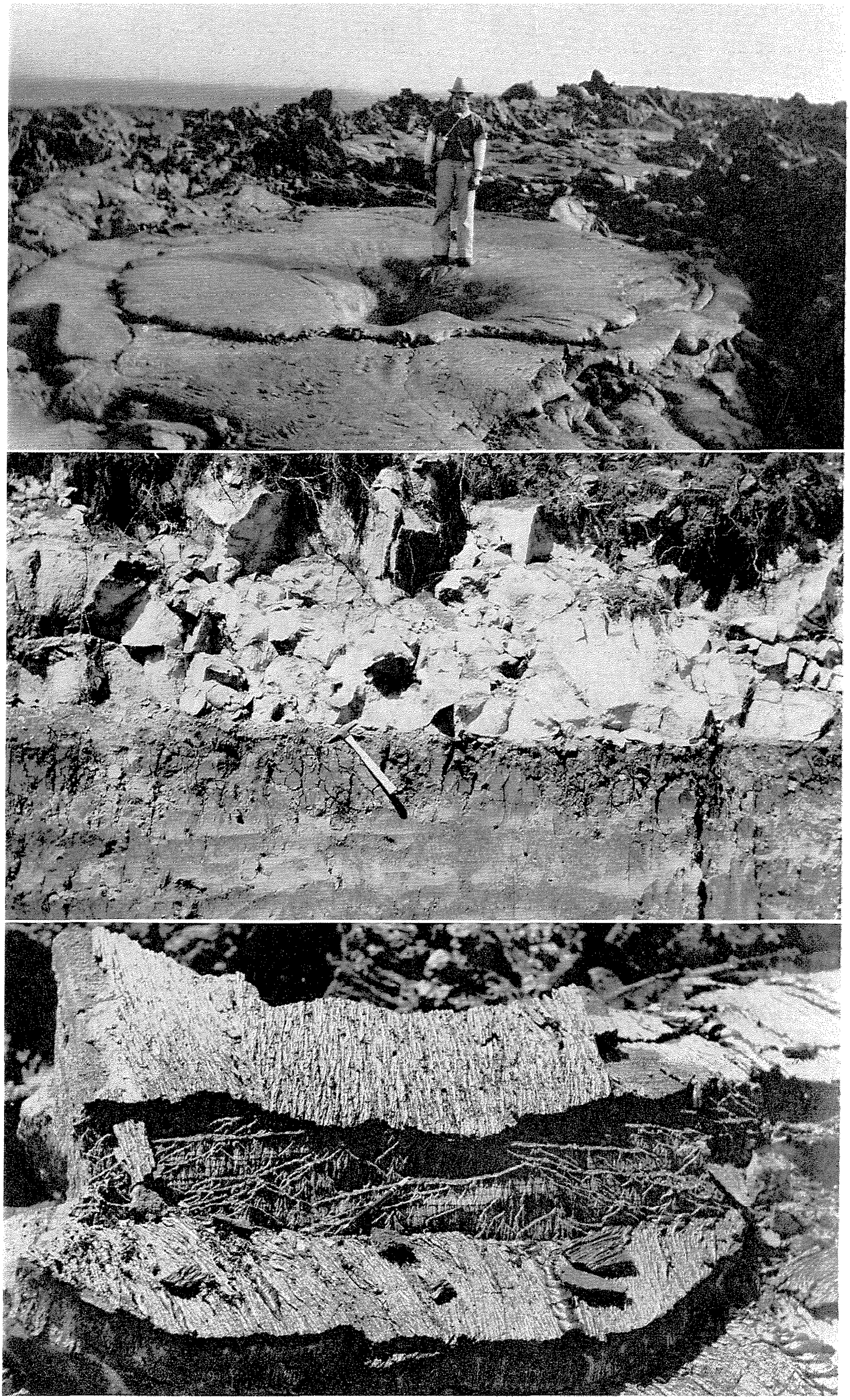
→

Opposite page, top: Plate 25A. Glacially striated ledge of andesite on the south slope of Mauna Kea at an altitude of about 11,750 feet. Photo by C. K. Wentworth.

Middle: Plate 25B. View of fossiliferous marine conglomerate about 20 feet above sea level north of Keawanui Bay on the west shore of Kohala Mountain. Photo by H. T. Stearns.

Bottom: Plate 25C. Tuff in the Ninole volcanic series in tunnel 99 in the Kau District, showing its dense nature and prominent jointing (pencil indicates scale). Photo by C. K. Wentworth.





sure almost certainly extended across the caldera floor, and the eruption is best classed as a summit eruption. A short flow poured down the southwest flank in 1903 from the South Pit area but the activity in that year, as reported by persons who reached the summit, was chiefly within the caldera. As early observations were made chiefly from the periphery of the mountain, perhaps other summit eruptions produced unobserved short-lived flank flows. The north and south flanks next to the caldera are veneered with many black flows unrecorded, but obviously historic.

Activity was reported for about 2 days in the caldera in January 1873. Molten lava was seen again at the top of the mountain in April. During the later phases of the eruption of 1940, for periods of several days at a time, activity diminished until the glow was insufficient to illuminate the mountain at night, but observers at the summit reported continuous activity in the caldera.[96] Thus, the activity in 1873 may have been more or less continuous from January to April but not visible from the periphery of the mountain.

Fume and steam were seen above the summit from January 1 to 15, 1870, from December 29, 1887 to early in February 1888, and during March 1921, November 1943, and August 1944. These eruptions probably represent liberation of gas with little or no accompanying lava. They have not been included in the table of eruptions, although they do represent one phase of activity of the volcano. That of 1943 was accompanied by tremor of the sort which accompanies lava eruption, and probably indicated the movement of magma at depth.[97]

The eruption of 1903 may have produced a submarine flank

---

[96] Schulz, P. E., Some characteristics of the summit eruption of Mauna Loa, Hawaii, in 1940: Geol. Soc. America Bull., vol. 54, pp. 739–746, 1943.

[97] Finch, R. H., Activity of Mauna Loa in November 1943: Volcano Letter, no. 482, 1943.

←

Opposite page, top: Plate 26A. Lily-blossom form caused by prehistoric pahoehoe lava welling through a hole in the roof of a lava tube a quarter of a mile northeast of the 8,800-foot vent of the lava flow of 1935 on Mauna Loa Volcano. Photo by H. T. Stearns.

Middle: Plate 26B. Prehistoric pahoehoe of the Kau volcanic series resting on Pahala ash, on the road from Hilo to Kaumana on the northeastern slope of Mauna Loa Volcano. Photo by H. T. Stearns.

Bottom: Plate 26C. Dendritic lava along a fissure in the crust of pahoehoe at the 8,800-foot vent of the lava flow of 1935 from Mauna Loa Volcano (pencil indicates scale). Photo by H. T. Stearns.

eruption, as boiling water was reported off the coast of Kona on October 5,[98] one day before the summit outbreak.

THE TYPICAL ERUPTION.—A typical eruption of Mauna Loa begins with a series of local earthquakes which indicates the splitting open of the mountain and which enabled Finch[99] in 1942 to predict the point of outbreak. Sometimes the earthquakes are sharp and perceptible but often they are weak and recorded by local seismographs only. Usually the eruption is accompanied by a fume cloud rising several miles into the air (pl. 29A) and lava fountains reaching a maximum height of 700 feet. The outbreak typically begins in Mokuaweoweo and extends down one of the rift zones either continuously along a fissure or by breaking out lower down along a newly opened fissure. Several days may intervene between the outbreak in Mokuaweoweo and that on the flank. Some eruptions occur in the caldera without any outbreak on the flank. During summit eruptions lava commonly erupts from wall cracks and pours down the wall into the caldera (pl. 30 and fig. 10). Where such flows plaster coarse talus and clinker, curious hummocky and bumpy lava surfaces are formed (pl. 33C). The cracks, usually a few inches to several feet wide, are enlarged at the main vents to fissures 10 to 25 feet wide by stoping, fluxing, and subsequent collapse. In other places pit craters develop by stoping.

At first the sudden gas release causes intense fountaining which commonly merges along the crack into veritable "curtains of fire" (pl. 8). Cones are not produced at first because the lava of the fountains is sufficiently liquid when it falls to the ground to flow away as very frothy pahoehoe. Highly cellular tan pumice clots up to 1 foot across are carried upward in the hot, rapidly ascending fumes. At various heights up to 1,000 feet the updraft becomes insufficient to support the clots and they fall, smashing into bits on the hard rocky surface. Some fall into the lava streams and are floated off. Pele's hair, delicate threads of glass spun by the lava fountains, drifts leeward for miles, causing the ground to glisten as though covered with jewels. The crust of pahoehoe formed close to the fountains where glass spinning is rapid, as was observed in the lava flow of 1935, may consist of welded mats of Pele's hair and coarser strands of spun glass.

Great volumes of very fluid pahoehoe lava are poured out during the first few days. The lava flows down the slope in two or more rivers at rates of 10 to 25 miles per hour (pl. 34A), at times merging below the vents to form a single flow. A short distance from the lava fountains these pahoehoe flows usually change to thin clinkery aa flows. The flows near the source on the upper

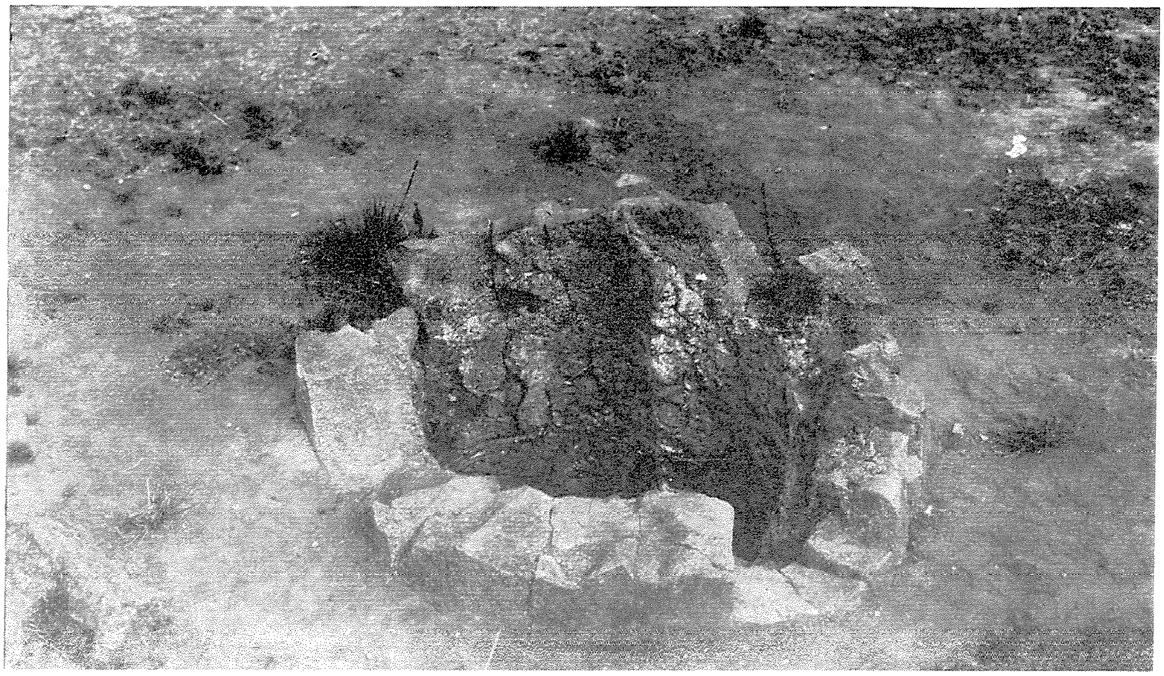
---

[98] Hitchcock, C. H., Hawaii and its volcanoes; p. 138, Honolulu, 1911.

[99] Finch, R. H., The seismic prelude to the 1942 eruption of Mauna Loa: Seismol. Soc. America Bull., vol. 33, pp. 237–241, 1943.

Above: Plate 27A. The Boiling Pots, large potholes cut in valley-filling lava of the Kau volcanic series in Wailuku River near Hilo. Photo by R. J. Baker.

Below: Plate 27B. Tree mold near golf links, Hawaii National Park. Photo by R. J. Baker.



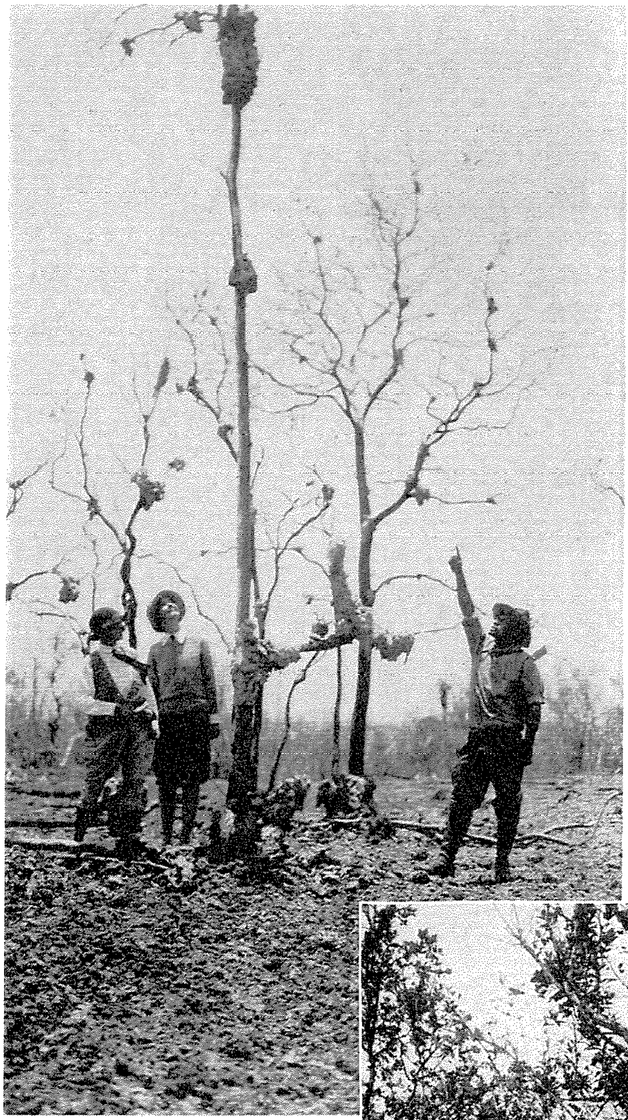


Plate 28A. Lava spatter in trees in the lava flow of 1923 along the Chain of Craters Road. The spatter has since fallen from the trees. Photo by Thomas Boles, National Park Service.

Plate 28B. A lava tree near Pahoa in the Puna District.

part of the mountain are commonly only 6 inches to 3 feet thick. On the lower slopes they are generally 10 to 15 feet thick, and where they pool in flats, they attain a thickness of 50 feet or more.

Generally the bulk of the gas is released in a few days and the fountains gradually die down, building chains of spatter cones, spatter ramparts, and cinder cones along the fissures (pl. 34B). The lava outflow typically becomes restricted to a single river issuing at the lower end of the cone chain.

During long eruptions the rivers of pahoehoe crust over and build one or more feeding tubes which conduct the lava with only slight loss of heat for many miles down the mountain. The 1859 flow is 33 miles long, the longest historic flow. It lasted 10 months, and pillow lava formed where it ran into the sea.[100] During some eruptions pahoehoe advances over and extends beyond the earlier aa. These pahoehoe flows are potentially the most destructive and may some day fill and destroy Hilo Harbor. The 1881 pahoehoe stopped in the outskirts of Hilo after flowing 29 miles.

SEISMIC PRELUDE TO ERUPTION.—In much of the older literature, the view is expressed that many outbreaks of Hawaiian volcanoes are unattended by earthquakes. This is true only because the quakes are not of sufficient intensity to be generally felt. It appears that eruptions are preceded by quakes which are recorded distinctly on seismographs.[1] The best studied seismic prelude is that which preceded the eruption of Mauna Loa in 1942, described by Finch.[2] A series of earthquakes started on February 8 with a shock with focus 27 to 30 miles deep on the northeast rift of Mauna Loa near Hilo. Thereafter, a progressive migration of epicenters occurred along the northeast rift, with a swarm of quakes centering at 9,000 feet altitude on February 21. The earthquake epicenters continued to migrate up the rift, reaching the northern end of Mokuaweoweo on March 7, and extending 5 miles down the southwest rift by March 20. Instead of continuing down the southwest rift, however, the epicenters returned to the northeast rift, and on that basis it was predicted that an eruption would soon take place on the northeast rift. On April 26 lava broke out in Mokuaweoweo Caldera and along the upper part of the northeast rift, and on April 28 the main eruption commenced on the northeast rift at 9,200 feet altitude, very near the epicenter of the earthquake swarm of February 21.

AREAS AND VOLUMES OF HISTORIC LAVA FLOWS.—In the table on page 79 the areas of the flows were determined from plate 1. The volume of each flow is based on the area and on certain assumptions as to average thickness. Accurate measurements are lacking, but the average thickness of most flank flows was assumed

---

[100] Green, W. L., Vestiges of the molten globe, vol. 2, p. 277, 1887.

[1] Wood, H. O., The seismic prelude to the 1914 eruption of Mauna Loa: Seismol. Soc. America Bull., vol. 5, pp. 39–51, 1915.

[2] Finch, R. H., op. cit., pp. 237–241.

to be about 12 feet. For unusually thin flows, or where more definite measurements were available, other average thicknesses were used. The figures for volume should be regarded as merely approximations, indicating an order of magnitude. For the most part the volumes given in the table are probably too small, as an effort has been made to be conservative. Also most or all of the flank eruptions, during the opening stages, produced thin flows from the upper parts of the fissures, few of which can now be identified. They probably would not add greatly to the total volume, however. Information is lacking as to the extent and thickness of any but the latest of the flows in the caldera, but many of them probably attained relatively great thickness owing to ponding in the depression. The volumes of lava extruded in the caldera in 1933 and 1940 are comparable to the volumes of many of the flank eruptions. Several flows have entered the sea, but there is no way of estimating with any accuracy the volume of lava below sea level. The figures in the table represent only the portions of those flows which are above sea level.

Previous estimates of volumes have generally run higher than those given here. For instance, J. D. Dana estimated the volume of the 1852 lava as 299,000,000 cubic meters. C. H. Hitchcock estimated the 1855 and 1880-1881 flows at 455,000,000 and 413,000,000 cubic meters respectively, and E. D. Baldwin estimated the 1907 flow at 153,000,000 cubic meters.[3] Penck's estimates are higher, being 510,000,000 cubic meters for the 1852 flow; 4,860,000,000 cubic meters for the 1855 flow; 2,730,000,000 cubic meters for the 1859 flow; 1,670,000,000 cubic meters for the 1868 flow; and 2,010,000,000 cubic meters for the 1880-1881 flow.[4] The larger figures probably result in part from erroneous assumptions for the areas of the flows, but largely from assuming too great an average thickness. Jaggar's figure of 68,000,000 cubic meters for the volume of the 1933 lava[5] does not differ greatly from the figure of 100,000,000 cubic yards (approximately 73,000,000 cubic meters) given in the table, and the estimate of 100,000,000 cubic yards by Schulz for the 1940 lava[6] is identical with that in the table. The area, and consequently the volume previously published for the 1887 flow,[7] have been found to be in error.

Historic eruptions produced 1,000,000 to 5,000,000 tons of lava an hour during their early phases. Since 1831, flank flows have added about 211 square miles and 0.60 cubic miles of rock to

---

[3] Daly, R. A., The nature of volcanic action: Am. Acad. Arts Sci. Proc., vol. 47, p. 106, 1911.

[4] Penck, Albrecht, Morphologie der Erdoberfläche, vol. 1, p. 436, Stuttgart, 1894.

[5] Jaggar, T. A., Summit outbreak of Mauna Loa, December, 1933: Volcano Letter, no. 439, p. 5, September 1936.

[6] Schulz, P. E., op. cit., p. 742.

[7] Stearns, H. T., and Clark, W. O., op. cit., p. 74. The time to reach the sea was 29 hours instead of 17 hours as published.

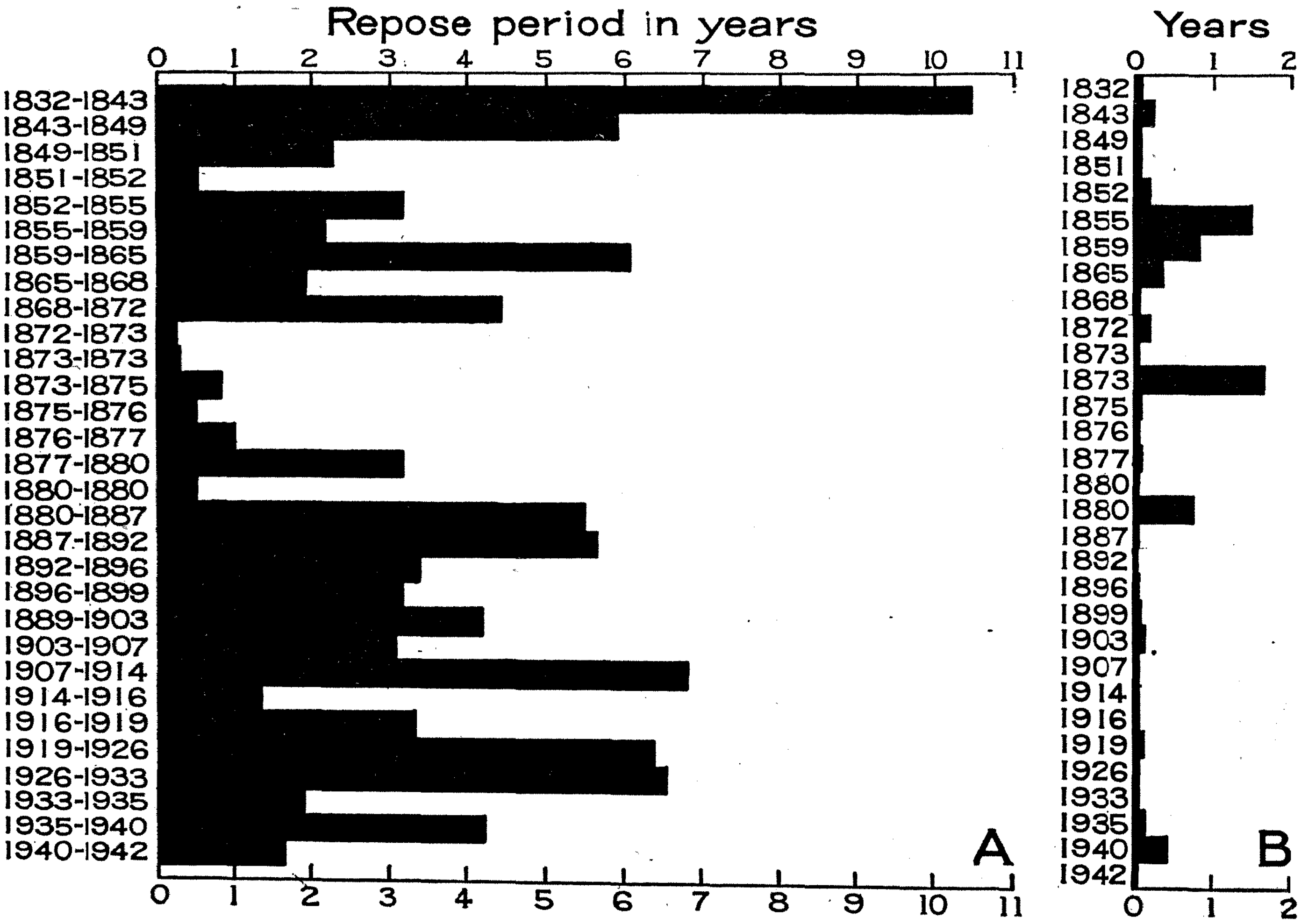


Figure 21. A, Graph showing repose periods between eruptions of Mauna Loa Volcano, 1832-1942. B, Graph showing the duration of historic eruptions of Mauna Loa Volcano.

Mauna Loa. Combined with about 0.14 cubic mile of filling in Mokuaweoweo since about 1870, when the central pit appears to have been deepest,[8] the total is 0.74 cubic mile or about .0065 cubic mile per year. At this rate, assuming the bulk of Mauna Loa above sea level as about 1,750 cubic miles, it took about 270,000 years to build that part of Mauna Loa. The erosional unconformity between the Ninole and Kahuku volcanic series indicates that this method of computing the total age of Mauna Loa is subject to large error. Moreover, the rate of lava outpouring may have been different in the past.

Periodicity.—Much has been written by Dana, Green, Wood, Jaggar, and others, about the periodicity of eruptions of Mauna Loa. Jaggar believes that there is an 11-year, 66-year, and 132-year cycle in Hawaiian volcanism.[9] It will be seen from the table on page 79 and the graph in figure 21A that the repose period between eruptions ranges from 2 months to 10½ years. Average time interval has little significance in predicting eruptions, where so great a variation exists. Twelve repose periods were less than 2 years long, 8 between 2 and 4 years, 5 between 4 and 6 years, and 6 between 6 and 10½ years. Thus the odds are about 2 to 1 that an eruption will occur every 4 years or less. If 3 years pass without an eruption, a prediction that an eruption will occur within the next two years becomes reasonable, though still far from certain.

The repose periods between flank eruptions are also irregular. They range from 2 years and 3 months to 12 years and 5 months. Four repose periods between flank eruptions are less than 4 years long, 6 between 4 and 8 years, and 5 between 8 and 12½ years as shown in figure 22. Nine of the 15 repose periods are more than 6 years long. Consequently, if a flank eruption has just ceased, the odds are 3 to 2 that a flank eruption will not occur within the following 6 years. The relation of eruptions to sunspots is discussed on page 126.

Duration.—The duration of each historic eruption is shown in the table on page 79 and graphically in figure 21B. Twenty of the 32 eruptions lasted less than a month, 7 lasted more than 2 months, and only 2 of these continued for more than a year. The longest eruption (1873) lasted 18 months in the caldera, and the next longest was 15 months (1855) on the northeast flank. A comparison of A and B, figure 21, shows that no relation exists between the length of repose of the volcano and the duration of the next succeeding eruption.

---

[8] Jaggar, T. A., The crater of Mauna Loa: Volcano Letter, no. 360, pp. 1–4, Nov., 1931.

[9] Jaggar, T. A., The Hawaiian volcanic cycle: Volcano Letter, no. 325, pp. 1–3, Mar. 19, 1931.

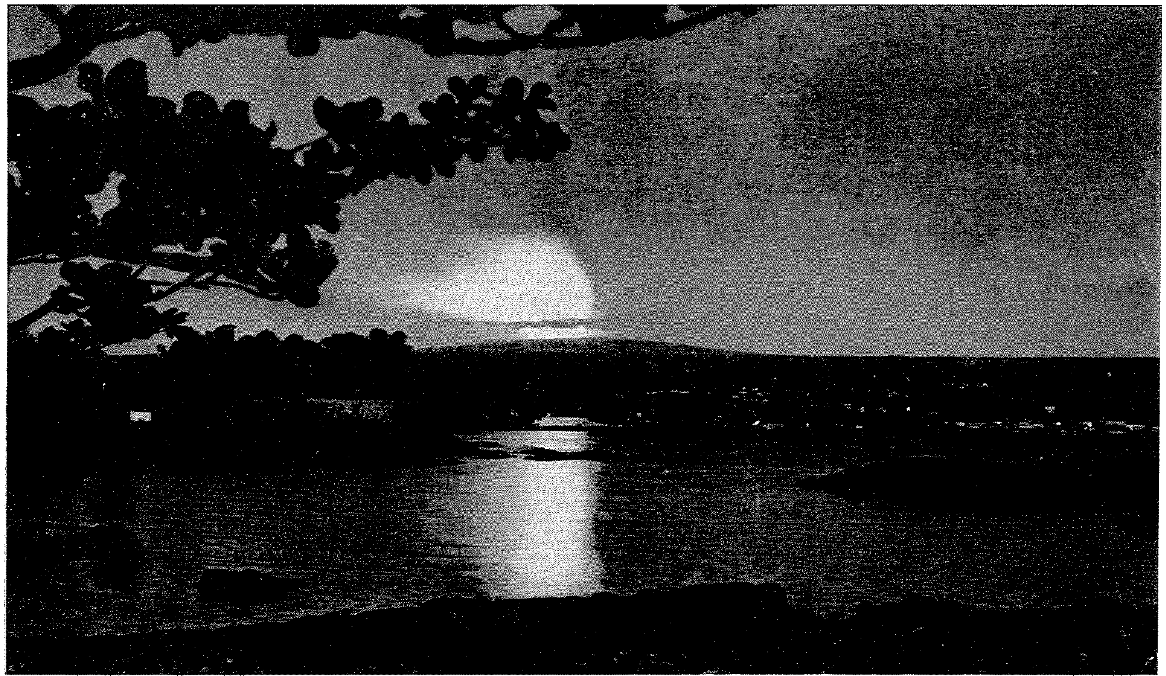


Plate 29A. Eruption of Mauna Loa Volcano in 1940 from Hilo, 36 miles away. Photo by Hilo Photo Supply, Ltd.

Plate 29B. Flank eruption of Mauna Loa Volcano, November 22, 1935, showing one of the main streams of the lava flow disappearing in a steaming fissure. Another stream sinking into an ancient crater caused the column of steam below the main vent. Snow-clad Mokuaweoweo Caldera in the background. Photo by U. S. Navy.

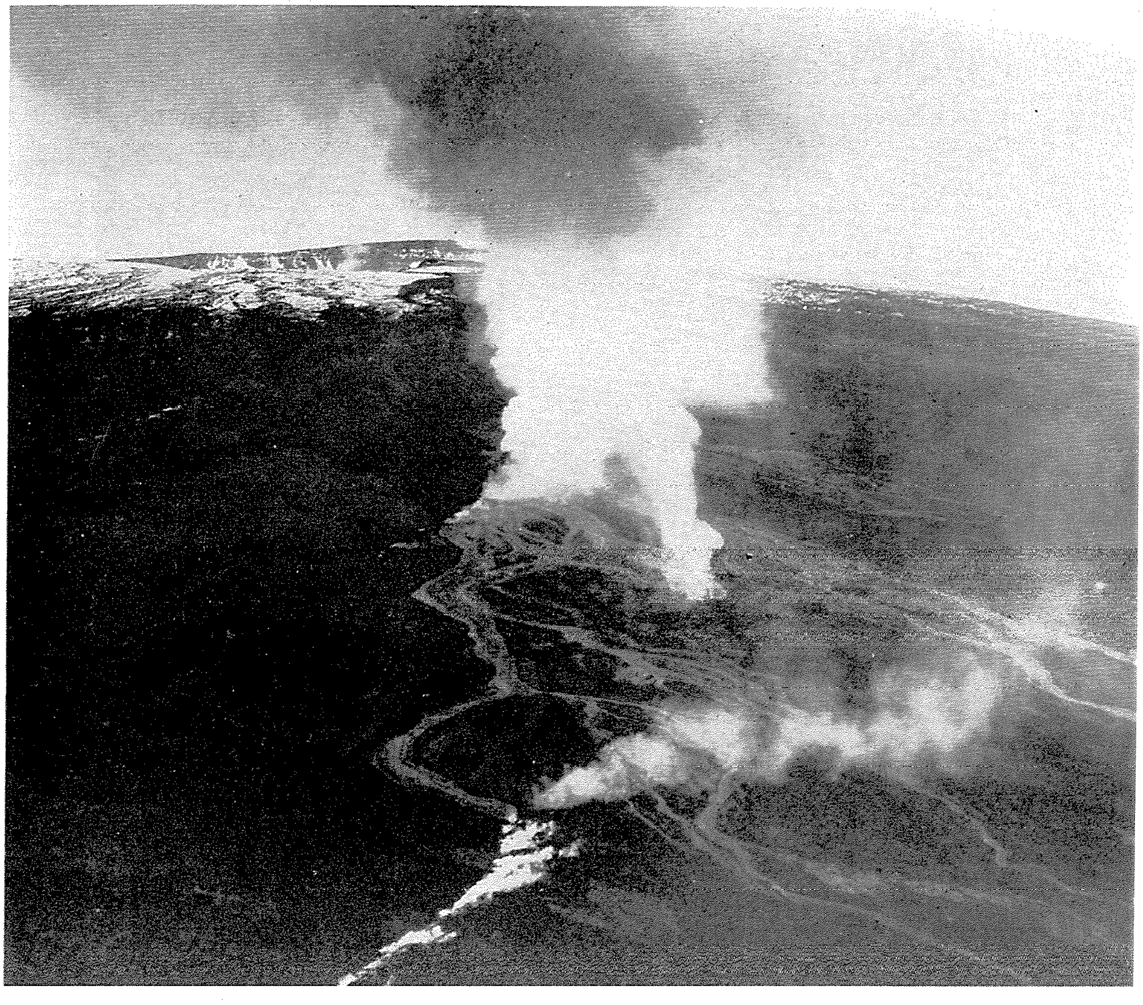


Plate 30. Eruption of Mauna Loa Volcano, December 2, 1933. The eruptive fissure crosses the caldera and extends down the southwest slope. Photo by U. S. Navy.

RELATION TO TIME OF YEAR.—The graph in figure 23 shows a predominance of outbreaks in January. Next come April, August, and November. The winter season, November to February, is certainly the dominant time of outbreaks. This is the season of low pressure kona (southerly) storms but it is doubtful if barometric pressure is important, otherwise April and August should not be favorable eruption months. Precipitation apparently is not a factor because no relation was found between average monthly rainfall on either the windward or leeward side of the mountain and the months of outbreak. August is not a rainy month.

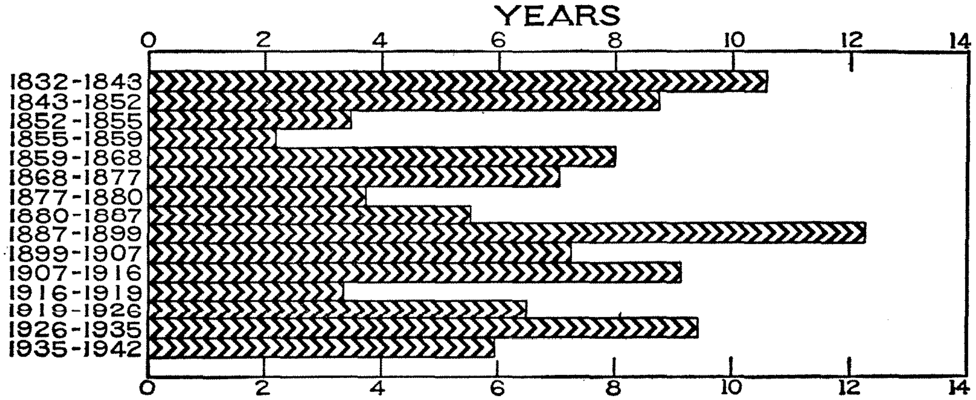


Figure 22. Graph showing the number of years between flank eruptions of Mauna Loa Volcano, 1832-1942. (The 1851 eruption is omitted because it was apparently a summit type.)

Eruptions are scarcest near summer solstice and during the months of the equinoxes. Three eruptions have occurred in December, the month of the winter solstice, but even this month is less favorable for outbreaks than the preceding and succeeding months. The greatest number of eruptions have occurred during January (the month following winter solstice) and April (the month following spring equinox). No suitable hypothesis is offered to account for the dominance of eruptions in certain months. It may well be entirely fortuitous, and different months may predominate in another hundred years of records.

LOCATION OF FLANK ERUPTIONS.—The location and altitude of flank eruptions are shown in figure 24. Omitting the 1832 eruption, the location of which is uncertain, 8 eruptions occurred on the north flank and 10 eruptions on the southwest flank in the last century. If we assign the letter S to all southwest flank eruptions and the letter N to all north flank eruptions the sequence from 1843 to 1942 will be as follows: N S N N N S S N S N S S S S S N S N. Lack of order is apparent. If the eruptions of 1851, 1933, and 1940 are omitted from the series on the basis that they represented summit eruptions and not typical flank eruptions, the sequence is: N N N N S S N S N S S S S N N. This sequence shows a tendency for the flank which erupted last to reopen generally once and sometimes 4 times. Also, the shorter the time interval between flows the greater the tendency of that rift to reopen, but the 1880 eruption on the north flank is a notable exception. It followed a southwest rift eruption by only 3 years and 7 months.

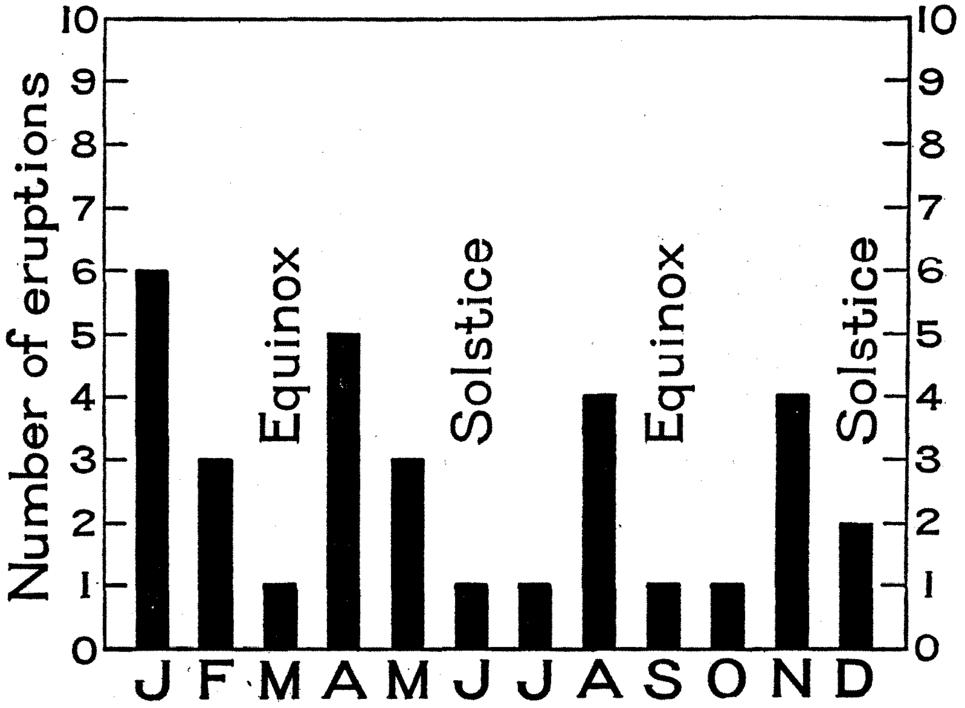


Figure 23. Graph showing occurrence of eruptions of Mauna Loa Volcano by months, 1832-1944.

Jaggar[10] wrote in 1914, "As the last flow in 1907 was to the south, the next, by the law of alternation which has held since 1868, should be on the north side of the mountain." As shown in figure 24 the next three flank flows were on the south side. There appears to be no "law of alternation" between the two rifts.

However, Jaggar's[11] prediction in 1937 was quite accurate as to the location of the 1942 flank flow:

> "The succession of newly opened vents since 1868 was from elevation 3,500 feet that year at the southern end of the Mauna Loa rift, progressively up the rift to 13,000 feet in 1926, 13,150 feet inside the crater in 1933, and 12,000 feet in 1935, on the northern extension of the rift down the Hilo slope.

---

[10] Jaggar, T. A., The outbreak of Mauna Loa, Hawaii, 1914: Am. Jour. Sci., vol. 39, p. 167, Feb. 1915.

[11] Jaggar, T. A., Protection of Hilo from coming lava flows: Volcano Letter, no. 443, p. 2, Jan. 1937.

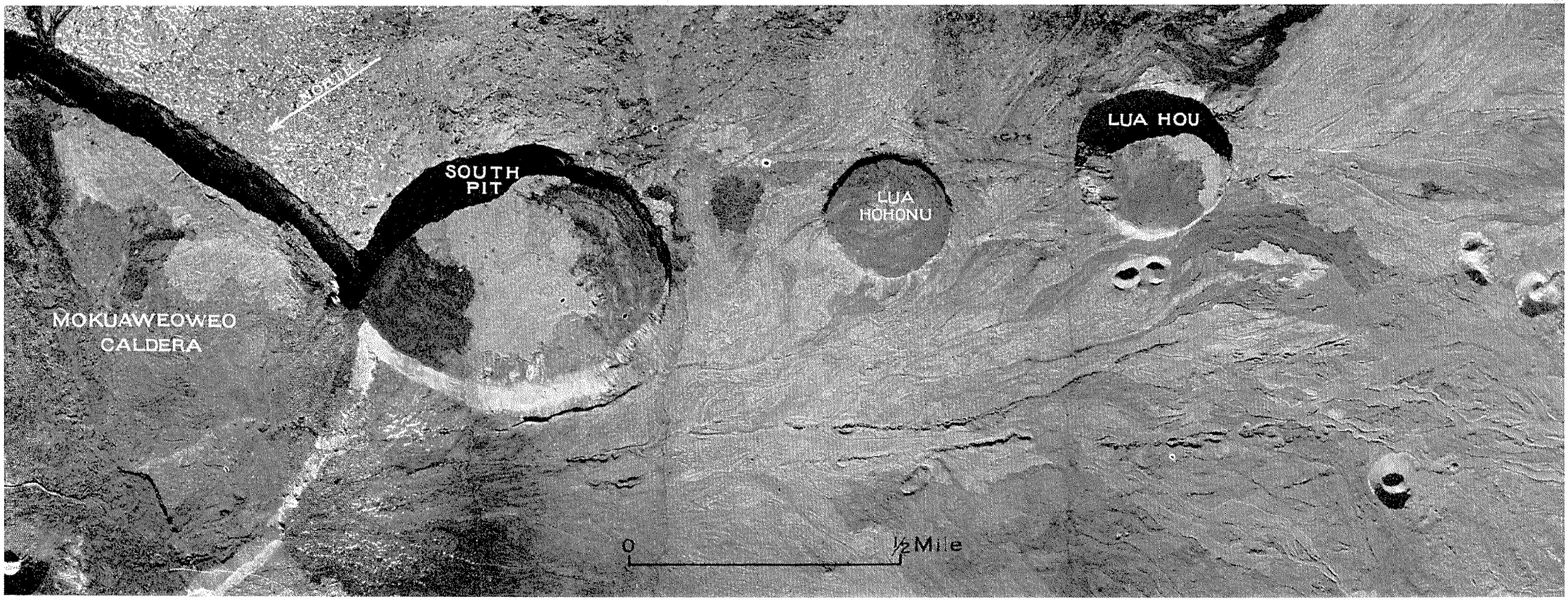


Plate 31. Vertical air view of the pit craters and the southwest end of Mokuaweoweo Caldera on Mauna Loa Volcano. The spatter ramparts along fissures and the congealed lava rivers are clearly discernible. Photo by USAAF.

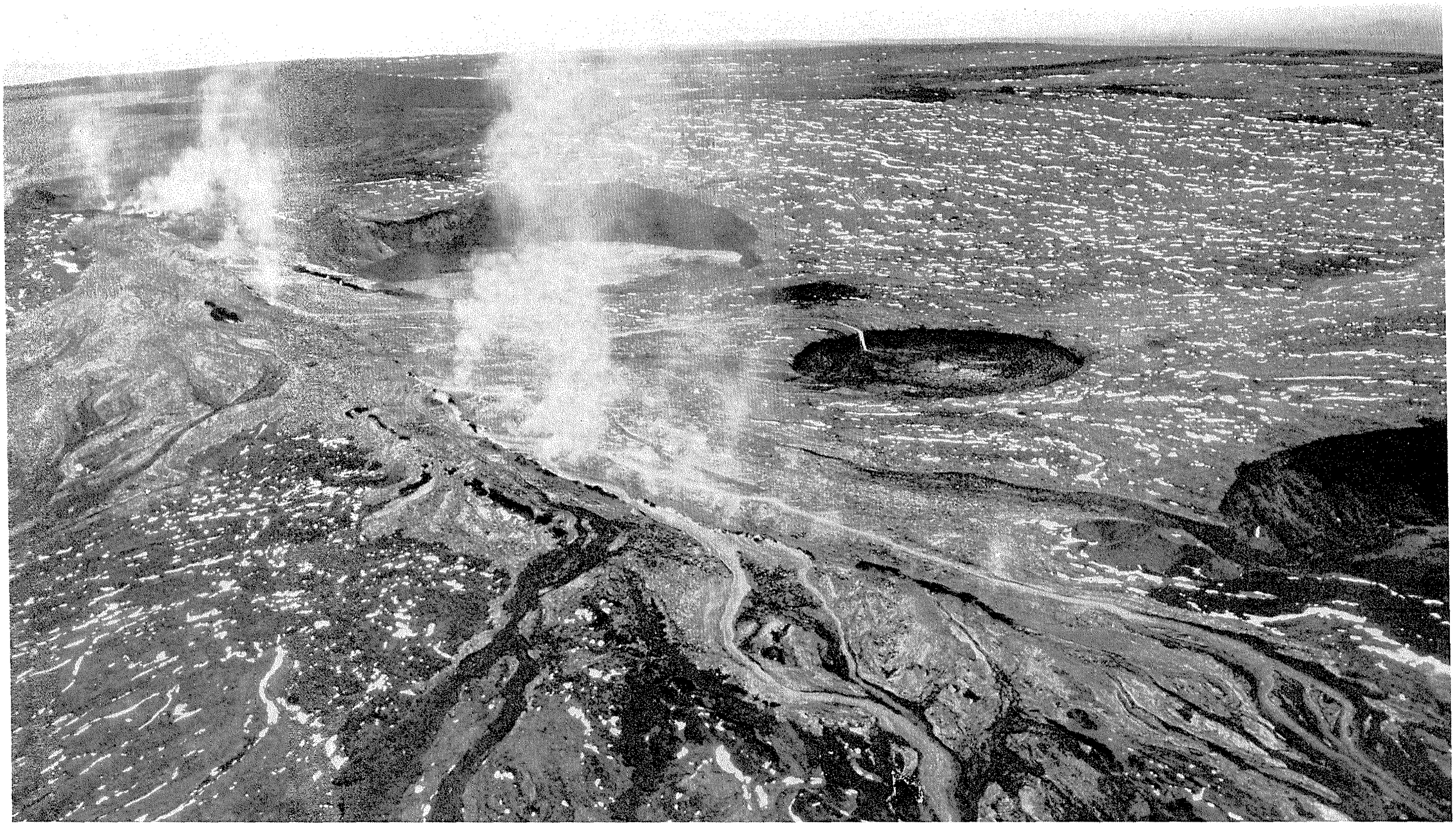


Plate 32. Lava flow and eruptive fissure along the southwest rift of MaunaLoa Volcano, April 8, 1940. Lava can be seen cascading into the pit craters. Mokuaweoweo Caldera lies in the background and snow occupies the depressions in the older lavas. Photo by USAAF.

"This was approximately five miles north of the 1933 eruption, and if the next flank outflow comes out five miles farther north, the place will be a half mile above Red Hill, close to the source of the 1881 flow which entered the city of Hilo. . . . We know, however, that fume and steam are rising, that the ground is hot, and that sulphur is depositing at the line of source cracks of 1935. That means that the north rift of Mauna Loa in the Hilo direction is open and ready for action which was not the case between 1900 and 1926 when all the outflows were from the south rift."

The main vent of the 1942 lava was about 2 miles below Red Hill at an altitude of 9,100 feet on the northeast rift.[12] The lava flow stopped about 10 miles from Hilo.

Figure 24 shows that the succession of newly opened vents since 1868 was not progressively up the southwest rift to the summit. The vent of 1877 was below sea level 30 miles northwest of the 1868 vent. The 1880 vent was at an altitude of 10,500 feet on the northeast rift. Lava in small quantities poured from the 1868, 1916, and 1926 fissures much of the way up the southwest rift from the main vents to the summit. Perhaps some of the other intervening eruptions behaved likewise, but observations were not made or the area was cloud-covered. It is clear however, that the southwest rift was not sealed progressively upward after 1868. It is still full of gaping fissures and cracks, some of which were steam-

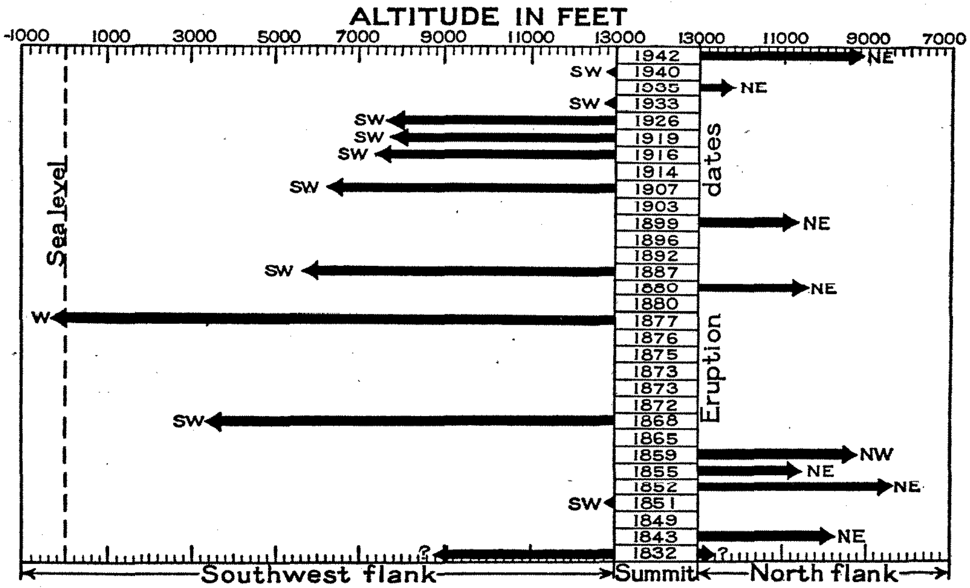


Figure 24. Graph showing the location and altitude of eruptions of Mauna Loa Volcano, 1832-1942.

---

[12] Macdonald, G. A., The 1942 eruption of Mauna Loa, Hawaii: Am. Jour. Sci., vol. 241, no. 4, pp. 241–256, 1943.

ing and depositing sulphur in 1942. Jaggar's successful prediction was apparently based on other premises than those stated.

Altitude of flank eruptions.—The altitude of the main vent of each flank eruption is shown graphically in figure 24. Lava discharged at lower altitudes from fissures during the first few days of some eruptions but did not persist long enough to build cones. Thus the 1868 lava is shown as having issued at 3,300 feet but some lava poured out of fissures as low as 1,500 feet. Some lava issued in the summit crater a few minutes to a few days before each flank eruption. Commonly, lava issues from several places along a fissure between the summit and the point where the main source cone develops. The lava flow of 1935 issued chiefly at 12,100 feet, flowed northeast for 2 miles and tumbled into a pre-existing gaping crack at an altitude of 11,300 feet (pl. 29B). It travelled underground from this fissure, presumably through an ancient lava tube and issued quietly at 8,800 feet where it formed a lava tube. The major flow that reached the upper drainage area of the Wailuku River issued at this latter point. This lower vent was Target No. 1 during the bombing operations in 1935. It was seen by the senior author during the eruption and examined in detail in 1938, and although positive proof of an ancient tube could not be found, no lava-fountain deposits were found such as always accumulate where Mauna Loa lavas break out (pl. 33A). A large tube in prehistoric lavas lies about a quarter of a mile to the east with a trend parallel to the direction the lava of 1935 travelled underground. Other tubes are common in this area; hence, it seems probable that the 1935 lava reached the point of emergence at 8,800 feet through an ancient tube.

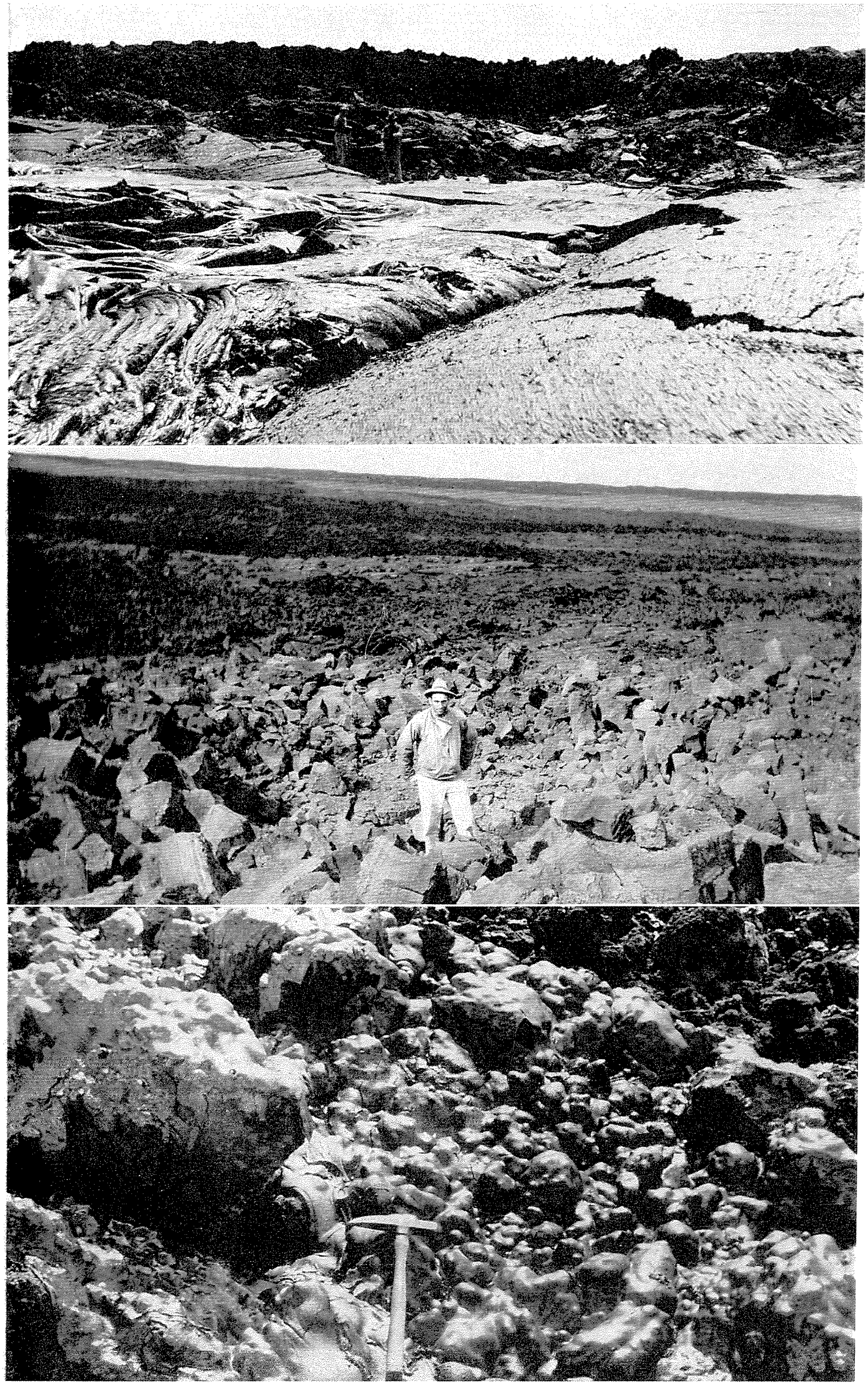
Some of the lava of 1942 likewise welled out of a hole at an altitude of 7,900 feet (pl. 35 and 36B), 2½ miles below the main

→

Opposite page, top: Plate 33A. Pahoehoe lava of 1935 at the 8,800-foot outlet on Mauna Loa Volcano. Lava near the close of the eruption oozed out and caused partial foundering of previously formed crust. The aa in the background is prehistoric. Photo by H. T. Stearns.

Middle: Plate 33B. Crater produced by 500-pound demolition bomb striking a prehistoric lava flow near the 8,800-foot vent of the 1935 flow, Mauna Loa Volcano. Photo by H. T. Stearns.

Bottom: Plate 33C. Spatter veneering old aa at the lowest vent of the lava flow of 1942, Mauna Loa Volcano. Photo by G. A. Macdonald.



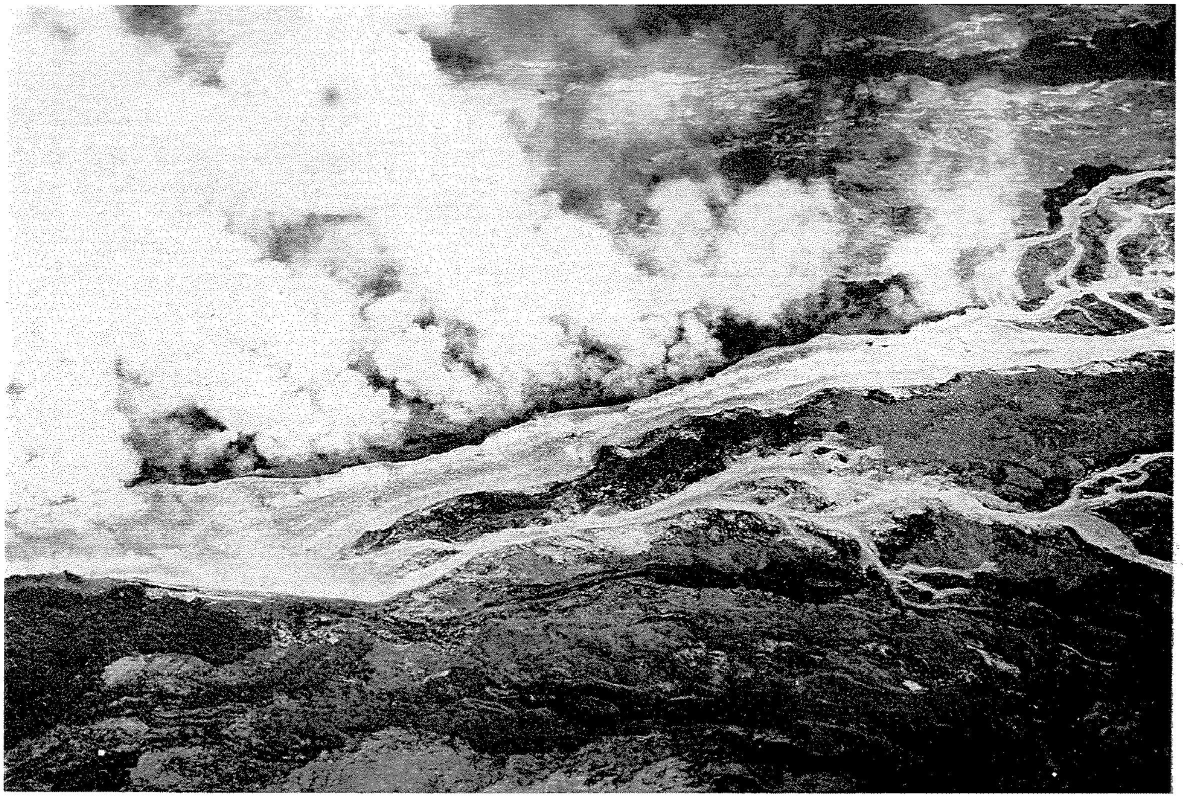
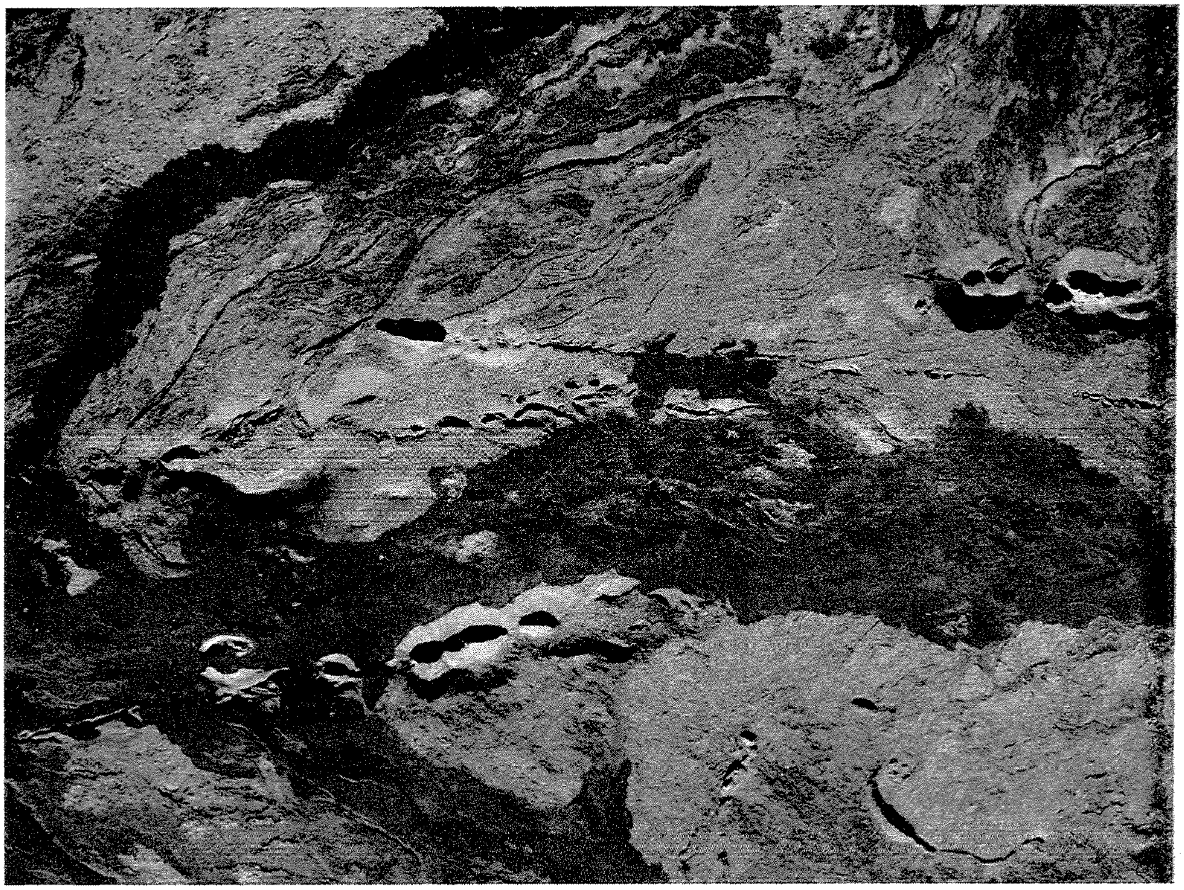


Plate 34A. Air view of the eruption at the 9,200-foot vent on Mauna Loa Volcano, April 28, 1942, showing lava distributaries. The lines of small fountains in the main lava river are over the main fissure vents.

Plate 34B. Vertical air view of typical chains of spatter and cinder cones along fissures in the southwest rift zone of Mauna Loa Volcano. The narrow ribbon-like patterns are congealed lava rivers. Photos by USAAF.



vent at 9,100 feet. Finch[13] and Macdonald[14] believe the lava reached the lower point through an ancient tube.

The graph of the main vents in figure 24 shows clearly that during the last century, at least, no flank flows have issued below 8,000 feet on the north flank and only one above 11,000 feet. Only 5 prehistoric vents of Kau lavas lie below 8,000 feet on the northeast rift, and none below 6,000 feet, but many lie between 8,000 feet and the summit. The scarcity of vents below the 8,000-foot level, which is 24 miles from Hilo, is the reason why the Hilo area is so rarely overrun by lava. It is probable that Mauna Kea extends 6 to 10 miles southward under the Recent lava flows of Mauna Loa directly athwart the latter's northeast rift. The hypothesis is offered that Mauna Loa Volcano terminates against the buried Mauna Kea dome approximately under the 8,000 foot level on the northeast rift and that only under exceptional conditions does the tumescence of Mauna Loa rupture the buried Mauna Kea dome.

The historic southwest flank eruptions show a relation to altitude nearly opposite from those on the north flank. In the last century all the main vents have formed below 8,500 feet. This accounts for the lack of historic lava flows on the rich agricultural land between Pahala and Waiohinu and for the absence of black lava flows on the high southeastern and western slopes of Mauna Loa. This condition seems to be entirely fortuitous, as many prehistoric vents exist in the southwest rift between 8,500 feet and the summit. The Puu o Keokeo area has been a focus for 5 historic and many prehistoric eruptions. The area is probably structurally weak, as the southwest rift changes its trend from S. 35° W. to due south near Puu o Keokeo.

EFFECTS OF BOMBING LAVA FLOWS.—The lower outlet of the 1935 lava flow, at an altitude of 8,800 feet, was bombed by the U. S. Army in an effort to stop the flow (pl. 33A). The main lava tube below this outlet was also bombed in an attempt to clog it. Jaggar[15] believes that the bombs, by breaking open the tube enclosing the lava river, resulted in a disturbance of the pressure-temperature equilibrium, releasing the gas and heat and causing a solidification of the lava back into the source vent.[16]

The senior author visited the bombed areas and found that many of the bombs fell on already hardened lava (pl. 33B). The few that fell into the molten lava threw out small clots of pahoehoe but otherwise seemed to have had no effect. The last lava to flow from this point, as shown by the congealed lava in the source tube, was

---

[13] Finch, R. H., The 1942 eruption of Mauna Loa: Volcano Letter, no. 476, p. 4, 1942.

[14] Macdonald, G. A., op. cit., p. 246.

[15] Jaggar, T. A., The bombing of Mauna Loa, 1935: Volcano Letter, no. 442, pp. 1–7, Dec. 1936.

[16] Jaggar, T. A., Volcanoes declare war, pp. 14–16, Honolulu, 1945.

fluid pahoehoe (pl. 33A), showing no features to support Jaggar's contention that the flow stopped because of violent gas release causing solidification of the lava. Until other flows are proved to have been stopped by bombing, the cessation of the 1935 flow soon after the bombing must be considered a coincidence.

Bombing to divert the lava river was tried again during the eruption of 1942 (pl. 35).[17] At one place a bomb broke the river levee causing the lava to spill out and form a new channel. The form of the terrane, however, caused the newly made lava river to rejoin the main flow a short distance downslope. Favorable terrane might have resulted in a new course for some of the lava, thereby delaying the advance of the main flow.

It is believed that precision bombing, at one or more carefully selected sites along the loosely consolidated, partly molten spatter ramparts at the source of a flow, will open new channels through which sufficient lava might be diverted to protect property endangered by the main lava river far down the slope.[18] Several weeks or months would elapse before the new flows could reach the level of the original flow front, and the terrane might change the course of the lava entirely. Also, the 500-pound bombs used heretofore produced such small bomb craters (pl. 33B), that it is believed a heavier bomb would be more effective.

SUMMARY.—The outbreaks of Mauna Loa for the period 1832 to 1942 show no periodicity, and no apparent relation to sunspots, precipitation, the equinoxes, or the solstices. They show only a tendency to start in the winter season, although April and August also are favorable months. The longest repose period was 10½ years and the shortest 2 months. The only generalization that is well supported by the recorded data is that Mauna Loa can be counted on to erupt at least once in 10½ years and usually once in 7 years or less; that the eruption will rarely last more than 4 months and is very unlikely to last more than 18 months. No relation exists between the repose period and the duration of the succeeding eruption.

Several summit eruptions, or none at all, may intervene between flank eruptions. Some of the most voluminous flank eruptions followed each other without intervening summit eruptions (fig. 24). All flank eruptions are characterized by short-lived lava fountains playing in the caldera a few minutes to a few days before the flank outbreak. A few typical summit eruptions spread lava for short stretches down the upper slopes as a result of the rift splitting open slightly beyond the caldera rim. Eruptions are preceded by tumescence of the mountain, followed by cracking and lava foun-

---

[17] Macdonald, G. A., op. cit., pp. 254–255.
[18] Macdonald, G. A., op. cit., p. 255.

taining along part or all the length of the crack or cracks. Ramparts of spatter are built along the erupting fissures and, if activity continues for more than a couple of weeks, one or more cinder and spatter cones are usually built where the lava fountains persist the longest. The fissures are commonly only a few inches to a few feet wide and average about 18 inches. They are locally widened at the surface due to collapse, and disruption of the wall by the lava fountains. Remelting also is a factor, although probably a minor one. Pahoehoe is always the first lava to be discharged. It changes quickly to aa as it moves down the flanks during the early phase of the eruption, but may continue to pour out for months during prolonged activity.

Flank eruptions are confined chiefly to the northeast and southwest rift zones although a few flows have issued on the north and west slopes. None has issued on the southeast slope in late geologic time. The interval between flank eruptions ranges from 2 years and 3 months to 12 years and 5 months. They may alternate first on one side of the mountain and then on the other, but such alternation is not characteristic. More commonly a group of eruptions on one rift is followed by a group on the other rift. No more than 4 eruptions have occurred in succession from the same rift. The main vents of the north flank eruptions have ranged in altitude from 8,400 to 12,500 feet. Those on the southwest rift have ranged from 3,300 feet to the summit. It is thought that the northeast rift may be interrupted at the 8,000-foot level by the buried cone of Mauna Kea. Lava flows have to travel about 24 miles to reach Hilo from the lowest historic vents on this rift, and as flows of this length are unusual it is seldom that the Hilo area is invaded by lava flows.

A few flank flows find their way underground through shallow pre-existing tubes in the surficial lava flows and escape low down on the slope. This was the case in 1935 and 1942.

No relation between the eruptions of Mauna Loa and Kilauea can be found in graphical analysis (fig. 20).

Seismic activity, often feeble, presages the breaking open of the rifts and indicates the lava column rises from depths of several miles. At the present time it forms the most reliable method for predicting flank eruptions.[19] Probably even this method is subject to error, because of subterranean injections, deep submarine flows, and interrupted rises in the magma column.

We know that gas provides one of the forces causing the rise of lavas. It expands rapidly with relief of pressure, resulting in intense effervescence of the magma and the production of spectacular lava fountains hundreds of feet high when the lavas reach the

---

[19] Finch, R. H., op. cit., p. 2.

surface. Apparently Mauna Loa erupts when the magma chamber has accumulated sufficient pressure to cause the rifts to crack open. The outbreak appears to be governed more by physical conditions and chemical reactions within the magma than by external forces. Great earth movements in the Pacific may renew volcanism in volcanoes long dead and dormant, but they are too infrequent to affect the ordinary activity of Mauna Loa Volcano.

INTRUSIVE ROCKS

Few intrusive rocks are exposed in Mauna Loa owing to the small amount of dissection. Several dikes are exposed in the walls of Mokuaweoweo, South Pit, and Lua Poholo. It can be seen that some have fed pod-shaped sills. All the visible intrusives belong to the Kau volcanic series. Dike swarms occupy the rift zones beneath the surface.

STRUCTURE OF MAUNA LOA

Rift zones.—The southwest, north, and northeast rift zones are indicated on the surface by cone chains and fissures (pl. 1). At depth they are occupied by dike swarms (section C-C′, pl. 1.) They intersect at the summit. Indeed, the location of the summit is apparently determined by the position of intersection, where lavas rise more easily and consequently eruptions are more frequent. The southwest and northeast rift zones are better developed than the north rift zone. The northeast rift fans out down the mountain, a branch extending eastward from Puu Ulaula through Kulani cone.

Convexity of the rift zone, such as that shown by the southwest rift of Mauna Loa (pl. 1), has not been noted on the other volcanoes of the Hawaiian Islands. Possibly this curvature results from the dominant rupturing being along a fault system dipping southeastward rather than along a vertical fault. The intersection of inclined fault planes with the curved dome of Mauna Loa would result in curved fissures. This hypothetical fault system would parallel the extensive Kaoiki and Honuapo fault system, a very likely structural relation.

Faults.—The faults fall into three groups: (1) Circular and concentric faults outlining pit craters and the caldera; (2) faults parallel to the rift zones with the downthrow on the side toward the rift; and (3) faults near the coast dipping seaward. The caldera and pit crater faults are all normal faults with dips ranging from 60 to 80 degrees. Their scarps range in height from a few feet to 600 feet. They are shown on plate 1. Lava sometimes erupts along them, as it did in a few places near North Pit during the 1942 eruption, but more often the lava rises through fissures of the rift zones that cut across them.

Other faults parallel to the rift zones show slight displacement and outline shallow grabens. They apparently originated from collapse along the rift zones. The Kahuku fault scarp in the southwestern rift is the only one of large size. It extends 10 miles to the north from South Point and its scarp reaches a height of 600 feet. It extends under the sea an unknown distance. Pali o Ka Eo, the scarp of an echelon extension northward, is 3 miles long and 250 feet high. The displacement is considerably more than is indicated by the height of the cliffs as many later flows cover the downthrown blocks.

Faults along which segments of the mountain have slipped seaward form the most prominent fault scarps on Mauna Loa. Systems of step faults arranged echelon fashion have dropped the entire southeastern slope and part of the western slope. The principal ones are the Kealakekua, Kaoiki, and Honuapo fault systems (fig. 11). The displacement of the various blocks ranges from a few feet to 1,250 feet and some faults extend for 18 miles. All are normal faults and with few exceptions dip seaward at high angles. These faults appear to be fractures outlining large landslide blocks. The Kaoiki system appears to have tapped magma in the Eastern Fundamental Fissure and initiated Kilauea Volcano.[20] The southwestern rift of Kilauea lies along the southeastern set of Kaoiki fractures.

The faults of the Honuapo system are similar to those of the Kaoiki system and the latter system may be an extension northeastward of the former. The southern part of Kaiholena ridge, 1½ miles inland of Hilea, is crossed by a graben half a mile wide. One of the small faults parallel to the graben is exposed in a landslide scar 100 feet below the top of the ridge on the northeast slope of Pakua Hill, 2 miles northwest of Hilea. The main Ninole ash bed is dropped 15 feet to the southeast.

The only rotational fault found on Mauna Loa is the Waiohinu fault which cuts transversely the southwestern end of the Honuapo system. The scarp made by this fault is 4½ miles long and less than 50 feet high. Details have already been published.[21]

EPOCHS OF FAULTING.—Faulting has been a more or less continual process since early in the history of Mauna Loa. The earliest epoch of faulting occurred along the Honuapo system in late Pliocene or earliest Pleistocene time at or near the end of the period of eruption of the Ninole rocks. The Kahuku and Kau volcanic series and the Pahala ash lie unconformably on faults

---

[20] Stearns, H. T., and Clark, W. O., Geology and water resources of the Kau District, Hawaii: U. S. Geol. Survey Water-Supply Paper 616, p. 105, 1930.

[21] Idem, pp. 92–93.

cutting the Ninole lavas. Movement along a few of these faults has occurred in late geologic time as fresh prehistoric lava flows are displaced by them.

A second epoch of faulting occurred during the deposition of the Pahala ash. The movement displaced the rocks of the Kahuku volcanic series northeast of Punaluu and gave rise to the Kaoiki fault system. At the surface the movement has broken chiefly Kahuku rocks, although in a few places lavas of the Kau volcanic series have been displaced. These faults may have resulted from renewed movement along earlier faults which displaced the underlying Ninole rocks.

A considerable number of Kahuku flows cross the faults but the accumulation of lava progressed more slowly than the deformation, with the result that the scarps are still preserved, although much smoothed. Movement along the faults has decreased progressively from northeast to southwest, suggesting that, as Kilauea was built up, movement of adjacent blocks decreased.

The Kealakekua-Kaholo fault scarps were made in this second epoch of faulting, as rocks of the Kahuku volcanic series are displaced but the overlying Kau and historic basalts are not.

Movement along a few of the faults has occurred in historic time. It amounted to 12 feet along the Waiohinu fault in 1868.

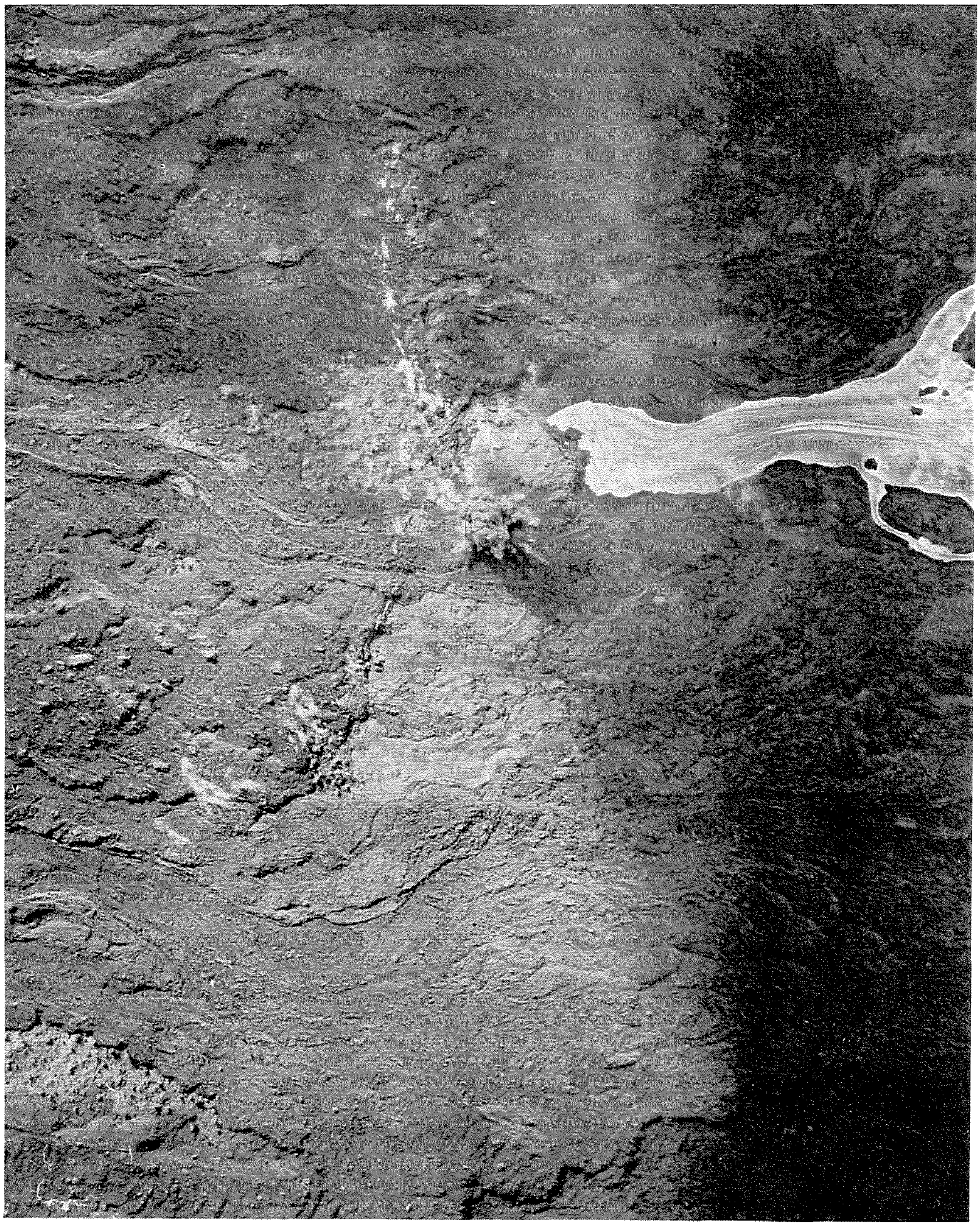


Plate 35. Vertical air view of the 7,900-foot vent of Mauna Loa eruption, May 1, 1942, showing lava issuing without spatter from a fissure transverse to the northeast rift zone. A bomb is exploding close to the vent. Photo by USAAF.

Plate 36A. The source fissure and cascades of the lava flow of 1942 on the west wall of Mokuaweoweo Caldera. The horizontal line at their foot is the congealed shore line of the 1942 lava. Photo by G. A. Macdonald.

Plate 36B. Detailed view of the 7,900-foot vent of the lava flow of 1942 from Mauna Loa Volcano shown in plate 35, after the eruption ceased. Photo by G. A. Macdonald.

GEOLOGY OF KILAUEA VOLCANO

PREVIOUS INVESTIGATIONS

Innumerable travelers and scientists have recorded volcanic events at easily accessible Kilauea since 1823 when William Ellis first visited it. Its lava lake has excited laymen, artists, and scientists who have left records in the form of descriptions in the old Volcano House register, colorful paintings of Halemaumau, and volumes of scientific literature. A partial bibliography has already been published.[22] Detailed observations were begun in 1909 by the Massachusetts Institute of Technology and in 1912 an observatory was constructed on the rim of the caldera. T. A. Jaggar, who first conceived the idea of the observatory, was placed in charge, and his researches have received world-wide recognition. Dr. Jaggar was retired in 1940 but still continues his work as a member of the staff of the University of Hawaii. He was succeeded by R. H. Finch. A splendid new building was constructed in 1942. The principal publication of the Observatory was the Bulletin, succeeded in 1928 by the Volcano Letter. Numerous articles by the staff have been published in scientific magazines, also. The first systematic areal geologic work on Kilauea was done in 1924 by Stearns[23] who mapped the summit, and the southern and western slopes. The rest of the mountain was mapped by Macdonald in 1939-40.

Jaggar and his associates have made invaluable studies of the lava lake. They established its shallow depth by soundings, found tidal motions in the lake, proved that it was hotter at the surface than at the bottom, observed flames due to burning gases, collected and analyzed the gases from source wells and cracks, and kept a detailed record of the cracks, the earthquakes, the area and volume of the flows, the tilting and tumescence of the mountain, and a vast amount of other data.

ROCKS OF KILAUEA AND THEIR WATER-BEARING PROPERTIES

The volcanic rocks comprise all the lava flows, pyroclastic rocks, and intrusive rocks in Kilauea. They have been subdivided into two series, the general character and water-bearing properties

---

[22] Stearns, H. T., and Clark, W. O., Geology and water resources of the Kau District, Hawaii: U. S. Geol. Survey Water-Supply Paper 616, pp. 36–41, 1930.

[23] Idem, pl. 1.

Stratigraphic section of Kilauea Volcano

(Littoral cones formed by lava flows exploding at the shore are specially designated on plate 1 to distinguish them from vents)

Major geologic unit	Rock assemblage	Thickness (feet)	Symbol on map (pl. 1	General character	Water-bearing properties
Historic volcanics	Lava flows, cones, and explosion deposits between 1750(?) and 1934 forming the historic member of the Puna volcanic series	15±	Hkl	Nonporphyritic and porphyritic aa and pahoehoe basalts. They form narrow black flows on the flanks of the mountain but are massive and columnar jointed in the caldera. Lithic ejecta a few inches to several feet deep laid down in 1924 and 1790 surround Halemaumau and the south rim of Kilauea Caldera.	Extremely permeable but carry no water except at the coast where it is brackish.
			Hkc	Cinder and spatter cones and fissure vents at source of flows.	Extremely permeable but carry no water
			Hkcl	Littoral cones formed where lava entered the sea.	Extremely permeable but carry brackish or salt water, or none.
			Hkp	Pit craters containing historic lava.	Contain no water.
Recent sedimentary rocks	Unconsolidated dunes	20±		Cross-bedded dunes composed of black volcanic sand derived from ash deposits.	Highly permeable but carry no water.
Recent and latest Pleistocene volcanic rocks	Prehistoric member of the Puna volcanic series	1-50	Qpa	Friable deposits of ash and explosion breccia composed of layers of both vitric and lithic tuff chiefly adjacent to the caldera. Deposits overlying Pahala ash not distinguished on plate 1.	The coarse-textured beds are permeable but the fine-textured deposits have low permeability. They do not carry water.
		50±	Qpl	Porphyritic and nonporphyritic aa and pahoehoe basalt flows nearly completely covering the surface of Kilauea.	Extremely permeable but chiefly valuable as an intake formation. They carry brackish water along the dry southern coast but fresh water along the eastern coast. The formation yields water freely to wells inland from the coast on the wet slope, and probably the east rift zone is underlain with water confined at high level by dikes.
			Qpc	Cinder and spatter cones and fissure vents at source of flows.	Extremely permeable but carry no water.
			Qpcl	Littoral cones formed where lava entered the sea.	Extremely permeable but carry brackish or salt water.
			Qpp	Pit craters.	Contain no water.
Pleistocene volcanic rocks	Pahala ash	10-60		Yellow friable ash 10 to 60 feet thick, in places laminated. It is composed chiefly of palagonitized basaltic pumice fragments and shards. It caps the basalt of the Hilina volcanic series everywhere except in the face of cliffs and crops out only in kipukas in the Puna volcanic series.	Relatively impermeable and may locally perch water in wet areas, but all exposures are in dry areas where the ash does not perch water.
	Hilina volcanic series	1,000±	Ph	Porphyritic and nonporphyritic aa and pahoehoe basalt flows ranging from 5 to 25 feet in thickness and averaging about 10 feet.	Highly permeable but carry only brackish water along the coast.

Correlation of nomenclature of rock units in Kilauea Volcano

Age	Used herein (Bull. 9)	Wentworth 3d Spec. Rept. H.V.O. (1938)	Stearns G.S.A. Abst. (1926) and U.S.G.S. W.S.P. 616 (1930)		Stone Bishop Mus. Bull. 33 (1926)	Noble and Clark Mss. rept. (1920)
Historic	Historic member of the Puna volcanic series	Keanakakoi formation (Name given to capping ash only) Uwekahuna formation (Name given to lowest interbedded ash only)	Kamehame basalt	Upper member	Kilauea series (Includes all ash deposits later than Pahala ash)	Post-Pahala series
Recent and latest Pleistocene	Prehistoric member of the Puna volcanic series (Includes all prehistoric ash deposits later than the Pahala ash)			Lower member (Includes all prehistoric ash deposits later than the Pahala ash)		
Late Pleistocene	Pahala ash	Pahala ash	Pahala basalt	Ash member	Pre-Kilauea series	Pahala series
Pleistocene	Hilina volcanic series (Does not include capping ash)	(Not mentioned)		Basalt member		
Pliocene	Not exposed					

of which are summarized in the accompanying table. The succeeding table gives the nomenclature of the rock units in comparison with their earlier use. The only sedimentary rocks on Kilauea are patches of drifting black sand derived from ash deposits in the Kau Desert, and small deposits of beach sand.

HILINA VOLCANIC SERIES

The Hilina volcanic series comprises the lava flows and pyroclastic rocks laid down by Kilauea Volcano prior to the deposition of the Pahala ash. The type locality is at Hilina Pali on the southern slope of Kilauea, where 1,000 feet of thin-bedded basalts and thin vitric tuff beds, capped with 30 feet of Pahala ash, are exposed. The lowest tuff bed is 200 feet above the base of the cliff and numerous thin tuff beds crop out between it and the top. All the beds have gentle dips to the south. The Hilina volcanic series is correlative in age with the Kahuku volcanic series erupted by Mauna Loa Volcano. They are the rocks originally mapped[24] as the Pahala basalt in Kilauea, less the capping Pahala ash. As the original term Pahala basalt included lavas from both Mauna Loa and Kilauea, a new name is used herein. The name Pahala is now restricted to the persistent ash formation, derived from several sources, which caps the Hilina volcanic series on Kilauea, the Kahuku volcanic series on Mauna Loa, and the Hamakua volcanic series on Mauna Kea.

The rocks of the Hilina volcanic series are exposed in windows in later rocks in the faces of fault cliffs on the southern slope of Kilauea (pl. 1). They are thin-bedded olivine basalt aa and pahoehoe flows. Three tuff beds, each less than 3 feet thick, are interstratified with the lavas 100 feet below the top of the section exposed in the scarp northwest of Ka Lae a Puki. A section of 1,000 feet of Hilina rocks is exposed in Kapukapu fault scarp (pl. 20A). A thin bed of tuff crops out in this section about half way up the cliff.

The Hilina volcanic series is highly permeable but carries brackish water only along the coast.

PAHALA ASH ON KILAUEA

Pahala ash is exposed only in windows at the top of fault cliffs on the southern slope of Kilauea. It is friable yellow vitric ash similar to that on Mauna Loa. The coarser beds at Hilina Pali consist largely of glassy, drop-shaped lapilli and Pele's tears such as are produced by lava fountains. They may have been derived chiefly from lava fountains in Kilauea Caldera. The ash is 40

---

[24] Op. cit., p. 65.

feet thick on top of Puu Kapukapu and 30 feet thick at the top of Hilina Pali.

The Pahala ash is exposed only in dry areas on Kilauea and does not perch water there. However, in the wet areas where it is buried it may perch water.

PUNA VOLCANIC SERIES

General statement.—Rocks of the Puna volcanic series cover most of Kilauea Volcano and were erupted by it in Recent and latest Pleistocene time. They are named from the Puna District where they are most abundant. Those on the western and southern slopes of Kilauea were mapped previously as the Kamehame basalt[25] but as this name includes both lavas from Mauna Loa and Kilauea, a new name is used herein. The rocks are correlative with the Kau volcanic series on Mauna Loa as both series overlie the Pahala ash.

PREHISTORIC MEMBER OF THE PUNA VOLCANIC SERIES

Lava flows.—The rocks of the Puna volcanic series range in thickness from a few feet in a flow adjacent to the outcrops of Pahala ash on the southern slope to more than 410 feet in Uwekahuna Bluff, at the western edge of Kilauea Caldera, where the base is not exposed. The section at Uwekahuna Bluff is given on page 193. Their thickness elsewhere is not known due to the absence of deep cuts.

The individual lava flows range from highly vesicular flows a few feet thick on the carapace of the volcano to massive columnar-jointed basalts several hundred feet thick ponded in Kilauea Caldera, pit craters (pl. 14A), and rift-zone grabens. The flows also thicken noticeably in the lava fans at the base of fault cliffs on the southern slope (fig. 13).

All the lavas are basaltic. Most contain small olivine phenocrysts, and in some the phenocrysts are 7 mm across. A few are picrite-basalts. Their surface is brown in contrast to the black of historic flows. Except where veneered with ash, the soil is too thin to be cultivated.

Tubes are numerous in the pahoehoe flows, especially on steep slopes. The Thurston Tube in the National Park is most accessible (pl. 12B). All minor features of flows exist, including the rare dendritic type of lava. Some of the flows interfinger with the Recent lavas from Mauna Loa. No erosional unconformities have been found between the flows. Some of the flows were extruded from a summit vent prior to the collapse that formed Kilauea Caldera, but many were poured from the two rift zones. Along the

---

[25] Op. cit., p. 69.

northeastern slope the flows overlap the Pahala ash and the lavas of the Kahuku volcanic series on Mauna Loa.

The usual dip of the Puna lavas ranges from 2° to 6°, but where they have spilled over fault scarps or walls of craters, they have dips of 25° to 45° (fig. 13). The lavas are chiefly pahoehoe on the upper slopes, but many of them change to aa downslope, making aa more abundant along the coast.

An exceedingly craggy aa flow partly surrounds Puu Kepaka in Puna. The largest crag is 35 feet high and 40 feet across, and resembles a monolith of slightly clinkery aa. A smaller crag exposed in a road cut is composed of a core of horizontally bedded cinder and spatter, sheathed with a thin coating of dense lava (fig. 25). The crags appear to be fragments of cones and channel ramparts floated away by the lava stream and veneered with liquid spatter. Similar transported cinder crags have been described in Idaho.[26]

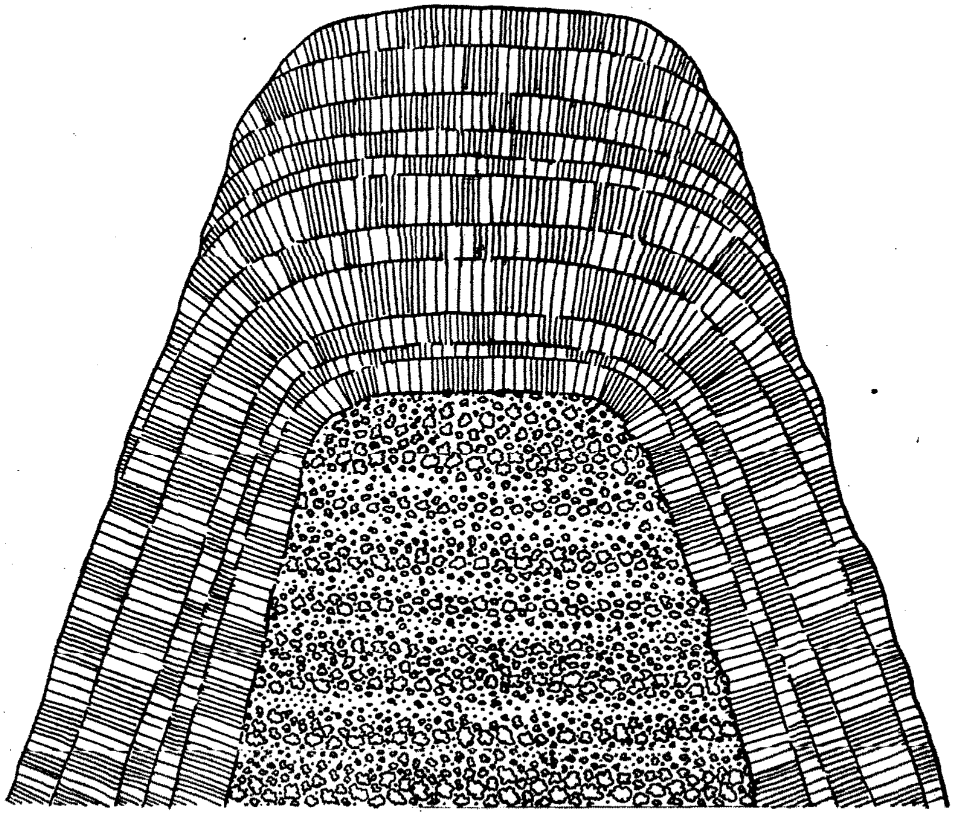


Figure 25. Section of lava pinnacle with cinder center near Puu Kepaka, in eastern Puna.

---

[26] Stearns, H. T., Craters of the Moon National Monument, Idaho: Idaho Bur. Mines and Geol. Bull., no. 13, p. 38, pl. 5, 1928.

Accretionary lava balls are present in some aa flows. They formed when solid or semisolid fragments were coated with liquid lava. The method of formation was clearly illustrated at the lower end of the active cone during the 1942 eruption of Mauna Loa. Large fragments of the spatter ramparts and levees of the lava river, cool at the surface but glowing within, were seen to break off and fall into the lava river, rolling over and over as they were moved along, thereby becoming sheathed with dense aa. The collapse of the ramparts and levees was caused by the lowering of the surface of the lava river.

Much of the fresh black lava certainly has been erupted since Hawaii was settled by the Hawaiians. Tradition records eruptions in the Puna District near Kapoho between 1340 and 1380[27] and one near Kaimu between 1730 and 1754.[28] The latter is probably the fresh black aa crossed by the road from Pahoa to Kalapana a mile north of Kaimu.

The lavas of the Puna volcanic series are exceedingly permeable but only those near sea level carry water and it is potable only in the eastern part of the mountain.

Cones and pit craters.—The Puna lavas issued from fissures a few feet wide. Some are marked by chains of low spatter cones and spatter ramparts. Others have little or no spatter along them. At the source of some of the eruptions, secondary lava cones were built which have small collapse craters on their summits. Some of the lavas issued from the walls and floors of pre-existing pit craters. A few eruptions built cinder cones.

Kane Nui o Hamo is typical of the secondary lava cones. It is a broad low symmetrical cone 1 mile across and 280 feet high. A small collapse crater indents its summit. Heiheiahulu, farther to the east, has nearly the same dimensions; it has a crater 200 feet across and 30 feet deep. The vent fissure in this cone is indicated by a double row of small spatter heaps extending down the northeastern side of the cone. Both cones are built of very thin flows of olivine basalt pahoehoe.

More than 60 cinder and spatter cones lie along the east rift zone and 40 along the southwest rift zone. The smaller cones are composed of spatter but the larger ones are composed of cinder or a mixture of cinder and spatter. The Kamakaia Hills, 150 feet high, on the southwest rift are typical cinder cones. Cinder cones are notably scarce on Kilauea in comparison with the number on Mauna Loa and are much scarcer on both these volcanoes than on Hualalai, Kohala, and Mauna Kea.

---

[27] Ellis, William, A narrative of a tour through Hawaii or Owhyhee, pp. 219–223, Honolulu, 1917. Macdonald, G. A., Lava flows in eastern Puna: Volcano Letter, no. 474, p. 1, 1941.

[28] Hitchcock, C. H., Hawaii and its volcanoes, 2d ed., p. 164, Honolulu, 1911. Buck, P. H., Vikings of the sunrise, p. 252, New York, 1938.

Puu Pilau in the Puna District, 0.4 mile south of Puu Honuaula, contains a larger number of cored bombs and lapilli, from 1 to 6 inches across, and many angular accessory blocks reaching 4 feet across. Some of the bombs are blocks derived from older beds below the cone; others have cores of the same lava as the cone.

The only tuff cone on Kilauea is Kapoho Cone in the Puna District. The cone is 350 feet high, 0.8 mile long, and 0.6 mile wide. It is composed of partly consolidated beds of buff and brown tuff and pumice containing numerous accessory blocks, some of which weigh a ton or more. The cone was formed by an explosion resulting from contact of the magma with either shallow ocean water near shore or shallow ground water close to the coast. It is described in detail by Stearns[29] who stated that it was formed by a submarine eruption. However, as pointed out by Wentworth[30] the eruption may have occurred on land near the shore line. The visible parts of the cone are obviously subaerial.

After 6 to 10 inches of ashy soil had accumulated on Kapoho Cone and silt and clay had been deposited in a lake on the crater floor, a fissure opened across the bottom of the crater, spatter heaps formed, and a small lava flow issued. Collapse following this eruption produced three pits, the largest of which is occupied by Green Lake, a shallow pond.

Ten littoral cones lie along the coast of Kilauea. They are distinguished from vent cones by the presence of much dense black glass sand.

Pit craters are numerous on Kilauea, especially on the east rift where several, called the "Chain of Craters", have been included in the Hawaii National Park (pl. 37A). Many are partly filled by congealed lava lakes (pl. 14A). Alae Crater contains solidified lava lakes of two different ages.

All cones are highly permeable but Kapoho Cone is the only one that carries water.

Ash deposits.—A few vitric ash and tuff beds are interstratified with the Puna lavas. The thickest one is typical coarse lava-fountain debris not far from its source, exposed near the base of Uwekahuna Bluff. Ash beds about 1 foot thick, intercalated with Puna lavas, lie 25 feet and 100 feet below the rim of Makaopuhi Crater. Intercalated ash layers form a very small part of the Puna volcanic series.

Much of the surface of Kilauea is covered by deposits of ash, ranging in thickness from a few millimeters to several feet (pl. 37B). The thickness is greatest around the edges of Kilauea Caldera, and decreases in all directions away from it (fig. 26). The

---

[29] Stearns, H. T., and Clark, W. O., op. cit., pp. 146–148.

[30] Wentworth, C. K., Ash formations of the island Hawaii: Hawaiian Volc. Obs., 3d Spec. Rept., p. 92, 1938.

thickness of ash is much greater on the southwestern side of the caldera than on the northeastern side (pl. 38B). This, together with the diminution in thickness away from the caldera, indicates clearly that the source of most of the ash in this vicinity was within the caldera, and that most of it was blown southwestward by the prevailing northeasterly trade winds. The distribution also indicates several loci of explosions within the caldera and burial in some places by lava flows. The distribution of the ash and the cause of local variations in its thickness have already been described.[31]

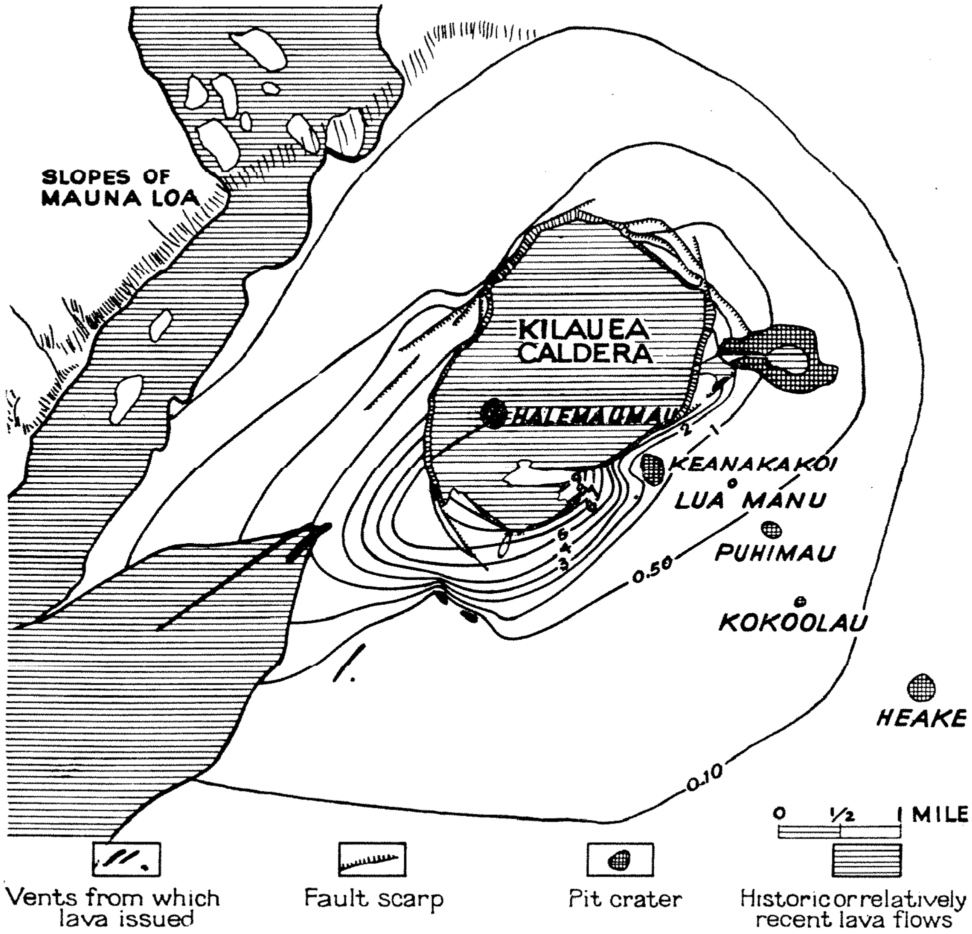


Figure 26. Map showing distribution and approximate average thickness of ash deposits around Kilauea Caldera exclusive of thin explosion deposits of 1924 on the caldera floor. Area of ash shown without pattern. Lines show thickness of ash in meters.

In the vicinity of Kilauea Caldera the surface ash deposits in-

---

[31] Stone, J. B., The products and structure of Kilauea: B. P. Bishop Mus., Bull. 33, pp. 28–35, 1926. Stearns, H. T., and Clark, W. O., op. cit., pp. 148–152.

clude a thin layer formed by the phreatic explosions of 1924,[32] a thicker layer formed by the explosions of 1790,[33] and several layers formed by earlier explosions. In cuts near the Volcano Observatory, on the northeastern edge of the caldera, Jaggar[34] reports six different humus layers in the ash, in which Stone recognized plant remains,[35] indicating at least six separate explosive periods preceding the 1790 eruption. Wentworth has proposed the name Keanakakoi formation to include this entire complex of surface ash deposits,[36] but herein it is treated simply as the aa member of the Puna volcanic series.

In the horst projecting into the southern part of Kilauea Caldera west of Keanakakoi, locally called the "Sand Spit", the ash deposits are more than 30 feet thick, and along the southwestern edge of the caldera the ash is commonly 10 feet or more in thickness. On Waldron's ledge, at the northeastern edge of Kilauea Caldera, it is more than 7 feet thick, and on the northeastern rim near the new Volcano House[37] it is more than 5 feet thick.[38] The ash decreases rapidly in thickness eastward, and in the area shown in plate 1 nowhere exceeds 2 feet. Close to the caldera, the ash in most places has a basal layer of brown pumice lapilli several inches thick. Individual lapilli range up to about 2.5 inches in diameter. Above this the ash consists of black, gray, or brown, sandy or silty material, partly decomposed to soil, and containing scattered lapilli less than an inch across. For the most part, the layers formed by the 1790 and 1924 explosions cannot be distinguished from the older ash, and it is likely that the 1924 ash, at least, is extremely thin.

A section of the ash measured by Stone along the highway near the Puna-Kau District boundary follows:[39]

	Thickness (inches)
Ash and lapilli	4.5
Fine, bedded ash	8.5
Fine, clayey ash with dark top	2.5
Thread-lace scoriae (pumice)	7.
Pahoehoe	...
	22:5

---

[32] Jaggar, T. A., Volcanic phenomena of the eruption: Hawaiian Volc. Obs. Bull., vol. 12, pp. 31–37, 1924. Stearns, H. T., The explosive phase of Kilauea Volcano, Hawaii, in 1924: Bull. volcanologique, nos. 5 and 6, pp. 193–209, 1925.

[33] Powers, Sidney, Explosive ejectamenta of Kilauea: Am. Jour. Sci., 4th ser., vol. 41, pp. 227–244, 1916. Stearns, H. T., and Clark, W. O., op. cit., pp. 152–153.

[34] Jaggar, T. A., quoted by Stearns, H. T., and Clark, W. O., op. cit., p. 151.

[35] Stone, J. B., op. cit., p. 34.

[36] Wentworth, C. K., op. cit., p. 93.

[37] The new Volcano House is situated on the very edge of the depression, at the site of the former Volcano Observatory.

[38] Stearns, H. T., and Clark, W. O., op. cit., pl. 28.

[39] Stone, J. B., op. cit., p. 31.

Along a driveway, 0.7 mile farther north, 18 inches to 2 feet of ash is exposed. The basal layer, 2 to 5 inches thick, is composed of pumice fragments reaching 2.5 inches across. The rest consists of poorly bedded brown to black glassy ash of medium sand grade. At an altitude of 3,600 feet on the Hilo-Volcano Road, 1.2 miles northeast of the Kau District boundary, Wentworth reports 10 to 15 inches of ash, but at an altitude of 2,850 feet, 3 miles farther northeastward on the same highway, he could recognize only 3 inches of ash.[40] Still farther eastward, many of the lavas are entirely devoid of ash cover. This eastward thinning of the ash is undoubtedly in part actual, but it is probably partly the result of the burial of some of the ash by later lavas. A similar abnormal thinning of the surface ash deposits east of Cone Peak, southwest of Kilauea Caldera, has been explained by burial,[41] and burial must have occurred near Maunaiki, where 1790 pisolitic ash containing footprints rests directly on the lava, the earlier ash deposits being absent.[42] Along the road between Olaa and Pahoa, the later lavas are nearly or entirely devoid of ash covering, but kipukas show 6 or 8 inches of ashy soil, probably at least partly equivalent to the pre-1790 ash deposits near the caldera. Similar deposits of ash lie in kipukas from 4 to 8 miles southeast of Kilauea Caldera.

In eastern Puna, the distribution of the ash cover is frequently indicated by the distribution of cane fields. Near Pahoa, lavas covered by 3 to 8 inches of ash support cane, but the later lavas, on which ash is largely absent, are covered with a dense growth of jungle. Along the southern coast of Kilauea the ash cover is generally absent, and the bare surface of the lavas is exposed over large areas.

The surface ash deposits of Kilauea are composed very largely of fragments of basaltic glass. Accessory lithic debris comprises all of the 1924 ash, and most of the upper part of the 1790 ash,[43] but the earlier ash is preponderantly magmatic (pl. 38A). The pumice and the glassy fragments of the ash are precisely like that formed by lava fountains on both Kilauea and Mauna Loa. It is concluded that the ash deposits were largely formed by lava fountains such as occur during normal Kilauean activity. The distribution and thickness of the ash shows that these fountains were most common within the caldera, but others undoubtedly occurred along the rift zones on the flanks of the volcano and contributed to the ash deposits.

It has been generally recognized that the ash deposits near

---

[40] Wentworth, C. K., op. cit., p. 96.
[41] Stearns, H. T., and Clark, W. O., op. cit., p. 150.
[42] Stone, J. B., op. cit., p. 33.
[43] Wentworth, C. K., op. cit., p. 100.

Kilauea Caldera post-date the formation of the caldera.[44] In fact, the existence of the caldera presumably made the accumulation of the thick ash deposits possible, the caldera walls sheltering the surrounding region from lava inundations which might otherwise have divided the ash into many thin layers. This division appears to have occurred lower on the flanks of the volcano, where the ash is partly buried by lava flows from the rift zones. Stone concluded that the age of the oldest surface ash at the calderá is probably not more than 300 to 500 years,[45] but the evidence he presents is not compelling.

A few paroxysmal explosions have occurred outside the caldera. A small one, the highest in the southwest rift, took place 1,200 feet northwest of the base of one of the Kamakaia Hills. The ejecta are composed of wall rock and lava clots. They lie within a radius of 50 feet of the vent. The wall rock fragments are glazed. The deposit is too small to show on plate 1. More details will be found elsewhere.[46] A phreatic explosion in Alae Crater hurled out blocks 3 feet across and deposited 6 inches of lapilli on the rim.[47] Phreatic explosions at Puulena Crater in eastern Puna threw out sand, lapilli, and lava blocks, some weighing several tons.

The ash deposits are fairly permeable but do not carry·water.

HISTORIC MEMBER OF THE PUNA VOLCANIC SERIES

The historic member of the Puna volcanic series and vitric ash deposits, spatter cones, and lava flows erupted since 1750(?). Significant data regarding the eruptions are given below:

The historic lava flows differ only in degree of blackness from the late prehistoric flows in the Puna volcanic series, indicating no perceptible change in the rate of volcanic activity in Recent time. They are separated on plate 1 only because they are dated. The flows are olivine basalts ranging from 1 to 20 feet thick on the flanks of the volcano. The flows ponded in the caldera are massive and columnar-jointed. A tremendous difference exists in the volume and physical form of the historic flows. The earliest historic flow listed is the 1750(?) lava flow in the Puna District. Its exact date is uncertain. The lava flow of 1790(?) was formerly included with that of 1840 on the topographic quadrangle sheets. The basis for its separation has been discussed elsewhere.[48]

---

[44] Stearns, H. T., and Clark, W. O., op. cit., p. 152. Wentworth, C. K., op. cit., p. 102.

[45] Stone, J. B., op. cit., p. 35.

[46] Stearns, H. T., and Clark, W. O., Geology and water resources of the Kau District, Hawaii: U. S. Geol. Survey Water-Supply Paper 616, p. 148, 1930.

[47] Idem, p. 143.

[48] Macdonald, G. A., op. cit., pp. 1–2.

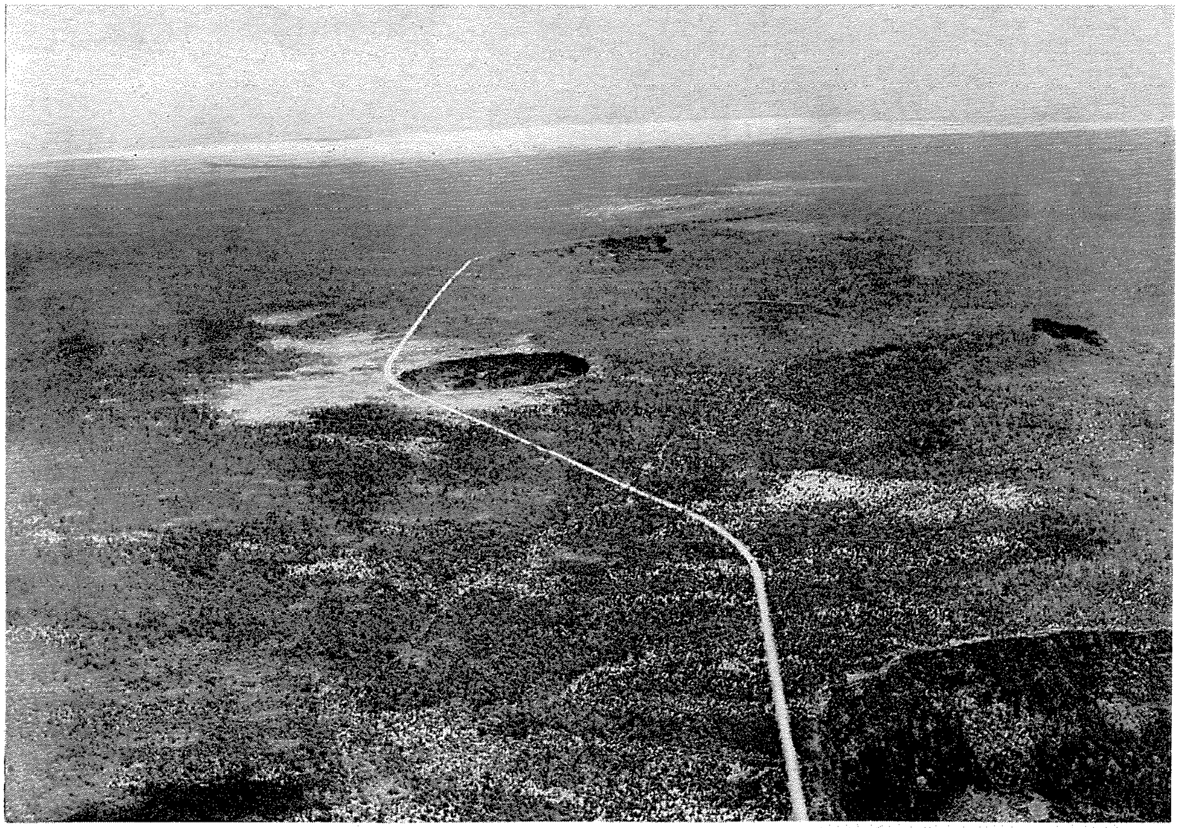
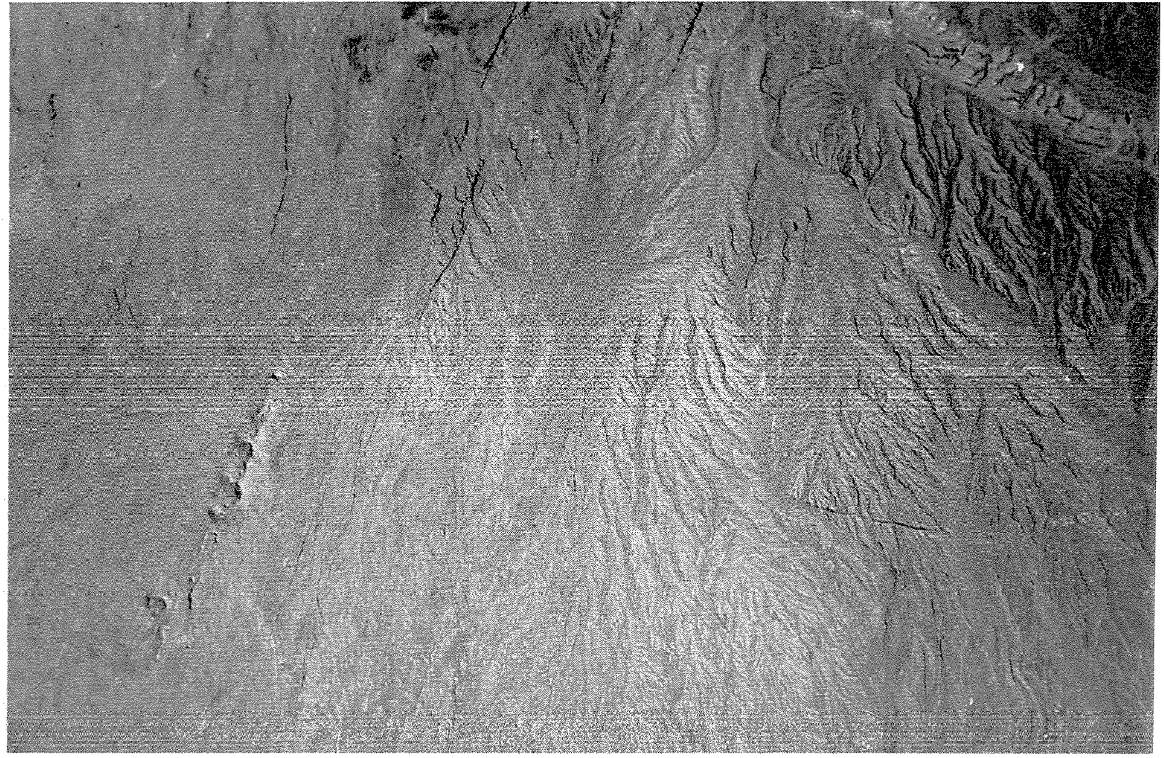
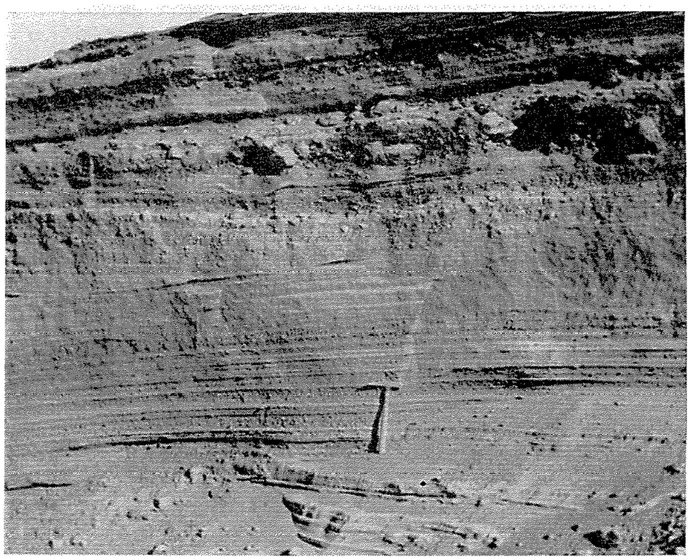


Plate 37A. Looking northwest to the pit craters along the Chain of Craters Road, Hawaii National Park. Alae Crater in right foreground and Aloi Crater in middle distance. Photo by USAAF.

Plate 37B. Vertical air view of the Kau Desert just southwest of Kilauea Caldera, showing fissures in the southwest rift zone and the dendritic stream pattern on the ash-covered surface southwest of the caldera. The rim of the caldera shows in the upper right corner. Note the line of spatter cones on the left along one of the radial fissures of the rift zone and in the center right, an arcuate fault crack and line of tiny spatter cones parallel to the rim of the caldera. Photo by USAAF.





Left: Plate 38A. Prehistoric ash deposits, largely vitric, overlain by 1790 explosion debris, which is largely lithic, in the southern rim of Kilauea Caldera. Photo by G. A. Macdonald.

Left: Plate 38B. Fissure in southwest rift zone of Kilauea Volcano showing bedded ash. Photo by G. A. Macdonald.

Below: Plate 38C. The Great Crack formed by collapse of the fissure from which the lava flow of 1823 issued from Kilauea Volcano. Photo by H. T. Stearns.

Data regarding historic eruptions of Kilauea Volcano[a]

Year	Date of outbreak	Duration (days)	Altitude (feet)	Location	Approximate repose period since last eruption (months)[b]	Area (sq. miles)	Volume (cu. yards)
1750(?)	....	.....	1,700	E. rift	....	1.57	19,500,000
1790(?)	....	.....	1,100-750	E. rift	....	3.04	37,670,000
[c]1790	November(?)	.....	....	Caldera	....	No lava flow	No lava flow
1823	Feb.-July	Short	1,700-250	SW. rift	....	[d]3.86	[d]15,000,000
1832	Jan. 14	Short	3,650	E. rim of caldera	....	(?)	(?)
1840	May 30	26	3,100-750	E. rift	....	[d]6.60	[d]281,000,000
1868	April 2	Short	3;350	Kilauea Iki	....	.07	(?)
1868	April 2(?)	Short	2,550	SW. rift	....	.04	250,000
1877	May 4	1(?)	3,500(?)	Caldera wall	....	(?)	(?)
1877	May 21(?)	.....	3,450(?)	Keanakakoi	....	.04	(?)
1884	Jan. 22[e]	1	—60(?)	E. rift	....	(?)	(?)
1885	March	80(?)	3,640(?)	Caldera	14	(?)	(?)
1894	Mar. 21	6+	3,690	Caldera	108	(?)	(?)
1894	July 7	4(?)	3,690	Caldera	3.5	(?)	(?)
1918	Feb. 23	14	3,700	Caldera	283	.04	250,000
1919	Feb. 7	[f]294	3,700	Caldera	11	1.60	34,500,000(?)
1919	Dec. 21	221	3,000	SW. rift	1	5.00	62,000,000
1921	Mar. 18	7	3,700	Caldera	7.5	.77	8,800,000
1922	May 28	2	2,650-2,400	Makaopuhi and Napau	14	.04	(?)
1923	Aug. 25(?)	1	3,000	E. rift	15	.20	100,000
[g]1924	May 10	17	....	Caldera	8	No lava	No lava
1924	July 19	11	2,365	Halemaumau	2.5	.02	320,000
1927	July 7	13	2,400	Halemaumau	35	.04	[g]3,160,000
1929	Feb. 20	2	2,500	Halemaumau	19	.06	1,920,000
1929	July 25	4	2,560	Halemaumau	5	.08	[h]3,600,000
1930	Nov. 19	19	2,600	Halemaumau	15.5	.09	[j]8,480,000
1931	Dec. 23	14	2,700	Halemaumau	12.5	.12	[k]9,640,000
1934	Sept. 6	33	2,800	Halemaumau	44	.16	9,500,000

---

[a] Many eruptions have occurred on the floor of the caldera, but only a few of the later ones are listed here, data being inadequate or totally lacking for the earlier ones. On January 11, 1928, a small amount of lava was extruded on the floor of Halemaumau, but this is believed to have been squeezed out by the weight of a heavy landslide on the crust of the 1927 lava which was still fluid beneath (Jaggar, T. A., Volcano Letter 370, 1932).

[b] During the early historic period Kilauea Caldera was observed only occasionally, and no definite record exists of the many caldera flows which are known to have occurred.

[c] Violently explosive.

[d] Area above sea level. The volume below sea level is unknown; but estimates give the following orders of magnitude: 1823—3,000,000 cubic yards; 1840—200,000,000 cubic yards. These are included in the volumes given in the table.

[e] Pacific Commercial Advertiser, Feb. 2, 1884. "A column of water, like a dome, shot several hundred feet up into the air, accompanied with clouds of smoke and steam." No further eruption was observed next day.

[f] Several separate flows, with short intervals without extrusion.

[g] Violent phreatic explosions, possibly accompanied by a submarine lava flow on the E. rift.

[h] Powers, H. A., Volcano Letter 243, 1929.

[j] Jaggar, T. A., Volcano Letter 311, 1930.

[k] Jaggar, T. A., Volcano Letter 366, 1931.

HISTORIC ERUPTIONS OF KILAUEA VOLCANO

GENERAL STATEMENT.—The eruptions of Kilauea Volcano from 1823 to 1945 are listed in the preceding table and periods of activity are shown graphically in figure 20. Kilauea has been active about 67 per cent of the time in the last 123 years and about 66 per cent in the last 113 years. This compares with 5.9 per cent for Mauna Loa in the last 113 years. The duration of the flank eruptions was about 1 per cent of the time Kilauea has been active. Native legend records about 40 to 50 eruptions from about A. D. 140 to 1823.[49]

The history of Kilauea Caldera, from 1823 to 1924, was essentially one of slow infilling, punctuated by occasional collapses. In 1823 the caldera contained a large central pit surrounded by a narrow "black ledge" left by an earlier collapse. A map of the caldera in 1825, based on the map by Malden[50] and descriptions by other visitors, is given in figure 9. In the same figure is given the plan in 1945, showing changes resulting from 120 years of volcanic action.

TYPES.—Eruptions of Kilauea fall naturally into four types: (1) Flank flows; (2) lava lakes in the caldera; (3) short-lived eruptions in Halemaumau resembling flank flows; and (4) paroxysmal explosions.

Two major kinds of paroxysmal explosions have occurred in historic time,[51] phreatomagmatic and phreatic. Phreatomagmatic explosions probably occurred in prehistoric time also. The phreatomagmatic explosions are characterized by violent blasts that hurl out both blocks of solidified lava from the walls and clots of magma, as in 1790. This explosion was accompanied by a great collapse or engulfment of the caldera floor. The phreatic explosions are also violent blasts that hurl out wall rock, but differ from the phreatomagmatic explosions in being free from liquid lava. The only one recorded occurred in May 1924. Thick explosion deposits about Kilauea are mute testimony of the many unrecorded explosions in the late history of Kilauea. Legend states that the eruption of 1620 was explosive,[52] and more violent than the one in 1790.

Flank flows issue from fissures in the east and southwest rift

---

[49] Hitchcock, C. H., The volcano Kilauea: Am. Geogr. Soc. Bull., vol. 41, p. 684, 1909; op. cit., p. 271, 1911.

[50] Byron, Lord George, Voyage of H.M.S. *Blonde* to the Sandwich Islands, in the years 1824–1825, pp. 181–190, London, 1826.

[51] Stearns, H. T., and Clark, W. O., op. cit., pp. 141–142.

[52] Hitchcock, C. H., op. cit., p. 684, 1909.

zones either above or below sea level. The flows of 1832 and 1868 (east rift flow) issued from fault cracks in the subsiding block between Kilauea Caldera and the pit crater of Kilauea Iki. They are questionable flank flows.

Lava lakes are formed when the Kilauean lava column rises into a pit crater in the floor of the caldera. Lava may be added to the caldera floor, or it may rise and fall within the lake or lakes for months or years without appreciable additions to the floor, much as a column of mercury rises and falls in a barometer. In 1921 the lava reached its all time high for the century and overflowed the caldera rim. The lake phase usually ends with rapid collapse of the floor of Halemaumau. The lava disappears underground and the vents become intakes.

The short-lived eruptions in Halemaumau since June 1924 are difficult to classify. They resemble flank flows in that the lava breaks out of cracks in Halemaumau with strong lava fountains, pours a flow into the pit and in a few days or a few weeks is dead. These eruptions are like the 1832 and 1868 flows in Kilauea Iki Crater or the flank flow of 1922 in Makaopuhi Crater. However, due to the confinement of the flows within Halemaumau a lava lake temporarily develops. Why the post-1924 eruptions have not re-established the lava lake is not apparent. It may be due to an insufficient supply of gas.

VOLUME OF HISTORIC LAVA FLOWS.—The volume of historic flank flows, excluding submarine eruptions, is given on page 111. The volume of lava added to the floor of the caldera from the 1823 collapse to April 1924 has been computed by Finch[53] to be 70,280,000,000 cubic feet. The explosions of 1924, together with the accompanying and succeeding engulfment, caused a loss of 7,120,000,000 cubic feet.[54] The net fill from June 1924 to 1945 is about 990,000,000 cubic feet.[55] Thus the net fill between 1823 and 1945 was about 64,150,000,000 cubic feet. The gross fill from 1823 to 1945, including that compensating for the engulfments from 1832-1922, was about 103,320,000,000 cubic feet. The 1823 engulfment is not included as it preceded the return of the lava in 1823. Computations of principal engulfments follow:

---

[53] Finch, R. H., The filling in of Kilauea Crater: Volcano Letter, no. 471, pp 1–3, 1941.

[54] Finch, R. H., Engulfment at Kilauea Volcano: Volcano Letter, no. 470, 1940.

[55] This is a little greater than the volume of 800,000,000 cubic feet estimated by Finch, Volcano Letter, no. 471, 1941.

Volume engulfed by principal collapses in Kilauea[a]

Year	Volume in cu. ft.
1823	[b]19,052,000,000
1832	[b]20,504,000,000
1840	7,752,000,000
1868	6,650,000,000
1886	1,400,000,000
1891	1,200,000,000
1894	300,000,000
1916	260,000,000
1919	354,100,000
1922	750,000,000
1924	7,120,000,000
	65,342,100,000

[a] Finch, R. H., Engulfment at Kilauea: Volcano letter no. 470, p. 2, 1940.
[b] Ten per cent added to published figures per instructions by Finch, Volcano Letter no. 471, p. 1, 1941.

The total production of lava by Kilauea Volcano since the beginning of the 1823 eruption including flank flows above sea level has equalled about 4,200,000,000 cubic yards or 0.77 cubic miles,[56] which is very nearly equal to that (0.74 cubic miles) produced by Mauna Loa since 1832.

FLANK ERUPTIONS.—The 1823 flow is unusual because it is extremely thin and issued from a crack without building spatter cones (pl. 38C). In many places it ranges from 1 to 12 inches in thickness and in no place does it exceed 5 feet. The lava cooled so quickly that it molded the grass it buried. The walls of the fissure are lined with lava balls—fragments of wall rock and clots of new lava that fell back into the magma and became coated with lava. Small phreatic explosions occurred at two places along the source crack immediately after the lava was erupted. Small fragments of detrital limestone were ejected, indicating that the prehistoric flows extended the coast and buried coral beach rock. The lava ran seaward as a great flood leaving crust shore lines on cinder cones that lay in its path as high as 34 feet above the present top of the flow. Details will be found elsewhere.[57]

The 1832 lava poured from a fault crack above Kilauea Iki and cascaded into Kilauea Iki Crater and Kilauea Caldera.

The 1840 flow in the Puna District is the first flow on record to destroy a village. It buried the village of Nanawale on June 3, 1840. The flow is a picrite-basalt containing abundant olivine phenocrysts.[58] It built three littoral cones, ranging from 150 to 250 feet in height, rich in olivine sand. Wave action has completely

---

[56] A small allowance is made for the lava flows of 1832 and 1868 in Kilauea Iki, 1877 in Keanakakoi, and 1922 in Makaopuhi and Napau craters.

[57] Stearns, H. T., The Keaiwa or 1823 lava flow from Kilauea Volcano, Hawaii: Jour. Geology, vol. 34, pp. 336–351, 1926.

destroyed one, and the highest point of the remaining two is only 78 feet above sea level.

The 1868 eruption is the only one in historic time that occurred simultaneously with an eruption of Mauna Loa. Strong earthquake shocks did great damage that year. Subsidence of the Puna coast near Kaimu buried palm trees to a depth of 8 feet. A church at Kalapana was nearly buried by beach sand. Eruptions occurred in the southwest rift of Kilauea and in the wall of Kilauea Iki. The lava at the latter place cascaded to the bottom of the crater and covered the entire floor. The under side of some of this lava molded fern leaves, it cooled so quickly. The lava in the southwest rift rose in a fissure 3 feet wide and 1½ miles long. It formed 9 small patches and four driblet spires, and where it did not overflow, it congealed to form a dike, the top of which is visible.[59]

The submarine eruption on the east rift zone off Cape Kumukahi, is recorded only in brief notes in the Volcano House register and in the Pacific Commercial Advertiser for January 31, 1884.

The lava flow of 1920 built the first secondary lava cone in historic time. The cone is called Maunaiki, and covers the fissure over which it formed. A pahoehoe lava flow spread 6 miles seaward from it and in one place rare arborescent lava formed.[60] Its origin is described on page 80. One unusual feature of this flow is that the lava lake in Halemaumau remained active throughout the period of the flank flow, although its surface fell as a result of the flank eruption. The lava was seen to pour southwestward from the lake through a tube in a dike filling one of the rift-zone fissures. Thus we have evidence of horizontal flow through a vertical dike. A daily account of this eruption was published in the Bulletin of the Hawaiian Volcano Observatory for that period.

The lava flow in 1921 from fissures on the caldera floor southwest of Halemaumau, was the first to overflow the rim of the caldera.

The eruption of May 28, 1922, broke out in the wall of Makaopuhi Crater and lasted one day. When it died down, another broke out for a day on the northeastern edge of Napau Crater. Fresh lava, probably erupted at the same time, was found in a small crater 1.2 miles northeast of Napau Crater.[61] The fact that the lava lake of Halemaumau sank more than 600 feet just prior to these eruptions suggests that the opening of fissures in the east rift zone permitted the magma to migrate laterally from Halemaumau.

---

[58] Macdonald, G. A., The 1840 eruption and crystal differentiation in the Kilauean magma column: Am. Jour. Sci., vol. 242, pp. 177–189, 1944.

[59] Stearns, H. T., and Clark, W. O., op. cit., pp. 78–79.

[60] Idem, pl. 11.

[61] Jaggar, T. A., Hawaiian Volc. Obs. Bull., vol. 10, no. 5, pp. 47, 55, 1922.

In 1923 a small lava flow erupted west of Makaopuhi Crater, just south of the present Chain of Craters Road (pl. 1). Clots of spatter, thrown into the air, congealed on surrounding trees, where they hung for several years (pl. 28A).

All eruptions since 1924 have been in the floor or walls of Halemaumau. The 1934 eruption was unique in that the lava rose through a crack considerably above the floor and formed a spectacular lava fall (pl. 39). The fountains on the floor of Halemaumau set up successive concentric waves in the crust that spread outward like the tiny waves set up when a stone is tossed into water. The only cinder cones formed in historic time by Kilauea Volcano have been built in the bottom of Halemaumau since 1924. Highly vesicular pumice, wafted upward by the heat and fumes from the lava fountains and blown southwestward by the prevailing winds, have made appreciable deposits on the floor and southwestern rim of the caldera. Beds of similar pumice are common in the ash deposits around the caldera and indicate former strong lava fountaining in the caldera.

All the flank flows of Kilauea have followed a rising stage and increased activity in the lava lake. After the flank outbreaks the lava lake subsides rapidly and commonly disappears from sight for a few weeks or a few months. The 1920 flank eruption was a notable exception. Also, the lava lake did not collapse at the time of the reported submarine eruption on January 2, 1884.

EXPLOSIONS.—The explosions of Kilauea in historic time have been described in numerous articles and therefore will be only briefly noted herein. About 1790, a series of paroxysmal explosions occurred in the caldera. The central pit was probably greatly enlarged by them and by concurrent and subsequent engulfment. The earliest description in 1823, indicates that the central part of the floor of the caldera had dropped several hundred feet leaving only a narrow terrace around the edge, called the "Black Ledge". Blocks 1 to 2 feet in diameter lie a mile beyond the rim of the caldera. The arrangement of the blocks indicates that the focus of the explosions was north or northeast of the present Halemaumau. During the earlier phases at least the explosions were partly or entirely magmatic, as blocks of wall rock ejected by the blasts are coated with fresh lava and small essential lapilli are present in the lower part of the deposits.[62] The ejecta from these explosions overlie the prehistoric ash deposits of the Puna volcanic series, adding to them only a thin veneer in most places. For this reason the 1790 deposits are not differentiated from the prehistoric ash on plate 1. In the Kau District, 6 miles southwest of Kilauea

---

[62] Macdonald, G. A., Petrography of the island of Hawaii: U. S. Geol. Survey Prof. Paper, in press.

Caldera, the ash of 1790 contains fossil human footprints (pl. 41A), believed to have been made by Hawaiian warriors fleeing from the explosions.

No paroxysmal explosions occurred at Kilauea from 1790 to 1924. On May 10, 1924, after an abrupt disappearance of the lava lake in Halemaumau and strong cracking both there and in eastern Puna, small explosions hurled rocks from Halemaumau. The explosions increased in violence until May 18 when cauliflower explosion clouds reached heights of more than 4 miles (pl. 9A). They continued at more or less regular intervals until May 27 when Halemaumau returned to a condition of steaming, landsliding, and dust-making, similar to the period prior to May 10. Halemaumau increased in diameter from 500 feet to 3,000 feet. No magmatic ejecta were thrown out by the explosions; hence, they were low-temperature phreatic explosions. The ash and ejecta of 1924 on the floor of the caldera are easily identifiable, but beyond the rim they cannot be separated from the earlier explosions. The deposits on the rim of Halemaumau average 1.5 feet in thickness, but a mile away they thin to a few inches or less. They cover too small an area to be shown on plate 1. Several articles[63] were published describing these explosions and all writers agreed that they were caused by basal ground water entering the throat of Halemaumau near sea level and forming steam on contacting hot rock.

However, subsequent studies of the structure and ground-water conditions in the dissected volcanic vents of other Hawaiian islands has led the senior author[64] to advance a new hypothesis to explain the explosions. He was convinced that the swarms of dikes about such vents effectively shut out basal ground water and that water confined at high levels between the dikes might well cause explosions. The same conclusion has been reached by Finch.[65] The intense cracking of the southeast rift of Kilauea preceding the explosions at Halemaumau probably fissured the dikes and allowed the confined water to flow towards Halemaumau. Thus the foci of the explosions probably were shallow and not at or below sea level.

THE LAVA LAKE.—Throughout much of the 19th and the first quarter of the 20th centuries, the most spectacular feature at Kilauea was the lava lake. Our detailed knowledge of its nature and activity is largely due to the work of Jaggar and his associates at the Hawaiian Volcano Observatory.

---

[63] Jaggar, T. A., and Finch, R. H., The explosive eruption of Kilauea in Hawaii, 1924: Am. Jour. Sci., 5th ser., vol. 8, pp. 353–374, 1924. Hawaiian Volc. Obs. Bull., vol. 12, nos. 5 and 6, 1924. Stearns, H. T., The explosive phase of Kilauea Volcano, Hawaii, in 1924: Bull. volcanologique, nos. 5 and 6, pp. 193–209, 1925.

[64] Stearns, H. T., Geology of the Hawaiian Islands: Hawaii Div. of Hydrography Bull. 8, p. 44, 1946.

[65] Finch, R. H., Lava surgings in Halemaumau and the explosive eruptions in 1924: Volcano Letter, no. 479, pp. 1–3, 1943.

The principal lava lake of Kilauea occupied Halemaumau pit, which appears to mark the position of the principal conduit, although lakes have existed for shorter periods at other places on the caldera floor. When Halemaumau lake is active, magma is present in two distinct, although probably intergradational, physical states. The lake proper consists of fluid, freely flowing pahoehoe, termed by Jaggar lake magma or pyromagma. This freely fluid portion of the lake is generally shallow, however, and rests on semisolid material resembling pasty aa, termed by Jaggar bench magma or epimagma.[66] The epimagma itself appears to be a semisolid plug with a more mobile magma column beneath. Crags of epimagma project as islands in the lake (pl. 40) and may change their position either vertically or laterally, giving the false impression of floating in the pyromagma. Both pyromagma and epimagma shift upward or downward within the confines of the pit, to some extent together, but also independently. The pyromagma, as might be expected from its fluidity, generally rises or sinks more rapidly than the epimagma. At times the central part of the epimagma plug rises more rapidly than its margin, carrying the central part of the lava lake with it. This forms a moat between the central bulge and the walls of the pit. Streams of pyromagma from the raised portion of the lake may then spill into the moat, the surface of which may be 100 feet or so lower than the central lake thus formed. The result is a ring of islands of epimagma, surrounded by the pyromagma in the moat and enclosing a central lake (pl. 40A). Measurements have shown the depth of the lake of pyromagma to be only about 50 feet, and the measurements have been confirmed by subsequent subsidences revealing the floor of the lake basin.[67]

The feature which distinguishes the true lava lake from ordinary ponds of lava accumulated by overflow on the caldera floor or in other depressions, is the system of circulation which connects the lake magma with the magma column at depth. Pyromagma rises through fissures and "source wells" in the epimagma, and descends again through sinkholes. Both the inlets and the outlets commonly persist for long periods.

Crusts form continuously on the lava lake, but generally movement in the pyromagma tears them apart. The fragments are swept into the sinkholes or are overflowed at the edges and sink into the pyromagma. Some are remelted; others become pasty and fuze together in the lake bottom, becoming a part of the epimagma.

---

[66] Jaggar, T. A., Seismometric investigation of the Hawaiian lava column: Seismol. Soc. America Bull., vol. 10, p. 163, 1920.

[67] Jaggar, T. A., Volcanologic investigations at Kilauea: Am. Jour. Sci., 4th ser., vol. 44, pp. 216–219, 1917.

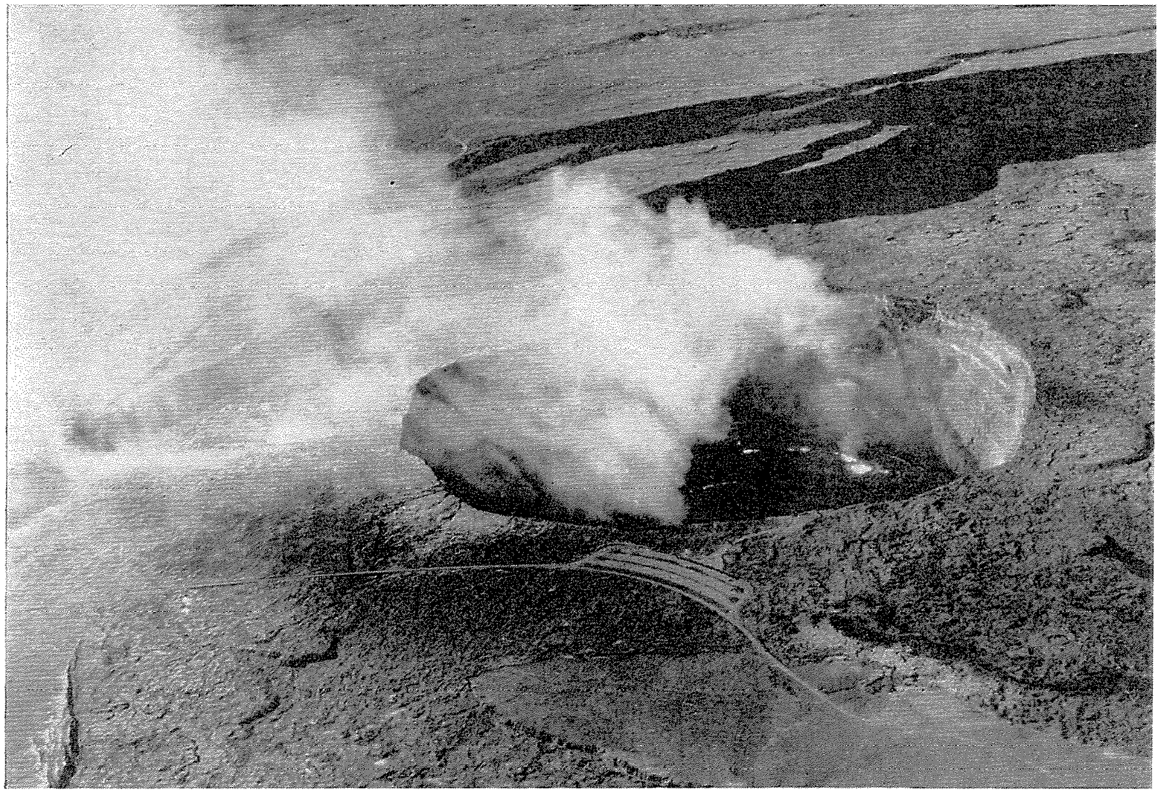
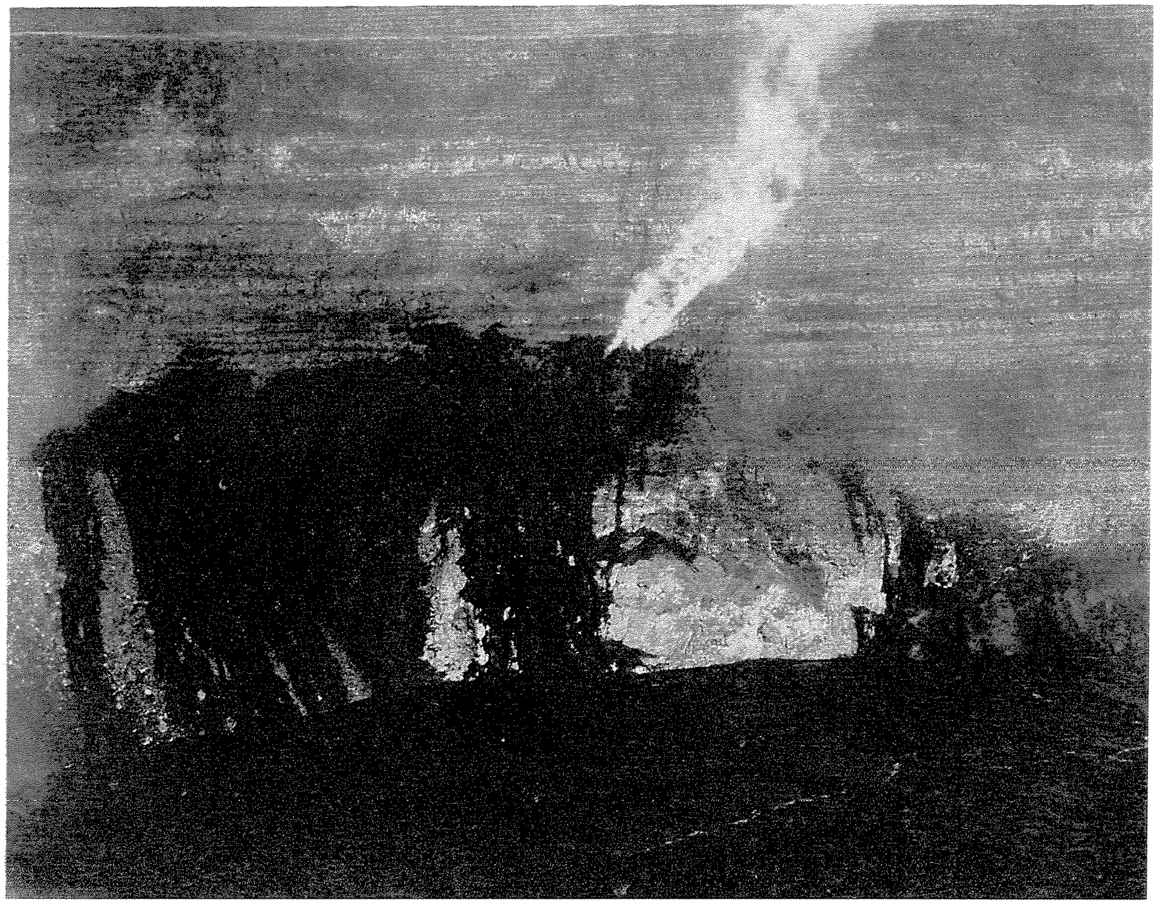
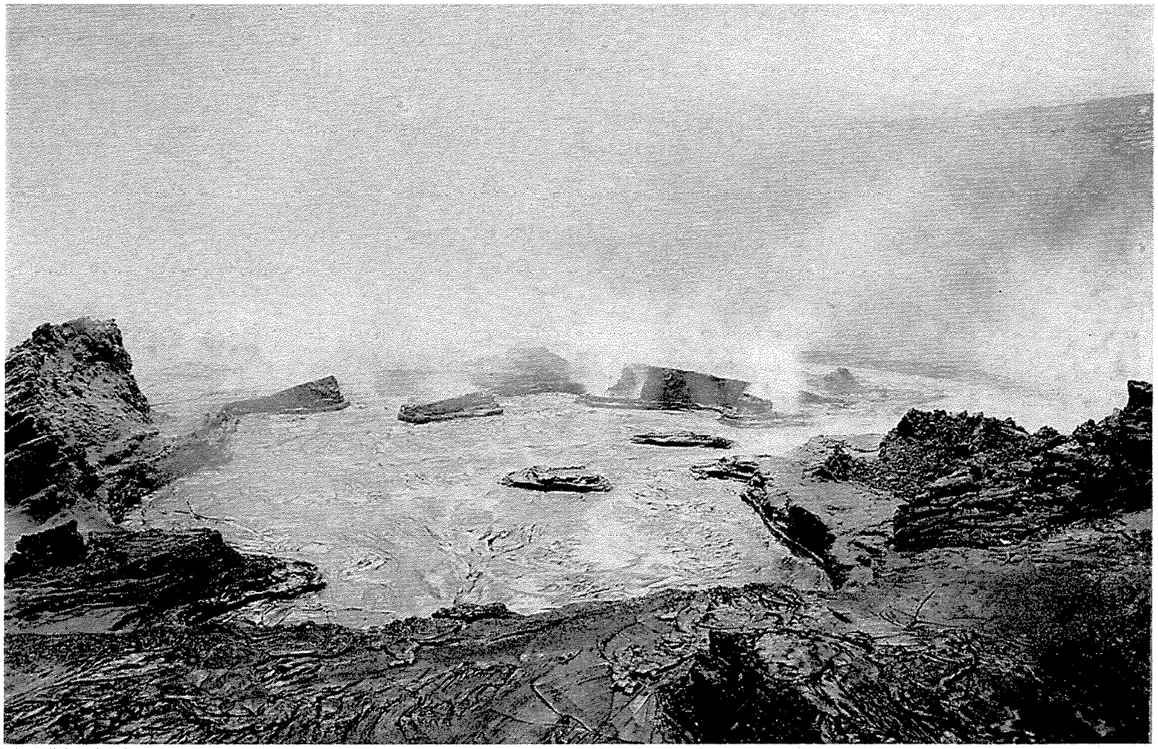


Plate 39A. Halemaumau in eruption on September 6, 1934. Note fault scarps of Uwekahuna Bluff in the background and the ash-covered spur in the foreground. Photo by USAAF.

Plate 39B. Cascade of lava about 400 feet high from a wall fissure in Halemaumau, September 7, 1934. Photo by USAAF.





Above: Plate 40A. Lava lake stage of Halemaumau showing islands of semi-solid epimagma in the fluid pyromagma, September 9, 1920. Photo by T. A. Jaggar.

Below: Plate 40B. Detailed view of islands in lava lake of Halemaumau, September 30, 1921. Photo by T. A. Jaggar.

Overflows on the shores of the lake also add to the solid upper part of the epimagma.

Lava fountains a few inches to 30 feet high play on the surface of the lake. Some of them are nearly constant in position and activity and mark underlying source wells or sinkholes. Others are evanescent and shift frequently, playing briefly at places where a crust fragment has just sunk carrying down air. The ejecta of these fountains range from clots and ribbons of relatively dense magma to fragments of pumice and finely drawn-out filaments of Pele's hair. Most of the ejecta fall back into the lake, but the more or less permanent fountains build spatter cones and driblet spires. Burning gases liberated at some of these result in so-called "blowing cones". The only ejecta carried away from the lava lake by the wind are pumice, Pele's hair, and Pele's tears. These accumulate to form vitric ash. Only a few inches of these ejecta have been deposited over the land just leeward of the caldera rim since 1790, although several feet of pumice has drifted into depressions near the rim.

At times the pyromagma drains away through the sinkholes, or even by reversal of flowage through the source wells, leaving the epimagma and the lake bottom and sides exposed to view. The epimagma may also sink, more slowly, or it may remain until the pyromagma again rises in the lake basin. At other times both pyromagma and epimagma may drop rapidly, as much as several hundred feet in one night. Such rapid sinkings are generally accompanied by collapse of the walls, and the island pinnacles crash down in great rock slides, revealing red-hot rock in their cores. Great quantities of dust-laden fume rise from the pit and generally obscure its floor.

Much has been published regarding the means by which high temperature and fluidity are maintained in the lava lake for long periods. Daly believes a two-phase convection is the chief mechanism, gas-rich magma rising to the lake, losing its gases, and descending again as gas-poor and consequently denser magma.[68] Still another probable mechanism is heating by exothermic reactions between gases.[69] Temperature measurements at the lake appear to support the latter mechanism, although not to the exclusion of others. These measurements show the temperature to decrease from about 1,175° C. at a depth of 13 meters to about 860° C. at a depth of 1 meter, and then rise again to about 1,000° C. at the lake surface. Temperatures of about 1,120° C. were measured in lava fountains,

---

[68] Daly, R. A., The nature of volcanic action: Am. Acad. Arts and Sci. Proc., vol. 47, no. 3, pp. 76–82, 1911; Igneous rocks and the depths of the earth, pp. 364–372, New York, 1933.

[69] Day, A. L., and Shepherd, E. S., Water and volcanic activity: Geol. Soc. America Bull., vol. 24, pp. 599–601, 1913.

and still higher temperatures, reaching 1,350° C., in cupolas over sinkholes and in the blasts of blowing cones, where the gases had free access to atmospheric oxygen.[70]

MAGMATIC AND SOLFATARIC GASES.—From 1912 to 1919, several collections of gas were made at the Halemaumau lava lake. Earlier observations had led Green,[71] and later Brun,[72] to the conclusion that the magmatic gases of Kilauea contained no water gas. Analyses of gases collected at Halemaumau in 1912 led Day and Shepherd to contradict these statements. They believed the analyses to indicate that water is one of the most abundant of the magmatic gases. The gases found by them include N_2, H_2O, CO_2, CO, SO_2, free H, free S, and comparatively small amounts of Cl, F, and perhaps NH_3. No argon or other rare gases, and no hydrocarbons, were found.[73] Later gas collections, in 1917 to 1919, analyzed by Shepherd, also showed that the most abundant emanation was water gas, averaging about 70 per cent of the total sample, followed in order of abundance by CO_2 and SO_2. Also present were SO_3, S, H_2, CO_2, A, N_2, and a little He, Ne and Cl. The gases collected at the surface of the lake were largely oxidized.[74] The results of the analyses have recently been summarized and restudied by Jaggar, who concludes that water vapor is not a primary constituent of magmatic gases, but the result of oxidation of magmatic hydrogen by reaction with CO_2, or with atmospheric oxygen. He believes the primary volcanic gases to be, in approximate order of abundance: CO_2, N_2, SO_2, S_2, H_2, CO, and A, with no H_2O, SO_3, or Cl_2.[75]

Gases issuing at the Sulfur Bank solfatara, at the northern edge of Kilauea Caldera, were analyzed in 1922 by Allen,[76] who found them to consist of: steam, 96.2 per cent; fixed gases, 3.7 per cent; sulfur dioxide, .096 per cent; sulfur vapor, .004 per cent; and a trace of hydrochloric acid. Later studies by Ballard and Payne showed that Allen's fixed gases probably consisted of air and carbon dioxide.[77] Analysis of 43 samples collected from September 1938 to August 1940 showed SO_2 to vary greatly in amount.[78] The values determined by Ballard and Payne for constituents other than steam are summarized below. That for sulfur dioxide includes

---

[70] Jaggar, T. A., Hawaiian Volc. Obs. Bull., vol. 5, no. 8, p. 84, 1917.

[71] Green, W. L., Vestiges of the molten globe, vol. 2, p. 82, Honolulu, 1887.

[72] Brun, A., Recherches sur l'exhalaison volcanique, p. 249, Geneva, 1911.

[73] Day, A. L., and Shepherd, E. S., op. cit., pp. 573–606.

[74] Shepherd, E. S., Hawaiian Volc. Obs. Bull., vol. 7, pp. 94–97, 1919; vol. 9, pp. 83–88, 1921.

[75] Jaggar, T. A., Magmatic gases: Am. Jour. Sci., vol. 238, pp. 313–353, 1940.

[76] Allen, E. T., Preliminary tests of the gases at Sulfur Banks, Hawaii: Hawaiian Volc. Obs. Bull., vol. 10, pp. 89–93, 1922.

[77] Ballard, S. S., The volcanic gas problem: Volcano Letter, no. 455, pp. 1–5, 1938.

[78] Ballard, S. S., and Payne, J. H., A chemical study of Kilauea solfataric gases, 1938–40; Volcano Letter, no. 469, pp. 1–3, 1940.

a very small amount of hydrogen sulfide during March and April, 1940.

	Average (percent)	Range (percent)
Air	7.9	0.0-40
Sulfur dioxide	4.6	0.5-18
Carbon dioxide	88.1	49.2-99.5

TUMESCENCE.—Investigations by Jaggar and his associates have demonstrated that both Mauna Loa and Kilauea swell up or tumesce, during periods of rising magma preceding eruptions.[79] This tumescence is indicated by actual level changes, determined by precise differential leveling, and by tilting of the ground surface measured by tilt meters and by displacements of the writing points of the seismographs. The Volcano Observatory is situated nearly north of the volcanic focus of Kilauea, and nearly east of that of Mauna Loa. Hence, tumescence of Kilauea causes a northward tilting and tumescence of Mauna Loa and an eastward tilting of the ground at the Observatory. Eruption of either volcano is accompanied by a reversal of the direction of tilt, indicating a shrinking of the mountain. The tilting resulting from magmatic changes is superimposed on a purely seasonal tilting, which must be allowed for in analysis of the tilt measurements. During the period of gradually rising magma levels at Kilauea between 1912 and 1921, a bench mark near the Observatory was elevated about 2 feet, the elevation increasing progressively from tide level at Hilo. During 1924, the great magmatic subsidence and attendant phreatic explosions at Kilauea occurred, and leveling in 1921 and 1927 demonstrates that between those years the bench mark was lowered 3.5 feet. Tilt measurements, combined with seismic studies, appear to be one of the most promising methods for prediction of volcanic eruptions.

CYCLE OF KILAUEA.—The cycle of activity at Kilauea Caldera appears to consist essentially of the gradual filling of a huge pit formed by collapse of part of the caldera floor, followed eventually by overflow of the pit and building up of the whole caldera floor, and terminated by a collapse which again establishes a large pit. The collapse may be accompanied by phreatic explosions, which are, however, merely incidental to the lowering of the magma level in the conduit. The essential parts of this cycle were recognized by Dana, who describes them as "(1) a rising in level of the liquid lavas and of the bottom of the crater; (2) a discharge of the accumulated lavas down to some level in the conduit de-

---

[79] Jaggar, T. A., and Finch, R. H., Tilt records for thirteen years at the Hawaiian Volcano Observatory: Seismol. Soc. America Bull., vol. 19, pp. 38–51, 1929. Waesche, H. H., Ground tilt at Kilauea Volcano: Jour. Geology, vol. 50, pp. 643–661, 1942.

termined by the outbreak; (3) a down-plunge of more or less of the floor of the region undermined by the discharge."[80]

The collapse which ends the cycle may result in engulfment of most of the caldera floor as in 1790, or only a small part of the floor as in 1924. The subsidence of the magma column which brings about the engulfment may result from lava effusion on the flanks of the volcano, both above and below sea level, draining the upper part of the conduit; from intrusion of sills or dikes at depth, with similar result; or possibly from a recession of the magma into the underlying magma reservoir.

Following the collapse, for several decades lava discharges, separated by intervals of several months or years, may enter the pit through cracks in the floor or talus fans, or cascade from cracks high on the wall. Lava fountains as high as 200 feet may accompany the outbreak. These eruptions produce cinder and spatter cones, and lava lakes which solidify soon after the fountaining ceases. Small quantities of pumice are wafted from the lava fountains and accumulate to leeward on the floor and rim of the caldera.

Slowly but steadily the pit fills and a quasi-permanent lava lake is established, kept hot and in motion for months or years by convective circulation, slowly rising gases, and exothermic chemical reactions near the surface. The lake may be present only a few months during a 10-year interval, as between 1895 and 1905; or it may be nearly constantly present, as between 1851 and 1894, when it was absent only a few months in 43 years (fig. 20). The lake may rise and fall within the pit, or slowly fill the pit and overflow onto the caldera floor as it did in 1921 and other times in the past. The overflows slowly build up the caldera floor. Twice during the past century, broad low lava cones with lava lakes at their summits have been built above the level of the surrounding caldera floor. The growth of these cones and the rise of the caldera floor itself, result partly from upbuilding by lava overflows, but also by tumescence of the whole structure. The phase of upbuilding is finally terminated by another collapse.

Since 1924 Kilauea has been in the early part of the cycle, characterized by the return of lava in the pit for short periods of 1 to 33 days, at intervals of 5 months to more than 10 years. During the 21 years since 1924, 9 eruptions have occurred, several of them accompanied by large lava fountains building cinder and spatter cones on the floor and lower talus slopes of Halemaumau pit. Eruptions similar to those of the present phase occurred in 1902 and 1903, indicating that the only unusual feature at present is the length of time the lava lake has been absent. The present period of more than 20 years, in which no permanent lava lake has been

---

[80] Dana, J. D., Characteristics of volcanoes, p. 141, New York, 1890.

present is twice as long as the similar period from 1895 to 1905. Presumably the lava will return some time in the next decade, and instead of forming a fill that congeals in a few days or weeks will set up a circulation system of heat and gas that will keep the lava liquid in the floor of Halemaumau. Several unsuccessful attempts may precede the establishment of a fairly permanent lake, as happened between 1905 and 1908 after the last dormancy.

PERIODICITY.—Measurements of the height of the pyromagma and epimagma surfaces in Halemaumau were made every 20 minutes for 23 days in 1919. As a result of these it was concluded that diurnal tidal fluctuations of 2 to 7 feet existed in the lava lake.[81] Careful analysis of the measurements by Brown failed to confirm this, however. His study suggests that a lunar tidal wave an inch high may occur in the lava lake, but further measurements are needed to confirm its existence.[82] At times there seems to be a noticeable sinking-after-rising of the lava level at equinox and a rising-after-sinking at solstice,[83] but at other times the effect does not appear in the measurements.

Jaggar believes that the Hawaiian volcano system, composed of Kilauea, Mauna Loa, and Hualalai, shows cycles of 11 and 66 years and a super-cycle of 132 years. (Also stated as 11-, 67-, and 134-year cycles.)[84] One supercycle is believed to have ended with the explosions of 1790 at Kilauea, and another with the explosions of 1924. Kilauea was apparently in a crater-filling stage from 1790 to 1822 but records are lacking until 1823, when the first missionaries visited Kilauea. Jaggar's cycles of 11 years, starting with 1815 to 1825 and ending with the present time, are listed in the accompanying table, together with the number of days lava was flowing on the flanks and in the summit calderas of Kilauea and Mauna Loa. The data are shown graphically in figure 27. The study of short-term cycles such as 11 years is complicated in treatment by the presence of lava most of the time in the lava lake of Kilauea. However, intense volcanic pressure in the Hawaiian system can be measured best by the number of days lava was flowing. Unfortunately, previous to 1880 records of flows on the floor of Kilauea Caldera are incomplete.

---

[81] Jaggar, T. A., Finch, R. H., and Emerson, O. H., The lava tide, seasonal tilt, and the volcanic cycle: Monthly Weather Review, vol. 52, pp. 142–143, 1924.

[82] Brown, E. W., Tidal oscillations in Halemaumau, the lava pit of Kilauea: Am. Jour. Sci., 5th ser., vol. 9, pp. 97–112, 1925.

[83] Jaggar, T. A., Seismometric investigation of the Hawaiian lava column: Seismol. Soc. America Bull., vol. 10, p. 177, 1920.

[84] Jaggar, T. A., The Hawaiian volcanic cycle: Volcano Letter, no. 325, pp. 1–3, 1931; The eruption cycles in Hawaii: Hawaiian Annual for 1932, pp. 83–93, 1931; Pele's Secret: Paradise of the Pacific, vol. 46, no. 8, pp. 21–26, 1934.

Approximate number of days of activity of Mauna Loa and Kilauea
(exclusive of lava lake activity in Halemaumau)

Period	Mauna Loa			Kilauea		Grand Total
	Summit	Flank	Total	Caldera	Flank	
1815-1825	(?)	(?)	(?)	(?)	7	7(?)
1826-1836	21	...	21	(?)	3	24(?)
1837-1847	5	90	95	(?)	26	121(?)
1848-1858	37	470 ±	507±	(?)	0	507(?)
1859-1869	122	305	427	(?)	3	430(?)
1870-1880	664	62	726	(?)	1(?)	727(?)
1881-1891	0	230	230	80±	1	311±
1892-1902	23	19	42	10	0	52
1903-1913	61	15	76	0(?)	0	76(?)
1914-June 1924	50	56	106	315	224	645
July 1924-July 1935	19	1	20	109	0	129
July 1935-July 1945	136	56	192	0	0	192

If Kilauean flank flows are singled out they are too few and short-lived to establish cycles. The plotting of the combined days of flowing lava indicates that the peak period was reached bebetween 1870 and 1880. Another peak nearly as high was reached between 1914 and 1924. If the number of days of flowing lava on the floor of Kilauea Caldera were known, the period 1848 to 1858 might represent a peak in the total number of days of flowing lava. Undoubtedly many such flows occurred, but no accurate record of them exists. If the number of days of flank flows only are used, the peak period is between 1848 and 1858. If intensity of seismic activity and number of days of flowing lava are considered most important, the peak period was between 1859 and 1869. Jaggar picks 1848-1858 as the peak period and the end of the 65-year cycle by using the number of days of flank flows from Mauna Loa and the activity in Halemaumau. No doubt exists that 1848 to 1881 represents the high period of Hawaiian volcanism during the past 150 years, if both volcanoes are considered together, but it is difficult to state the peak closer than this 23-year period.

According to Jaggar, the 132-year supercycle started with the cataclysmic explosion of 1790 at Kilauea, and ended with that of 1924. It is very doubtful, however, whether this use of the 1790 and 1924 explosions to delimit a cycle of volcanic activity is justified. The explosion of 1924 resulted from ground water entering the volcanic conduit, following a great subsidence of the magma column. That of 1790 was probably essentially similar in origin. The subsidence in 1924 is believed to have resulted from withdrawal of magma into the east rift of the volcano, and probable submarine outflow east of Cape Kumukahi.[85] The phreatic explosions resulting from the subsidence were volcanic accidents, and not to be

---

[85] Jaggar, T. A., and Finch, R. H., The explosive eruption of Kilauea in Hawaii, 1924: Am. Jour. Sci., 5th ser., vol. 8, p. 357, 1924. Jaggar, T. A., Kilauea's lost lava flow: Paradise of the Pacific, vol. 46, no. 6, pp. 5–9, 1934.

regarded as significant in the cyclic behavior of the volcano. Similar explosions on a smaller scale have occurred along the source fissure of the 1823 lava flow, at Mokuaweoweo, and at several small prehistoric vents on the slopes of Kilauea and Mauna Loa.

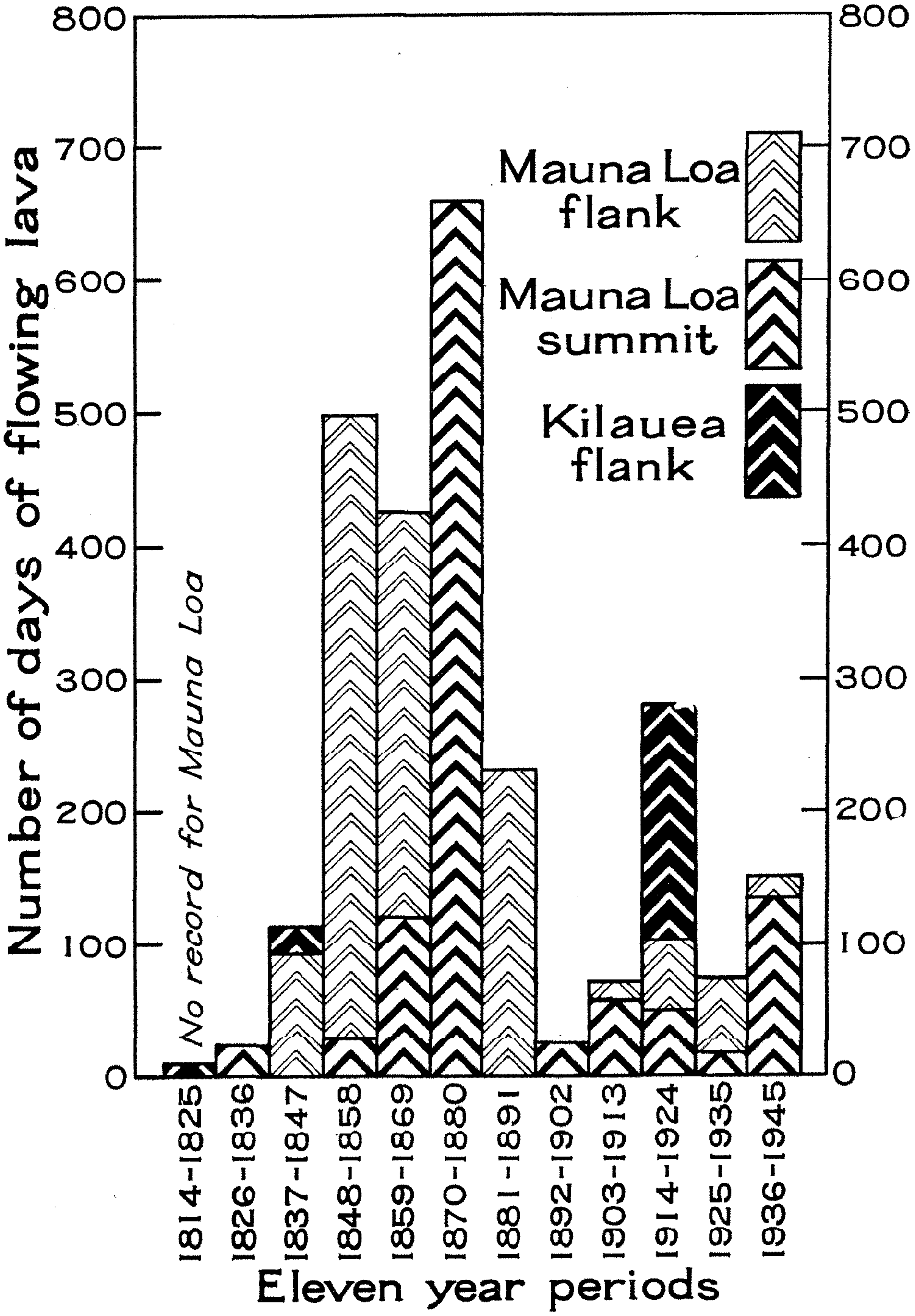


Figure 27. Graph showing the number of days lava was flowing on the flanks of Kilauea and Mauna Loa volcanoes and in Mokuaweoweo Caldera. Activity in Halemaumau omitted.

The important feature was not the explosion, but the subsidence of the magma column. Such great subsidences have not, however, been restricted to the years 1790 and 1924. Similar subsidences occurred in 1823, 1832, 1840, 1868, 1886, 1891, 1894, 1916, 1919, and 1922. The fact that they were not accompanied by phreatic explosions is accidental, and probably the result of the magma column not withdrawing below ground-water level, or cracking around the conduit being insufficient to admit any great amount of ground water. The whole sequence of events in 1924, (1) collapse in the lava lake, (2) faulting in eastern Puna, (3) assumed submarine eruption on the east rift, (4) steam-blast explosions, and (5) quiet return of the lava to Halemaumau a few months later, differs from many other recorded sequences only because of the spectacular phreatic explosions, which are accidental and inconsequential in the volcanic cycle.

Likewise, the great magmatic subsidences in Halemaumau listed above do not aid in demonstrating any 11-year cycle. The periods between them are exceedingly irregular, and range in length from two years to 28 years, and possibly to 33 years (1790 to 1823).

No evidence thus far produced appears to demonstrate any regular cyclic behavior in Hawaiian volcanoes.

Relation to sunspots.—Jaggar has correlated years of minimum sunspot activity with times of low pressure in the Hawaiian volcano system, and years of maximum sunspot activity with times of rising magma in the midst of his hypothetical 11-year cycle.[86] The following table lists years of sunspot maxima and minima, in relation to eruptions of Mauna Loa and Kilauea. Neither the amount of data nor the mathematical analyses appear sufficient to permit definite conclusions as to the relation of sunspots to volcanic activity. However, the closest correlation emerging from the table is between years of sunspot minima and eruptions of Mauna Loa. Six of the nine years of sunspot minima had contemporaneous eruptions of Mauna Loa, and two of the remaining three eruptions were removed only one year from sunspot minima. Neither this, nor the lack of correlation between sunspot minima and times of great magma subsidence and collapse at Kilauea, appear to support Jaggar's contention that times of sunspot minima are times of low pressure in the volcano system.

Summary.—The following summarizes much of our knowledge about Kilauea: (1) A lava lake commonly persists for a period of 6 to 10 years. (2) Rapid rise and much activity in the lake is accompanied by tumescence in the mountain. This phase often is terminated by fissuring of the mountain and a flank flow lasting

---

[86] Jaggar, T. A., Structural development of volcanic cones: Am. Geophys. Union Trans., p. 29, 1938.

Sunspots and volcanic eruptions

Sunspot minima	Closest eruption		Collapse at Kilauea	Sunspot maxima	Closest eruption		Collapse at Kilauea
	Mauna Loa	Kilauea			Mauna Loa	Kilauea	
1843	1843	(a)	1840	1837	1832	(a)	1840
1855	1855	(a)	1868	1848	1849	(a)	1840
1866	[b]1866	1868	1868	1859	1859	(a)	1868
1877	1877	1877	1868	1870	[c]1870	(a)	1868
1888	1887	1885	1886	1883	[d]1881	1884	1886
1899	1899	1894	1894	1894	1892	1894	1894
1912	1914	1918	1916	1906	1907	1894	1916
1922	[c]1921	1922	1922	1917	1916	1918	1916
1933	1933	1934	1924	1928	1926	1929	1924
				1937	1935	1934	1924

[a] Data on flows in Kilauea Caldera are inadequate.
[b] Started Dec. 30, 1865.
[c] Abundant fume liberation in Mokuaweoweo, but probably little or no lava extrusion.
[d] Started Nov. 1, 1880.

from less than a day to 7 months. (3) Most flank flows last less than a month. (4) Collapse of Halemaumau follows most flank flows, the lava generally but not always disappearing from sight through outlets in its bottom. (5) Heavy fuming accompanies the disappearance and reappearance of the lava in Halemaumau. (6) The lava disappears for periods ranging from 3 days to more than 10 years and the duration of periods of dormancy are unpredictable. (7) The lava lake is usually shallow, about 50 feet in depth. (8) On a few occasions low domical lava cones have been built, partly by overflow, but partly by tumescence and bodily uplift of the plastic epimagma. (9) The temperature of the lava lake is hotter at the surface where oxidation takes place than at a depth of 1 meter. (10) The temperatures range from 860° C. to 1175° C. in a vertical section of the lake. (11) The hottest temperatures are at fountains and blowing cones where the most gas is being discharged. (12) Northerly tilt at the Volcano Observatory accompanies a rising lava phase and southerly tilt a sinking lava phase. (13) Lava may rise into the pit quietly with little or no fountaining, or it may burst out in fountains 200 feet high. (14) The lava lake sometimes pulsates slowly as much as a foot every 6 hours. (15) Some evidence exists of lunar tides with double amplitudes of an inch or so. (16) Kilauea has paroxysmal phreatic explosions at rare intervals, induced by ground water percolating into the vent following rapid recession of the lava column. (17) Cycles may exist but their duration and causes are obscure. (18) The magma reaches the surface through narrow fissures usually less than 3 feet wide and sometimes cascades into the pit from cracks high on the walls. (19) At times of magmatic subsidence great quantities of broken rock fall into the vent. It forms a vent breccia filling a pipe, the lower end of which is probably being slowly melted and stoped where it is in contact with the magma chamber. (20) After the mountain is fissured the lava may form a dike by lateral injection from the lava lake and the lava may flow through the dike in a tube of its own making. (21) Sills and other irregular intrusive bodies are injected into the walls of Halemaumau. Similar injections lower in the mountain or submarine flank flows may account for most if not all the unexplained abrupt subsidences of the lava lake. (22) The lava lake may fall as much as 600 feet in a few hours. (23) The lava lake surface may lie from 400 to 1,500 feet below the highest point of the rim of the caldera. (24) Lava may break out several hundred feet above the lake on the adjacent caldera rim while the lake is full of lava. (25) Masses of aa and partly remelted crusts commonly form islands that rise and fall usually at a slower rate than the lake surface. (26) Most of the lava in the lake is pahoehoe. (27) The Kilauea Caldera is due to collapse, probably resulting from stoping and melting of its underpinning, and not to explosions. (28) The pyroclastic deposits from the lake phase consist of Pele's hair, Pele's tears, and very cellular pumice which form a thin cover of vitric ash to the leeward (southwest) side of the caldera. (29) The pyroclastic deposits of the paroxysmal phreatomagmatic explosions consist of essential bombs and lapilli, fragments of wall rock ranging from tiny pellets to 10-ton blocks, and vitric and lithic ash. (30) The phreatic explosions produce blocks and dust of solidified wall rock. (31) Fragments of partly crystallized hot intrusive bodies were ejected in 1924, the uncrystallized portion apparently congealing quickly into blebs of glass. (32) Earthquakes are more abundant during a collapsing than an erupting phase. (33) Flank eruptions have been followed by phreatic and phreatomagmatic explosions. (34) The lava lake sometimes shows a tendency to sink when an eruption of Mauna Loa ceases. This is thought to be a response to local earth forces and not indicative of a connection between the magma chambers of the two volcanoes. (35) The geologic history, as determined from geologic mapping, points to the main bulk of Mauna Loa being older than Kilauea, and that the latter volcano came into existence probably in the early Quaternary or late Tertiary at the intersection of a seaward-slip fault on the flanks of Mauna Loa with the Eastern Fundamental Fissure of the Hawaiian Archipelago.

INTRUSIVE ROCKS

Few intrusive rocks are exposed in Kilauea owing to the small amount of dissection. A 10-inch dike trending N. 50° W. cuts half way up the sea cliff of Puu Kapukapu, and a 6-inch dike striking N. 45° W. cuts an interstratified ash bed in Hilina Pali. Both dikes cut lavas of the Hilina volcanic series. Dikes striking parallel to the east rift zone are exposed in the southwestern wall of Makaopuhi Crater, and several dikes are exposed in the north wall of Kilauea Caldera. They range from 1 to 3 feet in width, and belong to the Puna volcanic series. All of the exposures are too short to show on plate 1. Several historic dikes and intrusive bodies are exposed in the walls of Halemaumau. Sill-like bodies in the wall glowed when first exposed by explosions in 1924 (pl. 41C).

Dike swarms occupy the rift zones beneath the surface and in the area of high rainfall along the east rift zone they probably confine ground water at high levels.

STRUCTURE OF KILAUEA

Rift zones.—Kilauea is an asymmetrical shield-shaped dome of stratified thin-bedded lavas with thin intercalated ash beds making up a small part of the bulk. The dome is transected by two zones of dikes identifiable on the surface by fissures and cone chains. Most of the fissures show no displacement parallel to the plane of the fissure. One zone trends southwest from the caldera into the Kau District; the other trends southeast for 4 miles and then turns N. 65° E. and extends to Cape Kumukahi (East Point) in the Puna District (fig. 6). This change in trend is unusual for rift zones in Hawaiian volcanoes. The southwest rift lies parallel to, and about 2 miles south of the Kaoiki fault system along which the southern edge of Mauna Loa has been downthrown. It has been suggested that Kilauea originated at the intersection of the Kaoiki fault system with the Eastern Fundamental Fissure of the Hawaiian Archipelago, which passes through Mauna Kea.[87] The east rift zone of Kilauea may have been determined by an ancient line of faulting similar to the Kaoiki system.

Faults.—The faults may be grouped into three large classes, as follows: (1) Circular and curved concentric faults associated with pit craters and the caldera; (2) faults in and bordering the rift zones, along which the downthrow is generally on the side toward the rift; and (3) faults along the southern coast, many with large downthrow on the southern or coastal side. The faults with few exceptions are normal. Two are rotational. The faults are characterized by echelon patterns and often rise in steps. The faulting started in late Pleistocene time at the close of the laying down of the Hilina volcanic series and Pahala ash, and has continued to the present. Along these faults the Hilina lavas and Pahala ash are displaced hundreds of feet, but the Puna lavas are displaced only tens of feet. The rocks of the Puna series are displaced

---

[87] Stearns, H. T., and Clark, W. O., Geology and water resources of the Kau District, Hawaii: U. S. Geol. Survey Water-Supply Paper 616, p. 100, 1930.

by faults in many other places. Some faults moved as much as 6 feet in 1868. A graben, or fault trench; subsided 12 feet near Kapoho in 1924.[88] Cracking and movement along a series of fractures crossing the Chain of Craters Road near Pauahi Crater began in May 1938,[89] and in 1942 was still occurring intermittently. The pavement of the Chain of Craters Road has been displaced by faulting more than a foot in some places; in other places it has been buckled by compression.

Along the southern coast the faults strike from N. 45° E. to S. 70° E. but the average trend of the group is slightly north of east (fig. 11 and pl. 1). Nearly all fault planes dip southward from 30 to 45 degrees. The aggregate displacement amounts to 1,500 feet in places (pls. 17A and 20A). It is greatest due south of the caldera and dies out both eastward and westward. The greatest displacement is where the dome is the highest. Many cascades of late Puna lavas over earlier fault scarps have been displaced by subsequent movement (fig. 13). The oldest scarps have been little eroded. The location of faults concealed by later lavas shown on plate 1 were mapped on the basis of abnormally steep slopes. The fact that less veneering has taken place in the region due south of the caldera shows that a southern caldera rim existed during the extrusion of most of the Puna lavas.

Some of the faulting has resulted in the formation of grabens and horsts. Kalapana lies in a graben[90] (pl. 41B) and Puu Kapukapu is a typical horst. The small graben just north of Kapoho was deepened as much as 12 feet in 1924.

The zone of normal faulting on the southern coast is probably caused by the instability of the dome and landsliding on a huge scale,[91] as Kilauea rises about 20,000 feet above the ocean floor to the south (fig. 4). The faults appear superficial, and although they are tensional no lava has erupted along them. They may flatten at depth and merge with the bedding planes.

The rift-zone faults usually bound grabens. Because of repeated filling of the grabens by lavas and burial of the marginal faults, the total movement is not measurable. The displacement of blocks not yet buried seldom exceeds 25 feet and is mostly vertical or nearly so. The subsidence appears to be due to the spreading of the dome under the influence of gravity, probably aided by the melting and absorption of the rock in the grabens by the magma

---

[88] Finch, R. H., The earthquakes at Kapoho, island of Hawaii, April 1924: Seismol. Soc. America Bull., vol. 15, pp. 122–127, 1925.

[89] Jaggar, T. A., Volcano Letter, no. 459, p. 2, 1938.

[90] Brigham, W. T., Notes on the volcanic phenomena of the Hawaiian Islands with a description of the modern eruptions: Boston Soc. Nat. History Mem., vol. 1, pp. 373–374, 1868.

[91] Stearns, H. T., and Clark, W. O., op. cit., p. 85.

below. Faults at Puu Nahaha, 3 miles southwest of Puu Kou, and near Pauahi Crater are rotational, but all others are normal.

The concentric and circular faults bounding pit craters are formed by collapse resulting from the withdrawal of the underlying magma and probably by the sinking en masse of a cylinder bounded by ring fractures nearly vertical at the surface. The blocks probably settle into small stocks, which have stoped and fluxed their way upward. The faults bounding the caldera (pl. 16) similarly outline a cylindrical mass of rock that is settling into the underlying magma reservoir, where most if not all is probably being remelted.

RELATION OF KILAUEA AND MAUNA LOA

Three distinct questions arise regarding the relationship of Kilauea and Mauna Loa volcanoes—(1) Is the dome of Kilauea, 4,000 feet high, composed chiefly of Kilauea lavas, or is it composed of a platform of Mauna Loa lavas with a thin cap of Kilauea lavas? (2) Is the volcanic action of Kilauea directly related to or independent of Mauna Loa? (3) Is Kilauea older or younger than Mauna Loa?

ORIGIN OF KILAUEA DOME.—Dana, in 1849, advanced the idea that Kilauea Caldera is merely a subsidiary vent developed by the corrosive action of magma along a fissure in the flank of Mauna Loa.[92] The lavas exposed in the walls of the caldera would, according to that theory, be flows from Mauna Loa. Later, Dana reversed his viewpoint and considered Kilauea to be an independent volcano, the southernmost of the row of major volcanoes, termed by him the "Kea Range", which marks the course of the more easterly of the two fundamental crustal fissures believed to determine the location of the volcanoes of the Hawaiian Archipelago.[93] The independent topographic form of Kilauea appears to have been first pointed out in 1883 by Dutton,[94], but it was not until a survey of the area in 1912 by the United States Geological Survey that the topographic separation of Kilauea from Mauna Loa was clearly demonstrated.

Although recognizing the distinctness of the Kilauea dome, Daly, in 1911, suggested that it might be the result of arching of the flank of Mauna Loa by a laccolithic intrusion, which by perforating its roof had given rise to the Kilauea vent.[95] He believed the lavas in the caldera walls to be flows from Mauna Loa.

---

[92] Dana, J. D., Geology: U. S. Explor. Exped. during the years 1838–1842, rept., vol. 10, pp. 224–225, 1849.

[93] Dana, J. D., Characteristics of volcanoes, pp. 260–263, New York, 1890.

[94] Dutton, C. E., Hawaiian volcanoes: U. S. Geol. Survey 4th Ann. Rept., p. 120, 1883.

[95] Daly, R. A., The nature of volcanic action: Am. Acad. Arts Sci. Proc., vol. 47, pp. 109–112, 1911.

Stearns regarded Kilauea as an independent volcano formed on the southern flank of Mauna Loa at the intersection of faults of the Kaoiki system with the Eastern Fundamental Fissure.[96] Stone pointed out anew the topographic independence of Kilauea, and demonstrated that the flows in the caldera wall were erupted by Kilauea, not by Mauna Loa.[97]

Projections of the slope of Mauna Loa southeastward indicate that the entire series of rocks exposed in Hilina Pali were probably erupted by Kilauea. Even without allowance for faulting, the projected slope of Mauna Loa passes beneath Hilina Pali at about sea level (section B-B′, pl. 1). If allowance is made for offset on the known faults, the depth of the projected Mauna Loa surface is still greater. Likewise, the projected Mauna Loa surface is deeply buried under eastern Puna, the great bulk of the Puna Ridge apparently being composed exclusively of volcanics erupted by Kilauea. The rift zone which follows the Puna Ridge bears no apparent genetic relationship to the rift zones of Mauna Loa, although both it and the southwest rift zone of Kilauea may be directly related to the Kaoiki fault system on the southern flank of Mauna Loa.

Although interfingering of Mauna Loa and Kilauea flows occurs along the contact, it is concluded that the great bulk of the Kilauea dome above sea level is composed of lavas erupted by Kilauea Volcano.

INTERCONNECTION BETWEEN THE MAGMA RESERVOIRS.—Granting the separate entity of the Kilauea dome, there still remains the possibility that in its volcanic action Kilauea may be satellitic to, or at least connected with, Mauna Loa. Although Dana, in 1849, noted the apparent independence in action of the two volcanoes, he believed them to be connected at depth. The difference in altitude of the molten magma in the two arms of the great siphonal U-tube thus postulated, he attributed to different specific gravities resulting from different amounts of gas inflation in the two arms of the tube.[98] Brigham also pointed out independence in action of Mauna Loa and Kilauea.[99] This independence of action, together with the great difference in altitude of the vents, led Scrope[1] and Judd[2] to the conclusion that they are independent volcanoes. Dutton also pointed out the difference in altitude of more than 9,000 feet between the simultaneously active vents, and

---

[96] Stearns, H. T., Origin of the volcanoes of Mauna Loa and Kilauea (abst) : Geol. Soc. America Bull., vol. 37, pp. 150–151, March 30, 1926.

[97] Stone, J. B., The products and structure of Kilauea : B. P. Bishop Mus. Bull. 33, pp. 36–37, 1926.

[98] Dana, J. D., op. cit., 1849.

[99] Brigham, W. T., Notes on the volcanic phenomena of the Hawaiian Islands : Boston Soc. Nat. Hist. Mem., vol. 1, pt. 3, p. 404, 1868.

[1] Scrope, G. P., Volcanoes, 2d ed., p. 262, London, 1862.

[2] Judd, J. W., Volcanoes, pp. 138 and 326, New York, 1881.

stated that "The idea of a liquid connection . . . through subterranean passages between these lava lakes seems to be so thoroughly opposed to all hydrostatic laws as to be incredible". He therefore considered the two volcanoes to be independent, and to be fed from separate reservoirs.[3]

W. L. Green believed that an interconnected system could exist, the connection lying in a liquid substratum at a depth of about 20 miles, the different altitudes of the upper ends of the magma columns being caused by differences in density of the two columns resulting from differences in temperature. The temperature difference he believed might result from differing widths of the magma columns, a wide column being more effectively stirred by convention and therefore kept hotter than a narrow column. Nevertheless, he agreed with Dutton that Kilauea and Mauna Loa are independent volcanoes, and advanced as supporting evidence the fact that the distance between them is about the average distance between neighboring major vents in the Hawaiian Islands.[4]

Baker also considered the two volcanoes to be independent.[5] Alexander suggested that they might be connected, the lava rising higher in Mauna Loa without sympathetic overflow at Kilauea because of the smaller diameter of the Mauna Loa conduit.[6] Friedlaender regarded Mauna Loa and Kilauea as independent in action, but connected at great depth, the independence being attributed to the lower specific gravity of the Mauna Loa magma, resulting from a greater abundance of gas.[7] Hitchcock believed the two to be independent volcanoes, but deduced some degree of sympathy in their activity.[8] Cartwright believed Mauna Loa and Kilauea to be connected, and the apparent independence of action to be due to a longer feeding conduit for Kilauea than for Mauna Loa, resulting in a larger mass of lava under Kilauea with a greater lag in responding to external forces.[9]

Jaggar believes that Kilauea and Mauna Loa are interconnected at depth and that a sympathy of action exists between them. The evidence consists in contemporaneous or nearly contemporaneous activity of the two volcanoes in the years 1832, 1849, 1855, 1868,

---

[3] Dutton, C. E., op. cit.

[4] Green, W. L., Vestiges of the molten globe, vol. 2, pp. 155–165, 179–181, Honolulu, 1887.

[5] Baker, E. P., Hawaiian volcanism: Overland Mag., 2d ser., vol. 6, pp. 602–605, 1885.

[6] Alexander, J. M., The craters of Mokuaweoweo, on Mauna Loa: Nature, vol. 34, pp. 232–234, 1886.

[7] Friedlaender, Benedict, Der Vulkan Kilauea auf Hawaii: Himmel und Erde, Bd. 8, Heft 1, 38 pp., 1895; reviewed in Nature, vol. 53, pp. 490–491, March 26, 1896.

[8] Hitchcock, C. H., Hawaii and its volcanoes, 2d ed., pp. 276–280, Honolulu, 1911.

[9] Cartwright, Bruce, Halemaumau and Mokuaweoweo: Paradise of the Pacific, vol. 26, no. 8, pp. 10–11, 1913.

1877, and 1907,[10] pointed out by Hitchcock,[11] and of marked collapses at Halemaumau during June 1916 and November 1919, a few days after cessation of eruptions of Mauna Loa, and a smaller collapse during December 1914, about two weeks before the end of a Mauna Loa eruption.[12] He states that the sympathy of action results at times in simultaneous eruption and at other times in alternate activity of the two volcanoes,[13] and indicates that the volcanoes are connected as correlated gas vents, but not as a hydrostatic siphon tube.[14]

This subject is beyond the scope of this bulletin, but the duration of activity in the two volcanoes in the last century as shown in the graphs in figure 20 is striking for its difference rather than for its similarity, if duration of activity is used as an indicator of connection between the two magma reservoirs. It should also be noted that many other great collapses have occurred at Kilauea, at times when there was no activity of Mauna Loa.

Eight flank eruptions of Kilauea, one of which was submarine, have been recorded since 1831 when the record of Mauna Loa begins. Mauna Loa has poured out 14 major flank flows in this period or 18 flank flows if the eruptions of 1832, 1851, 1933, and 1940 are included.

The time interval between Kilauea flank eruptions and outbreaks of Mauna Loa both on the flank and the summit are given in the following table:

---

[10] Jaggar, T. A., Seismometric investigation of the Hawaiian lava column: Seismol. Soc. America Bull., vol. 10, p. 192, 1920.

[11] Hitchcock, C. H., op. cit., p. 277.

[12] Jaggar, T. A., and Finch, R. H., Tilt records for thirteen years at the Hawaiian Volcano Observatory: Seismol. Soc. America Bull., vol. 19, pp. 45–48, 1929.

[13] Jaggar, T. A., Kilauea and Mauna Loa in 1914: Hawaiian Volc. Obs. Bull., vol. 3, no. 4, pp. 29–42, 1915.

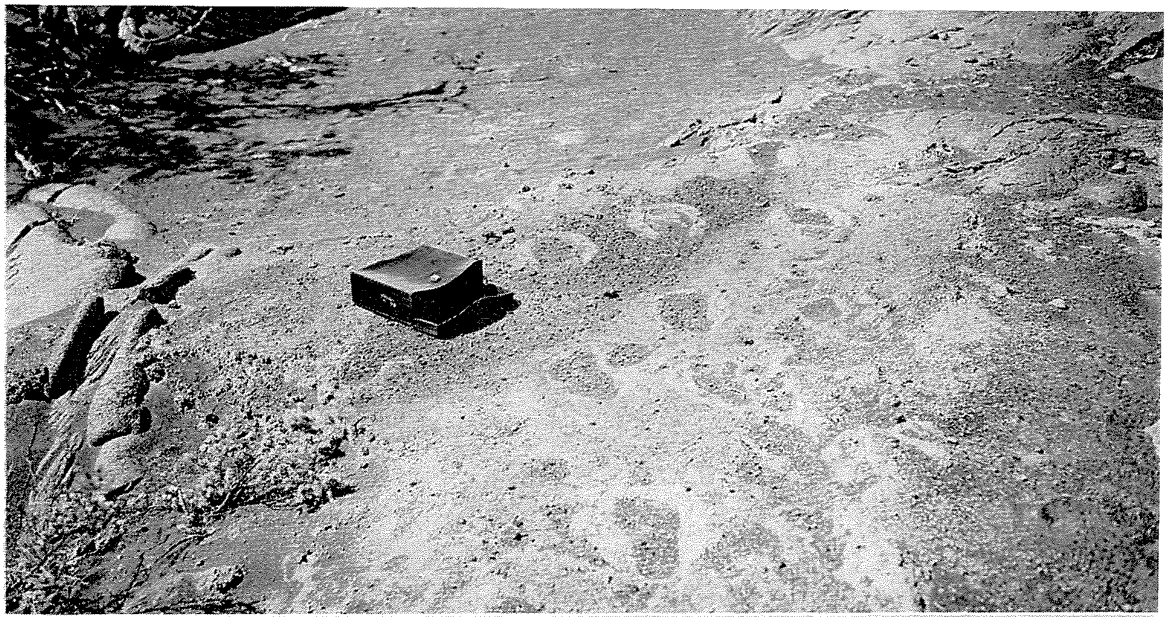
[14] Jaggar, T. A., Lava flow from Mauna Loa, 1916: Am. Jour. Sci., 4th ser., vol. 43, pp. 255–288, 1917.

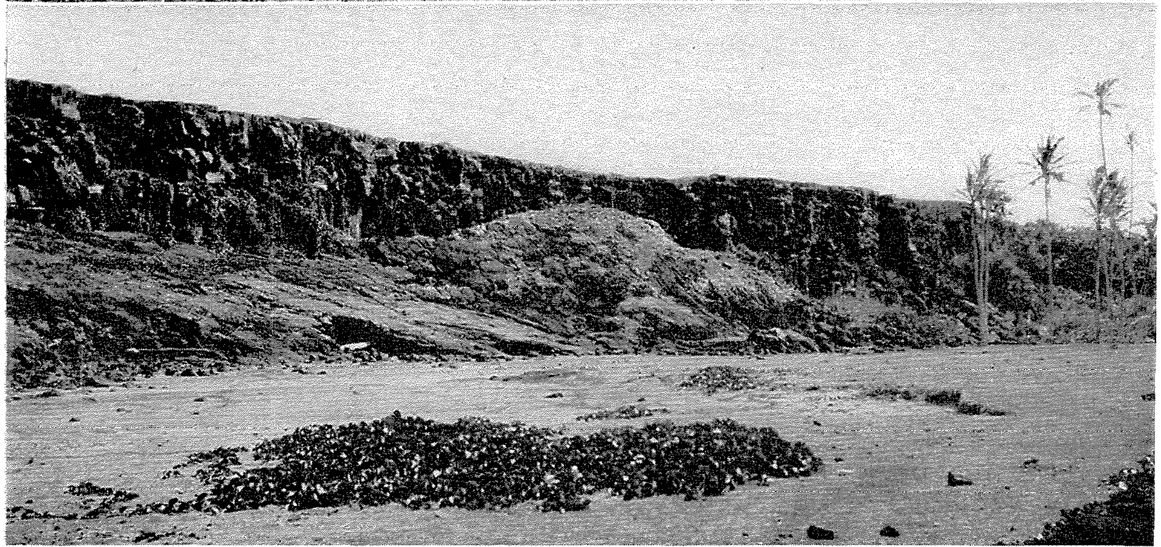
→

Opposite page, top: Plate 41A. Fossil human footprints in the Kilauea ash of 1790, Kau Desert, 6 miles southwest of the caldera. The prints are believed to have been made by soldiers in Keoua's army, many of whom were killed by the explosions. Photo by Hawaiian Volcano Observatory.

Middle: Plate 41B. Fault scarp along edge of horst just south of Kalapana village, Puna District. The land in the foreground subsided several feet during the earthquakes of 1868. Photo by C. H. Merriam.

Bottom: Plate 41C. Canoe-shaped intrusive body and dike in northeast wall of Halemaumau in July 1924. The sill was glowing when the photograph was taken. Photo by O. H. Emerson.





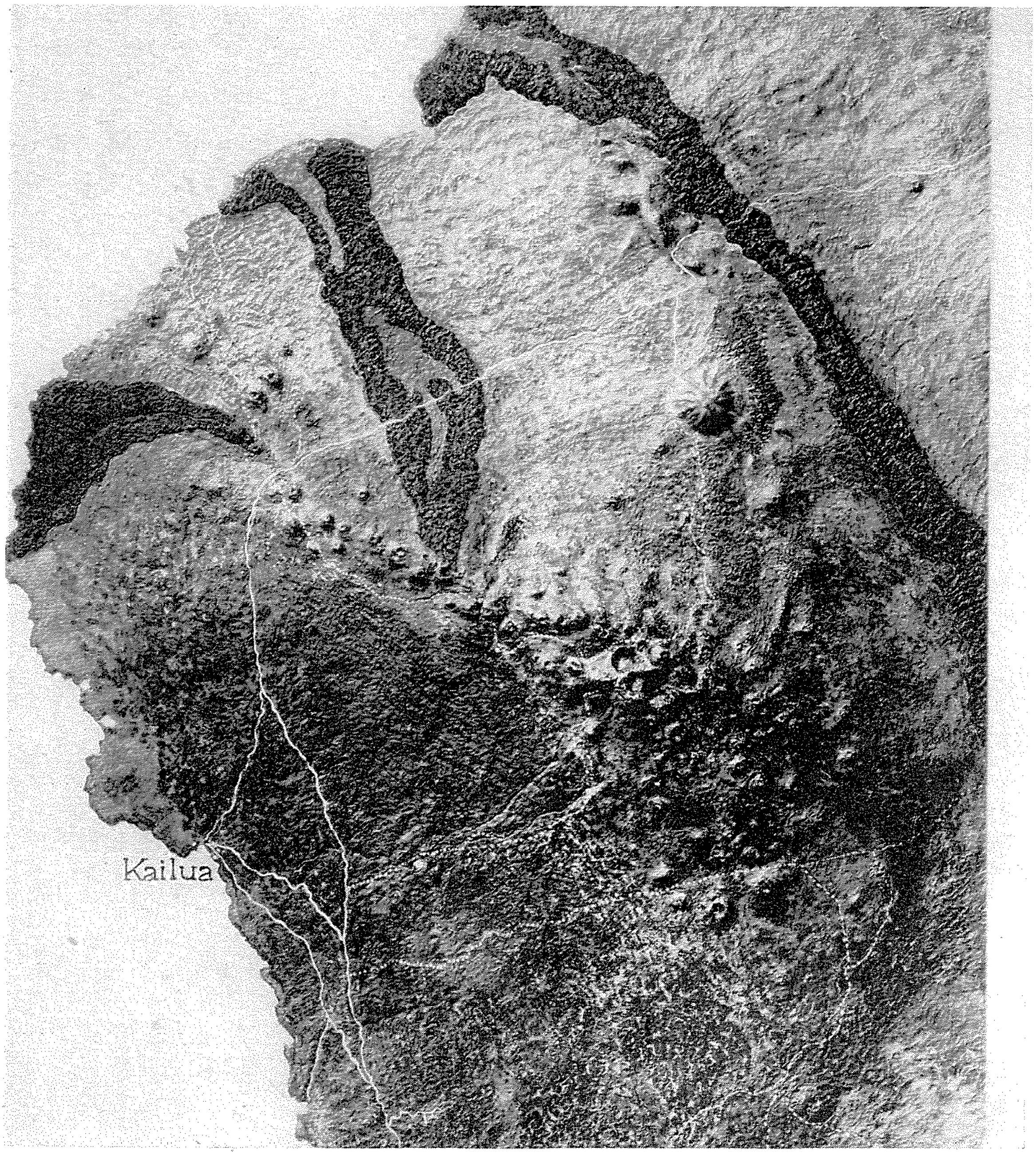


Plate 42. Model of Hualalai Volcano by W. T. Pope. The large cone on the north slope is Puu Waawaa.

Interval between outbreak of Kilauea flank eruptions and nearest Mauna Loa eruptions

Kilauea eruption			Nearest Mauna Loa eruption			Interval		
Year	Month	Day	Year	Month	Day	Years	Months	Days
1832	Jan.	14	1832	June	20	0	5	6
1840	May	30	1843	Jan.	9	2	7	9
1868	April	2	1868	Mar.	27	0	0	6
1877	May	4	1877	Feb.	14	0	2	18
1884	Jan.	22	1880	Nov.	1	3	2	21
1919	Dec.	21	1919	Sept.	29	0	2	22
1922	May	28	1919	Sept.	29	2	7	29
1923	Aug.	25	1926	April	10	2	7	16

The interval between a Kilauean flank flow and a Mauna Loa outbreak was less than 3 months for three flows and for the remaining five ranged from 5 months to more than 3 years. These intervals do not indicate alternation or contemporaneity. The only coincidence of outbreak was in 1868 when the outbreaks were 6 days apart. This was the most intense seismic year in Hawaii in the last century and was characterized by very destructive earthquakes, mudflows, and seismic sea waves.

It is generally agreed that volcanoes are acted upon by various extraneous terrestrial and astrophysical forces which may serve as trigger forces to set off eruptions. Such trigger forces act simultaneously on adjacent volcanoes, and provided conditions are ready for eruption, simultaneous outbreaks might conceivably occur repeatedly without any subsurface connection whatsoever. There is considerable evidence that the simultaneous eruptions of 1868 may have been thus set off by tectonic disturbances unrelated to local volcanism.[15] It is hardly surprising, therefore, that Kilauea and Mauna Loa should show occasional similarities in behavior.

AGE OF KILAUEA IN RELATION TO MAUNA LOA.—Dana, in pointing out Kilauea's position as the most southeasterly volcano of the Eastern Fundamental Fissure, implied that it may be younger than Mauna Loa.[16] Stearns believed Kilauea to have started activity later than Mauna Loa, but that the uppermost part of Mauna Loa is younger than Kilauea.[17] Stone believed Kilauea to be younger than Mauna Loa, and to have formed at the head of a graben crossing Mauna Loa's southeastern slope.[18] He also believed that the lavas in Kilauea that are older than the Pahala ash (lavas of the Hilina volcanic series) were poured from Mauna Loa. He interpreted native traditions as indicating that Kilauea Caldera

---

[15] Wood, H. O., On the earthquakes of 1868 in Hawaii: Seismol. Soc. America Bull., vol. 4, pp. 169–203, 1914.

[16] Dana, J. D., Characteristics of volcanoes, pp. 262–264, New York, 1890.

[17] Stearns, H. T., op. cit., p. 151.

[18] Stone, J. B., op. cit., pp. 38, 49–50.

probably formed within the last few hundred years.[19] The present writers interpret the traditions differently and believe the caldera is much older than suggested by Stone. Both Jaggar[20] and Powers[21] considered Kilauea to be older than Mauna Loa, but the evidence presented is not at all convincing, and Jaggar now agrees that it has been invalidated by more recent geologic work.[22]

Much of the Pahala ash in the Kau District apparently originated at Kilauea, so that Kilauea must have been in existence in the Pleistocene. The deposition of Pahala ash occurred late in the building of the Kilauea dome, which has already been shown to be independent of Mauna Loa. The Hilina volcanic series, which comprises the bulk of the Kilauea dome, is correlative with at least part of the Kahuku volcanic series (p. 62). It appears probable that Kilauea Volcano was localized by the intersection of fractures belonging to or related to the Kaoiki fault system with the Eastern Fundamental Fissure of the Hawaiian Archipelago. If that is the case, however, much of the bulk of Mauna Loa is older than Kilauea, for the Kaoiki faults, 15 miles from Mokuaweoweo, could not have formed until the Mauna Loa dome had been built to considerable size.

The gently sloping lava plain rising southwestward from Hilo for 16 miles, composed chiefly of Mauna Loa lavas, is typical of the plains built by lava flows confined in the trough between two pre-existing mountains. It was built chiefly by lava flows from Mauna Loa filling the trough between Kilauea and Mauna Kea in post-Ninole time. Its presence proves that the Kilauea shield has been in existence for a considerable period.

As already pointed out, the lesser degree of intratelluric crystallization in the Kilauea lavas as compared to those of Mauna Loa also is suggestive of the greater youth of Kilauea. The Kau volcanic series and the Puna volcanic series are regarded as correlative, the accumulation of both having started after the deposition of the Pahala ash, and continued essentially without interruption until the present time.

---

[19] Idem, p. 47.

[20] Jaggar, T. A., The cross of Hawaii, 12 pp., Honolulu, 1912; Seismometric investigation of the Hawaiian lava column: Seismol. Soc. America Bull., vol. 10, p. 198, 1920.

[21] Powers, Sidney, Tectonic lines in the Hawaiian Islands: Geol. Soc. America Bull., vol. 28, p. 507, 1917.

[22] Jaggar, T. A., letter of February 24, 1945.

GEOLOGY OF HUALALAI VOLCANO

PREVIOUS INVESTIGATIONS

Menzies, a botanist with the Vancouver expedition, ascended Hualalai in January 1794, but he noted little of geologic interest.[23] He recorded the native name for the mountain as Worroray. Dutton, viewing the mountain from a passing boat in 1882, thought that the Anahulu terrace might be a fault escarpment.[24] Several scientists have ascended the mountain since and described the numerous cinder cones, deep craters, and other features of topographic interest.[25] The account given by Brigham[26] is typical. No systematic study of the mountain was made by any of them. Cross describes it as a typical basaltic volcano with the form of Mauna Kea.[27]

Cross made the important discovery that Puu Waawaa and Puu Anahulu are composed of trachyte.[28] He suggested that the Anahulu terrace was part of an ancient trachytic land mass under Hualalai, Mauna Kea, and Mauna Loa. As pointed out on page 143, the topography is that of a trachyte cone and flow modified only slightly by erosion and weathering, hence evidence that it is not an older land mass under Hualalai (pl. 42). Daly[29] described the petrography of a few projected blocks from the summit, and Sidney Powers[30] the 1801 lava flow.

From a study of the topographic map of Hualalai, Jaggar pointed out the presence of two zones of cones, one extending due north from the summit and the other N. 65° W.[31] Dana ascribed the cliff at Kealakekua Bay to faulting.[32] H. A. Powers made a de-

---

[23] Vancouver, George, A voyage of discovery to the North Pacific Ocean and round the world, vol. 3, p. 14, London, 1798.

[24] Dutton, C. E., Hawaiian volcanoes: U. S. Geol. Survey 4th Ann. Rept., p. 173, 1884.

[25] Pickering, W. H., Lunar and Hawaiian physical features compared: Am. Acad. Arts Sci. Mem., vol. 13, pp. 151–178, 1906.

[26] Brigham, W. T., The volcanoes of Kilauea and Mauna Loa on the island of Hawaii: B. P. Bishop Mus. Mem., vol. 2, no. 4, pp. 9–14, 1909.

[27] Cross, Whitman, Lavas of Hawaii and their relations: U. S. Geol. Survey Prof. Paper 88, p. 34, 1915.

[28] Cross, Whitman, An occurrence of trachyte on the island of Hawaii: Jour. Geology, vol. 12, pp. 510–523, 1904.

[29] Daly, R. A., Magmatic differentiation in Hawaii: Jour. Geology, vol. 19, no. 4, p. 304, 1911.

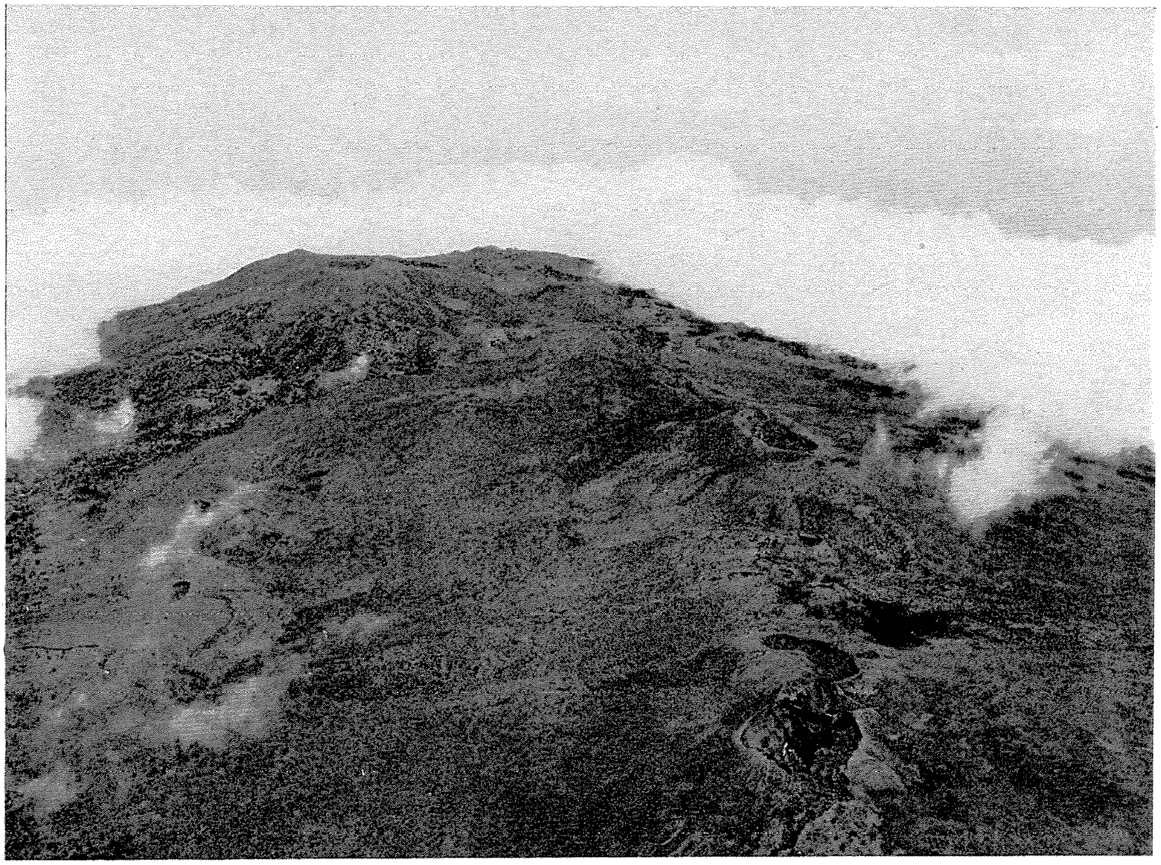
[30] Powers, Sidney, Notes on Hawaiian petrology: Am. Jour. Sci., 4th ser., vol. 50, pp. 266–267, 1920.

[31] Jaggar, T. A., Seismometric investigation of the Hawaiian lava column: Seismol. Soc. America Bull., vol. 10, no. 4, p. 189, 1920.

[32] Dana, J. D., Characteristics of volcanoes, p. 30, New York, 1890.

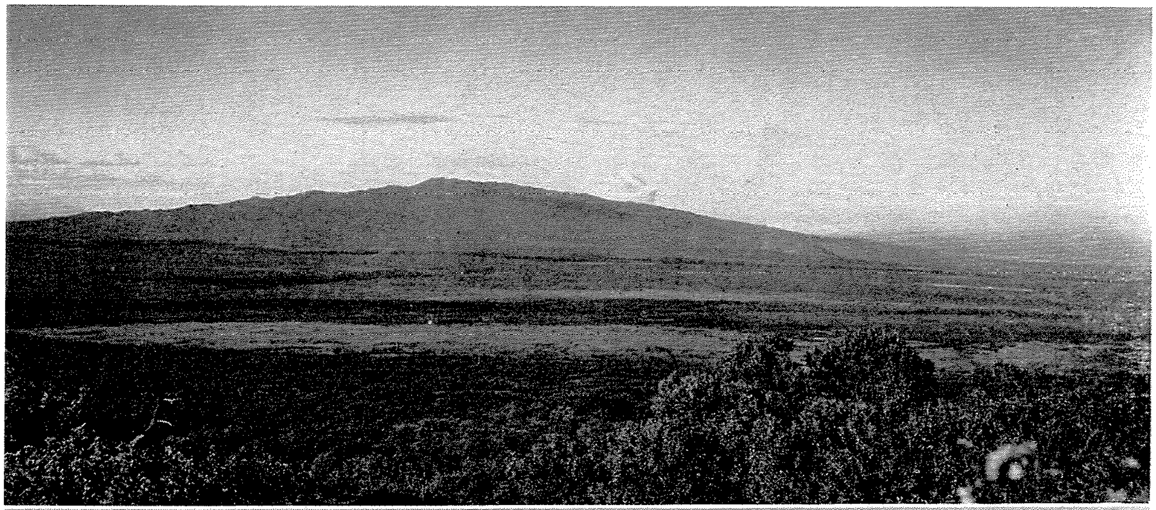
Stratigraphic section of Hualalai

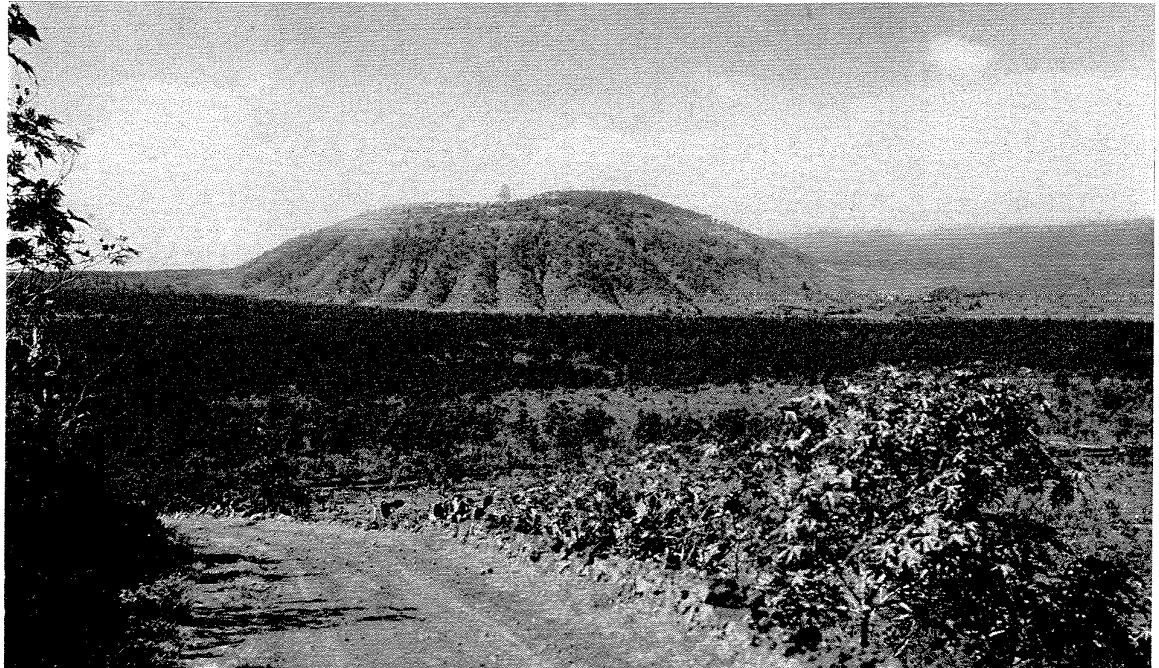
Major geologic unit	Rock assemblage		Thickness (feet)	Symbol on map (pl. 1)	General character	Water-bearing properties
Quaternary volcanic rocks	Flows and cones of 1800-1801, the historic member of the Hualalai volcanic series		15±	Hhl	Olivine basalt pahoehoe and aa flows carrying numerous dunite and gabbro xenoliths.	Extremely permeable but carry no water except at the coast, where it is brackish.
			50±	Hhc	Spatter cones and ramparts at the sources of the flows.	Highly permeable but carry no water.
	Prehistoric member of the Hualalai volcanic series. (Partly younger and partly older than the Waawaa volcanics)	Basalt member	8,000+	Qhl	Porphyritic and nonporphyritic basalt aa and pahoehoe flows ranging from 5 to 100 feet in thickness and averaging 20 feet.	Highly permeable, carrying brackish water near the coast but fresh water near sea level farther inland.
			150±	Qhc	Cinder and spatter cones at the source of the lava flows.	Highly permeable but carry no water.
			5±	Qha	Vitric ash and cinder deposits.	Highly permeable but those at the surface carry no water.
		Waawaa volcanics (trachyte member)	900+	Pwl	Fine-grained trachyte aa partly covered with basaltic lavas and Pahala ash.	Poorly permeable and carries no water.
			1,300+	Pwc	Trachytic pumice cone at the source of the flow.	Permeable but carries no water.



Above: Plate 43A. Cones on the summit and southeast rift zone of Hualalai Volcano. Photo by USAAF.

Below: Plate 43B. Chain of spatter vents at the source of the Huehue lava flow of 1801, Hualalai Volcano. Photo by R. J. Baker.





tailed geologic map of the coffee district on the southwestern slope of Hualalai and noted the thin vitric tuff beds between lava flows.[33] He has also published a brief description of the mountain.[34]

ROCKS OF HUALALAI AND THEIR WATER-BEARING PROPERTIES

The volcanic rocks comprise all the lava flows, intrusive rocks, and pyroclastic rocks of Hualalai. Their general character and water-bearing properties are summarized in the table on page 138.

HUALALAI VOLCANIC SERIES

GENERAL STATEMENT.—All the volcanic rocks of Hualalai Volcano are grouped together in the Hualalai volcanic series. These rocks comprise the entire mountain and all are basalts except the Waawaa volcanics, which consist of a trachyte cone and flow and are distinguished from the basalt on plate 1. It is assumed that the whole mountain was built by continuous activity, but erosional unconformities may exist within the mountain. Also, it may be built upon a basement of Ninole basalts extruded from Mauna Loa. The lavas of the Hualalai volcanic series definitely interfinger with the lavas of the Kau volcanic series of Mauna Loa on the southern and eastern slopes. The prehistoric basalts of the Hualalai volcanic series both underlie and overlie the Waawaa volcanics. For convenience the basalts and their cones will be described first. The freshness of the flows in the exposed part of the Hualalai volcanic series, indicates that the rocks are mostly Recent, although a few flows may be late Pleistocene in age. The bulk of the lavas is not exposed. The core of the mountain may be as old as Pliocene.

PREHISTORIC MEMBER OF THE HUALALAI VOLCANIC SERIES

The lavas cover about 310 square miles of the northwestern part of Hawaii (pl. 1). They resemble the lavas of Mauna Loa in

---

[33] Powers, H. A., Ripperton, J. C., and Goto, Y. B., Survey of the physical features that affect the agriculture of the Kona District of Hawaii: Hawaii Agr. Expt. Sta., Bull. 66, 29 pp., 1932.

[34] Powers, H. A., Hualalai: Volcano Letter, no. 347, pp. 1–3, Aug. 20, 1931.

Opposite page, top: Plate 44A. Looking southwest from Ahumoa cone to Hualalai Volcano. Photo by G. A. Macdonald.

Middle: Plate 44B. Tumulus in a prehistoric pahoehoe lava flow from Hualalai Volcano near Kaupulehu, North Kona District. Photo by H. T. Stearns.

Bottom: Plate 44C. Puu Waawaa, a trachyte pumice cone corrugated by erosion. Kona District. Photo by R. J. Baker.

outward appearance and thickness, but some are dissimilar in that they carry prominent pyroxene as well as olivine phenocrysts. The pyroxenes indicate more advanced crystallization in the magma reservoir. Several flows of basaltic andesite have been found, and one of andesite lies near the forest cabin at Puu Laalaau. Both aa and pahoehoe are abundant, the flows averaging 20 feet in thickness. Large tumuli are present on pahoehoe flows near the coast (pl. 44B.) Kimble[35] found that the weight of the lavas in the Kona District ranged from 75 to 207 pounds per cubic foot.

A thick black aa lava flow enters the sea just north of Keauhou on the southwestern coast. It issued from Waha Pele and an unnamed cone 1½ miles to the northeast of it. The flow is 12 miles long and in places 2½ miles wide. Judging from its unweathered appearance, it probably issued about 250 years ago. South of this flow the flows from Mauna Loa and Hualalai cannot be distinguished with certainty; hence, this flow is shown on plate 1 as the southern boundary of the Hualalai lavas. The 1859 lava flow from Mauna Loa is shown as the northern and eastern boundaries of the Hualalai lavas. It is probable that some outcrops of Hualalai lavas lie east of this flow, but they have not been identified with certainty.

The lava flows are highly permeable but carry brackish water only along the coast.

About 120 cinder, spatter, and lava cones lie on Hualalai at the source of the flows (fig. 17). Some of the cinder cones reach a height of 300 feet but most are 100 to 200 feet high. They contain a good deal of spatter, like those of Mauna Loa. They are notably smaller than those on Mauna Kea and Kohala Mountain, and only small quantities of vitric ash were produced when they formed (pl. 43A). Cones are far more abundant about the summit of Hualalai than on Mauna Loa, and the profile is steepened by them (fig. 4). This does not mean necessarily that cinder and spatter cones formed more commonly on Hualalai than in the Mokuaweoweo Caldera. Each eruption in the caldera builds cones, but the flows soon bury the cones, as the lava pools in the caldera and is not free to run down the mountain. Also, progressive sinking of the caldera floor carries the cones downward out of sight. If a caldera ever existed on the summit of Hualalai it has been completely buried by the later volcanics. Hualalai is close to extinction but is not necessarily extinct. The 1801 flow and several black prehistoric flows show that the time interval between eruptions is probably several hundred years instead of 2 to 4 years as at Mauna Loa.

---

[35] Kimble, H., North and South Kona, Hawaii, water investigation: Hawaii Div. Hydrography, Spec. Rept., p. 5, 1915.

Numerous craters, mostly small and deep, pockmark the upper part of Hualalai. Many of the craters indent lava and spatter cones and are not pit craters. These depressions led Pickering[36] to compare the surface of Hualalai with that of the moon. The so-called Bottomless Pit near the top, first reported to be 1,400 feet deep,[37] was found to be only 194 feet deep.[38]

An unnamed crater 4¼ miles S. 65° E. from the summit has a veneer of lava on its walls a few inches to 2 feet thick and has a distinct well-shaped sinkhole near the bottom (fig. 28). The veneer was formed by lava welling up in an ancient crater, overflowing the rim and, while still very liquid, being drained off through a vent lower on the mountain. Such veneers commonly fall from the walls leaving no evidence that the lava on the rim came from the crater. Where the veneer is missing in this crater, two dikes trending N. 40° W. are exposed. They terminate in a cave near the rim. A third dike fills a wall crack. This crater like many others on Hualalai has been cut by fissures of later eruptions; hence, it contains lava of several ages.

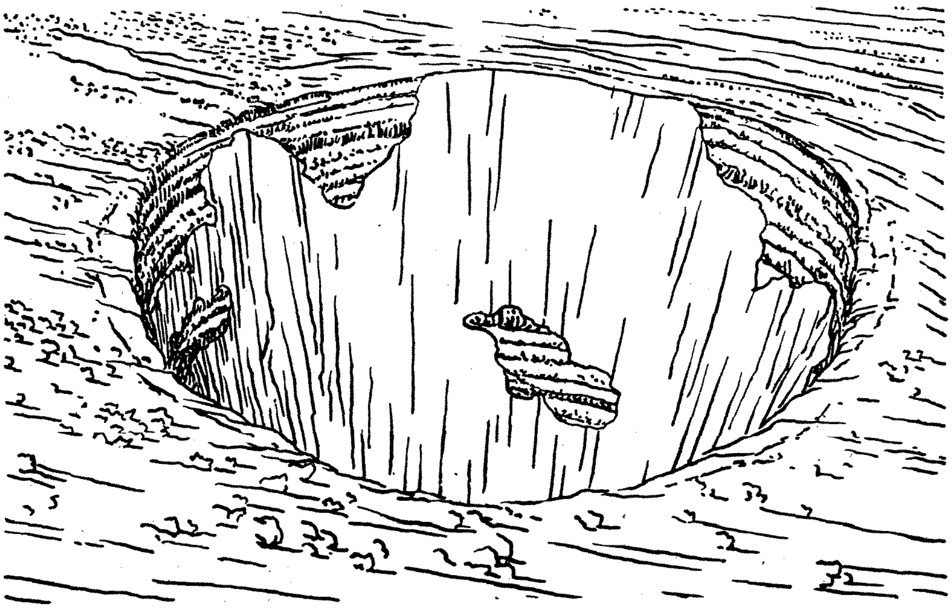


Figure 28. Sketch of pit crater with remnants of lava veneer on its walls in the southeast rift zone of Hualalai Volcano.

Collapse has shattered about half a square mile of aa around an unnamed cone near the saddle between Hualalai and Mauna Loa, 1¼ miles northeast of Puu Ikaaka. The fault scarps are mostly 5 to 15 feet high and are distinctly concentric near this cone.

---

[36] Pickering, W. H., op. cit.

[37] Hitchcock, C. H., Hawaii and its volcanoes, p. 159, Honolulu, 1909.

[38] Thurston, L. A., On the "bottomless pit" of Hualalai: Hawaiian Ann. for 1916, p. 139, 1915.

Shallow collapse of this sort is unusual in Hawaii except at Kilauea.

The geologic assignment of three cinder cones on the northwestern slope of Mauna Loa, the largest of which is Puu Lehua, is uncertain. They are shown on plate 1 as Mauna Loa cones because they are elongated in the direction of a Mauna Loa radial fissure. They may belong to the Hualalai volcanic series.

No littoral cones exist along the coast of Hualalai, probably because they are destroyed so quickly by erosion after they form. Some beaches contain considerable volcanic glass sand indicative of littoral explosions.

Much of the summit area and the Kona slope of Hualalai are covered with loose cinders and pumice from adjacent cones. The depth of the pumice averages about 1½ feet, but is very irregular, partly because of subsequent movement by torrential rains. An extensive field of coarse cindery pumice, deposited by lava fountains along the southeastern rift of Hualalai, covers the Mauna Loa-Hualalai saddle and the slope farther north. The larger areas of pyroclastics on Hualalai are distinguished on plate 1. The cindery pumice averages about 2 feet in depth. Much of the coffee produced on the island is grown on the older lava flows of Hualalai, which, between Kailua and Keauhou, are covered with ½ to 2 feet of ashy soil. The distribution of the ash on the slopes below 5,000 feet in this area has been mapped[39] in detail by Powers who concludes, "All the Hualalai ash beds increase in thickness and also in coarseness of material toward the large source cones on the top of the mountain."

The depth of the ash increases with the length of time a flow remains uncovered by later lavas, indicating that the ash accumulates slowly, being carried by the wind from numerous lava fountains accompanying eruptions rather than from any single explosion. The ash deposits are all vitric, mostly palagonitized, but even the ones interbedded with lava flows are scarcely compacted enough to be called tuff.

Two beds of vitric ash separated by lava flows are exposed in a small pit crater 100 feet deep on the north rift above the uppermost vent of the lava flow of 1801. Beds of interstratified ash a few inches to 18 inches thick are exposed in several places along the coast and in road cuts, but they are too small to show on plate 1.

Wentworth has named this series of ash beds, including those on the adjacent slopes of Mauna Loa, the Kona tuff formation.[40]

---

[39] Powers, H. A., Ripperton, J. C., and Goto, Y. B., op. cit., soil map.

[40] Wentworth, C. K., Ash formations of the Island Hawaii: Hawaiian Volc. Res. Assoc., 3d Spec. Rept., pp. 90–91, 1938.

The ash beds were derived chiefly from the cinder cones of the Hualalai volcanic series and are not named herein.

Evidence was found of only one paroxysmal explosion on the entire mountain. Scattered accessory blocks, already described by Daly,[41] lie about the summit. They are fragments of basalt containing phenocrysts of either feldspar, olivine, or olivine and augite. They are all angular and range from 2 inches to 2 feet across. They indicate a weak explosion, probably phreatic, which was the most recent eruptive event at the summit.

WAAWAA VOLCANICS.—The Waawaa volcanics, the trachyte member of the Hualalai volcanic series, consist of a trachyte flow and its source cone. They are named from the cone which is called Puu Waawaa.[42] The flow and cone lie on the northern slope of Hualalai (pl. 1).

The top of the cone rises 3,971 feet above sea level, and is 1,300 feet above the lava fields to the northwest and 460 feet above those to the south. The cone is horseshoe-shaped, its breached crater opening to the southeast. The slopes are fluted with gullies possibly originating from landslides soon after the cone was formed and only subsequently enlarged by stream erosion (pl. 44C). It is composed of bedded large and small gray pumice and obsidian fragments typical of large trachytic pumice cones elsewhere in the world. An analysis of the obsidian is given on page 205. Scrapers, chipped from this obsidian, were found in burial caves near Kaupulehu. The cone, which lies in the midst of the northern rift zone of Hualalai, is entirely surrounded with basaltic lavas from that rift. On the southwestern and northern slopes of Puu Waawaa are small basaltic spatter cones which erupted through the trachyte cone. The basaltic spatter from these cones lies upon weathered trachyte pumice and pumiceous alluvium indicating that they are much later than Puu Waawaa. Bulky alluvial fans of pumice lie at the foot of the cone and probably interfinger with and bury the later basalts.

No exposures exist to show the relation of the cone to its flow, but it appears geomorphically to have been built during the early days of the eruption and before much of the lava was extruded (fig. 29D). Although Puu Waawaa is a large cone as compared with basaltic cones, it is not unusually large as compared with trachytic cones elsewhere. It was built by intense frothing of viscous magma, but it was not paroxysmally explosive as no crater was blasted in the pre-existing terrane.

The cone is highly permeable but carries no water.

The trachyte flow from Puu Waawaa extends 6 miles to the

---

[41] Daly, R. A., op. cit.

[42] Wentworth, C. K., 3d Spec. Rept., Hawaiian Volc. Obs., pp. 35, 86, 1938; uses the name Waawaa pyroclastic materials for the material forming Puu Waawaa.

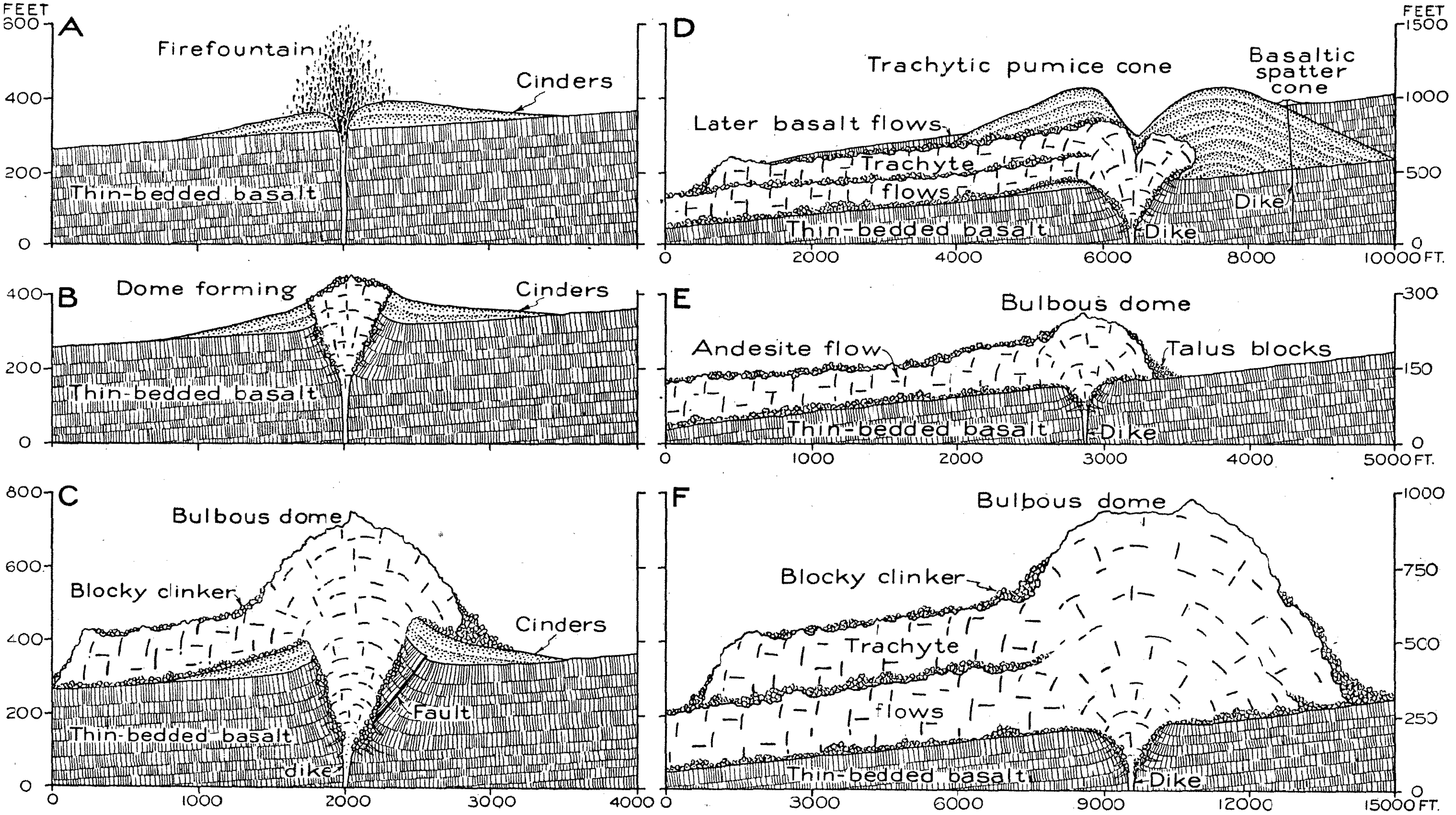


Figure 29. Sections of typical bulbous domes. A to C, formation of common bulbous dome underlain with cinders; D, Puu Waawaa; E, andesite dome and flow; F, trachyte bulbous dome on Kohala Mountain.

north. It is partly buried by later basalts from Hualalai and Mauna Loa, including the 1859 flow from the latter volcano. Excellent exposures of the weathered blocky margin under nearly vertical veneers of later basalts a foot or two thick are exposed in cuts along the highway on the western slope. The steep dips in the later basalt flows indicate that the trachyte flow terminated about three quarters of a mile farther north than the northermost exposure shown on plate 1. The flow is more than 900 feet thick, as its base is not exposed. The top of the flow is blocky and scoriaceous and grades downward into dense rock typical of such flows (pl. 45A). Crescentic flow ridges range from 10 to 50 feet in height. They increase in height toward the terminus of the flow. Terraces on its slopes indicate that it is composed of several flow units 250 to 500 feet thick. The hills on its surface, Puu Anahulu, Puu Huluhulu, and others, are typical of the hummocks formed on such thick viscous flows.

It has not been recognized previously as a lava flow because the eastern and terminal margins are buried completely by about 1,000 feet of basalt. Also it is separated from Puu Waawaa by a mile of veneering basalt. Stage A in figure 30 shows the flow at the time of its eruption and stage B shows it at the present time.

The barrier formed by the lava flow has shunted later flows to the northeast, thereby causing the area to the northwest to remain relatively unfilled so that there is now a broad swale whose surface is 500 to 900 feet lower than the adjacent country.

The cone and the flow show considerable weathering. Fine-grained Pahala ash, chiefly from Mauna Kea cones, and residual soil cover much of the surface to a depth of a foot or more, forming fertile farm land. The degree of weathering and the coating of Pahala ash indicate that it is pre-Wisconsin in age. Because of the chemical affinity of the trachyte to flows on Kohala, one is tempted to consider the magma reservoir of Kohala Mountain as the source of the Waawaa volcanics, and their eruption on Hualalai as an accident. However, the vent lies within the northern rift zone of Hualalai, along which basaltic flows have been erupted for centuries, both before and after the trachyte flow. It appears probable, therefore, that the trachyte was formed in a local magma reservoir related to Hualalai Volcano. The 400-foot trachyte flow in the Waianae Range, Oahu, is overlain and underlain by basalts,[43] which confirms the fact that trachytes can be

---

[43] Macdonald, G. A., Petrography of the Waianae Range, Oahu: Hawaii Div. Hydrography, Bull. 5, p. 81, 1940.

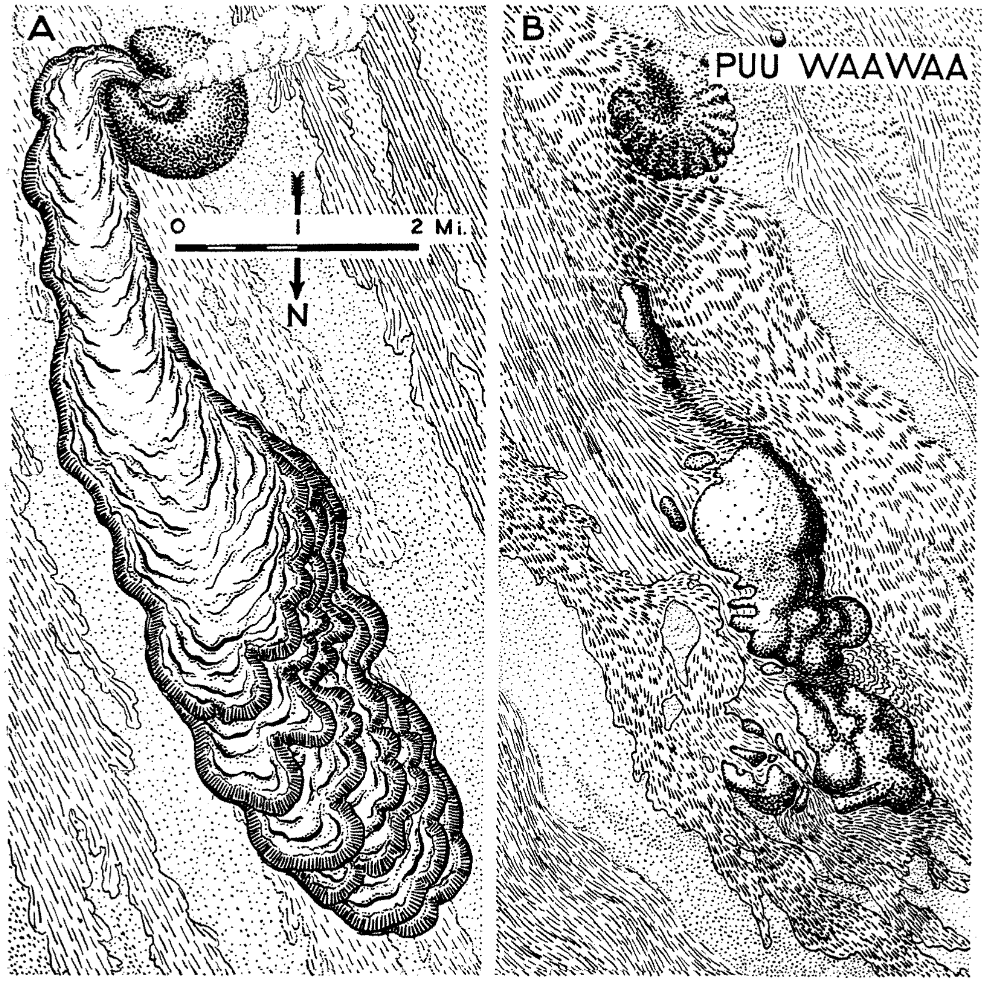


Figure 30. Puu Waawaa pumice cone and massive trachyte lava flow at close of the eruption lying on thin basalt flows, A; present stage showing cone eroded and lava flow weathered and nearly buried by later basalt flows, B.

erupted during basaltic volcanism in the Pacific volcanoes. Daly[44] found a similar relationship in Ascension Island.

The flow has low permeability and carries no water.

HISTORIC MEMBER OF THE HUALALAI VOLCANIC SERIES

Hualalai was last active in 1800-1801, when voluminous lava flows were poured from several stretches of a long crack on the northwestern flank.[45] The main vent of the flows lies between

---

[44] Daly, R. A., The geology of Ascension Island: Am. Acad. Arts Sci. Proc., vol. 60, no. 1, p. 68, June 1925.

[45] In a personal communication dated January 14, 1938, Dr. T. A. Jaggar states that "Miss Paris says natives told her father the Kaupulehu flow was the first (1800) and higher, and the Huehue flow was the second (1801) and lower flow." Miss Ella Paris lives in Kona. Mrs. John Maguire, 80-year-old owner of the Maguire Ranch in Kona, when interviewed in 1931, said that, so far as she knew, the Kaupulehu flow was poured out in 1801 and that Mr. Young visited it and told Reverend William Ellis about it in 1823. The eruption may have been like some on Mauna Loa that break out late in the year and continue several months into the next year. Persons remember the date as either of the two years. It is shown as 1800–1801 on plate 1.

5,500 and 6,000 feet above sea level. It is an old fissure vent thinly veneered with 1801 lava. Several lava rivers flowed seaward from this vent to form the Kaupulehu flow. This flow contains many thousands of angular and subangular xenoliths of dunite and gabbro mostly under a foot in diameter. Some of the xenoliths formed spheroidal masses which lie loose on the top of the clinkery surface of the flow. Their angularity has been smoothed by a coating of 1801 lava. Feldspar crystals reaching three-quarters of an inch across, some of gem quality, are found in the Kaupulehu flow also. Around one of its source vents, xenoliths, a fraction of an inch to several inches across with a coating of black 1801 lava, are piled up like cobbles. The dunite xenoliths look like green candies dipped in chocolate. Apparently the magma stoped away a large precooled mass of dunite and gabbro before eruption.

The flow is notable also for its numerous accretionary lava balls, its aa channels in places 30 feet deep, the remarkable lava stalactites, and the brown, red, and black spatter bordering the channels (pl. 45B). In places the levees of the channels touched at the top, forming natural bridges. In other places the levees slumped while the lava was flowing between them, probably because of a drop in the level of the lava river. The gaping slump cracks subsequently were bridged by spatter from the splashing torrent of molten lava.

Just above the main vent of the Kaupulehu flow is a pit crater 150 feet deep and 200 feet across with dribbles of 1801 lava on its western wall.

Powers[46] states that the flow overwhelmed Paiea fishpond and Hawaiian villages at the shore. One can see today partly buried native house foundations covered with sea sand and shells along the margin of the flow near the beach. Sea sand is buried by the flow for a quarter of a mile from shore. Scattered over the pahoehoe at the beach are clots of lava indicating an occasional mild explosion. Such clots have not been reported in Hawaii before and probably resulted from steam explosions due to the lava burying saturated sand and the ancient fishpond. A few of the bombs dropped by the Army on the 1935 lava flow of Mauna Loa threw out similar clots when they exploded after breaking through the pahoehoe crust.

Three small pahoehoe flows, each about 100 yards long, issued from vents between altitudes of 2,400 and 4,000 feet.[47] At an altitude of 6,050 feet, and separated from the main vent of the Kaupulehu flow, are three short flows and a lava lake congealed

---

[46] Powers, Sidney, op. cit., p. 267.
[47] Idem.

in a prehistoric crater. The fresh black color makes it certain that the flows and the lake were formed in 1801. After a short existence the lake level fell about 6 feet, the lava being partially drained out at a lower elevation, and a pronounced rampart similar to the rim of the former lava lake of Halemaumau was left (pl. 45C). A description which fits this crater is given by Jaggar[48] who points out that such lakes and ramparts are rarely preserved, as collapse concurrent with draining usually destroys them.

During the mapping, a hitherto unrecorded branch of the Kaupulehu flow was found on the western slope, its lower end extending into the forest. It offers a striking example of the effect of rainfall on the growth of vegetation. The branch on the dry slope is plainly traceable after 140 years, but the one on the wet slope half a mile away is hidden by vegetation.

A line of 14 spatter cones ranging in height from 5 to 70 feet lies below the main highway (pl. 43B). The cones were the source of a flow, pahoehoe near the cones and aa below, which was erupted shortly after the Kaupulehu flow. It is called the Huehue flow. It is an olivine basalt and contains pieces of partly charred wood in its tree molds, as does the Kaupulehu flow. Some of the charcoal contains lava glass in the checks.

The 1800-1801 lavas are permeable but do not carry potable water.

STRUCTURE OF HUALALAI

Lines of cones and fissure vents delineate three rift zones intersecting at the summit of the mountain. They trend N. 60° W., N. 20° E., and S. 40° E. (fig. 6). The north rift is of least importance, as shown by the small amount of bulge in the dome in

---

[48] Jaggar, T. A., op. cit., p. 188.

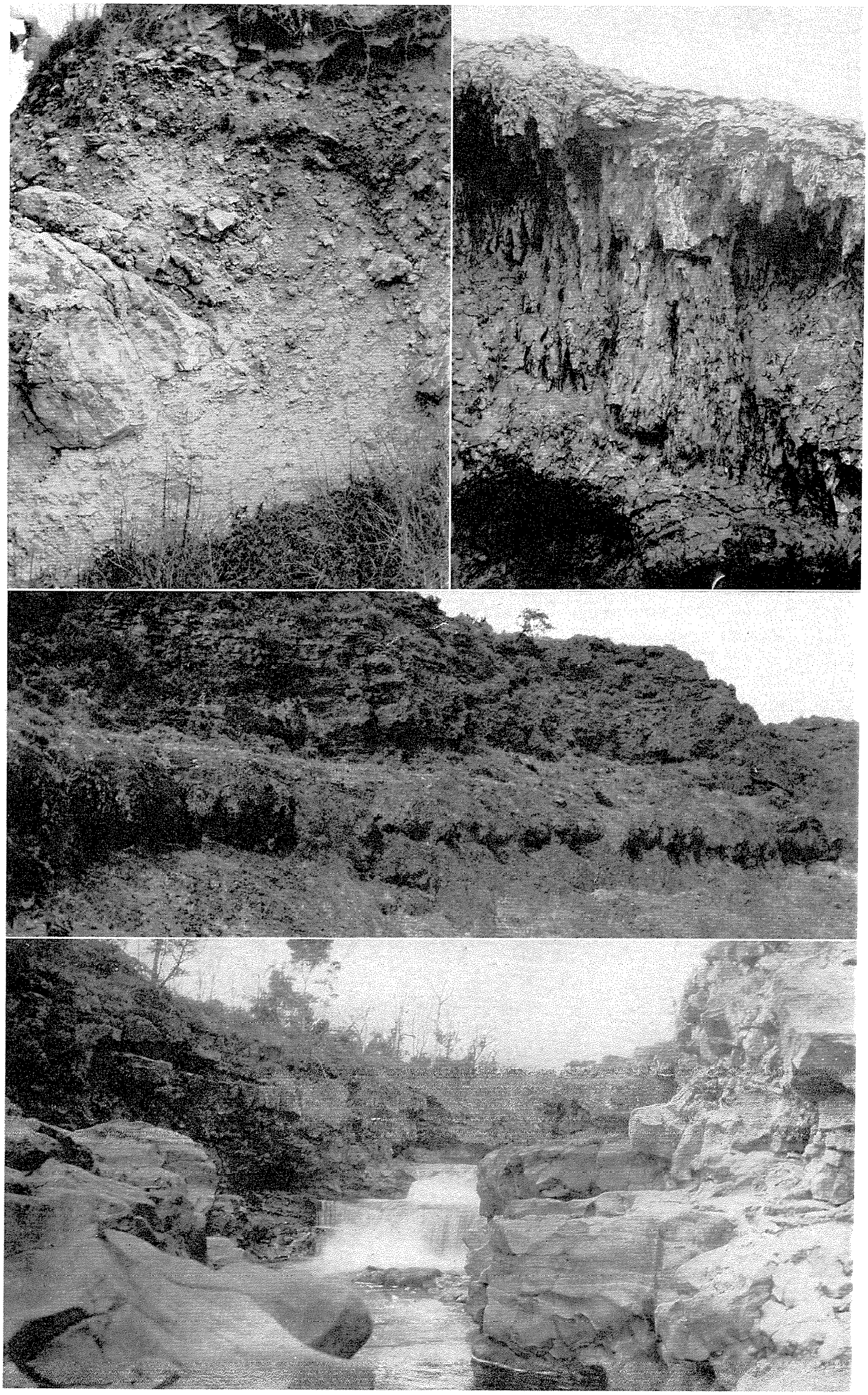
⟶

Opposite page, top left: Plate 45A. Weathered blocky top of the Waawaa trachyte flow on the north side of the main highway, Kona District. Photo by H. T. Stearns.

Top right: Plate 45B. Lava spatter and stalactites on the wall of the lava channel in the Kaupulehu flow of 1800-1801 from Hualalai Volcano. Photo by H. T. Stearns.

Middle: Plate 45C. Congealed shore line of a lava lake formed in 1800-1801 in a prehistoric crater on Hualalai Volcano. Photo by H. T. Stearns.

Bottom: Plate 45D. Wailuku River just above Pukamaui, showing flow units and internal structure of thin-bedded pahoehoe. Photo by M. H. Carson.



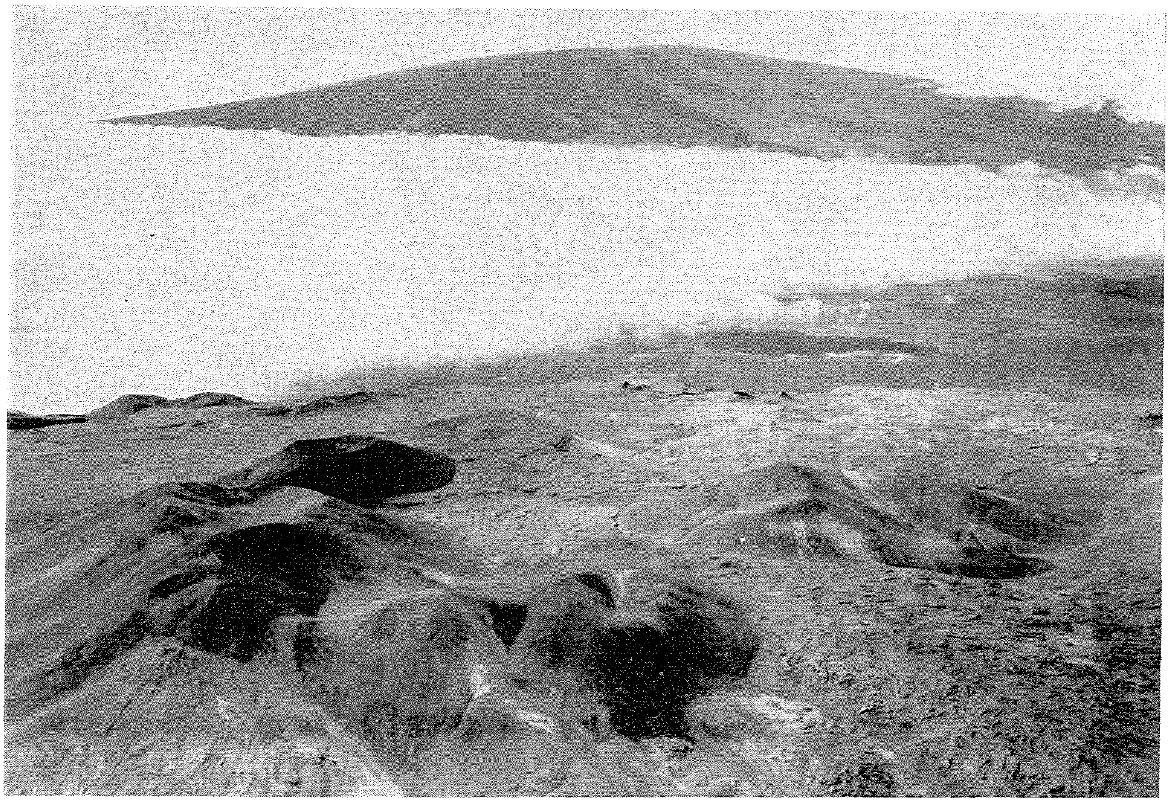
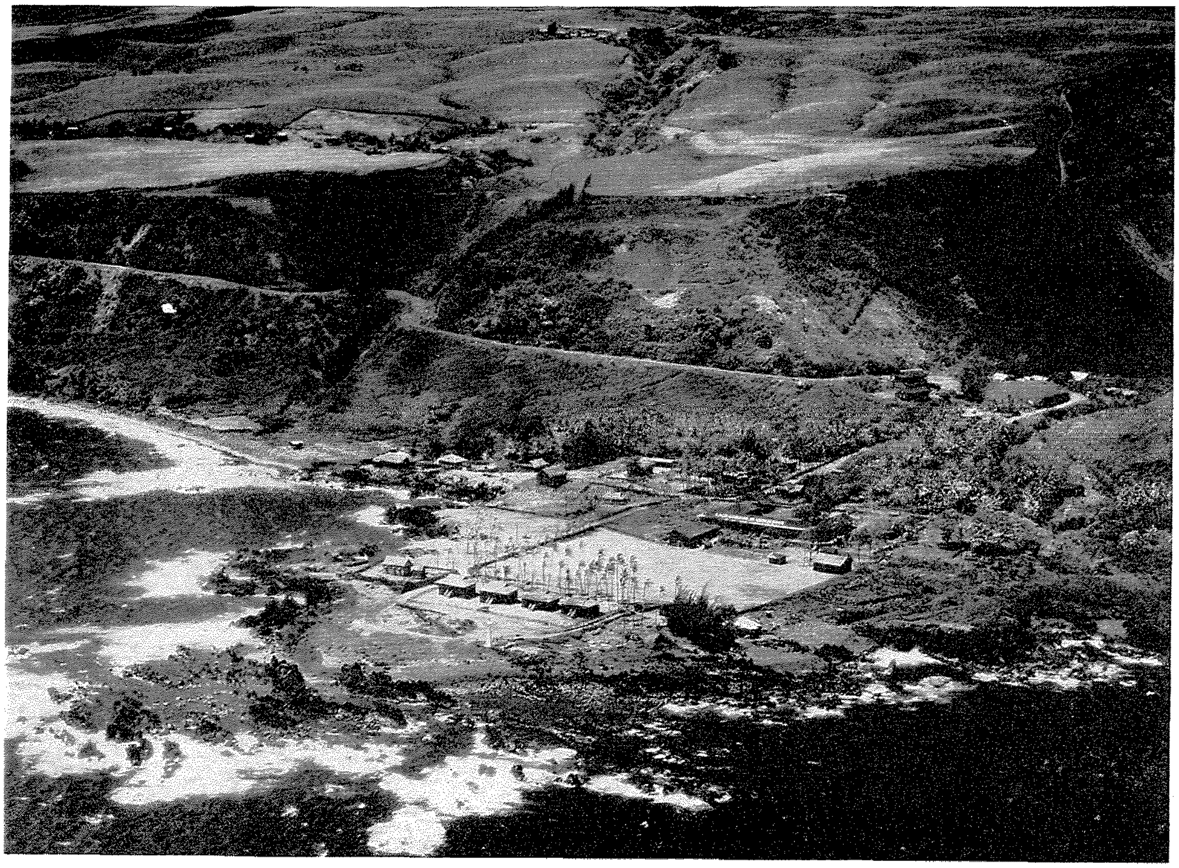


Plate 46A. View of the northeast slope of Mauna Loa Volcano. The Humuula Saddle lies under the clouds and in the foreground are andesitic cinder cones of the Laupahoehoe volcanic series on Mauna Kea. Photo by USAAF.

Plate 46B. Laupahoehoe Peninsula, a lava delta built at the mouth of Laupahoehoe Gulch by a late flow of the lower member of the Laupahoehoe volcanic series. Exposed in the cliffs are rocks of the Hamakua volcanic series. Photo by Hawaiian Airlines, Ltd.



that direction and by fewer vents. The northwest rift appears to have poured out more lava than the southeast rift, but that may be more apparent than real, as many of the southeast rift cones and flows may be buried under flows of Mauna Loa. The overlap with Mauna Loa causes the egg shape of Hualalai.

The internal structure of Hualalai is not exposed but presumably it is a typical shield-shaped dome of primitive lavas cut by three dike complexes. No faults are known on Hualalai except those bounding small pit craters, those involved in the collapse of a cinder cone, and minor displacements along fissures in the rift zones. The lavas have unusually steep slopes about a mile inland from Keahole Point. Steep terminal margins of flows, ancient sea cliffs, or faults, smoothed by later flows, may be the cause of the steep slopes, some of which are 100 feet high.

A few re-entrants in the slope inland from Huehue Ranch house may indicate former valleys deeply buried by lava flows, or they may be re-entrants developed by lava burying a rough terrane of cones.

If fault scarps, subsequently veneered with lava, caused the steep western coast of Mauna Loa, the point of intersection of the faults with the Western Fundamental Fissure of the Hawaiian Archipelago would be directly under the summit of Hualalai. If this is true, it may be more than a coincidence that both Hualalai and Kilauea were formed at the intersections of Mauna Loa faults with the Eastern and Western Fundamental Fissures.

GEOLOGY OF MAUNA KEA

PREVIOUS INVESTIGATIONS

Mauna Kea has been studied in regard to certain special features by several earlier investigators, but this is the first report of the geology of the entire mountain. The first recorded ascent of Mauna Kea was in 1823 by the Reverend Joseph Goodrich, who again climbed the mountain in 1832. Goodrich described what he termed "fragments of granite" embedded in lava,[49] which probably were the inclusions of gabbro quite common in the later cones of Mauna Kea. James Macrae, botanist attached to the British warship *Blonde,* commanded by Lord Byron, climbed Mauna Kea in 1825, recording his observations in his diary.[50] David Douglas, exploring botanist, climbed Mauna Kea in 1834,[51] and shortly afterward met a tragic death in a wild bull pit on the eastern flank of the mountain. Charles Pickering and W. D. Brackenridge, of the United States Exploring Expedition under the command of Lieutenant Charles Wilkes, U. S. N., climbed Mauna Kea in 1841.[52] All of these early explorers briefly describe some of the general volcanic features of the mountain, but none of them were trained geologists, and the accounts are too vague to furnish much geological information.

C. E. Dutton was the first trained geologist to examine Mauna Kea. During 1882 he ascended the mountain from Humuula Saddle, and spent a few hours in the summit region. He noted the lighter color and lesser vesicularity of the lavas of the summit region as compared with many of those at lower altitudes, and recognized the work of frost and ice in splitting apart many of the exposed rocks.[53] E. D. Baldwin, in 1889, also recorded the difference between the lavas of the summit region and those typical of the lower slopes. He described the mountain as covered mostly with aa flows and "sand" cones.[54] Hitchcock climbed Mauna Kea in 1886, but his observations were not published until 1909. He

---

[49] Goodrich, Joseph, (On the volcanic character of the island of Hawaii) : Am. Jour. Sci., vol. 16, pp. 345–347, 1829 ; . . . volcanoes and volcanic phenomena of Hawaii (Owyhee) : Am. Jour. Sci., vol. 25, pp. 199–203, 1833.

[50] Wilson, W. F., With Lord Byron at the Sandwich Islands in 1825, being extracts from the diary of James Macrae, 75 pp., Honolulu, 1922.

[51] Wilson, W. F., David Douglas, botanist at Hawaii, 83 pp., Honolulu, 1919.

[52] Wilkes, Charles, U. S. Exploring expedition during the years 1838–1842, Narrative, vol. 4, pp. 202–203, New York, 1845.

[53] Dutton, C. E., Hawaiian volcanoes : U. S. Geol. Survey 4th Ann. Rept., pp. 161–164, 1884.

[54] Baldwin, E. D., A trip to the summit of Mauna Kea : Hawaiian Annual for 1890, pp. 54–58, 1889.

cited the erosional valleys about the base of Mauna Kea as evidence of its greater age as compared to Mauna Loa. Bombs from the summit cones containing cores of dunite ("solid olivine") were described.[55] Daly climbed the southern slope of Mauna Kea in 1909, and was the first to recognize evidence of a former glacier.[56] He also recognized the andesitic nature of the lavas of the upper part of the cone, and suggested that the mountain consists of basalt below an altitude of 3,500 meters, and of andesitic basalt and trachydolerite above that level.[57] Bryan described the general features of the mountain, and concluded that because the numerous large gulches are restricted to the lower part of the mountain, volcanic activity must have survived longer on the upper slopes.[58] In 1925 T. A. Jaggar visited the southern slope and summit region of Mauna Kea, confirming Daly's conclusion of the former presence of a glacier, and calling attention to the large alluvial fans at the southern base of the mountain.[59]

A more detailed description of the glaciation of Mauna Kea was published by Gregory and Wentworth in 1937,[60] and in 1941 Wentworth and Powers described what they believed to be the deposits of four separate stages of glaciation.[61] Two of these have been shown by recent work to be explosion deposits, and the third to consist of torrential fanglomerates probably deposited by floods released by volcanic melting of the icecap.[62] Other related features also have been described by Wentworth and Powers.[63]

Contributions to the knowledge of the petrography of Mauna Kea have been made by Cohen, Merrill, Daly, Cross, and Washington.[64] Sidney Powers mistakenly believed that the lava flow which forms the Laupahoehoe peninsula issued from fissures near

---

[55] Hitchcock, C. H., Hawaii and its volcanoes, pp. 50–54, Honolulu, 1909.

[56] Daly, R. A., Pleistocene glaciation and the coral reef problem: Am. Jour. Sci., 4th ser., vol. 30, pp. 297–308, 1910.

[57] Daly, R. A., The nature of volcanic action: Am. Acad. Arts Sci. Proc., vol. 47, pp. 103–105, 1911.

[58] Bryan, W. A., Natural history of Hawaii, p. 151, Honolulu, 1915.

[59] Jaggar, T. A., Geological notes on Mauna Kea: Hawaiian Volc. Obs. Bull., vol. 13, pp. 75–77, 1925; The Daly glacier on Mauna Kea: Volcano Letter, no. 43, Oct. 22, 1925.

[60] Gregory, H. E., and Wentworth, C. K., General features and glacial geology of Mauna Kea, Hawaii: Geol. Soc. America Bull., vol. 48, pp. 1719–1742, 1937.

[61] Wentworth, C. K., and Powers, W. E., Multiple glaciation of Mauna Kea, Hawaii: Geol. Soc. America Bull., vol. 52, pp. 1193–1218, 1941.

[62] Stearns, H. T., Glaciation of Mauna Kea, Hawaii: Geol. Soc., America Bull., vol. 56, pp. 267–274, 1945.

[63] Wentworth, C. K., Ablation of snow under the vertical sun in Hawaii: Am. Jour. Sci., vol. 238, pp. 112–116, 1940. Wentworth, C. K., and Powers, W. E., Glacial springs on the island of Hawaii: Jour. Geology, vol. 51, no. 8, pp. 542–547, 1943.

[64] Cohen, E., Ueber Laven von Hawaii: Neues Jahrb., 1880, Band 2, pp. 23–62. Merrill, G. P., in Preston, E. D., Determination of latitude, gravitation, and magnetic elements at stations in the Hawaiian Islands, etc.: U. S. Coast and Geodetic Survey, Ann. Rept., pt. 2, appendix 12, pp. 630–632, 1893. Daly, R. A., Magmatic differentiation in Hawaii: Jour. Geology, vol. 19, pp. 297–303, 1911. Cross, Whitman, Lavas of Hawaii and their relations: U. S. Geol. Survey Prof. Paper 88, pp. 36–38, 1915. Washington, H. S., Petrology of the Hawaiian Islands; I. Kohala and Mauna Kea, Hawaii: Am. Jour. Sci., 5th ser., vol. 5, pp. 487–502, 1923.

the mouth of the valley.[65] Wentworth has described the pyroclastic rocks of Mauna Kea.[66]

ROCKS OF MAUNA KEA AND THEIR WATER-BEARING PROPERTIES

The rocks of Mauna Kea are largely volcanic. Only minor amounts of sedimentary rock are present. The largest alluvial terraces, fans and valley fills are shown on plate 1, but other similar deposits and areas of shifting fluviatile gravels which partly cover the beds of most of the streams are too small to show on the map. Glacial debris occurs on the upper part of the mountain (pl. 1). The great bulk of the mountain, however, consists of lava flows, with associated cinder cones and ash beds. The volcanic rocks of Mauna Kea are divided into two series, the general character and water-bearing properties of which are summarized in the accompanying table.

HAMAKUA VOLCANIC SERIES

Lava flows.—The Hamakua volcanic series is named for its exposures along the Hamakua coast from Hilo to Honokaa. The type section is in the southern wall of Laupahoehoe Gulch (pl. 46B), and is given in detail on page 195. It consists preponderantly of lavas, with only a minor amount of interbedded volcanic tuff. The lavas include olivine basalt, picrite-basalt, and andesite. The picrite-basalts in turn can be divided into the primitive type, containing many phenocrysts of olivine, but few or none of augite, and a type which contains abundant augite phenocrysts as well as olivine phenocrysts. The olivine basalts nearly always contain at least a few phenocrysts of olivine, and as these increase in abundance the lavas grade into picrite-basalt. The andesites typically are nonporphyritic, although a few small phenocrysts of olivine, and less commonly of augite, may be present. They are generally lighter in color than the basalts and many outcrops are characterized by platy jointing.

The greatest exposed thickness of the Hamakua volcanic series is 650 feet at Maulua Gulch. The unexposed part of the section, below sea level and beneath the upper slopes of the mountain, is many thousands of feet thick.

Pahoehoe and aa flows are present in approximately equal abundance among the olivine basalts and picrite-basalts. The flows of

---

[65] Powers, Sidney, Notes on Hawaiian petrology: Am. Jour. Sci., 4th ser., vol. 50, p. 266, 1920.

[66] Wentworth, C. K., Ash formations of the Island Hawaii: Hawaiian Volc. Obs., 3d Spec. Rept., pp. 72–86, 143–145, 1938.

Stratigraphic section of Mauna Kea

Major geologic unit	Rock assemblage	Maximum thickness (feet)	Symbol on map (pl. 1)	General character	Water-bearing properties
Recent sedimentary rocks	Fluvial gravel deposits	100±	Qa	Moderately well bedded, poorly consolidated and poorly sorted gravels deposited as alluvial fans and aprons along the southern base of Mauna Kea, and as shifting bars along the present streams.	Poorly permeable as a whole, although some better sorted gravel beds probably carry water.
Recent volcanic rocks	Upper member of the Laupahoehoe volcanic series	250±	Rkc	Cinder cones at the source of lava flows.	Highly permeable, but do not yield ground water.
		50±	Rkl	A few small aa flows of andesite.	Moderately permeable, but cover too small an area to have an important effect on ground water. Yield no water.
Pleistocene sedimentary rocks	Fluvial, periglacial, and glacial conglomerates	100±	Qa	Poorly sorted conglomerates forming alluvial terraces in the lower parts of the large canyons, and a sheet of debris over part of the southern slope, deposited by glacial meltwater. A ridge of terminal moraine is indicated on plate 1 by a line marking its outer edge only.	Poorly to moderately permeable. Yield a little water to shallow dug wells near the coast. Some of the better sorted beds buried beneath lavas in the Humuula Saddle may contain small amounts of perched water.
Pleistocene volcanic rocks	Lower member of the Laupahoehoe volcanic series	600±	Plc	Cinder cones at the source of lava flows.	Highly permeable, but do not yield ground water.
		3,000±	Pll	Massive dense flows of andesite, and less massive and dense flows of basalt, ranging from 10 to 75 feet thick.	Moderately permeable. Carry a little water perched by beds of ash or hill wash or by the dense middle parts of aa flows.
		200±	Pld	Viscous domes.	Moderately permeable but do not yield ground water.
		75±	Pla	Thick deposits of ash overlying lava flows.	Highly permeable, but do not yield ground water.
	Pahala ash	20±		Yellow to reddish-brown friable ash, composed chiefly of palagonitzed dust- to sand-sized shards of volcanic glass and pumice lapilli, not differentiated on plate 1 from underlying lavas of the Hamakua volcanic series.	Generally less permeable than the associated lavas. Decreases ground-water recharge where it forms the surface. Where buried by lava flows, it perches a little water. Locally yields a little perched water at its base.
	Hamakua volcanic series	500±	Pmc	Cinder and spatter cones at the source of lava flows.	Highly permeable, but do not yield ground water.
		12,000+	Pml	The upper member consists of thin flows of olivine basalt, andesite, and augite-rich picrite-basalt. The lower member consists largely of olivine basalt, with occasional flows of primitive picrite-basalt.	Moderately to highly permeable. Locally a little water is perched by ash beds or the dense interior phase of aa flows. Yield basal water freely to wells and springs.

the augite-rich type of picrite-basalt tend, however, to be thicker and more massive than those of olivine basalt and primitive picrite-basalt. The andesite flows are nearly all aa. Flows of all types rarely are more than 20 feet in thickness, and generally not more than 10 feet. Most of the flow units of olivine basalt pahoehoe are between 1 and 5 feet thick. The aa layers are generally thicker than those of pahoehoe. They average 5 to 10 feet in the lower part of the section, but thicker in the upper part. Vesicularity is moderate to low in the aa flows, and moderate to high in the typical pahoehoe flows, although parts of some of the thicker pahoehoe flows are quite dense. Aa beds consist typically of a central massive portion, overlain and in most places underlain by clinker members. The lower clinker member, where present, is generally thinner than the upper. Locally the middle massive member pinches out and the entire thickness of the flow consists of clinker. Lenses of clinker may occur within the massive central phase. The proportion of clinker in an aa flow is generally between 20 and 50 per cent.[66a]

The Hamakua volcanic series can be separated into two members. The lower member consists very largely of olivine basalt with less abundant primitive picrite-basalt. The upper member also consists largely of olivine basalt, but associated with it are andesites and picrite-basalts of the augite-rich type. The andesites and picrite-basalts increase in abundance upward in the upper member. The contact between the two members is gradational, and although in some places their separation is fairly sharp and has been mapped in the field, in other places the contact is indefinite. Moreover, it is not everywhere at precisely the same stratigraphic level. Because of these facts, together with the lack, in some areas, of exposures sufficiently continuous for satisfactory mapping of the contact, the two members have not been mapped separately on plate 1, although they are shown separately in figure 31 for the area between Paauilo and Hilo.

PYROCLASTIC ROCKS.—Many tuff beds, from less than an inch to 10 inches thick, are intercalated with the lavas along the Hamakua coast. They vary rapidly in thickness laterally and in many places lens out, their thickness being largely determined by the irregularities in the top of the underlying lava flow. All are composed of vitric ejecta, although some also contain scattered crystals of olivine, augite, and feldspar. They are vitric or vitric-crystal tuffs formed by lava fountains at the sources of the flows. No accessory or accidental rock material has been found in them. All the tuff

---

[66a] Macdonald, G. A., Structure of aa lava flows: Geol. Soc. America Bull., vol. 56, pp. 1179–1180, 1945.

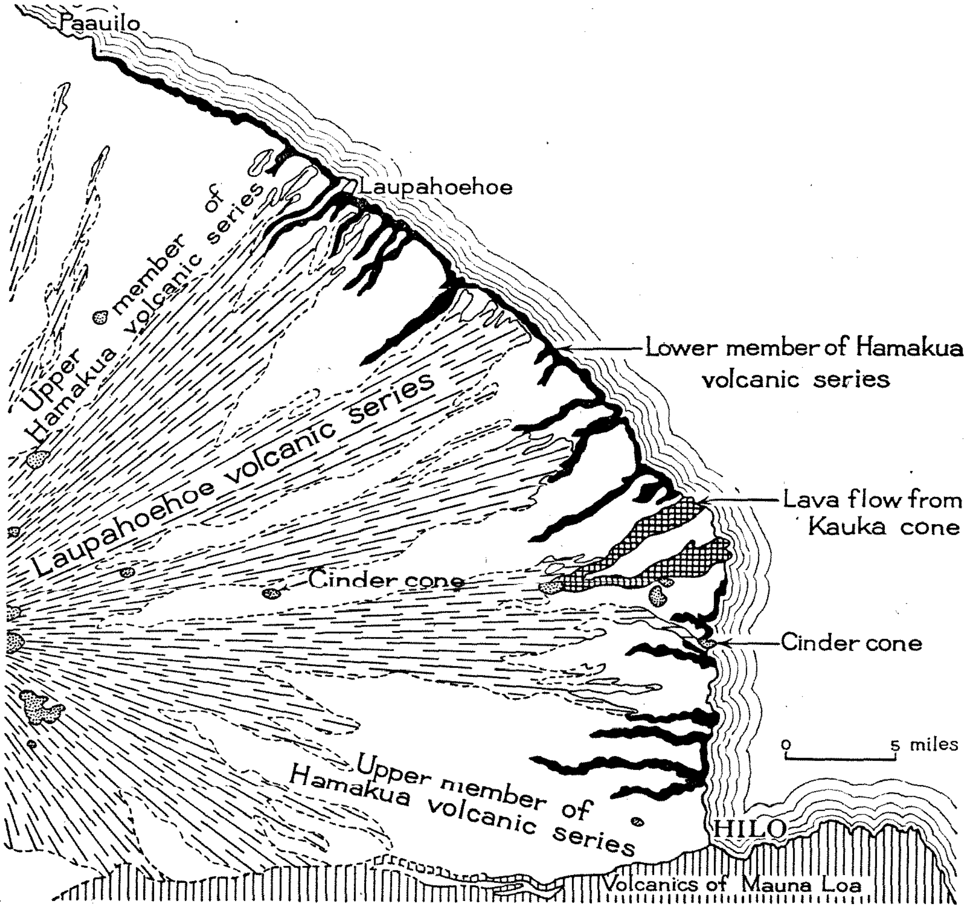


Figure 31. Geologic map of the eastern slope of Mauna Kea, showing the upper and lower members of the Hamakua volcanic series. The lava flow from Kauku cone, one of the late flows in the upper member, is mapped separately.

beds now appear to be fine grained, but extensive decomposition and compaction may have destroyed larger pumice lapilli originally present. The tuff is everywhere partly or entirely altered to yellowish-brown or reddish-brown earthy palagonite.

Deposits of explosion breccia as much as 90 feet thick are exposed at an altitude of approximately 10,000 feet in Pohakuloa and Waikahalulu gulches, and in a small gulch 0.25 mile east of Pohakuloa Gulch.[67] They consist largely of accessory blocks of lava in a matrix of vitric-crystal ash. The blocks are fresh, but have surfaces more or less powdered and abraded by collision during flight (pl. 47A). The deposits are moderately well bedded (pl. 47B) and show a fair degree of sorting, cobbles and boulders up to 2 feet in diameter being abundant in some beds but absent in others. Beds of lapilli, typical of many lithic explosion de-

---

[67] Stearns, H. T., op. cit.

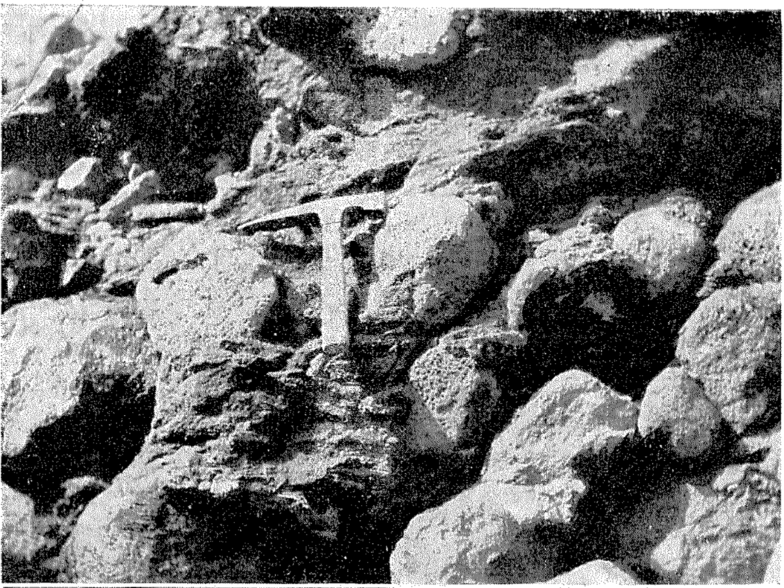
posits, are found also. The beds dip southward and southwestward at an angle averaging about 30 degrees. In Waikahalulu Gulch, they rest on a buried cinder cone, but probably are not genetically related to the cone. In the small gulch a quarter of a mile east or Pohakuloa Gulch the explosion breccias are overlain unconformably by stream gravels derived from the explosion deposits (pl. 47). At the Waikahalulu Gulch locality the blocks are all olivine basalt, but in the more westerly gulches many blocks of augite-rich picrite-basalt are present also, indicating that at least two explosions occurred. If similar unexposed deposits occur at lower levels, they may in large part account for the steeper slopes of the portion of the mountain between 7,000 and 12,000 feet altitude (pl. 48A and section C-C′, pl. 1).

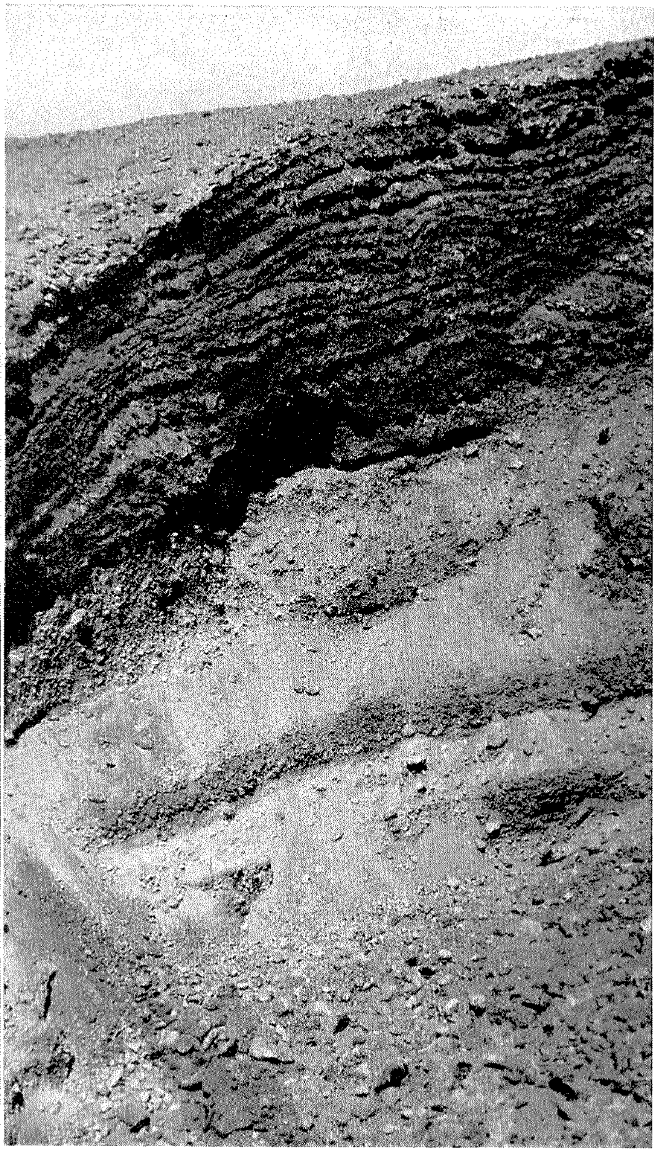
Cinder and spatter cones belonging to the Hamakua volcanic series are numerous on the lower slopes of the volcano. They range from 25 to 300 feet in height, and from a few tens of feet to half a mile across. The later ejecta commonly were more spattery than the earlier ejecta, forming a rim of agglutinate about the edge of the crater. This is a common feature in basaltic cinder cones, and results from a decrease in gas pressure as the lava fountain dies.

The ejecta in the cinder cones range from fine ash to bombs a foot or two in length. The bombs are Strombolian in type, blown out as liquid lava and largely solidified in the air. Nearly spherical bombs are typical of the picrite-basalt cones, whereas spindle-shaped bombs characterize the andesitic and basaltic cones. Spherical bombs, resembling in shape those ejected at Kilauea Volcano during the explosive eruption of 1790, indicate a low viscosity of the lava, permitting surface tension to draw the ejected drop or filament into a spherical shape before cooling, further deformation being prevented by increasing viscosity. During formation of the andesitic spindle bombs the lava was too viscous for surface tension to draw it completely into a spherical shape. Both the spherical and spindle bombs show typical small projections at the poles and represent local thickening of lava ribbons.

The picrite-basalt cones are composed of vitric-crystal tuff and cinder, containing many loose crystals of augite and olivine. Many of the crystals are well formed and some are as much as a centimeter or more in length. Excellent crystals of augite and olivine can be collected on the slopes of Puu Io, Puu Kaalialia, Puu Papapa, and Puu Pa. Puu Holoholoku, a cone of olivine basalt transitional toward picrite-basalt, yields abundant, loose, well-formed, partly decomposed crystals of olivine.

Water-bearing properties.—The lavas of the Hamakua volcanic series are in general moderately to highly permeable. They contain basal ground water which is fresh along the Hamakua coast but

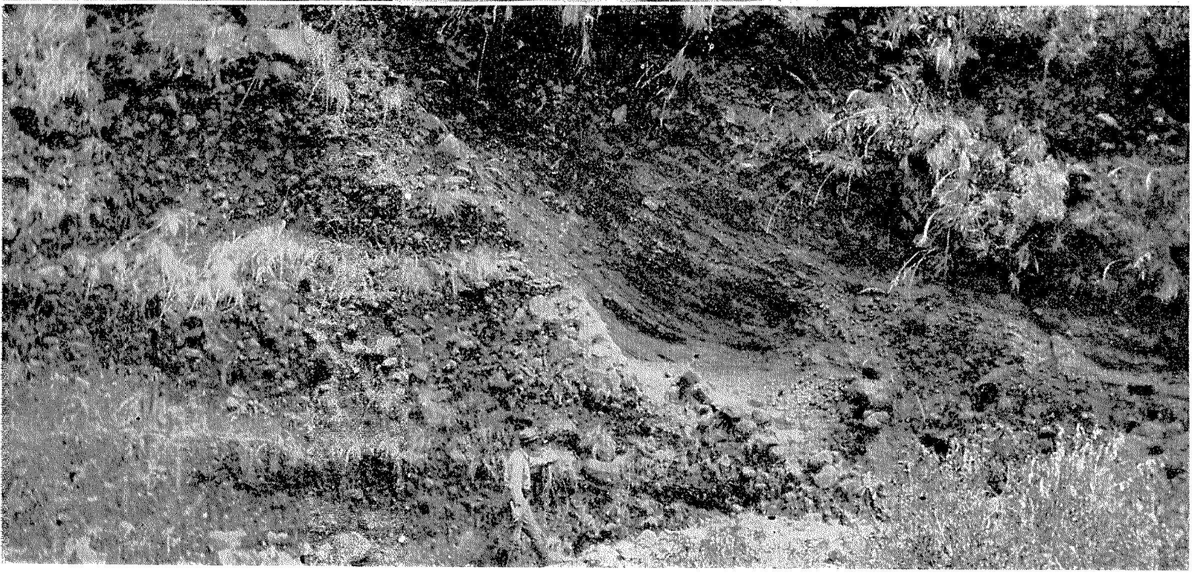


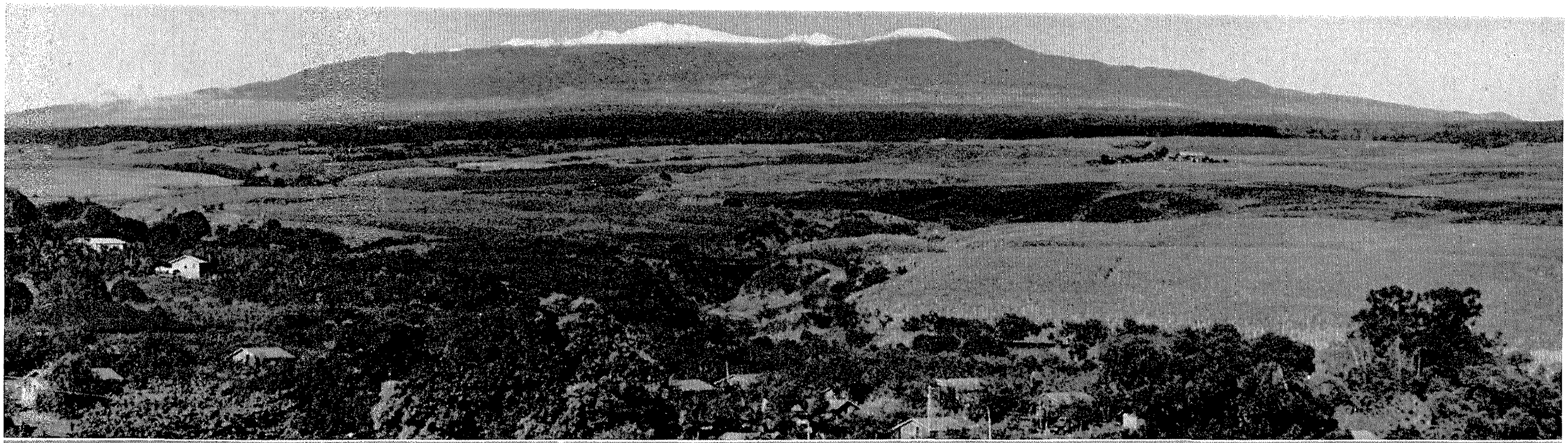


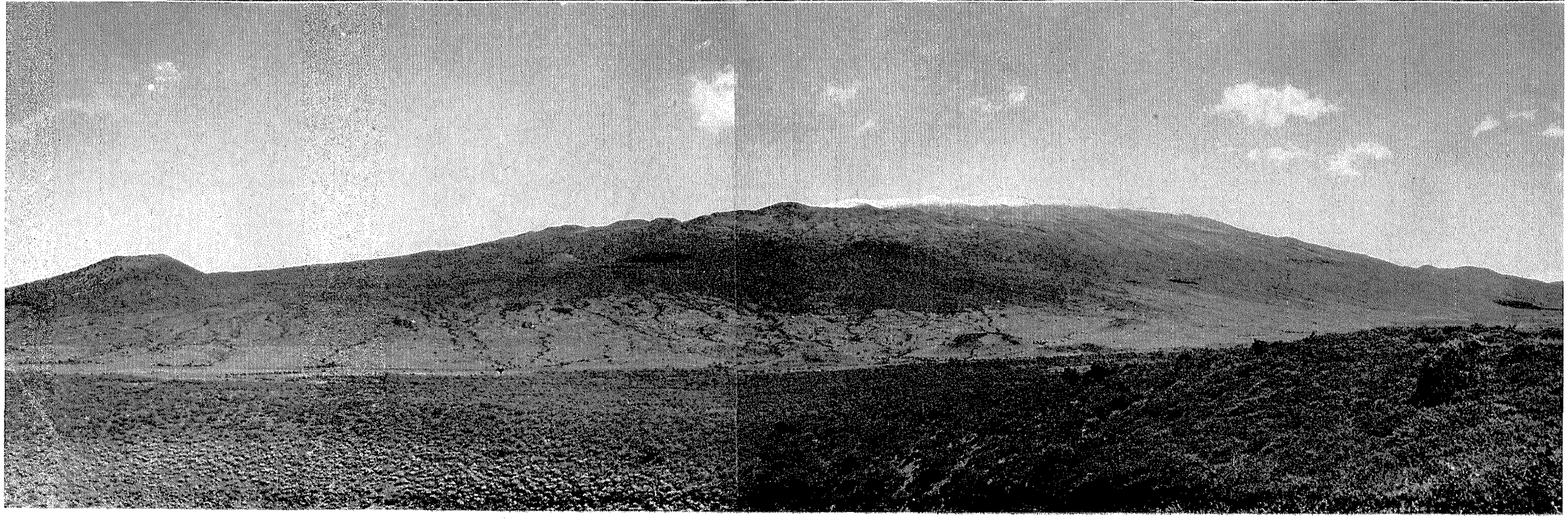
Left: Plate 47A. Detailed view of olivine basalt explosion blocks in laminated lapilli and ash matrix 20 feet above the base of the deposit in Waikahalulu Gulch, about 9,000 feet altitude, Mauna Kea, Hawaii. Photo by H. T. Stearns.

Right: Plate 47B. Bedded lithic explosion debris 90 feet thick in the western wall of Waikahalulu Gulch overlain by thin-bedded lavas, Mauna Kea, altitude 10,200 feet. Photo by H. T. Stearns.

Below: Plate 47C. Erosional unconformity in explosion debris a quarter of a mile east of Pohakuloa Gulch on the southwestern slope of Mauna Kea, altitude 9,000 feet. Photo by H. T. Stearns.







slightly brackish along the western coast. Small amounts of perched water occur along the wet slope in the Hamakua and North Hilo districts, held at high level by intercalated soil and ash beds, decomposed aa clinker, and the dense inner portions of aa flows.

PAHALA ASH ON MAUNA KEA

Distribution and thickness.—The Pahala ash on Mauna Kea represents the accumulation of pyroclastic debris during the entire interval from the time of eruption of the late Hamakua lavas to the close of volcanism on Mauna Kea, and in places it has probably received minor contributions from eruptions of Mauna Loa until the present time. Its maximum thickness is attained in kipuka areas of the older surficial Hamakua lavas. Thin ash deposits are present on most of the Laupahoehoe lavas. The distribution and systematic variations in thickness (fig. 19) indicate that the ash was derived largely from eruptions on Mauna Kea but during the interval of ash accumulation, favorable wind directions must have resulted in small contributions to its bulk from eruptions on neighboring volcanoes. Where it has not been covered by later lavas, therefore, the Pahala ash on Mauna Kea represents an accumulation of ash over a long period of time and probably from several sources.

The greatest observed thickness of the Pahala ash is on the lower southeastern slopes of Mauna Kea, near Hilo. In cuts along the main highway and the Amauulu road, just north of Hilo, 12 to 15 feet of ash are exposed. Similar amounts are found along several of the small streams farther west, at altitudes between 1,500 and 2,500 feet. At higher altitudes exposures are poor, owing to shallow dissection and the dense jungle cover, but the ash thickens upslope, probably attaining a thickness of 20 feet or more. On the upper slopes of the mountain, however, the maximum thickness of the ash decreases, even in kipukas of Hamakua lavas, owing to interruption of accumulation by lava flows and to wind erosion

---

[68] Wentworth, C. K., op. cit., pp. 75–82.

[69] Idem, p. 83.

←

Opposite page, top: Plate 48A. Snow-capped Mauna Kea from Hilo showing the gentle lower slopes in the foreground and the steep upper slopes in the background. Photo by G. A. Macdonald.

Bottom: Plate 48B. The southwestern side of Mauna Kea as seen from Puu ka Pele. The light area just below the snow line is glacial drift. Photo by G. A. Macdonald.

because of less effective binding by vegetation. At an altitude of 6,000 feet, near Puu Oo Ranch, the greatest depths of ash are 8 or 9 feet.

Northwestward from Hilo, along the main highway near the coast, the ash cover gradually decreases (fig. 19), until between Ookala and Paauilo the greatest depths are 5 to 6 feet. Wherever it is not complicated by external factors, the ash becomes thicker upslope. This is well shown along the road from Kukaiau to Umikoa, where the maximum depth of ash cover increases more or less regularly from 4.2 feet at 1,000 feet altitude to 13 feet at 3,500 feet altitude. In the vicinity of Waimea the greatest depths are generally between 4 and 5 feet. Southwest of Waimea, however, an area of late Hamakua lavas about 40 square miles in extent, south of the Kawaihae road and mostly west of the Kona road, has been largely swept free of ash by the wind because the plant cover is too sparse to be effective in holding the soil in place. In recent years the condition has been aggravated by heavy grazing.

General character.—The Pahala ash on Mauna Kea was originally largely vitric, with scattered crystals of feldspar, olivine, and augite. The granularity appears to be have been fine in most places, gradually coarsening as the vents were approached. Typically, however, the ash has been largely altered to palagonite, and the original textures destroyed. Along the lower eastern and northeastern slopes the Pahala ash is yellowish-brown to reddish-brown, and less frequently red or gray, with an earthy texture. It is generally moderately well bedded. Some thin especially compact layers show a waxy luster. A crude columnar jointing is present at many places. Thin dark brown or gray streaks probably represent plant debris at ancient soil horizons. The thickness of individual layers ranges from an inch or less to about 4 feet, but most beds are less than a foot. Much of the ash is a fine-grained sticky material, easily cut with a knife when wet, but powdery and friable when dry. Several sections have been described in detail by Wentworth.[68] In the drier areas of the western slopes the ash loses much of its cohesion and is largely a loose powdery material of silt grade, yellow or buff in color.

On the upper slopes of the mountain, where weathering is slow, large areas are covered with black sandy ash, extensively wind drifted, and composed almost entirely of fresh glass. Ash of the same age must occur on the lower slopes as well, but it is so highly altered it is indistinguishable from the older ash. At a few places on the upper slopes, however, the fresh black vitric ash lies with a sharp contact on older decomposed reddish-brown ash. This relationship is found along Nauhi Gulch at an altitude of 7,900 feet on the east flank of the volcano, where a small spring issues from the black ash at the contact with the underlying less permeable older ash, and at 3,300 feet altitude in Kemole Gulch on the west slope, where dark gray ash overlies unconformably older yellowish-red tuff.[69] At both places erosion at the contact and the highly altered condition of the underlying ash in comparison with the freshness of the younger ash indicate a considerable interval between the two deposits. In such areas it would be feasible to restrict the Pahala ash to the older altered material, but in most areas, such as the wet lower northeastern slopes, any such distinction between older and younger ash is impossible.

Water-bearing properties.—The Pahala ash on the flanks of Mauna Kea is less permeable than most of the associated lava flows. It therefore increases runoff and decreases the proportion of rainfall which enters the rocks as ground water. In a few places, however, the ash appears to be more permeable than the immediately underlying dense aa flows, with the result that small springs issue at the base of the ash. In such places the relatively low permeability of the underlying lava surface is probably at least partly caused by decomposition products sealing the fractures. Where beds of Pahala ash are buried by later Laupahoehoe lavas, the ash may perch ground water in the overlying rock. In general, however, the ash is not sufficiently impermeable to perch water.

LAUPAHOEHOE VOLCANIC SERIES

General statement.—The Laupahoehoe volcanic series has been named from the Laupahoehoe Peninsula where a typical andesite flow has built a lava delta (pl. 46B). The series is separated into two members. The lower member, which comprises most of the series, is of Pleistocene age. The upper member includes the few Recent cinder cones and lava flows, mostly small, erupted since the disappearance of the glacier (p. 57).

At the type locality, the Laupahoehoe lavas are separated from the older lavas of the Hamakua volcanic series by a profound erosional unconformity, expressed by the cutting of a canyon 400 feet deep. In other places, they are separated by local erosional unconformities. No general widespread unconformity between the two series exists, however, as volcanism was continuous from one to the other. In areas temporarily uninundated by lava flows, streams cut small gullies, and in a few instances fairly large canyons, as at Laupahoehoe, but in most areas the time between successive lava flows was too short for any appreciable erosion or weathering. The change in lava types occurred gradually. Andesites and basalts occur in both series. Picrite-basalts, however, appear to be restricted to the Hamakua lavas, where they are abundant in the upper part, and for that reason were useful in the geologic mapping. All picrite-basalts were mapped in the Hamakua volcanic series.

The most useful criterion in separating the two series is the thickness of ash cover on the lavas. Where they form the land surface, the lavas of the Hamakua volcanic series have been subject to the accumulation of ash throughout the entire period of extrusion of the Laupahoehoe volcanic series. The Laupahoehoe lavas, being younger than the Hamakua lavas, have, for the most part, a thinner ash cover. However, the depth of the ash on the Laupahoehoe lavas depends on the age and location of the particular flow, and the older flows may be buried under nearly as much ash as the adjacent Hamakua lavas. In such transitional examples the depth of the ash cover is not diagnostic.

Locally, the criteria of ash cover and picrite-basalts fail, and assignment of the flow to one series or the other depends entirely on the judgment of the field geologist. This is especially true in the jungle-covered areas on the eastern slope, roughly between 2,000 and 5,000 feet altitude, where exposures are exceedingly poor and the depth of ash cover frequently cannot be determined. Even where assignment of the rock to one series or the other is certain, locations in this jungle area often are doubtful. This portion of the map should be regarded as of only general reconnaissance character.

The entire top of Mauna Kea is composed of rocks of the Laupahoehoe volcanic series. On the lower slopes they extend across the Hamakua lavas in long bands composed of either a single flow or of several superimposed flows. On the southern side of the mountain the Laupahoehoe lavas overlap the Hamakua lavas, and are interbedded with and partly buried by lavas of the Kau volcanic series of Mauna Loa. The total thickness of the Laupahoehoe volcanic series is not known. Hamakua lavas are exposed at the surface in kipukas extending to an altitude of more than 10,000 feet on the southern flank of the mountain, and somewhat lower altitudes at other places. On the flanks of the mountain, therefore, the thickness of the Laupahoehoe volcanic series probably nowhere exceeds a few hundred feet, and in many places may be measured in tens of feet. If a caldera occupied the summit of the mountain before the extrusion of the Laupahoehoe lavas, as appears likely, the Laupahoehoe rocks filling and surmounting this caldera are probably two or three thousand feet thick (fig. 32).

LOWER MEMBER OF THE LAUPAHOEHOE VOLCANIC SERIES

LAVA FLOWS.—The lower member of the Laupahoehoe volcanic series consists very largely of lava flows. Pyroclastic rocks probably constitute about 4 or 5 per cent in the upper part of the mountain. The lavas are predominantly andesitic, but olivine basalts are present also, even among the latest lavas. Basalts are especially abundant on the western flank above 7,000 feet altitude.

Many of the andesite lavas form massive flows of aa, some of them more than 100 feet in thickness. The upper surface of the very thick flows is exceedingly irregular, characterized by hillocks and undrained hollows, many of the latter 20 or 30 feet deep. The drifting of ash into these hollows by wind and rainwash has, in places, formed poorly permeable floors which support quasi-permanent ponds, such as the small ponds south of the highway 10 miles east of Waimea, and the Waikoloa Ponds southeast of Puu Oo Ranch. Some of the hillocks are large and regular enough to be mistaken at a distance for small cinder cones. Puu Loe, 10 miles east of Waimea, a hill of this sort, is nearly 100 feet high. These hills appear to be monolithic crags of solid lava rising from the clinker of the typical aa surface. Similar crags have been observed at other volcanoes, and are well shown on the floor of the Koolau Gap in the summit depression of Haleakala, Maui. Their mode of formation is not definitely known, but it is probable that they represent spines of lava protruded from the surface of viscous aa flows in much the same manner as the small spines which form abundantly on the surface of many viscous domes.[70]

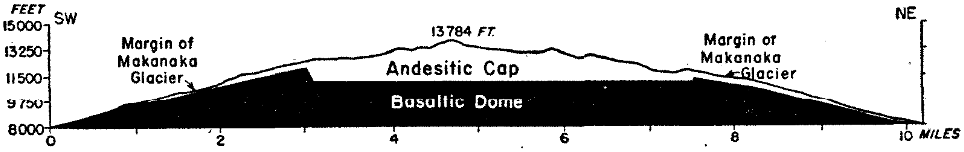


Figure 32. Section of Mauna Kea showing hypothetical caldera filled with andesites of the Laupahoehoe volcanic series.

Some of the lava extrusions were sufficiently viscous to pile up around the vent forming small viscous domes. Two of the best developed are those at the side of Puu Loa and of Aahuwela cinder cone, 1.3 miles northwest of Laumaia, at 7,250 feet altitude on the southeastern flank of the mountain. That at Puu Loa is about 200 feet high. A thick andesitic lava flow poured eastward from it (pl. 1). The Puu Loa dome has an eastward-facing crescentic scarp about 50 feet high at its top, formed by partial collapse of the dome, the upper eastern part of which tended to slide eastward with the lava flow. The lowest vent of Laupahoehoe age is a small viscous dome a mile southeast of Ookala, from which a short thick flow of andesite extends northeastward for half a mile.

---

[70] Williams, Howel, History and character of volcanic domes: California Univ., Dept. Geol. Sci. Bull., vol. 21, pp. 51–146, 1932.

At several places voluminous extrusions have built up small lava shields on the flanks of the major cone. Some, such as that at Papalekoki, are crowned with cinder cones. Others, like the one which lies 1.25 miles north of Puu Makanaka, have little or no visible associated pyroclastic ejecta.

Most of the lavas are sparingly vesicular, and many are locally quite dense. However, some moderately vesicular flows are present also. Aa flows are dominant, but some pahoehoe flows are found, particularly near the vents. Within the glaciated summit region clinkery aa flow tops have been largely removed by ice abrasion. An exceptionally dense, dark gray andesite crops out on the southern flank of the mountain above 12,250 feet altitude, and blocks of it are scattered widely over the southern slope in the glacial moraine and outwash. It was used by the ancient Hawaiians for the manufacture of stone adzes, many partly finished specimens of which still can be found at the heaps of chips which mark the workshops.

Although the Laupahoehoe lavas are most abundant on the upper slopes of the mountain, a few flows continued all the way to the coast (pl. 1). One of these, in its lower course, followed Laupahoehoe Gulch and advanced into the sea, building a small lava delta (pl. 46B) which forms a flat a few feet above sea level and extends a short distance seaward beneath the ocean. Another followed a smaller gulch along the middle and lower stretches of Kawainui Stream, which at that time emptied into Onomea Bay. This flow also built a small lava delta, which is largely submerged. Other flows advanced to the coast across the little-dissected upland areas between the large gulches. A feature which for a time was puzzling is the fact that the flows at Laupahoehoe and Onomea Bay show only very small sea cliffs, whereas other flows which otherwise appear to be of about the same age, form the tops of sea cliffs 200 feet high. The explanation is that the large cliffs are not the result of cutting since the eruption of the Laupahoehoe lavas, but were largely cut before they were erupted. The flows cascaded over a high sea cliff, forming a thin veneer on the cliff face and large masses of loose clinker at its base which were rapidly removed by the sea, leaving no trace of their former presence. The actual amount of cutting by the sea since the eruption of these flows has been little or no greater than at the localities where the sea cliff is only a few feet in height.

Cinder cones.—The upper slopes of Mauna Kea, and the Humuula area, are thickly sprinkled with about 150 cinder cones (pls. 46A and 48B), most of which belong to the lower member of the Laupahoehoe volcanic series (pl. 1). Many more cones have, of course, been buried by later lavas, and are no longer visible. Ash deposits not directly associated with the cones are widespread both on the surface and interbedded with the lavas.

The cinder cones range in size from mere hillocks to hills several thousand feet in diameter and several hundred feet high. The largest single cone in areal extent is Puu Makanaka, which is 4,000 feet in diameter. The highest cone is the Summit Cone, which rises 650 feet above its southwestern base. Compound groups of two or more overlapping cones, arranged irregularly or along a line, are common. The only nested cone observed is at Puu Keonehehee, on the southern flank of the mountain at 11,500 feet altitude. There the outer cone has a broad crater 800 feet across and nearly 150 feet deep, within which lies a smaller cone.[71] Apparently, vents with eruptive axes recurring at the same point were rare.

Some cones have perfect bowl-shaped craters, but most are breached, generally on the downhill side. In some the breaching was undoubtedly caused by an emerging lava stream carrying away the cinder as fast as it fell, thus preventing the building of one sector of the cone. In others the cone wall probably collapsed, and the debris was carried away by the escaping lava. In still others, lava flows which burrowed through the sides of the cones probably floated away the overlying cone segment. Commonly, however, the cone wall above a burrowing flow was little affected, as on the southern flank of the Summit Cone where escaping lava built a distinct hump at the head of an extensive flow without apparently affecting the slope of the cone above its point of emergence. Some cones are locally armored by thin outer shells of lava, which escaped at or near the rim of the cone.

The cones are composed largely of gray, black, or red cinders, mostly from half an inch to an inch across, with which are admixed progressively less abundant larger fragments up to 8 inches in diameter. Some cones contain abundant finer cinders and ash, but others are nearly devoid of fine material, at least in the surface layers. Intermixed with the cinders are spindle-shaped bombs, from an inch or less to 6 feet in length. A few bombs show shallow, poorly developed breadcrust cracking. Accessory blocks of older lava have not been identified. Spatter cones are rare. The ejecta are largely Strombolian, hurled out in a fluid condition but essentially solidified before striking the ground.

Many of the cones contain coarsely crystalline inclusions carried up by the rising magma. Inclusions of dunite and gabbro are especially abundant on Puu Haiwahine, 1 mile southwest of Hale Pohaku, Puu Kalepeamoa, and the cone nearly due west of Hale Pohaku. Most of them form the cores of bombs. Inclusions of

---

[71] Wentworth, C. K., Ash formations of the Island Hawaii: Hawaiian Volc. Obs. 3d Spec. Rept., p. 65, 1938.

dunite, troctolite, and olivine-augite gabbro occur in the cones on the western flank of the mountain. Inclusions of dunite and lherzolite occur in the Summit Cone.

ASH DEPOSITS.—Extensive surficial deposits of ash are found on the upper slopes of the mountain. Although derived from nearby cones, the ash in general cannot be referred to any particular cone, but represents an accumulation of material from many eruptions. Similar ash deposits have been found interbedded with the lavas on the southern and eastern sides of the mountain (pl. 49A), and although dissection is nowhere deep enough to expose more than the outermost carapace of the cone, it is probable that ash layers are interbedded with the lavas throughout the section.

The surface ash deposits are composed of dark gray to black ash, largely of medium to fine sand grade, moderately well bedded and sorted. Most of the bedding is essentially parallel to the underlying rock surface, but locally wind transportation has produced cross-bedding. Some of the ash grains are individual small drops of solidified lava spray, but most of them are fragments of larger ejecta. They are composed largely of glass, with a refractive index close to 1.566. Scattered crystals of olivine and sodic labradorite are enclosed in the glass.

Within the boundaries of the glacier the ash cover was removed by ice erosion, but on the slopes below the moraine, nearly all the lava flows have some ash on their surface. The thickness of the ash varies from a few inches to tens of feet, and Wentworth states that in places it reaches as much as 100 feet.[72] In many places it is 30 or 40 feet thick. Deep deposits of surficial ash are shown by an overprint on plate 1. The boundaries are indefinite and arbitrary, as the thick deposits grade gradually into thinner deposits in most places. As shown on the map, the areas of thickest surficial ash are on the southern and southwestern slopes of the mountain, accumulation having been much influenced by the prevailing northeasterly winds. Similar local wind influence is shown in many places where the deepest ash deposits accumulated to the lee of cinder cones.

Below about 6,000 feet altitude, particularly on the humid northeastern and eastern slopes, the ash correlative to the surficial ash on the upper slopes becomes more and more decomposed to soft yellow, buff, or reddish-brown palagonitic material. Where it does not rest on lavas of the Laupahoehoe volcanic series it is indistinguishable from the older ash, and can be treated only as the upper part of the Pahala ash.

WATER-BEARING PROPERTIES.—The lavas of the lower member of the Laupahoehoe volcanic series are poorly to moderately permeable.

---

[72] Idem, pp. 64–65.

Basal water occurs in them only in the small lava deltas at Laupahoehoe and Onomea Bay, where it is brackish. High level springs issue from them along the lower northeastern slope (table, p. 291), the water in most instances being perched by underlying Pahala ash, but in some by the dense middle parts of aa flows. Ash beds within the Laupahoehoe volcanic series are too permeable to perch water, but at 8,000 feet altitude in Nauhi Gulch a small spring issues from fresh black ash and is perched by underlying decomposed Pahala ash.

UPPER MEMBER OF THE LAUPAHOEHOE VOLCANIC SERIES

Several small lava flows on the upper part of Mauna Kea are shown by their relationship to the glacial moraine to be of postglacial age.[73] Because of their late date they have been separated as the upper member of the Laupahoehoe volcanic series, although actually the volcanism which produced them was continuous with that of the lower member of the series. For other flows and cones lower on the flank of the mountain there is no direct evidence of age in relation to the glacial deposits, but owing to their very fresh appearance they have been included with the postglacial lavas.

All six lava flows of the upper member are andesites. One of the flows, resting on fresh black ash, is well exposed just east of the road to Hale Pohaku, on the southern flank of the mountain (pl. 49A). Half a mile east of the Pohakuloa Gulch a small flow broke out along the lower side of the terminal moraine, and extended downslope for half a mile. Another small flow was erupted at a row of small vents just west and northwest of Puu Keonehehee, and poured down Waikahalulu Gulch for a distance of 1.4 miles (pl. 49B). Its relation to the moraine and the gulch walls shows that it was erupted during post-glacial time when Waikahalulu Gulch had already reached essentially its present stage of development. A small flow three-quarters of a mile east of Puu Keonehehee was mapped by Wentworth and Powers as post-glacial but is actually glacial in age, as shown by the occurrence of many outwash boulders on its surface.

Large cinder cones are associated with the upper member of the Laupahoehoe volcanic series at Puu Kole and Puu Lehu. The flow near Hale Pohaku built only a small cone of cinder and spatter, and very little cinder is present at the vent of the small flow which broke through the moraine between Pohakuloa and Waikahalulu gulches. The larger cones probably produced some black ash, but it is indistinguishable from the slightly older Laupahoehoe ash.

---

[73] Wentworth, C. K., and Powers, W. E., Multiple glaciation of Mauna Kea, Hawaii: Geol. Soc. America Bull., vol. 52, p. 1212, 1941.

The lavas and pyroclastic rocks of the upper member of the Laupahoehoe series are too limited in their extent to have any importance as water-bearers.

INTRUSIVE ROCKS

A few small dikes belonging to the Hamakua volcanic series are exposed along Waikahalulu and Pohakuloa gulches between the altitudes of 9,000 and 10,500 feet. Many other dikes must be present at depth in the rift zones, but erosion has been too slight to uncover them. The presence of gabbro inclusions in lava flows and pyroclastic ejecta indicates that intrusive bodies of gabbro, probably in the form of small stocks, also must be present at depth.

SEDIMENTARY ROCKS

Sedimentary deposits on the slopes of Mauna Kea include water-laid gravels, ice-laid moraine, and wind-transported ash and dust. Much of the ash has been shifted by the wind since its original deposition, and in places it forms small areas of migrating black sand dunes.

Glacial deposits include a belt of terminal moraine and a thin discontinuous layer of ground moraine. The terminal moraine extends entirely around the mountain as an easily recognized belt (pl. 48B). Its edge is shown on plate 1. Locally, as along Pohakuloa Gulch, lobes of the glacier extended beyond the general margin of the ice and formed prominent lateral moraines. Recessional moraines deposited at successive positions of the retreating ice front are recognizable southeast of Puu Lilinoe. The terminal moraine ranges from a few feet to about 100 feet in thickness. It is composed of angular blocks, set in a fine sandy matrix. The great majority of the blocks are of andesite, which forms the surface of most of the mountaintop. Where they are fresh, both the blocks and the matrix have a pale, slightly bluish-gray color, but shallow weathering changes the matrix and surfaces of the blocks to an ochre-yellow. Striated and soled blocks are present, but are very rare. Bedding is absent except in small local pockets. Small amounts of outwash gravel were deposited by glacial melt-water outside the limits of the terminal moraine. The outwash gravel resembles the moraine, except that the typical bedding of water-laid deposits is clearly recognizable.

Much of the surface of the kipuka of Hamakua lavas on the southern side of the mountain is covered with water-laid gravel. The oldest of these deposits is an extensive sheet of well-cemented purplish-brown gravel, believed by Wentworth and Powers to be moraine of an earlier glacial stage.[74] It has been shown, however,

---

[74] Idem, p. 1207; termed the Waihu stage.

on the evidence of its distinct fluvial bedding (pl. 49C), to be a water-laid rather than an ice-laid deposit. It may have been laid down by catastrophic floods which resulted from volcanic eruptions melting glacial ice during the early part of the Wisconsin glacial stage.[75]

Younger gravels, formed in part by reworking of the older deposits, cover a large part of the lower slopes of the kipuka. They were formed before the cutting of the present major canyons, and as suggested by Jaggar,[76] probably were deposited in large part by glacial meltwater. They are now undergoing erosion. At the base of the slope they merge to form a broad alluvial apron. Other alluvial fans are forming at the present time.

The mouths of the large gulches along the windward coast were cut during a stand of the sea somewhat lower than the present. A subsequent rise of sea level relative to the land caused alluviation of the mouths of the valleys, building small gently sloping plains composed of poorly sorted gravel in a sand and silt matrix. Many of these are now being trenched by streams, indicating a lowering of base level either by a lowering of sea level or by retreat of the shoreline through marine erosion. The latter in general appears slight. Several of the alluvial plains appear to be graded to a stand of the sea approximately 25 feet above that of the present, evidence of which appears on many of the islands of the North Pacific Ocean.[77]

Thin beds of hill-wash gravel are intercalated with lavas on the upper slopes of the mountain, and shifting gravel bars occur along most of the present streams. Both are too small to be shown on plate 1.

The alluvial deposits in the mouths of the large gorges along the northeastern coast of Mauna Kea contain small amounts of basal ground water. Some water is recovered from the alluvium by the dug well at the mouth of Kaawalii Gulch, owned by the Laupahoehoe Sugar Company. Permeable sand lenses interbedded with less permeable material in the alluvial fans along the northern edge of the Humuula Saddle may also contain small amounts of perched ground water. On the upper slopes of Mauna Kea, particularly along the west fork of Pohakuloa Gulch, relatively impermeable beds of hillwash perch water in the overlying lavas giving rise to several small springs.

---

[75] Stearns, H. T., Glaciation of Mauna Kea, Hawaii: Geol. Soc. America Bull., vol. 56, pp. 267–274, 1945.

[76] Jaggar, T. A., The Daly glacier on Mauna Kea: Volcano Letter, no. 43, Oct. 22, 1925.

[77] Stearns, H. T., Shore benches on North Pacific Islands: Geol. Soc. America Bull., vol. 52, p. 779, 1941.

STRUCTURE OF MAUNA KEA

The lavas of Mauna Kea dip outward in all directions from the summit. The prominent broad arches of lavas dipping away from rift zones, which are conspicuous on Mauna Loa, and on Haleakala Volcano on the island of Maui,[78] are not developed on Mauna Kea. Eruptions were more centralized, and the radial erupting fissures were less concentrated into definite rift zones than on Mauna Loa or Haleakala.

Radiating rift zones are present in Mauna Kea, however, although less clearly defined than in most Hawaiian volcanoes. These rift zones are three in number, and radiate from a center near the Summit Cone (pl. 1). One trends northeastward, and includes Puu Makanaka, Puu Kanakaleonui, Puu Lehu, Puu Kihe, and many other vents. A branch of this rift diverges northward, and includes among other cones Puu Kole and Apakuie. Another of the major rift zones trends west-northwestward, along the line of cinder cones which includes Puu Nanaha and Puu Hinai. It appears to be prolonged to the eastward beyond the summit. Kauku cone, the small cones near Pepeekeo, and one at Onomea Bay (pl. 23A) are situated on it. A prominent ridge extending eastward below sea level was built by eruptions along this rift (fig. 4). The third major rift zone extends southeastward through Puu Lilinoe and Puu Keonehehee, another Puu Kole, and Huikau hill. Each of the three rift zones diverges fanwise downslope.

Many cones on the flanks of Mauna Kea appear to be arranged along arcuate lines roughly concentric to the summit. A conspicuous example is the line of picrite-basalt cones on the northwestern slope extending from Puu Io to Puu Kanalopakanui, 2 miles south of Waikii. The surficial fissures from which these

---

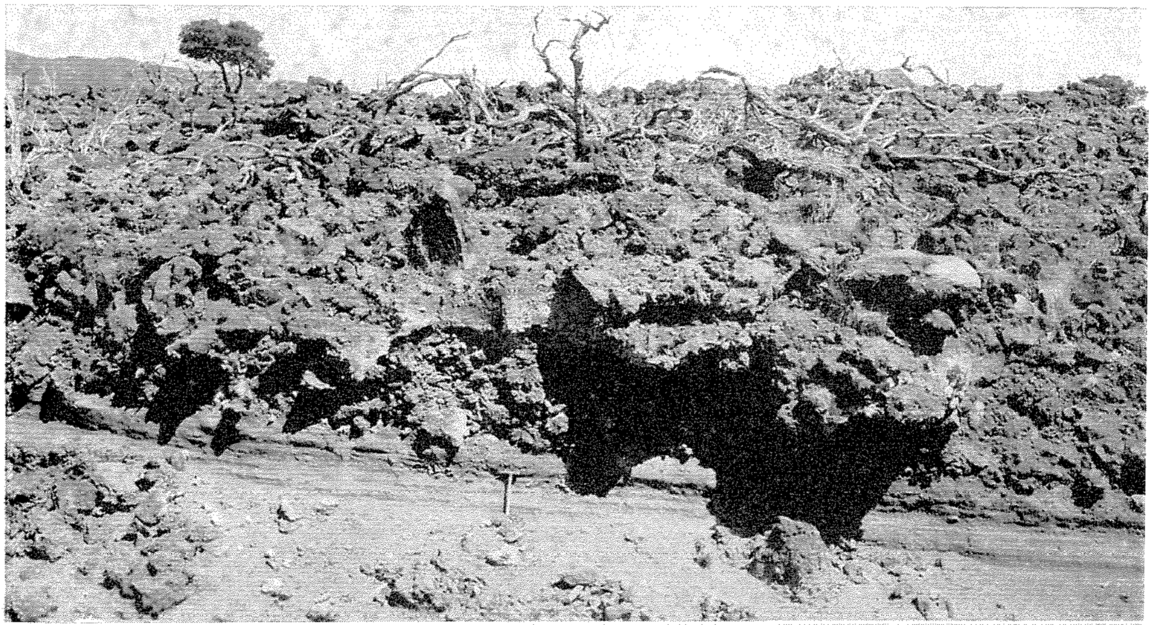
[78] Stearns, H. T., and Macdonald, G. A., Geology and ground-water resources of the island of Maui, Hawaii: Hawaii Div. Hydrography, Bull. 7, p. 111, 1942.

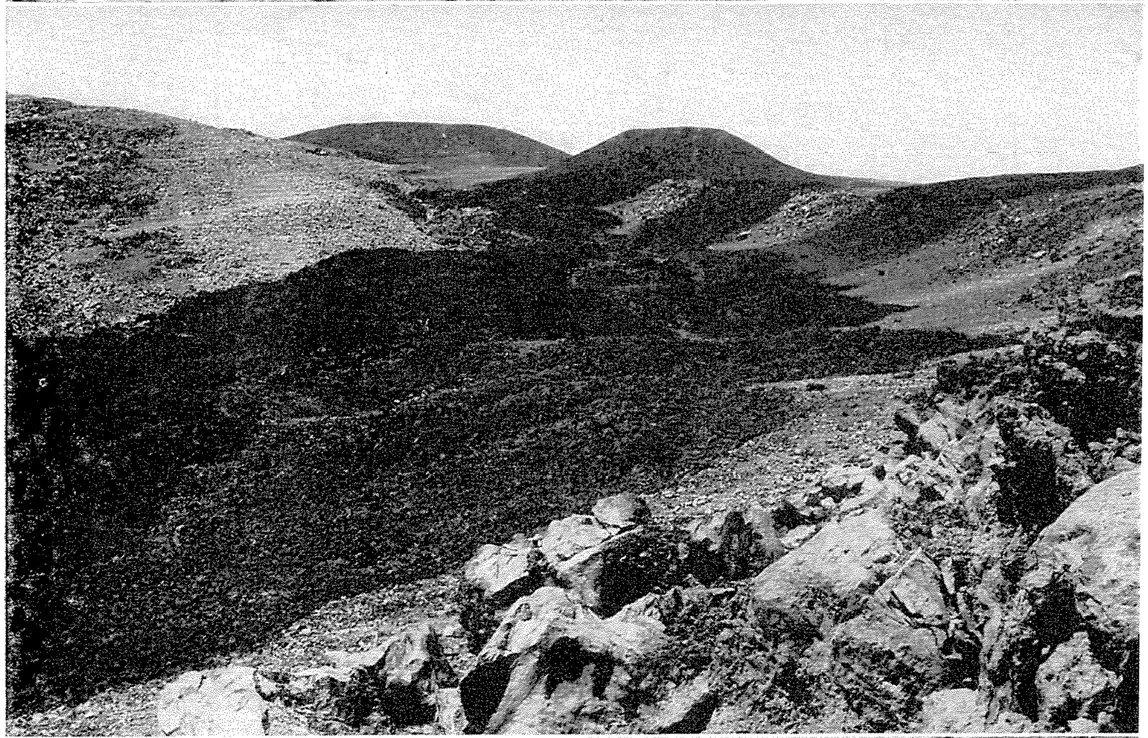
→

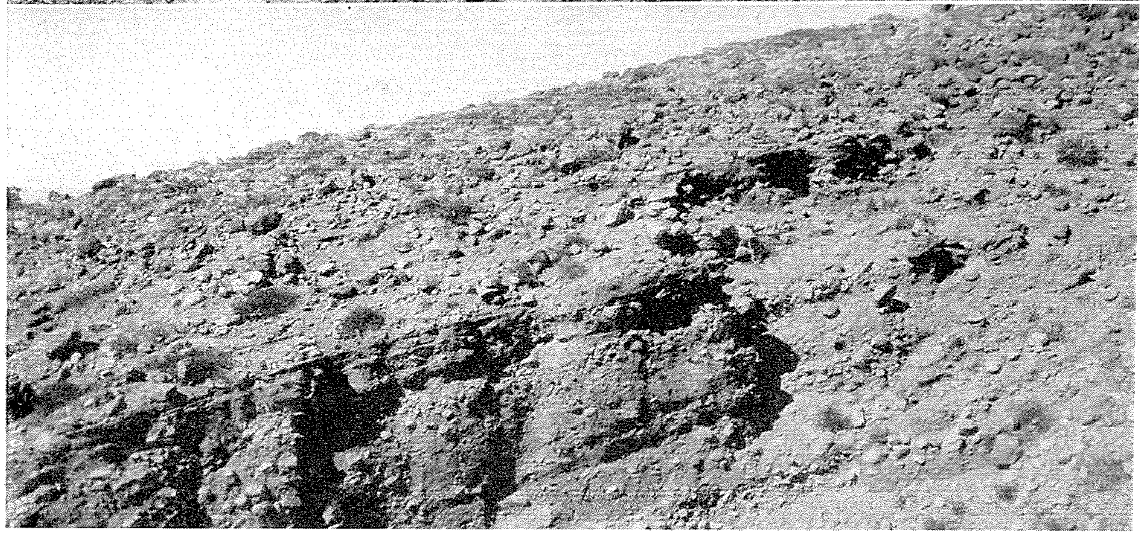
Opposite page, top: Plate 49A. Aa in upper member of the Laupahoehoe volcanic series overlying black vitric ash in a gully 1½ miles north of Hookomo Cone, Mauna Kea. Photo by G. A. Macdonald.

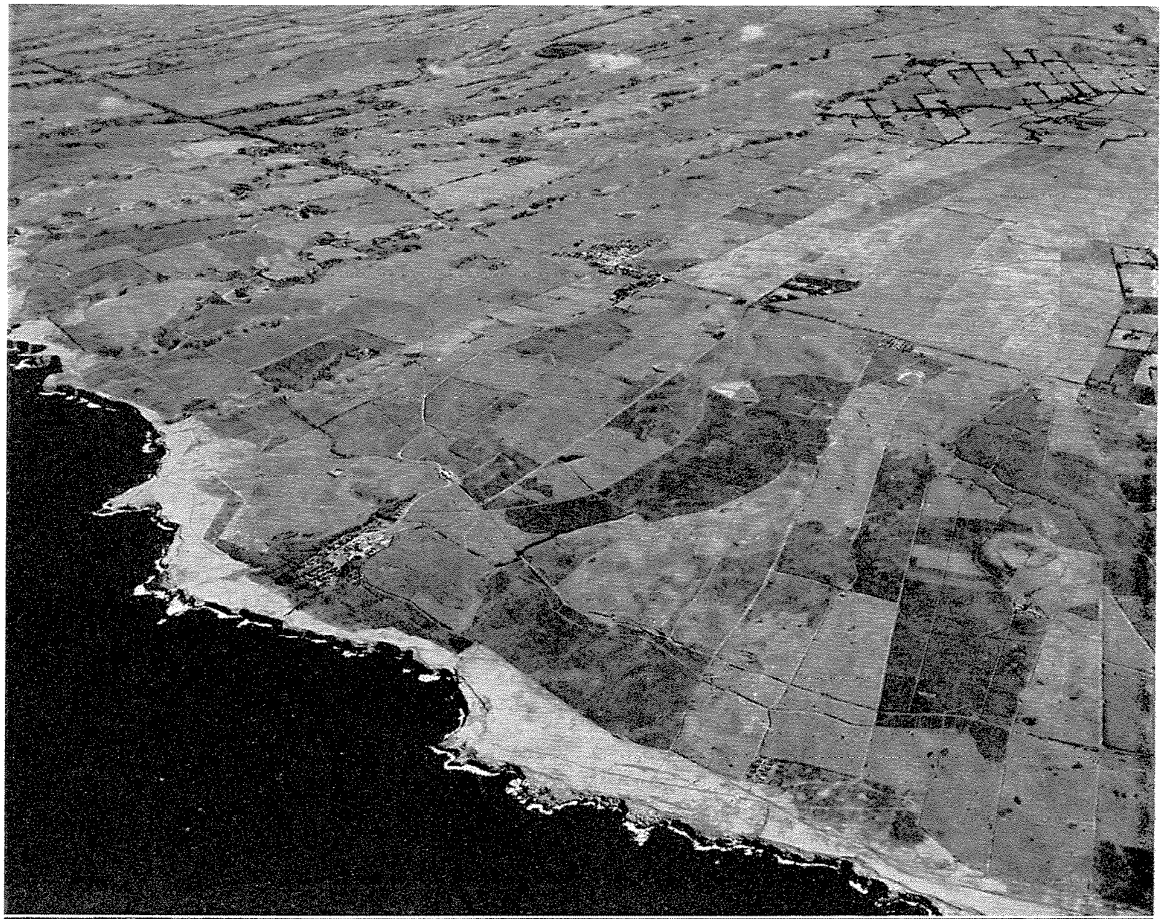
Middle: Plate 49B. Black aa lava flow of the upper member of the Laupahoehoe volcanic series overlying glacial drift at the head of Waikahalulu Gulch, near the summit of Mauna Kea. Photo by C. K. Wentworth.

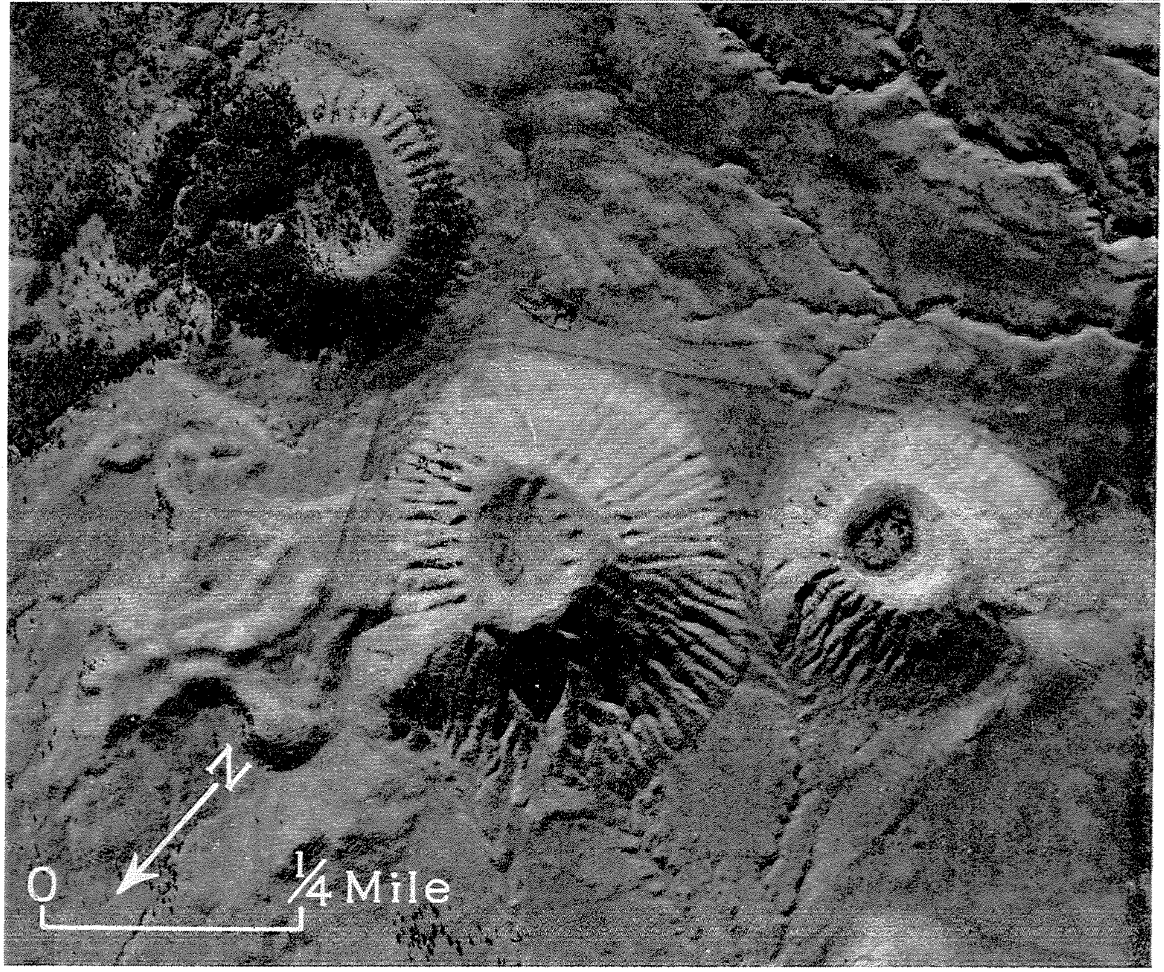
Bottom: Plate 49C. Bedded Waihu fanglomerate 50 feet thick half a mile east of Pohakuloa Gulch on the southwestern slope of Mauna Kea, altitude 9,500 feet. Photo by H. T. Stearns.










N
0
¼ Mile

eruptions occurred are radial, but the concentric alignments of cones suggest the existence of concentric arcuate fissures at depth, occupied by ring dikes or cone sheets, which fed the rising magma to the shallower-seated radial fissures.[79]

The radial rift zones are occupied beneath the surface by swarms of dikes. These dikes increase in number from the surface downward, until at a depth of a few thousand feet the rift zone areas probably are occupied almost entirely by intrusive rock. Most of the dikes are probably essentially vertical, and nearly parallel within any one rift zone, occasionally crossing each other at low angles. Between the dikes in the upper part of the rift zone are thin slabs of extrusive lavas. The dikes are much less permeable than the lavas enclosed by them, and the compartments of lava are probably saturated to high levels with ground water, the movement of which has been restricted by the dikes.

RELATION OF MAUNA KEA TO MAUNA LOA

The building of Mauna Kea was at least in part contemporaneous with that of Mauna Loa. When the latest Laupahoehoe lavas of Mauna Kea poured down the southern slope of the mountain and reached the level of the Humuula Saddle, they were deflected eastward and westward along a depression which already existed between Mauna Kea and Mauna Loa (pl. 1). This clearly indicates that the slope of Mauna Loa had been built out nearly to its present position by the end of Laupahoehoe time. Throughout much of the growth of the two volcanoes, the lavas of Mauna Loa and Mauna Kea were probably interfingering along the contact. Similar relations probably occurred between the lavas of Mauna Kea and those of Hualalai Volcano.

---

[79] Macdonald, G. A., Ring structures at Mauna Kea, Hawaii: Am. Jour. Sci., vol. 243, pp. 210–217, 1945.

←

Opposite page, top: Plate 50A. Flow slopes of deeply weathered lava planted to sugar cane on the northern side of Kohala Mountain. Note the circular pattern of a weathered cinder cone of the Polulu volcanic series on the right side of the picture. Photo by U.S.A.A.F.

Bottom: Plate 50B. Vertical air view of large corrugated andesite cinder cones near Kahua Ranch on Kohala Mountain. Photo by U.S.A.A.F.

GEOLOGY OF KOHALA MOUNTAIN

PREVIOUS INVESTIGATIONS

The geology of Kohala Mountain has been a subject of speculation by geologists, but actual field work by previous investigators was limited apparently to travelling the main road to Mahukona from Waimea and to viewing Waipio Valley at the coast.

Dutton[80] noted the presence of andesites on the western side and the profound marine and stream erosion of the northeastern side. Dana[81] stated that the upper stretches of Waipio and Waimanu streams are so bent around into parallelism with the coast that erosion cannot explain their origin. Powers thought that faults determined their courses.[82] Branner[83] pointed out that the flat floor of Waipio Valley is proof of deep submergence. Jaggar,[84] believed that a great block was downfaulted to make the high sea cliffs between Waipio and Pololu valleys, and that a parallel block extending inland to the crest of Kohala Mountain has slipped eastward. This hypothesis is not supported by field observations. Lyons,[85] Cross,[86] and Washington[87] have contributed to the petrography of the mountain.

ROCKS OF KOHALA AND THEIR WATER-BEARING PROPERTIES

The volcanic rocks comprise all the lava flows, intrusive rocks, pyroclastic rocks, and intercalated soils. They have been divided into two series whose general characteristics and water-bearing properties are summarized in the accompanying table. The sedimentary rocks consist of dunes of loose black sand, landslide debris, unconsolidated younger alluvium, consolidated older alluvium, and fossiliferous marine calcareous conglomerate. The younger alluvium lies in stream beds and forms the lowlands at

---

[80] Dutton, C. E., Hawaiian Volcanoes: U. S. Geol. Survey 4th Ann. Rept., p. 171, 1884.

[81] Dana, J. D., Characteristics of volcanoes: p. 28, New York, 1890.

[82] Powers, Sidney, Tectonic lines in the Hawaiian Islands: Geol. Soc. America Bull., vol. 28, p. 511, 1917.

[83] Branner, J. C., Notes on the geology of the Hawaiian Islands: Am. Jour. Sci., 4th ser., vol. 16, p. 303, 1903.

[84] Jaggar, T. A., Seismometric investigation of the Hawaiian lava column: Seismol. Soc. America Bull., vol. 10, no. 4, p. 182, 1920.

[85] Lyons, A. B., Chemical composition of Hawaiian soils and of the rocks from which they have been derived: Am. Jour. Sci., 4th ser., vol. 2, p. 425, 1896.

[86] Cross, Whitman, Lavas of Hawaii and their relations: U. S. Geol. Survey Prof. Paper 88, pp. 31–34, 1915.

[87] Washington, H. S., Petrology of the Hawaiian Islands; I. Kohala and Mauna Kea, Hawaii: Am. Jour. Sci., 5th ser., vol. 5, pp. 465–502, 1923.

the mouths of the large canyons. The older alluvium lies in the larger gulches and deep canyons in the windward slope and crops out from 50 to 1,200 feet above sea level. The older alluvium was deposited during several epochs and is separated by erosional unconformities. The alluviums are not differentiated on plate 1. The marine conglomerate crops out near the dry leeward coast, in patches too small to be shown on plate 1. The dunes reach a height of 50 feet and lie at the mouths of Waipio and Pololu valleys. The sand is blown from the beaches by the prevailing trade winds.

The composition and stratigraphy of the volcanic rocks are similar to those in the West Maui Mountains.[88] The great bulk of Kohala Mountain is primitive olivine basalt bearing a thin incomplete cap of oligoclase andesites and trachyte separated from the basalt by a thin layer of red soil and an erosional unconformity.

POLOLU VOLCANIC SERIES

The Pololu volcanic series is named from Pololu Valley five miles southeast of Hawi. The type section is exposed in the trail that zigzags down the northwestern wall at the end of the automobile road near the coast. It consists of 450 feet of thin-bedded highly vesicular aa and pahoehoe primitive-type basalts dipping about 5° NE. They extend an unknown distance below sea level. The section is capped by a flow of andesite of the Hawi volcanic series. The lava beds are partly altered by weathering, especially near the top. A detailed stratigraphic section of the Pololu lavas in the east wall of Waipio Valley is given on page 197.

Small olivine and feldspar phenocrysts are common but a few lavas are nonporphyritic. A few lava flows carry abundant olivines 1 to 5 mm across, especially in the walls of Waihilau and Waimanu valleys. One flow, 8 feet thick, in the sea cliff just west of the mouth of Waimanu Valley, shows definitely that the olivines become progressively larger and more abundant toward the center of the distributing lava tubes.

A few flows not far below the rim of Waipio and Waimanu canyons carry abundant feldspar phenocrysts one half to one inch wide. Flows containing phenocrysts of augite and olivine, or augite, olivine, and feldspar, are common at the top of the series. They form a good horizon marker in the tunnels on the northern slope. An andesine andesite exposed in the railroad cut at Mahukona has been mapped with this series because of the overlying ashy soil.

---

[88] Stearns, H. T., and Macdonald, G. A., Geology and ground-water resources of the island of Maui, Hawaii: Hawaii Div. Hydrography, Bull. 7, p. 160, 1942.

Stratigraphic section of Kohala Mountain

Major geologic unit	Rock assemblage	Thickness (feet)	Symbol on map (pl. 1)	General character	Water-bearing properties
Recent sedimentary rocks	Unconsolidated dunes	25±	[1]Ra	Cross-bedded dunes composed of uniform grains of black basaltic beach sand.	Highly permeable and carry brackish water.
	Unconsolidated alluvium and landslides undifferentiated	25±	Ra	Poorly sorted boulder deposits in stream beds and fine-grained silts and sands forming "alluvial flats" in the broad floors of the large canyons. The landslide deposits contain blocks of volcanic rock in an earthy matrix.	The ribbons of gravel carry water but the formation as a whole is poorly permeable and yields water slowly to dug wells. The landslide deposits carry little water.
Pleistocene sedimentary rocks	Consolidated alluvium and landslides undifferentiated	500±	[1]Ra	Poorly sorted boulder conglomerates forming terraces in the lower stretches of large canyons and gulches. The landslide deposits consist of blocks of volcanic rock firmly cemented in an earthy matrix.	Poorly permeable as a whole but some boulder beds yield water.
	Consolidated fossiliferous marine calcareous conglomerates	3±	(2)	Conglomerates composed of basaltic gravel in a cream colored calcareous matrix, commonly fossiliferous.	Do not carry water.

Pleistocene volcanic rocks	Pahala ash	2±	(3)	Yellow, friable ash a few inches to 5 feet thick composed chiefly of dust- and sand-sized particles of palagonitized glass shards and pumice. It lies chiefly on the southern slopes of the mountain.	Relatively impermeable and where interstratified with lava perches small quantities of water in wet areas.
	Hawi volcanic series	100±	Phl	Fairly dense nonporphyritic gray lava flows commonly columnar jointed and chiefly oligoclase andesites, ranging from 20 to 75 feet in thickness except in Pololu Valley where a valley-filling flow attains a thickness of several hundred feet. A few trachytes are included.	The clinker phases are highly permeable but the dense parts transmit water poorly and in a few wet areas perch water.
		500±	Phc	Cinder cones at the source of lava flows.	Highly permeable except where their craters have been puddled by animals. These perch small ponds in wet areas.
		200±	Phd	Bulbous domes of oligoclase andesite and trachyte formed where viscous lava flows issued.	Poorly permeable.
			Red lines	Dense cross-jointed andesite dikes 3 to 10 feet wide and three trachyte dikes 18 to 40 feet wide. Too few to be differentiated from basaltic dikes on plate 1.	Confine water at high levels.
Great erosional unconformity in places					
Pliocene and older volcanic rocks	Pololu volcanic series	4,000+	Tpl	Thin-bedded, highly vesicular porphyritic and nonporphyritic aa and pahoehoe basalt flows ranging from 5 to 50 feet thick, and a few thin interbedded vitric tuff beds. A dark red fossil soil a few inches to several feet thick lies between these lavas and those of the Hawi volcanic series.	Highly permeable and freely yield basal water to wells and to high-level springs in the dike complex. The soil separating the Pololu and Hawi volcanic series gives rise to many perched springs.
		200±	Tpc	Cinder and spatter cones at the source of lava flows.	Highly permeable but do not carry water.
			Red lines	Basaltic dikes mostly less than 5 feet wide and usually dense and cross-jointed.	Confine water at high levels if in swarms.
		2,000	Tpf	Crater fill of dense basalts overlying breccia in Kawainui Canyon.	Yields small flows of water from joint cracks.
			Ti	Intrusive bodies, principally sills.	Dense and impermeable.

---

[1] Not mapped separately from the younger alluvium.

[2] Outcrops are too small to show on plate 1.

[3] Not differentiated from underlying lavas on Kohala Mountain on plate 1.

Individual flows range from a few to 50 feet in thickness, and in fresh specimens the color varies from blue to gray. The basalts of the Pololu volcanic series weather to deep red-brown soils in sharp contrast to the gray soils on the Hawi lavas. They are almost completely decomposed for depths of 50 to 200 feet in the lower windward slope, especially where they have not been covered with Hawi lavas. The Pololu lavas dip 3 to 10 degrees away from their sources. Amygdaloidal basalts are rare. A flow with vesicles containing small hemispheroids of calcite (Pele's pearls) and stellate clusters of aragonite crops out along the main highway 5½ miles east of Hawi.[89] Intercalated soils more than a few inches thick are scarce except near the top, indicating that the lavas accumulated rapidly. Also, neither intercalated gravels nor local erosional unconformities were found, and few tree molds are exposed in cuts—further evidence of the brief intervals between eruptions.

The Pololu basalts are exposed at the surface in the northwestern end of the mountain, in kipukas along the leeward slope, and in the area of the great canyons. A few outcrops near Waimea are too small to show on plate 1. The basalts are extremely permeable owing to their vesicular, tubular, fractured, clinkery character. Potable basal water issues from them along the windward coast, but along the leeward coast the water in them is apt to be brackish. Basal water in them in large quantities awaits development.

Thin vitric and vitric-lithic tuff beds, interbedded with the lavas, occur sparingly. Because of their small areal extent they are not shown on plate 1. Three beds, ranging in thickness from 6 to 18 inches and separated by flows, crop out in the east wall of Honokane Nui Canyon. They carry accessory ejecta up to 3 inches in diameter. Water perched on these beds has been recovered by tunnels 33, 34, and 35. Thin beds of tuff crop out in the sea cliff between Waimanu and Honokane Nui canyons and give rise to lines of springs 150 to 250 feet above the sea. Seven vitric tuff beds crop out in the east wall of Waimanu Valley at the coast, but they do not carry water.

Many of the cones from which the Pololu basalts issued have been buried by later flows. However, a chain of cones covered with thick red lateritic soil is exposed near Hawi (pl. 50A). The cones range from 50 to 250 feet in height. Puu Kamalii and Puu Ulaula, respectively 1 mile northeast and 4½ miles north of Kawaihae, and Puu Neenee half a mile northeast of Waimea, are cones in this series. Puu Ulaula lies on the coast, but it lacks the sandy beds typical of a littoral cone and is not shown as such on plate 1.

---

[89] The specimens studied were collected by Kenneth Bond.

It must have formed during a stand of the sea lower than the present and was brought to sea level by Pleistocene submergence.

The cones are highly permeable but carry no water.

The heads of the great canyons cut swarms of closely spaced dikes. In the canyons tributary to Waipio the dikes trend chiefly N. 50°–80° W. and dip northeast about 75°. Farther north the trend is chiefly N. 40°–60° W. No canyon penetrates into the heart of the dike complex. The accompanying table gives the number of dikes exposed in each canyon, including those of the Hawi volcanic series.

Dikes in canyons in Kohala Mountain

Canyon	Number
Waipio	
Hiilawe Branch	4
Waima Branch[1]	36
Koiawe Branch	78
Alakahi Branch	62
Kawainui Branch	16
Waimanu	7
Waihilau Branch and tributaries	9
Honokane Nui	
East Branch	35
West Branch[2]	3
Pololu	1
	251

[1] Includes 20 dikes exposed in the ditch tunnel in the east wall of Waima Canyon.
[2] A recent landslide at an altitude of 1,500 feet prevented examination above it.

The dikes belonging to the Pololu volcanic series range in width from a few inches to 10 feet and average about 2 feet, as shown in the table below. All the dikes wider than 15 feet are trachytes and belong to the Hawi volcanic series.

Dikes in Kohala Mountain

Width (feet)	Number[1]
½ - 1	40
1 - 1½	48
1½ - 2	38
2 - 3	25
3 - 6	46
6 - 12	14
12 - 24	4
More than 24	2
	217

[1] Some of the dikes cut across the country and are measured in more than one canyon. Thick dikes are more apt to be measured at more than one place than thin dikes as they tend to crop out in spite of heavy vegetation.

Some of the dikes are platy and vesicular but most are dense and cross-jointed. A few multiple dikes were recorded. Most dikes have ⅛- to ½-inch glassy selvages. All petrologic types represented in the flows, ranging from fine-grained basalt to olivine-rich porphyries, are found among the dikes. A dike 5 feet wide, containing abundant feldspar phenocrysts 1 inch across, crops out along the ditch trail in Kawainui Canyon.

A large intrusive crops out for three quarters of a mile along the bed of Kawainui Stream (pl. 1). The stream has cut a series of spectacular pools and cascades in the columnar-jointed top of the intrusive. The dense fine grained basalt at the top grades downward into gabbro. The flat contact between it and the overlying lava flows suggests a sill but it may be the top of a stock.

The dike swarms confine large quantities of ground water in the intervening permeable Pololu lavas. The dry-weather flow of all large streams in Kohala Mountain is chiefly from high-level springs discharging from dike swarms. The flow of such springs is about 100 million gallons a day.

A crater fill 2,000 feet thick and 1 mile in diameter is exposed in Kawainui Stream (pl. 1). The fill is composed chiefly of massive columnar-jointed basalt flows that accumulated in a deep pit crater. Some of the flows are 100 feet thick. In the west side of the ancient crater at an altitude of 1,750 feet, the lavas overlie 600 feet of firmly cemented bedded talus breccia striking due west and dipping 32° S. This breccia overlies vent breccia which is cut by a 2-foot dike striking due west and dipping 40° N. The heavy horizontal lava beds in the crater fill stand in strong contrast to the thin-bedded basalts forming the walls of the ancient crater.

EROSIONAL UNCONFORMITY

A great erosional unconformity separates the Pololu from the Hawi volcanic series over much of the wet northeastern slope, but on the dry western slope the two series are separated by a red soil and a disconformity. The wet slope was eroded more rapidly than the dry slope; but also, as shown on page 181, the wet slope was a kipuka during the eruption of most of the Hawi lavas; hence, difference in rate of erosion of the two slopes is not the only factor involved.

A massive flow of oligoclase andesite of the Hawi volcanic series spilled into the east branch of Pololu Canyon and for 1½ miles the floor of the main canyon was covered with 200 feet of lava (fig. 33). Terraces of columnar-jointed andesite border Pololu Stream where it has cut a new gorge. At an altitude of 400 feet the stream tumbles off the lava leaving a terrace on the east bank only. At this place the base of the lava lying unconformably on boulder conglomerate is exposed in two waterfalls. The evidence is conclusive that Pololu Canyon had reached essentially its present size prior to the emplacement of the andesite. It is possible that the conglomerate under the lava was laid down by the stream during one of the high stands of the sea in the Pleistocene, as similar high level conglomerates in adjacent Honokane Nui Canyon owe their deposition to a higher stand of the sea.

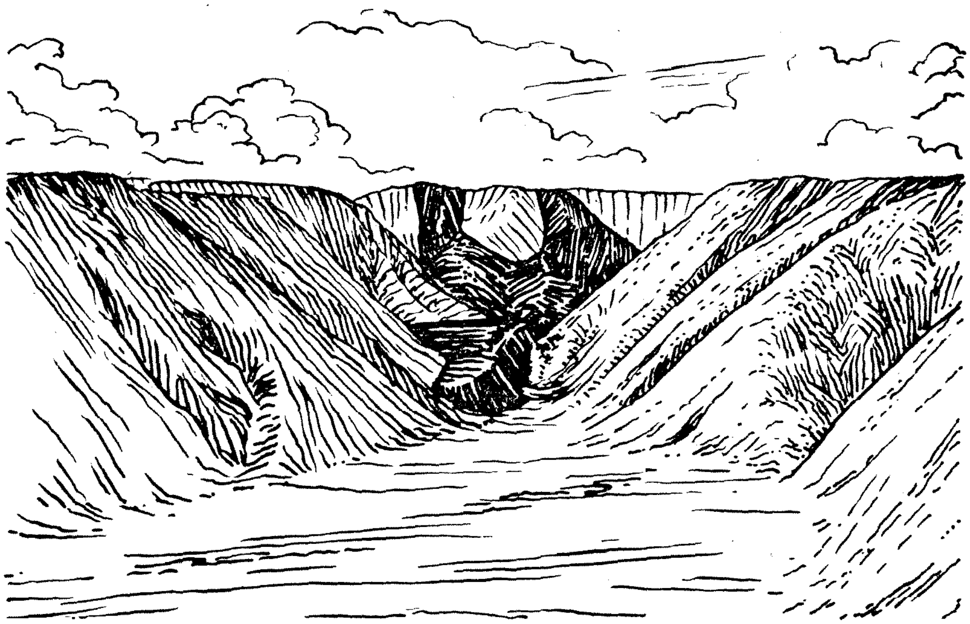


Figure 33. Sketch of Pololu Valley showing late valley-filling andesite lava flow.

A valley 325 feet deep cut in deeply weathered Pololu rocks, was filled with olivine basalt and capped with oligoclase andesite. It is exposed along the trail from Kukuihaele to the abandoned Honokaape Landing half a mile to the west. Waiulili Spring issues from the contact of the olivine basalt and the Pololu basalts. The olivine basalt is from Mauna Kea but the capping flow of andesite belongs to the Hawi volcanic series. Similar unconformable relationships exist in the sea cliff under the Pacific Sugar Mill, 1 mile east of Honokaape. The fact that beneath the unconformities at Honokaape and Pacific Sugar Mill the Pololu basalts are almost completely decomposed for a depth of 50 feet and the overlying andesites are fresh, is further evidence of the long time interval between the laying down of the Pololu and Hawi lavas in this area.

The valleys cut prior to the emplacement of the Hawi lavas were relatively shallow west of Pololu Valley. Tunnel 10 near Kapaau penetrated 5 feet of conglomerate under the basal andesite flow of the Hawi volcanic series. The andesite flows in this area thicken and thin abruptly showing that they commonly filled ravines 25 to 50 feet deep. A soil bed a few inches to 3 feet thick commonly separates the Pololu and Hawi lavas in this area and also on the western slope of Kohala Mountain. The evidence is conclusive that a repose period intervened between the eruption of the Pololu and Hawi volcanic series.

HAWI VOLCANIC SERIES

The Hawi volcanic series derives its name from Hawi, the main town on Kohala Mountain. The type section is exposed at an altitude of 400 feet in the quarry of the Kohala Sugar Company half a mile east of Hawi in Kumakua Gulch. A bed of massive columnar-jointed oligoclase andesite aa, 25 feet thick, rests on 6 inches of red soil that overlies weathered Pololu basalts. The lava extends inland as a narrow flow. The clinker on its surface is deeply weathered indicating that the flow is one of the oldest in the Hawi series.

The Hawi flows range from 10 to 150 feet thick and average about 40 feet. They dip 3° to 12° except where they spilled into ancient canyons and attained dips as high as 32°. The Hawi lavas consist of one flow near the perimeter of the mountain but inland increase, shingle fashion, to as many as four flows. They probably attain a total thickness of 500 feet near the summit, due to the fact that most of the flows were fairly viscous and only a few reached the coast. Many of those that reached the coast issued from cones part way down the slope. Their areal distribution is shown on plate 1.

The area of Hawi lavas shown on the ridge between Waipio and Waimanu streams is approximate only. The ridge is a swamp covered with dense jungle growth. Owing to deep weathering, only one specimen, collected one mile northeast of the summit, could be positively identified under the microscope as an oligoclase andesite. The swamp contains numerous sinkholes which are in nonporphyritic weathered aa, probably andesite.

The lavas are chiefly oligoclase andesites but several flows of trachyte and one of andesine andesite were found. One trachyte flow 150 feet thick issued from a bulbous dome 2 miles north of Waimea (fig. 29). Another crops out a quarter of a mile south of Kawainui Stream along the Upper Hamakua Ditch and at Upper Kawainui Springs (No. 23). It apparently issued from Puu Kaiholena half a mile south of the Kawainui intake of the Upper Hamakua Ditch. A third lies half a mile north of Puu Loa. It issued from a vent in the northern end of the summit graben. The andesine andesite issued from Puu Kawaiwai 5 miles northwest of Waimea. It carries considerable soil and is transitional between the Pololu and Hawi volcanic series. Possibly it is a Mauna Kea cone.

The lavas are identified in hand specimens by platy cleavage and minute fish-scale appearance produced by the reflection of light from the small uniform feldspars in the groundmass. The trachytic texture produced by the minute oriented feldspars is readily discernable in partly weathered specimens. A few of the flows carry equant feldspar phenocrysts but most flows are nonporphyritic. All the flows are aa except a few near the vents where they have poorly developed pahoehoe surfaces. Many are typical block lavas. The younger flows have abrupt terminal margins where the lava piled up, too sticky to move farther. The rough nature of their surface is not lost even when considerably weathered and covered with grass. A strong sidelight enables one from a distance to distinguish the areas covered by the rough andesites in contrast to the smoother areas underlain by the Pololu basalts.

The flows carry a few inches to 3 feet of soil depending on their age, the amount of rainfall on them, and their nearness to cones which sprinkled ash on them. In dry areas they are commonly rocky. Cane is grown on them between Pololu Valley and Hawi, but the soil is thin and ploughed fields expose gray partly weathered clinker. The clinker imparts an ashy gray color to the soil in contrast to the brown and red-brown deep soils on the adjacent Pololu basalts. The gray color and shallow soil make the Hawi lavas easily mappable as they crop out almost continuously in secondary roads.

The Hawi lavas, because of their massiveness and youth, form a protective armor over the easily eroded, deeply weathered Pololu basalts. Streams commonly develop deep plunge pools where they leave the andesites. Thin ashy soil beds and small lenses of gravel lie between some of the andesite flows, indicating that the andesites accumulated more slowly than the basalts.

The Hawi lavas carry small quantities of water perched on the intervening soils and dense layers. Most of the water however, moves through the basal lavas where they lie in shallow valleys and swales on the decomposed surface of the underlying Pololu lavas (fig. 45).

Most of the andesites issued in a more viscous state than the basalts and the gases escaped more violently. Consequently, the lava fountains built bulky cinder cones mostly more than 250 feet high and some 700 feet high (pl. 50B). These prominent cinder cones lie chiefly along the crest of the mountain in the main rifts but are more scattered than the basaltic cones (pl. 1). The cinders are notably fresher than those in the basaltic cones, making them useful for road metal. A sufficient number of andesite dikes are exposed to prove that the Hawi lavas were erupted from fissures which are now masked by the cones. Vitric ash deposits mantle the lavas adjacent to the cones and ash beds 2 to 6 feet thick are interstratified with the flows. The thickest ash lies on the slope above Waimea and around Puu Pili near Kahua Ranch. Puu Kaiholena is apparently a trachyte cone, as a broad flow of trachyte extends eastward from it. The trachyte dike in Alakahi Canyon strikes toward Puu Kaiholena and also toward the cone on the northern rim of the canyon. Perhaps the latter is also a trachyte cone.

Six bulbous domes were found at the source of six flows but only four are large enough to be shown on plate 1. They indicate that a few flows reached the surface either too low in gas content or too viscous to form lava fountains; hence, they squeezed out like paste from a tube (fig. 29). The largest dome, composed of trachyte, is half a mile in diameter and 250 feet high. It lies 2½ miles north of Kamuela Post Office. Details of the emplacement of similar domes on West Maui have been described.[90]

The dikes of the Hawi volcanic series range in width from 3 to 40 feet but widths greater than 10 feet are rare. A 30-foot dike of hornblende-biotite trachyte striking N. 65° W. crops out at an altitude of 1,250 feet in Alakahi Canyon (pl. 51C). A 40-foot dike of similar trachyte striking N. 80° W. cuts across Koiawe Canyon at an altitude of 1,150 feet. They may be the same dike. An 18-foot trachyte dike strikes N. 40° W. and dips 75° N. across the West Branch of Honokane Nui Canyon at an altitude of 850 feet. It separates into two 12-foot dikes 6 feet apart in the east wall of the East Branch of the canyon, but crops out as a single dike 20 feet wide in the head of Pololu Valley. Most of the dikes are fine grained and cross jointed. They are not differentiated from basaltic dikes on plate 1. They trend N. 40° to 80° W. and commonly dip northward about 75°.

STRUCTURE OF KOHALA MOUNTAIN

Kohala Mountain is an asymmetrical dome elongated northwest-southeastward (pl. 51A). The lava beds dip 2° to 12° away from Opaeloa, a late cone at the apex of the mountain. Part of the apex of the dome is missing due to collapse. No folding was observed. Two main rift zones, one trending N. 35° W. and the other S. 65° E. intersect at the summit. A third poorly developed rift trends S. 50° W. from the summit area. Lavas have been erupted along all rifts but the northwest rift has been most productive.

An unusual number of dikes dip northward from 60° to 85° in the northern side of the mountain. They may indicate collapse over

---

[90] Idem, pp. 175–179.

an elongate magma reservoir. The collapse produced a trough or graben that extends for 6 miles N. 50° W. across the summit. The main trough is half a mile wide but it is paralleled by echelon faults that bound a sunken area 3 miles wide. The curved pattern of the faults (pl. 1) suggests the former existence of an oval caldera about 3 miles long and 2 miles wide. It probably existed at the close of Pololu activity. After that, a lava cone about 1,000 feet high was built in the caldera but this also partly collapsed. The collapse continued through Hawi time as shown by numerous faults displacing flows and cones of this volcanic series. However, the rate of collapse decreased and flows gradually buried some of the fault scarps.

The fault scarps played an important role in the distribution of the andesites. The graben was deep enough to direct all the andesite flows that issued in it toward either the southeast or the northwest for a distance of 3 miles. Apparently no flows passed over either the scarp between Kawainui and Honokane Nui streams or over the scarp on the opposite side of the graben. Thus, two large areas of basalt were not covered with andesite flows (pl. 1). Lahikiola is the northwesternmost andesite cone. Thus a large segment of the northwestern end of the mountain is not covered with andesite. The distribution of the andesite was controlled by the loci of eruption also. The andesite vents were restricted to the summit portion of the mountain directly over the magma reservoir, indicating that the rifts were less subject to rupture than during the preceding repose period.

Many faults are probably concealed by vegetation. Air photographs clearly show the fault scarps in the summit area, and most of them were mapped from air pictures. A few faults are exposed conspicuously in canyon walls (pl. 51B) such as those in Waihilau Canyon.

The fault nearest the head of this canyon strikes N. 30° W. and dips 60° SW. It is bordered by two feet of red gouge on the east side and 8 inches of gray gouge on the west side. Two dikes, 18 inches wide, trending N. 40° W., are truncated by the fault. They are downthrown out of sight, or more than 100 feet.

In the southern wall half a mile downstream next to a waterfall is another fault striking N. 40° W. and dipping 75° NE. Three feet of breccia lies along the northeast side of the fault trace and 1 foot along the southwest side. Four inches of gouge parallels the trace. An 18-inch dike cuts irregularly through the breccia on the northeast side. The lava beds dip about 12° NW. The downthrow is not measurable. The compact breccia and gouge along the fault have resisted erosion and form a sheer smooth cliff 200 feet high.

The two faults in Waihilau Canyon parallel the faults at the head of Honokane Nui Canyon and bound a horst or raised block half a mile wide. The block does not show in the topography to the northwest, indicating either that the displacement died out quickly or that the fault scarps were buried by later flows. The latter is a more probable explanation.

A fault striking N. 15° W. and dipping 80° W. cuts across the head of the East Branch of Honokane Nui Canyon.

RELATION OF KOHALA MOUNTAIN TO MAUNA KEA

The steep dip of the lavas in Kohala Mountain between Waimea and Kawaihae in contrast to the adjacent flat dips in the Mauna Kea lavas is proof that the Mauna Kea lavas are banked against Kohala lavas, which in this area chiefly belong to the Pololu volcanic series. The almost imperceptible boundary between Mauna Kea and Kohala northeast of Waimea is due to the fact that the lavas of the Hawi and Hamakua volcanic series interfinger, as shown by the section exposed in the cliff under the Pacific Sugar Mill.

Oligoclase andesites have not been found in Mauna Kea, but they are abundant in Kohala Mountain; hence, bed 5 belongs in the Hawi series. An olivine basalt from Mauna Kea underlies an oligoclase andesite from Kohala Mountain above the erosional unconformity at the top of the Pololu series in the trail to Honokaape Landing, 1 mile southwest of the section described above. Thus the late lavas on Kohala Mountain were erupted concurrently with the late lavas of the Hamakua series on Mauna Kea or before the deposition of the bulk of the Pahala ash.

Section under Pacific Sugar Mill near Kukuihaele, Hawaii

	Thickness (feet)
Aa picrite-basalt with phenocrysts of olivine and augite, the olivines altered to iddingsite (Mauna Kea)	30
Ashy soil mixed with clinker	0.3
Basalt with phenocrysts of olivine, augite, and feldspar (Mauna Kea)	40
Red vitric ash	0.3
Nonporphyritic oligoclase andesite (Kohala)	25
Picrite-basalt with phenocrysts of olivine and augite larger than in bed No. 1 (Mauna Kea)	15
Erosional unconformity	....
Deeply weathered olivine basalt pahoehoe (Kohala) extending below sea level	30+
	140.6+

GEOLOGIC HISTORY OF HAWAII

Much of the geologic history of the island is not decipherable because of the lack of deep dissection and because so much of the island lies below sea level. How long ago the first lava issued from a fissure on the ocean floor at the present site of Hawaii, and which of the great domes was born at that time, are questions that will long remain unanswered. The permanence of rifts makes it likely, but not certain, that the island is built from the ocean floor by the coalescence of the five volcanoes we now see plus a submarine dome west of Kohala Mountain (fig. 4). We know that only primitive basalt, the undifferentiated parent magma of the basaltic substratum, is exposed in the base of all five volcanoes. No indication exists of other buried volcanoes. The stratigraphic units shown on plate 1 can be dated only approximately, by means of eustatic shore lines and evidences of glaciation on Mauna Kea. The history of the island as summarized below relates to the part above present sea level.

TERTIARY TIME

1. Primitive olivine basalts were poured out rapidly to build shield-shaped islands over the Western Fundamental Fissure at the sites of Mauna Loa and Hualalai, and over the Eastern Fundamental Fissure at the sites of Mauna Kea and Kohala Mountain. Apparently most of the Ninole, Hualalai, Pololu, and the lower part of the Hamakua volcanic series had been erupted by the end of Tertiary time. A caldera caused chiefly by collapse had probably developed on Kohala Volcano and faulting had produced scarps in the southeastern slope of Mauna Loa. Lava flows were erupted chiefly from fissures bordered by spatter ramparts or marked by chains of small cinder and spatter cones.

EARLY AND MIDDLE PLEISTOCENE TIME

2. Coalescence of the several separate island domes to form a single island. Cessation of volcanism on Kohala Volcano and probably on Mauna Loa, at least on its southeastern slope. Weathering and vigorous stream erosion of the northeastern slope of Kohala Volcano and the southeastern slope of Mauna Loa. Eruption of the Hamakua volcanic series on Mauna Kea continued. Kilauea was probably born at the intersection of the faults on the southeastern slope of Mauna Loa with the Eastern Fundamental Fissure, resulting in the eruption of the Hilina volcanic series. Continued eruption of the Hualalai volcanic series. Differentiation proceeding in the Kohala magma reservoir.

3. Canyons reached a depth of about 3,000 feet in Kohala Mountain and Mauna Loa and high sea cliffs were cut. Eruption of the Waawaa volcanics on the north rift of Hualalai. Renewed volcanism on Kohala Volcano and the outpouring of the Hawi volcanic series. Renewed volcanism on Mauna Loa and the eruption of the Kahuku volcanic series. The Hawi and Kahuku lavas in places spilled into and nearly filled some of the canyons cut in the preceding repose period. Progressive decline in the rate of volcanism on Mauna Kea and possibly on Kilauea as the upper parts of the Hamakua and Hilina volcanic series were laid down.
4. Submergence of the island an unknown amount, perhaps as much as 2,500 feet, causing alluviation of canyon mouths, especially those in Kohala Mountain.
5. Rapid re-emergence of the island perhaps as much as 1,500 feet. Concurrent stream erosion removed the alluvium in small canyons but left high gravel terraces in the large canyons on Kohala Volcano. A short halt occurred, forming the Olowalu shore line 250 feet above present sea level. Continued volcanism on Mauna Loa, Mauna Kea, Kilauea, and Hualalai, and dying volcanism on Kohala Volcano. The re-emergence halted about 300 feet below present sea level. Marine erosion made high cliffs along shores exposed to strong wave action. Streams began to cut gulches into the wet northeastern slope of Mauna Kea.
6. Rapid resubmergence of 400 feet to the Kaena shore line about 100 feet above present sea level. Renewed alluviation in the large canyons of Kohala Volcano. Kohala Volcano became extinct.

Late Pleistocene time

7. Accumulation of the Pahala ash on all five volcanoes on slopes not being overflowed by lava. Increase in the explosive activity of Mauna Kea and possibly of Kilauea. Decline in the volcanic activity of Hualalai and probably Mauna Loa. The earliest flows of the Kau and Puna volcanic series on Mauna Loa and Kilauea were laid down. Extrusion of the lower member of the Laupahoehoe volcanic series on Mauna Kea, some of the flows filling stream valleys and others spilling over sea cliffs. These volcanics also probably filled a caldera in the summit of Mauna Kea. The ocean receded to a shore line about 60 feet below present sea level, then rose 85 feet, benches and sea caves being cut 25 feet above present sea level. It then receded 20 feet to cut sea caves and benches 5 feet above present sea level. A glacier formed on the top of Mauna Kea.

RECENT TIME

9. During prehistoric Recent time, the glacier on Mauna Kea melted. Weathering and erosion continued on Kohala Mountain. Mauna Loa and Kilauea were very active laying down the remaining part of the Kau and Puna volcanic series. Occasional phreatic and phreatomagmatic explosions occurred at Kilauea and Mauna Loa. Activity on Hualalai and Mauna Kea continued to wane. The upper member of the Laupahoehoe volcanic series was erupted on Mauna Kea. The sea dropped 5 feet, abandoning a bench at that level.
10. During historic time Mauna Kea has not erupted; Hualalai erupted in 1800-1801; Mauna Loa has poured out numerous flows; Kilauea exploded violently in 1790 and 1924, has had a lava lake part of the time in its summit crater, and has poured out a few flank flows.

ROAD METAL

Many small quarries, worked principally for road metal, are shown on plate 1. Both basalts and andesites are quarried for this purpose, but andesites are generally superior, being denser and more massive. Along the Hamakua coast of Mauna Kea, where both are available, most of the quarries are in andesite. Elsewhere, however, basalt is quarried extensively, and supplies excellent road metal. The county quarry in the North Kona District, 3 miles north of Kainaliu, is working a dense bed of basalt. A quarry east of Honuapo, in Kau, yields crushed basalt from the dense central phase of a late thick aa flow. Road metal is obtained also from quarries in basalt on the flanks of Kilauea and Mauna Loa in both the Kau and Puna districts. A quarry 0.7 mile north of Kapoho, in eastern Puna, produced large blocks of basalt for construction of the breakwater at Hilo. Rock for the breakwater was taken from the sea cliff near Kukuihaele also, being loaded directly into barges anchored off shore. Most quarries on the slopes of Kohala Mountain are in dense flows of oligoclase andesite.

In many places loose clinker from the tops of aa flows is used in road building. Roads are constructed across aa much more easily than across pahoehoe because the clinker can be levelled with a bulldozer. Much of the road from Hilo across the Humuula Saddle was built in this way. Clinker from road cuts is used in constructing adjacent sections of highway. Along the road from Honokaa to Waimea are many small caves and tunnels which were excavated to obtain aa clinker for the road.

Cinder cones in all sections of the island have yielded material for roads. Quarries in cinder cones are prominent along the highway on the western slope of Kohala Mountain and along the cross-island road from Hilo to Waimea. The small cinder cone just west of Halai hill in Hilo has been almost completely removed for road surfacing. In eastern Puna, cinder cones such as Puu Kukae and Puu Kea near Kapoho, and littoral cones such as Kaakepa, have supplied cinder for roads.

PETROGRAPHY OF HAWAII

BY GORDON A. MACDONALD

INTRODUCTION

The petrography of the island of Hawaii has been discussed in detail elsewhere[91] and will be only briefly summarized here. The account is based on study of about 400 thin sections, supplemented by microscopic examinations of crushed material in oil of known refractive index, and hand lens examinations. Several thin sections of pyroclastic rocks were made available through the courtesy of C. K. Wentworth; one specimen of trachyte from Kohala was collected by W. O. Clark.

The classification of the rocks is based largely on the composition of the feldspar, those in which the average feldspar is labradorite or bytownite being termed basalt, those in which it is andesine or oligoclase being termed andesite, and those in which the predominant feldspar is alkalic being termed trachyte. The composition of the feldspar in most specimens was determined by immersion in oils of known refractive index, but in some by extinction angle methods. Those rocks containing 5 per cent of olivine are called olivine basalt; those containing less than 5 per cent of olivine are called basalt. Basaltic rocks which contain less than 35 per cent feldspar are called picrite-basalt. The picrite-basalts include a type in which the phenocrysts are almost entirely olivine, termed primitive picrite-basalt, and a type containing in addition to the olivine many phenocrysts of augite, termed augite-rich picrite-basalt. Andesites in which the dominant feldspar is andesine are called andesine andesite. They grade into the basalts, and commonly resemble them in habit and abundance of mafic minerals. Andesites in which the dominant feldspar is oligoclase are called oligoclase andesite. They appear to grade into both andesine andesites and trachytes.

The composition of the principal types of lava on the island of Hawaii is shown in the accompanying table (p. 189).

LAVA FLOWS

MAUNA LOA.—The Ninole volcanic series consists of predominant olivine basalt, with less abundant basalt and primitive picrite-basalt. Hypersthene-bearing lavas also occur. Hypersthene has not been found by the writer, but was reported by Cross in a speci-

---

[91] Macdonald, G. A., Petrography of the island of Hawaii: U. S. Geol. Survey Prof. Paper (waiting publication).

men from Clover Hill near Naalehu.[92] Among 12 specimens chosen at random from the Ninole volcanic series, the approximate proportions of rock types are: olivine basalt, 62%; basalt, 15%; primitive picrite-basalt, 15%; hypersthene-bearing basalt, 8%.

The constitution of the Kahuku volcanic series resembles that of the Ninole volcanic series in types of lavas, but proportions differ. The relative abundance of types among the Kahuku lavas is as follows: olivine basalt, 42%; basalt, 28%; primitive picrite-basalt, 20%; hypersthene-bearing basalt, 10%. The principal difference is the increase in abundance of primitive picrite-basalt and basalt, and a corresponding decrease in olivine basalt.

The prehistoric lavas of the Kau volcanic series contain the same rock types as the Kahuku lavas, in very nearly the same abundance. Among the historic lavas, picrite-basalt is less abundant and hypersthene-bearing basalt is much more abundant (47%), whereas olivine basalt without hypersthene comprises only 16 per cent. A typical assemblage of Kau lavas is represented in the accompanying stratigraphic section measured in the western wall of Mokuaweoweo Caldera. The lower part of the section is shown in plate 15B.

A late aa flow of basalt, characterized by the abundance of large accretionary lava balls, on the north flank of Mauna Loa 4.35 miles N. 22° W. of Puu Ulaula, is believed by Jaggar to be part of the lava flow of 1880.[93] The lava near Hilo, which is known to have been extruded during the latter stages of the eruption of 1880-81, contains microphenocrysts of both hypersthene and olivine, but neither has been found in the lava flow characterized by accretionary lava balls on the north slope of Mauna Loa. Hence, it is believed that the latter lava is probably not part of the flow of 1880.

The primitive magma of the Hawaiian province almost certainly corresponds in composition to olivine basalt. The large proportion of olivine basalt in the Ninole lavas thus represents a relatively small departure from the original magma. The picrite-basalts were probably formed by gravitative settling and accumulation of olivine crystals in the lower part of the magma column, leaving in the upper part a reciprocal phase of basalt poor in olivine. The greater abundance of basalt and picrite-basalt in the Kahuku and Kau lavas indicates that an increase in the amount of differentiation, or splitting of the magma into two complementary portions, by this process of crystal settling, occurred with the passage of time.

---

[92] Stearns, H. T., and Clark, W. O., Geology and water resources of the Kau District, Hawaii: U. S. Geol. Survey Water-Supply Paper 616, p. 160, 1930.

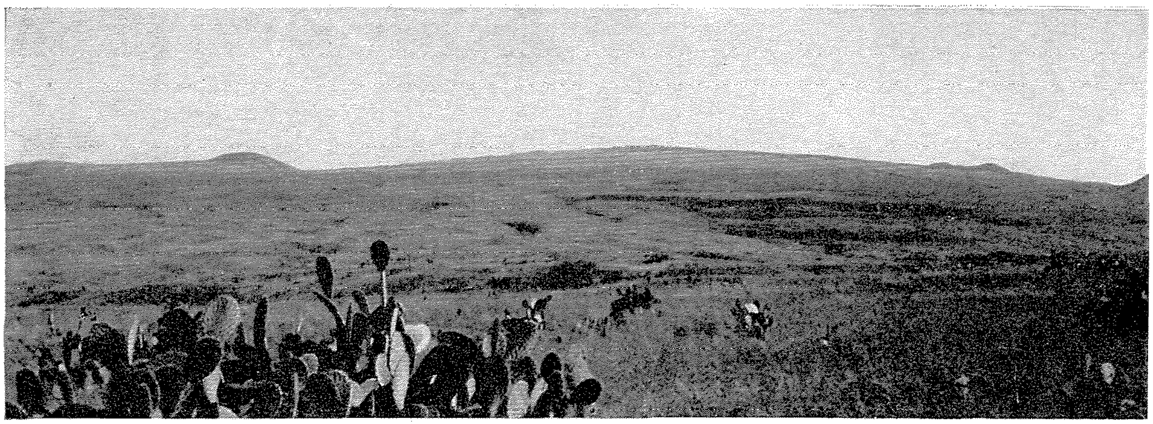
[93] Jaggar, T. A., Volcano Letter, no. 465, July-September, 1939.

Description of principal rock types of the island of Hawaii

Rock name	Texture		Composition	
	Megascopic texture	Groundmass texture	Phenocrysts	Groundmass
Olivine basalt	Porphyritic, less commonly nonporphyritic	Generally intergranular or intersertal. Thin chilled crusts and glassy pyroclastic ejecta are hyalopilitic or hyaloophitic. Average grain size 0.02 to 0.2 mm, most commonly about 0.07 mm.	Olivine, 0-20%, 1-8 mm long. Plagioclase, 0-25%, rarely more; 1-10 mm long, rarely up to 25 mm; zoned from Ab_{20}-Ab_{50}. Augite, 0-15%, 1-10 mm long.	Plagioclase (Ab_{35}-Ab_{50}), 25-45%; a little interstitial andesine; monoclinic pyroxene, 25-45%; olivine, 1-15%; iron ore, both magnetite and ilmenite, 7-15%; apatite recognizable in a few specimens; some contain glass.
Basalt	Porphyritic, less commonly nonporphyritic		Olivine, 0-3%, 1-4 mm long. Plagioclase, 0-20%, 1-5 mm long, zoned from Ab_{20}-Ab_{50}. Augite, 0-3%, 1-5 mm long.	Plagioclase (Ab_{35}-Ab_{50}), 30-50%; a little interstitial andesine; monoclinic pyroxene, 30-50%; olivine, 0-3%; iron ore, both magnetite and ilmenite, 7-15%; rare rutile; apatite recognizable in a few specimens; some contain glass.
Hypersthene-bearing basalt	Porphyritic, rarely nonporphyritic		Olivine, 0-10%, 1-8 mm long. Plagioclase, 0-20%, 1-5 mm long, zoned from Ab_{25}-Ab_{45}. Augite, rare. Hypersthene, 1-5%, rarely more; 0.4-1.5 mm long.	Plagioclase (Ab_{35}-Ab_{50}), 27-45%; a little interstitial andesine; monoclinic pyroxene, 30-48%; olivine, 0-7%; iron ore, both magnetite and ilmenite, 8-15%; apatite recognizable in some specimens; some contain glass.
Primitive picrite-basalt	Porphyritic		Olivine, 20-50%, 1-10 mm long. Plagioclase, 0-5%, 1-5 mm long, zoned from Ab_{20}-Ab_{45}. Augite, 0-5%, 1-10 mm long.	Plagioclase (Ab_{30}-Ab_{45}), 20-30%; monoclinic pyroxene, 20-35%; olivine, 1-5%; iron ore, both magnetite and ilmenite, 5-15%; rare rutile; some specimens contain glass.
Augite-rich picrite-basalt	Porphyritic		Olivine, 15-25%, 5-10 mm long. Plagioclase, 0-7%, 1-5 mm long, zoned from Ab_{20}-Ab_{45}. Augite, 10-30%, 6-10 mm long.	Plagioclase (Ab_{35}-Ab_{45}), 20-30%; monoclinic pyroxene, 20-35%; olivine, 1-5%; iron ore, both magnetite and ilmenite, 5-10%; some specimens contain glass.
Andesine andesite	Porphyritic or nonporphyritic		Olivine, rare, 0-5%, 1-4 mm long. Plagioclase, 0-15%; 1-5 mm long, rarely up to 20 mm; zoned from Ab_{20}-Ab_{70}. Augite, rare, 0-1%, 1-2 mm long.	Plagioclase (Ab_{50}-Ab_{70}), 40-55%; monoclinic pyroxene, 20-40%; olivine, 1-10%; iron ore, magnetite commonly predominant over ilmenite, 10-20%; biotite, 0-3%; apatite recognizable in many specimens; a riebeckite-like amphibole, rare; some specimens contain glass.
Oligoclase andesite	Porphyritic or nonporphyritic	Trachytic. The trachyte pumice of Puu Waawaa is largely glass, but glass is not abundant elsewhere. Average grain size is commonly about 0.04 mm.	Olivine, rare, 0-1%, 1-7 mm long. Plagioclase, 0-5%, 1-8 mm long, zoned from Ab_{45}-Ab_{80}. Riebeckite-like amphibole, 0-1%, less than 1 mm long. Basaltic hornblende, rare.	Plagioclase (Ab_{70}-Ab_{85}), 50-60%; monoclinic pyroxene, 15-30%; olivine, 1-8%; iron ore, mostly magnetite but some ilmenite, 10-25%; biotite, 0-2%; riebeckite-like amphibole, 0-1%; apatite, about 1%; hornblende, rare, 0-1%; some specimens contain glass.
Trachyte	Porphyritic or nonporphyritic		Olivine, 0-1%, rarely more; up to 1 mm long. Plagioclase, 0-10%, 1-4 mm long, zoned from Ab_{70}-Ab_{95}. Hornblende, 0-1%, 1-2 mm long, both brown and green. Riebeckite-like amphibole, 0-1%, less than 1 mm long. Biotite, rare.	Plagioclase (Ab_{90}-Ab_{95}), 65-85%; monoclinic pyroxene, 5-25%; olivine, 0-5%; iron ore, largely or entirely magnetite, 5-15%; apatite, about 1%; biotite, 0-2%; green hornblende, 0-1%; some specimens contain glass.

Stratigraphic section in west wall of Mokuaweoweo Caldera

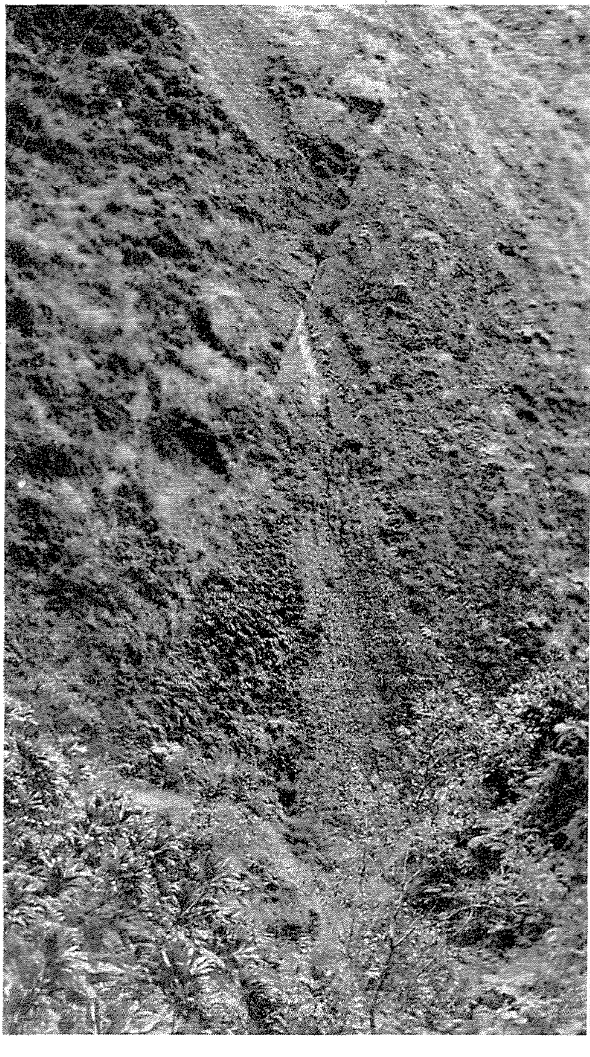
	Thickness (feet)
Basalt aa, with about 1% olivine phenocrysts and 2% feldspar phenocrysts, reaching 2 mm long	5
Olivine basalt pahoehoe, with about 5% olivine phenocrysts up to 2 mm long, and 2% feldspar phenocrysts up to 1 mm	8
Basalt pahoehoe, with about 1% each of olivine and feldspar phenocrysts up to 1 mm long	10
Basalt pahoehoe, with about 2% each of olivine and feldspar phenocrysts up to 1.5 mm long	5
Like above	4
Olivine basalt pahoehoe, with about 10% olivine phenocrysts up to 3 mm long	4
Olivine basalt pahoehoe, with about 8% olivine phenocrysts up to 2 mm long. Composed of several thin flow units averaging about 8 inches thick	8
Olivine basalt pahoehoe, with about 7% olivine phenocrysts up to 2 mm long	5
Like above	3
Like above, with about 4% olivine phenocrysts	4
Like above, with about 7% olivine phenocrysts	3
Basalt pahoehoe, with about 2% olivine phenocrysts up to 1.5 mm long	3
Olivine basalt pahoehoe, with about 5% olivine phenocrysts up to 3 mm long	4
Basalt pahoehoe, with about 2% olivine phenocrysts up to 2 mm long	2
Like above	1
Like above	11
Break in section. Continued 300 feet to the southwest.	
Basalt pahoehoe, with about 2% olivine phenocrysts up to 2 mm long	9
Olivine basalt pahoehoe, with about 7% olivine phenocrysts up to 2 mm long. Composed of several thin flow units averaging about 6 inches thick	3
Olivine basalt pahoehoe, with about 7% olivine phenocrysts and a few feldspar phenocrysts up to 2 mm long	4
Like above; some of the olivine phenocrysts very tabular	2
Like above	5
Like above; olivine phenocrysts up to 1.5 mm long	5
Basalt pahoehoe, containing about 1% each of olivine and feldspar phenocrysts up to 1 mm long. The rock is moderately dense, and banded, with some very dense bands	19
Basalt pahoehoe, nonporphyritic	14
Olivine basalt pahoehoe, with about 3% each of olivine and feldspar phenocrysts up to 2 mm long	4
Like above	8
Olivine basalt pahoehoe, composed of many thin flow units averaging about 5 inches thick, with 4-10% of olivine phenocrysts up to 3 mm long	34
Olivine basalt pahoehoe, with about 10% olivine phenocrysts up to 3 mm long	10
Olivine basalt pahoehoe, containing about 5% each of olivine and feldspar phenocrysts up to 2 mm long. Consists of many thin lenticular flow units averaging about 3 inches thick	2
Olivine basalt pahoehoe, containing about 20% olivine phenocrysts up to 5 mm long	15
Olivine basalt pahoehoe, containing about 20% olivine phenocrysts up to 6 mm long, and many feldspar phenocrysts up to 1.5 mm long	7
Picrite-basalt pahoehoe, with about 30% olivine phenocrysts up to 8 mm long, and many feldspar phenocrysts up to 1.5 mm long	4
Like above	5
Olivine basalt pahoehoe, with about 15% olivine phenocrysts up to 7 mm long	8
Picrite-basalt pahoehoe, containing about 25% olivine phenocrysts up to 8 mm long. The lower part is very dense	20
Picrite-basalt pahoehoe, with about 30% olivine phenocrysts up to 1 cm long	10
Olivine basalt pahoehoe, composed of thin flow units averaging about 8 inches thick. Olivine phenocrysts up to 4 mm long range in abundance from about 10 to 15%	12
Like above, with about 8% olivine phenocrysts up to 3 mm long, and less abundant feldspar phenocrysts up to 1.5 mm long	5
Basalt pahoehoe, nonporphyritic	5
Basalt pahoehoe, containing about 2% olivine phenocrysts up to 1.5 mm long. Consists of many thin flow units averaging about 6 inches thick	12
Pod-shaped basalt porphyry intrusive body, fed by a dike and showing slightly discordant relations to the enclosing beds (see pl. 15B)	26
Olivine basalt pahoehoe, with about 4% olivine phenocrysts up to 2 mm long largely altered to iddingsite	4
Olivine basalt pahoehoe, with about 15% olivine phenocrysts up to 3 mm long. The groundmass is reddish-brown in color	8
Olivine basalt pahoehoe, with about 5% olivine phenocrysts up to 2 mm long	3
Basalt pahoehoe, with about 2% olivine phenocrysts up to 1.5 mm long	5
Basalt pahoehoe, essentially nonporphyritic but with rare olivine phenocrysts up to 1 mm long. Consists of many thin flow units averaging about 2 inches thick. Cut by a dike of olivine basalt 1 foot thick, containing about 5% olivine phenocrysts up to 2 mm long	10
Olivine basalt pahoehoe, containing about 7% olivine phenocrysts up to 3 mm long. The size and abundance of the phenocrysts decrease slightly upward	12
Basalt pahoehoe, nonporphyritic	5
Olivine basalt pahoehoe, with about 15% olivine phenocrysts up to 4 mm long, and a few feldspar phenocrysts up to 1 mm long. Cut by a dike of olivine basalt 9 inches thick, containing about 5% olivine phenocrysts up to 2 mm long	6
Picrite-basalt pahoehoe, with about 35% olivine phenocrysts up to 1 cm long. Composed of thin flow units averaging about 6 inches thick	4
Picrite-basalt pahoehoe, like above, but consisting of a single massive bed. The vesicles contain small botryoidal growths of calcite. Base hidden by the 1942 lava	7
Slump scarp of 1942 lava; black glassy crustal phase of olivine-poor basalt	18
Total thickness of section	410

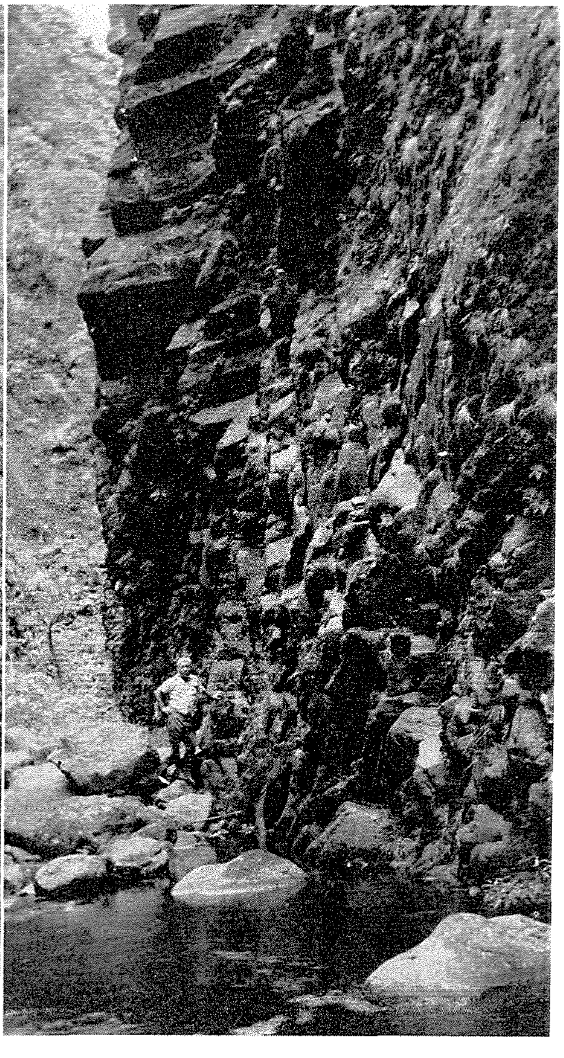


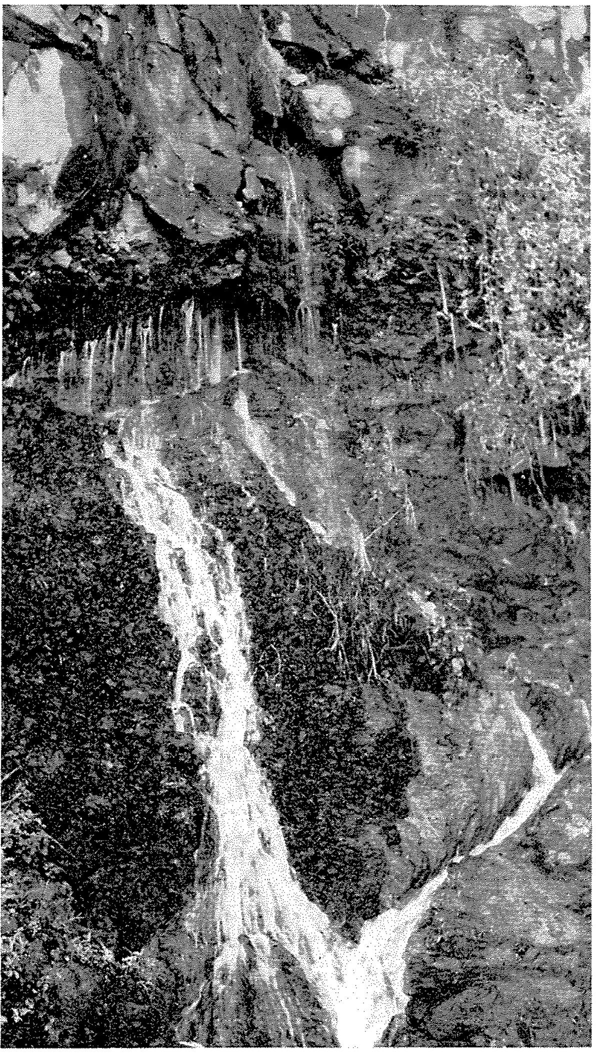
Above: Plate 51A. The basaltic dome of Kohala Mountain with superimposed andesite cinder cones as seen from the road to Kawaihae. Photo by H. T. Stearns.

Below, left: Plate 51B. Fault cutting lavas of the Pololu volcanic series in Waihilau Canyon, Kohala Mountain. Photo by H. T. Stearns.

Below, right: Plate 51C. Horizontally jointed hornblende-biotite trachyte dike in Alakahi Canyon, a tributary of Waipio Valley, Kohala Mountain. Photo by H. T. Stearns.



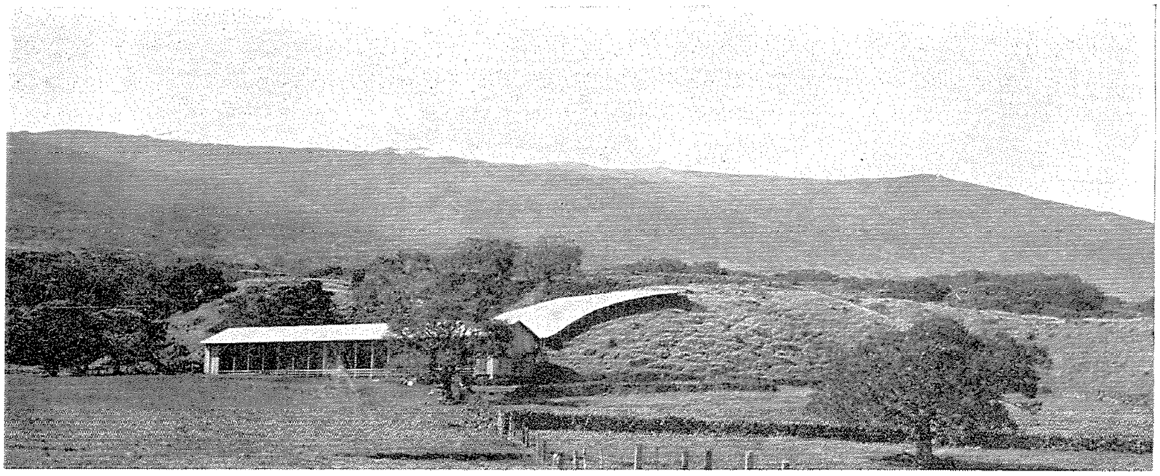




Above, left: Plate 52A. Spring 27 discharging about two million gallons a day from eroded dikes in the head of Koiawe Canyon, a tributary of Waipio Valley. Photo by H. T. Stearns.

Above, right: Plate 52B. Spring 49 issuing from the top of a soil bed in a road cut half a mile southeast of Laupahoehoe Gulch, Mauna Kea. Photo by G. A. Macdonald.

Below: Plate 52C. Sheet-iron rain sheds at Hopuwai, Mauna Kea. Photo by G. A. Macdonald.



KILAUEA.—About two-thirds of the lavas of the Hilina volcanic series are olivine basalt. Most of the rest are basalt. Primitive picrite-basalt is rare and hypersthene-bearing lavas have not been found. The accompanying stratigraphic section at Hilina Pali illustrates the general character of the Hilina volcanic series.

Stratigraphic section at Hilina Pali, 1 mile southwest of observation point at end of road

	Thickness (feet)
Basalt of the Puna volcanic series	100
Pahala ash. Thin-bedded ash of medium to fine sand size, some beds largely buff palagonite, others containing as much as 50% black glass fragments. Red soil 0-8 inches thick at top. Middle part of section contains numerous irregular beds up to 6 inches thick composed of cinders up to ¾ inch in diameter	50
Thin-bedded olivine basalt pahoehoe	25
Buff to yellow palagonitized ash, the lower half containing many cinders up to 1½ inches in diameter	2
Thin-bedded olivine basalt pahoehoe	50
Thin-bedded aa flows, 8 to 15 feet thick; a few thin beds of pahoehoe; largely basalt, some olivine basalt	180
Thin-bedded pahoehoe	50
Dense aa	10
Fine-grained buff palagonitized ash	5
Aa, two or more flows	30
Buff palagonitized ash	4
Dense aa	15
Buff palagonitized ash	20
Thin-bedded aa	60
Buff palagonitized tuff	3
Thin-bedded pahoehoe	35
Buff palagonitized ash, containing beds up to 3 inches thick of glassy lava-fountain ejecta up to ⅝ inch in diameter	10
Thin-bedded olivine basalt pahoehoe	50
Dike, striking N. 75° E., vertical, center vesicular; a 6-inch apophysis cuts the neighboring lavas	2
Thin-bedded pahoehoe	10
Fine-grained buff palagonitized ash	2
Olivine basalt aa	20
Thin-bedded pahoehoe	30
Total thickness of section	763

Among the prehistoric lavas of the Puna volcanic series the proportions of rock types are nearly the same as in the Hilina lavas. One hypersthene-bearing basalt was found half a mile east of Pahoa. The accompanying stratigraphic section at Uwekahuna Bluff, on the western wall of Kilauea Caldera, is typical of the prehistoric Puna lavas. Among the historic lavas, olivine basalt and primitive picrite-basalt are a little more abundant than in the prehistoric lavas and basalt is a little less abundant. However, the differences are probably not significant. The only historic lava found to contain hypersthene is the 1840 flow near Makaopuhi Crater, and in that it is very rare.

An interesting example of gravitative crystal differentiation is furnished by the lavas of 1840. Flows erupted from vents at altitudes of 3,100 to 2,650 feet, from Alae to Napau craters, contain very few phenocrysts of olivine; whereas lavas erupted a day or two later from vents at altitudes of 750 to 850 feet, in eastern Puna, are picrite-basalts containing about 30 percent of olivine phenocrysts. It is believed that the difference resulted from the settling of olivine phenocrysts in the Kilauean magma column, the upper portion becoming impoverished in olivine, and a lower portion being greatly enriched in olivine.[94]

SOLFATARIC ALTERATION AT KILAUEA CALDERA.—Gases escaping along faults at Kilauea Caldera have altered the adjoining rocks, both lavas and tuffs. Most prominent is a type of alteration caused by steam containing low concentrations of sulfuric, sulfurous, and carbonic acid. The resultant product is a rock composed largely of opal, with smaller amounts of kaolinite or related clay minerals, and relict magnetite and ilmenite. It has approximately the same volume as the unaltered rock, and original structures and textures are surprisingly well preserved.

Another type of alteration, caused by steam containing less acid, results in the formation of red powdery material composed largely of limonite and goethite, with some clay minerals.

These types of alteration were originally described on the basis of petrographic studies, supported by only meager chemical evidence.[95] A series of chemical analyses of altered rocks and their fresh or nearly fresh parent rocks, from the solfataric area at the southeastern edge of Kilauea Caldera has since come to the writer's attention.[96] The values for silica and alumina in the fresh rocks appear to be too high,[97] but the analyses, nevertheless, demonstrate the general course of changes involved in the alteration and confirm the petrographic deductions.

Figure 34 indicates graphically the changes demonstrated by the chemical analyses. Figure 34A shows the changes which take place in the alteration of basalt to the opaline product by sulfur-bearing gases, plotted on the basis of no change in the silica content. Actually, the amount of silica may have slightly increased in the altered rock. Figure 34B shows the changes occurring in the alteration of basalt to the limonite-goethite-clay mixture by nearly pure steam, plotted on the basis of no change in the alumina content. The alteration closely resembles that occurring in the formation of lateritic soils by normal weathering. Figure 34C shows, for comparison, the changes involved in the alteration of basalt to lateritic soil near Wahiawa, on the island of Oahu.[98]

Gases issuing from fissures on the caldera floor near the southeastern edge of Kilauea Caldera have deposited a white powdery substance which also was analyzed by Mau. It appears to consist

---

[94] Macdonald, G. A., The 1840 eruption and crystal differentiation in the Kilauean magma column: Am. Jour. Sci., vol. 242, pp. 177–189, 1944.

[95] Macdonald, G. A., Solfataric alteration of rocks at Kilauea Volcano: Am. Jour. Sci., vol. 242, pp. 496–505, 1944.

[96] Mau, K. T., A study of the chemical decomposition of rocks at Kilauea: Unpubl. thesis, Univ. Hawaii library, June, 1940.

[97] Another analysis in Mau's thesis has been shown by a partial check in the laboratory of the U. S. Geological Survey to be too high in silica and alumina, and too low in iron.

[98] Palmer, H. S., Soil forming processes in the Hawaiian Islands from the chemical and mineralogical points of view: Soil Science, vol. 31, pp. 254–255, 1931.

largely of gypsum and melanophlogite, with a small amount of opal.[99]

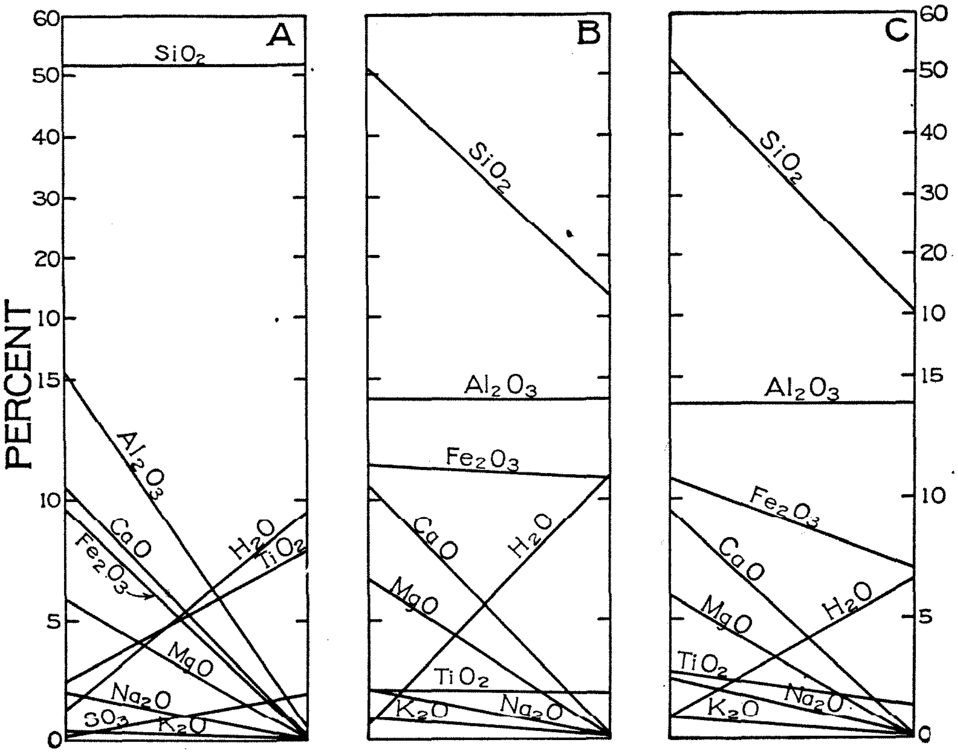


Figure 34. Graph showing alteration of rocks by (A) the action of steam containing weak concentrations of sulfuric, sulfurous, and carbonic acid at Kilauea Caldera, SiO_2 assumed to remain constant; (B) the action of steam containing little or no acid at Kilauea Caldera, Al_2O_3 assumed to remain constant; (C) normal lateritic weathering, Al_2O_3 assumed to remain constant. The total iron content is plotted as Fe_2O_3.

Stratigraphic section at Uwekahuna Bluff, Kilauea Caldera

	Thickness (feet)
Tuff-breccia, largely lithic, containing a few blocks up to 3 feet across; probably largely the result of the 1790 eruption. Locally, small pockets of pumice overlie the tuff-breccia. (Top of fault block 42 feet below Uwekahuna triangulation station)	3
Pumice and vitric ash	1
Olivine basalt pahoehoe, with moderately abundant olivine phenocrysts up to 2 mm long	12
Like above	14
Basalt pahoehoe, with a few olivine and feldspar phenocrysts up to 1.5 mm long	12
Olivine basalt pahoehoe, with moderately abundant olivine phenocrysts up to 1.5 mm long. Composed of several lenticular flow units from 8 inches to 2 feet thick	12
Basalt pahoehoe, with a few olivine phenocrysts up to 1 mm long	35
Basalt pahoehoe, with rare olivine phenocrysts up to 1.5 mm long. Consists of thin flow units averaging about 10 inches thick	9
Basalt pahoehoe, with scattered olivine phenocrysts up to 1.5 mm long	20
Basalt pahoehoe, essentially nonporphyritic, but with rare olivine phenocrysts less than 1 mm long	5
Basalt pahoehoe, with scattered olivine phenocrysts less than 1 mm long	4
Olivine basalt pahoehoe, with moderately abundant olivine phenocrysts up to 1.5 mm long	16
Like above	6
Basalt pahoehoe, nonporphyritic	23
Olivine basalt pahoehoe, with moderately abundant olivine phenocrysts up to 1.5 mm long	16
Basalt pahoehoe, with rare olivine phenocrysts up to 1 mm long	10
Basalt pahoehoe, essentially nonporphyritic, but with rare olivine phenocrysts less than 1 mm long. Ropy tachylite top. Composed of several thin lenticular flow units 1 to 3 feet thick	9

---

[99] Winchell, Horace, Unpublished statement quoted by Mau, K. T., op. cit.

Olivine basalt pahoehoe, with abundant olivine phenocrysts less than 1 mm long	10
Basalt pahoehoe, nonporphyritic	12
Olivine basalt pahoehoe, with olivine phenocrysts up to 6 mm long forming about 15 percent of the rock. The lower 4 feet is massive and dense, but the upper part is moderately to highly vesicular and formed of many thin flow units averaging about 5 inches thick	13
Olivine basalt, transitional to picrite-basalt. Consists of many thin layers of frothy pahoehoe, averaging about 2.5 inches thick, probably all parts of one flow. Olivine phenocrysts up to 5 mm long form 20 to 30 percent of the rock	19
Olivine basalt pahoehoe. Olivine phenocrysts up to 6 mm long form about 20 percent of the rock	4
Olivine basalt pahoehoe. Olivine phenocrysts up to 4 mm long form 15 to 20 percent of the rock	8
Olivine basalt, transitional to picrite-basalt. Olivine phenocrysts up to 6 mm long form about 25 percent of the rock. The upper 5 feet consists of many thin flow units averaging about 4 inches thick	17
Olivine basalt pahoehoe, with olivine phenocrysts up to 2 mm long forming about 5 percent of the rock	7
Basalt pahoehoe, essentially nonporphyritic, but with rare olivine phenocrysts up to 0.5 mm long	11
Olivine basalt pahoehoe. Olivine phenocrysts up to 2.5 mm long form about 10 percent of the rock	1
Olivine basalt pahoehoe, with about 15 percent olivine phenocrysts up to 6 mm long	8
Olivine basalt pahoehoe. Olivine phenocrysts up to 2.5 mm long form about 15 percent of the rock near the base, but decrease upward in both size and abundance, forming only about 7 percent near the top	16
Picrite-basalt pahoehoe, with about 35 percent olivine phenocrysts up to 3 mm long	4
Like above. May be another member of the same flow	9
Uwekahuna tuff of the Puna volcanic series; overlaps underlying lavas	7
Unconformity	
Basalt aa, with clinkery top. Contains scattered olivine phenocrysts up to 1 mm long	5
Like above	6
Basalt pahoehoe, with a few olivine phenocrysts less than 1 mm long. Consists of several thin flow units	6
Basalt pahoehoe, with scattered olivine phenocrysts up to 1.5 mm long	14
Like above; top poorly exposed	19
Like above; reddened top	13
Basalt pahoehoe, nonporphyritic, the vesicles lined with minute plates of feldspar	8
Not exposed; probably clinkery top of underlying aa flow	5
Olivine basalt, nonporphyritic, with the irregular vesicle shapes of aa. Many crystals of feldspar project into the vesicles. The rock is very massive. Although no olivine phenocrysts are present, the microscope reveals about 7 percent of olivine	17
Total thickness of section	446

HUALALAI.—The lavas of the Hualalai volcanic series are mostly olivine basalt, with less abundant basalt and rocks transitional from olivine basalt to picrite-basalt. One flow of andesine andesite was found. It crops out near the gate of the Territorial Forest Service cabin at Puu Laalaau. A few flows were found to be transitional between andesite and basalt. The rocks resemble those of the Kau volcanic series, except that augite phenocrysts are more common. The proportions of the principal rock types are approximately: olivine basalt, 67%; basalt and rocks transitional to picrite-basalt, in about equal amounts, 33%.

The lava of 1800-1801 is olivine basalt. The Kaupulehu flow contains numerous inclusions of gabbro, dunite, and augite peridotite (wehrlite).

The trachyte of Puu Anahulu consists largely of albite, probably containing occult potash-feldspar. Mafic minerals constitute only about 16 percent of the rock. They include magnetite, diopside, aegirine-augite, a few flakes of biotite, and a few grains of an amphibole resembling riebeckite. Locally it contains a few flakes of hematite, and rare small grains of a pale yellow mineral which may be acmite. Trachyte obsidian from Puu Waawaa is dark gray to black, and crudely banded. It contains a few microlites of alkalic feldspar and a mafic mineral. The pumice resembles the obsidian in composition, but is highly vesicular.

Mauna Kea.—The lower member of the Hamakua volcanic series consists largely of olivine basalt, with much less abundant primitive picrite-basalt and a little basalt. It grades into the upper member. Among the lavas of the upper member, olivine basalt is still predominant but basalt is more abundant than in the earlier lavas, and the place of the primitive picrite-basalt is taken by augite-rich picrite-basalt. Andesine andesite also is present in the upper member, as well as rocks transitional from andesite to basalt. The general characteristics of the Hamakua volcanic series are well exemplified by the accompanying stratigraphic section up the eastern wall of Laupahoehoe Gulch (pl. 46B). The preponderance of olivine basalt in the lower member and the relative abundance of other types in the upper member are evident.

The lavas of the Laupahoehoe volcanic series are mostly andesine andesite, but olivine basalt also is present. Neither basalt nor picrite-basalt has been found among them, but the amount of erosion has been small, and in most places only the uppermost part of the series can be studied. All of the post-glacial lavas are andesine andesite.

A variety of very fine grained dense nonporphyritic andesine andesite, which crops out on the upper southern slopes of Mauna Kea and is widespread as boulders in the glacial drift, was much used by the ancient Hawaiians in the manufacture of stone adzes.

Stratigraphic section along the highway up the south wall of Laupahoehoe Gulch

	Thickness (feet)
Upper member of the Hamakua volcanic series	
Olivine basalt pahoehoe, thin bedded, moderately to highly vesicular, with moderately abundant phenocrysts of olivine up to 3 mm long	10
Red tuffaceous soil	0.1–0.5
Local unconformity	
Andesite aa, containing a few olivine phenocrysts up to 4 mm long, and many plagioclase phenocrysts up to 2 cm long	35
Local unconformity	
Basaltic andesite aa, with scattered olivine phenocrysts up to 3 mm long	10
Red fine grained tuff	0–0.1
Basaltic andesite aa, with rare olivine phenocrysts up to 2 mm long	8
Red fine grained tuff	0.1–0.4
Olivine basalt aa, with scattered olivine phenocrysts up to 6 mm long	10
Local erosional unconformity	
Picrite-basalt aa, with abundant phenocrysts of olivine and augite, some up to 1 cm long	15
Poorly sorted boulder conglomerate	4
Buff fine grained tuff	0–0.7
Picrite-basalt aa, with abundant phenocrysts of olivine and augite up to 7 mm long	8
Lower member of the Hamakua volcanic series	
Reddish to grayish-brown tuffaceous silty soil	0.3–1.3
Olivine basalt pahoehoe, consisting of many thin flow units 0.6 to 8 feet thick, mostly between 1 and 2 feet. Olivine phenocrysts up to 3 mm long are moderately abundant in some units, but rare in others	65
Olivine basalt aa, with moderately abundant olivine phenocrysts up to 2 mm long	6
Olivine basalt aa, with a few olivine phenocrysts up to 5 mm long	9
Olivine basalt aa, with moderately abundant olivine phenocrysts up to 3 mm long	5
Olivine basalt aa, locally grading into pahoehoe, with moderately abundant olivine phenocrysts up to 4 mm long	6
Olivine basalt pahoehoe, locally grading into aa, with a few olivine phenocrysts up to 1.5 mm long	5
Olivine basalt pahoehoe, like above	6

Olivine basalt aa, with a few olivine phenocrysts up to 1.5 mm long	4
Olivine basalt pahoehoe, with scattered olivine phenocrysts up to 5 mm long, some of them very tabular. Composed of flow units 0.6 to 2 feet thick	8
Olivine basalt aa, with a few olivine phenocrysts up to 1.5 mm long	3
Olivine basalt aa, like above	6
Red fine grained tuff	0.1–0.3
Olivine basalt pahoehoe, with moderately abundant olivine phenocrysts up to 7 mm long. Composed of flow units 0.5 to 2 feet thick	7
Olivine basalt aa, with moderately abundant olivine phenocrysts up to 5 mm long	9
Picrite-basalt pahoehoe, of primitive type, with abundant olivine phenocrysts up to 8 mm long, but only rare augite phenocrysts. Base hidden by talus	7+
Total thickness of section	246+

KOHALA.—Nearly all of the lavas of the Pololu volcanic series are olivine basalt, although a few flows of basalt and picrite-basalt occur. In the lower part of the series the picrite-basalts are of the primitive type. In the uppermost part of the series augite phenocrysts are common in the olivine basalts, and the picrite-basalts are of the augite-rich type. The lavas are richer in feldspar phenocrysts than those of the other volcanoes on the island of Hawaii, and in flows exposed in the southeastern wall of Waipio Valley they reach lengths of 2 to 2.5 cm and form 30 to 50 percent of the rock. The accompanying stratigraphic section, measured along the trail up the southeastern wall of Waipio Valley, illustrates most of the characteristics of the Pololu lavas, except the increase in augite phenocrysts in the late lavas.

A single occurrence of oligoclase andesite has been included in the Pololu volcanic series. The rock crops out in a railroad cut 0.1 to 0.4 mile north of Mahukona. It appears to be the lava analyzed by Washington (column 7, p. 207). It is considered to belong to the Pololu lavas because of a capping of red ashy soil, 0 to 12 inches thick, which is missing from near-by Hawi lavas.

Most of the lavas of the Hawi volcanic series are oligoclase andesite. The dominant feldspar is calcic oligoclase in most specimens, but in some it is medium oligoclase. Biotite is a common minor constituent, and hornblende occurs in a few rocks. Many contain a few grains of a riebeckite-like amphibole. The only andesine andesite found among the Hawi lavas is the flow from Puu Kawaiwai, west-northwest of Waimea. The flow and cone are undoubtedly of Hawi age, but may belong to the contemporaneous upper member of the Hamakua volcanic series of Mauna Kea.

Several domes, flows, and dikes of trachyte were found. The dominant feldspar is albite, probably containing some potassic feldspar. Aegirine-augite occurs in a few specimens, but the dominant mafic mineral in most is diopside. The trachytes are less sodic than that of Puu Anahulu and those of West Maui.[1]

---

[1] Macdonald, G. A., Petrography of Maui: Hawaii Div. Hydrography, Bull. 7, pp. 323–325, 1942.

A list of localities at which trachyte has been discovered follows:

Dike, 40 feet thick, in south wall of Waima Canyon near its head.

Dike, 1,250 feet altitude, in Alakahi Stream; may be feeder for Kaholopoohina and Kahonohono cones, on the north and south rims of Alakahi Canyon respectively.

Dike, 18 feet thick, in West Branch of Honokane Nui Stream 0.25 mile above junction with East Branch.

Dike, 20 feet thick, at head of Pololu Valley; probably the same dike as the last.

Dome 1.6 miles N. 10° E. of Hokuula, and flow extending south-southwestward to 3,250 feet altitude.

Puu Kaiholena, cinder cone, and flow extending east-northeastward to rim of Kawainui Canyon.

Dome, at western side of Puu Kaiholena, and flow extending northeastward to rim of Kawainui Canyon.

Dome, 0.8 mile northwest of Kaunu o Kaleioohie, and flow extending southwestward to a point below the Waimea-Hawi road. The flow crosses the road a mile northwest of Puu Loa.

Stratigraphic section along trail up southeast wall of Waipio Valley

Hawi volcanic series	Thickness (feet)
Red ash	2
Oligoclase andesite aa	33
Pololu volcanic series	
Olivine basalt pahoehoe, thin bedded, much weathered, reddish-brown and soft, many joint surfaces coated with a purplish-black submetallic substance, probably manganese oxide. Many vesicles partly filled with calcite and probably zeolites	89
Olivine basalt pahoehoe, with scattered phenocrysts of feldspar up to 3 mm long	4
Basalt pahoehoe, nonporphyritic	9
Olivine basalt pahoehoe, very rich in feldspar phenocrysts up to 1 cm long, in thin flow units averaging 3 to 4 feet thick. Upper 6 inches reddened	20
Olivine basalt pahoehoe, containing up to 50 percent of feldspar phenocrysts up to 2.5 cm long	67
Olivine basalt pahoehoe, with a few feldspar phenocrysts up to 7 mm long	6
Olivine basalt pahoehoe, thin bedded, with abundant feldspar phenocrysts up to 2.5 cm long, forming 10 to 25 percent of the rock	7
Olivine basalt pahoehoe, thin bedded, with a few feldspar phenocrysts up to 7 mm long	10
Olivine basalt pahoehoe, with feldspar phenocrysts up to 2 cm long, forming 60 per cent of the rock	2
Olivine basalt pahoehoe, nonporphyritic, thin bedded	12
Olivine basalt pahoehoe, with scattered feldspar phenocrysts up to 1 cm long	9
Olivine basalt aa, with feldspar phenocrysts up to 2 cm long, forming about 20 percent of the rock	17
Olivine basalt pahoehoe, with scattered olivine phenocrysts up to 1 mm long, thin bedded	6
Red ash	0–0.2
Olivine basalt pahoehoe, thin bedded, with scattered olivine phenocrysts up to 1 mm long	50
Olivine basalt aa, with rare phenocrysts of olivine and feldspar up to 1 mm long	6
Red ash	0.1–0.2
Olivine basalt pahoehoe, with scattered olivine phenocrysts up to 1 mm long, thin bedded	83
Olivine basalt, nonporphyritic, thin bedded, largely aa but with a few layers of pahoehoe. Beds average 2 to 3 feet thick	50
Olivine basalt aa, with rare olivine phenocrysts up to 1.5 mm long	15
Olivine basalt pahoehoe, nonporphyritic	12
Olivine basalt aa, nonporphyritic	9
Olivine basalt pahoehoe, thin bedded, nonporphyritic	13
Olivine basalt aa, nonporphyritic, alternate massive and clinkery beds averaging about 2 feet thick	15
Olivine basalt pahoehoe, nonporphyritic	5
Olivine basalt aa, with rare olivine phenocrysts up to 1 mm long	8
Olivine basalt pahoehoe, with scattered olivine phenocrysts up to 1 mm long, thin bedded	53
Olivine basalt aa, with rare olivine phenocrysts up to 1 mm across	7
Olivine basalt aa, like above, upper 8 feet clinker	15
Olivine basalt pahoehoe, with scattered olivine phenocrysts up to 1 mm long	10
Olivine basalt aa, nonporphyritic, upper 7 feet clinker	18
Olivine basalt, with scattered olivine phenocrysts up to 1 mm long, thin bedded	78
Olivine basalt aa, nonporphyritic, close to pahoehoe in structure	10

Olivine basalt pahoehoe, with scattered olivine phenocrysts up to 1 mm long	4
Olivine basalt aa, with moderately abundant olivine phenocrysts up to 6 mm long. Trace of red ash at top	4
Olivine basalt aa, like above	6
Olivine basalt aa, nonporphyritic, upper 3 feet clinker	10
Olivine basalt aa, nonporphyritic	6
Olivine basalt aa, nonporphyritic, upper 4 feet clinker	17
Olivine basalt pahoehoe, with scattered olivine phenocrysts up to 1 mm long, thin bedded	22
Olivine basalt pahoehoe, massive, with a few olivine phenocrysts up to 3 mm long	12
Olivine basalt pahoehoe, thin-bedded, with scattered olivine phenocrysts up to 1 mm long, and in some flow units apparently absent; base not exposed	60+
Total thickness of section	891+

INTRUSIVE ROCKS

The large valleys on the windward slopes of Kohala Mountain expose a great many dikes and a few bodies of coarse grained rock. The dikes are identical in composition and texture to the lava flows. The coarse grained intrusives are olivine gabbro, ranging in texture from granitoid to diabasic.

Elsewhere, erosion has been too slight to expose many intrusive bodies. A few small dikes occur along the upper part of the deep section of Waikahalulu Gulch, on the southern slope of Mauna Kea. Dikes of olivine basalt and basalt are exposed in the walls of Mokuaweoweo Caldera and the adjoining South Pit and Lua Poholo, at the summit of Mauna Loa. Some of them fed lenticular sills (pl. 15B).

A few dikes are exposed in the walls of Kilauea Caldera, and in the face of Hilina Pali. The dikes are both olivine basalt and basalt. Also present are lenticular intrusive bodies of essentially sill-like character, which locally have arched their roofs in a laccolithic manner. Several of the latter are visible in the walls of Halemaumau (pl. 41C). They are not accessible for direct study, but are probably represented by blocks of olivine gabbro and olivine basalt hurled out during explosive eruptions. Blocks of picrite-basalt, apparently from one of these hills, exhibit peculiar textural and compositional features. The rock appears to have been recrystallized in the solid state, owing to prolonged heating, with the production of a mosaic texture in the groundmass resembling that found in contact-metamorphic hornfels. Recrystallization resulted also in the unmixing of original pigeonite, yielding in its place augite and hypersthene.[2] A laccolithic intrusive near the base of the cliff at Uwekahuna Bluff, on the western side of Kilauea Caldera, consists of olivine gabbro porphyry.

COARSE-GRAINED INCLUSIONS

Inclusions of coarse grained plutonic or hypabyssal rocks have been found in the lavas of all the volcanoes of the island, except Kilauea. On Hualalai and particularly on Mauna Kea, they

---

[2] Macdonald, G. A., Unusual features in ejected blocks at Kilauea Volcano: Am. Jour. Sci., vol. 242, pp. 322–326, 1944.

occur also among the ejecta in cinder cones. Dunite and gabbro are present on all five volcanoes. On Hualalai and Mauna Kea occur also inclusions of augite peridotite (wehrlite), and on Kohala occur inclusions of augite-hypersthene peridotite (lherzolite). Inclusions of gabbro, dunite, and augite peridotite are exceptionally abundant in the Kaupulehu lava flow of 1800-1801 on Hualalai, and are well exposed in road cuts on the main highway. The peridotites grade into dunite on one side and olivine gabbro on the other.

PYROCLASTIC ROCKS

Thin beds of ash are intercalated with the lavas of all the volcanoes. They are numerous in the Hilina, Hamakua and Pololu volcanic series (see stratigraphic sections, pp. 191, 195, and 197). The Hilina, Kahuku, and Hamakua volcanic series are capped by a thick layer of Pahala ash (pp. 71, 102, 157). The ash is typically sandy and silty in nature; in some places it contains scattered lapilli up to 2 cm across. Most of the lapilli are pumice but some are partly or even entirely crystalline. All of the ash beds were originally composed principally of the glassy ejecta formed by lava fountains, but in most places both the ash and lapilli are now largely or entirely altered to yellowish-brown or orange palagonite. Even in the completely altered material the original pumiceous and shard structures can be recognized. Where it is unaltered, the fine material consists of pale brown or brownish-green pumiceous glass fragments.

The Pahala ash is composite in origin and variations occur in the composition of the original material. Much of the ash near Kilauea, especially to the south and west of Kilauea Caldera, was derived from that volcano. In that area the refractive index of the fresh glass is generally close to 1.60, corresponding to a basaltic composition. The phenocrysts are olivine, and plagioclase ranging from sodic bytownite to medium labradorite, resembling those in the basaltic lavas. On the slopes of Mauna Kea and the eastern slope of Mauna Loa the Pahala ash is largely derived from Mauna Kea. On the dry western slopes of Mauna Kea the feldspar microlites in little-altered glassy lapilli appear to be andesine, and the erupted lava was probably andesite.

Along Kaoiki Pali, southwest of Kilauea Caldera, some of the coarse beds in the Pahala ash contain abundant fragments of lithic material, hurled from the volcanic throat in a solid condition. The restriction of this accessory lithic material to the vicinity of Kilauea indicates that it was produced by that volcano. Its presence demonstrates that even as far back as the time of deposition of the Pahala ash, Kilauea was the site of phreatic or phreatomagmatic explosions like those of 1924 and 1790. The following stratigraphic section illustrates the character of the Pahala ash southwest of Kilauea Caldera.

Stratigraphic section through the Pahala ash along Peter Lee Road at the base of Kaoiki Pali, about 5 miles southwest of Kilauea Caldera
By R. H. Finch and G. O. Fagerlund

	Thickness	
	(feet)	(inches)
Fine yellowish-brown vitric-crystal ash, the vitric portion largely altered to palagonite. Contains a few layers having the texture of coarse sand and fine gravel. One such layer, 9 to 10 feet below the top, contains abundant lithic accessory debris	17	
Gray sandy vitric (?) ash, with gravelly ash at top, resting unconformably on the underlying bed		2–10
Yellowish-brown vitric ash, mostly fine	2	9
Alternate layers of fine brown vitric ash and coarse gray lapilli	2	0
Coarse yellow and black lapilli-ash, the lapilli ranging up to 2 cm long; largely composed of vitric cinder, but including some gray lithic material		5
Yellowish-brown vitric ash of sand and silt texture		10
Brown and gray lapilli-ash, composed about equally of essential vitric material and accessory lithic material		7
Fine black sandy vitric ash		1
Fine yellowish-brown partly indurated vitric ash	1	11
Brownish-gray fine vitric ash containing some black sandy ash		2
Fine indurated brownish-gray vitric ash		3
Black sand-textured vitric-crystal ash		6
Brownish-gray vitric lapilli-ash containing some pisolites		2
Gray and brownish-gray vitric lapilli-ash, the lapilli up to 2 cm long, containing some pisolites. The lapilli are normal lava-fountain ejecta		5
Brown and gray laminated sandy vitric ash, the gray layers well indurated	3	8
Brownish-gray vitric lapilli-ash. A few small chips appear to be lithic accessory material		4+
Base of Pahala ash not exposed.		
Thickness of exposed section	31	11+

Ash covering much of the slope of Hualalai is largely palagonitized. It probably was originally of basaltic composition, although some andesitic ash from Mauna Kea may have been present also.

Black ash composed of fresh andesite glass covers broad areas on the upper slopes of Mauna Kea. It was derived from the cones of the Laupahoehoe volcanic series, and has been much drifted by the wind.

The breccia beds exposed in Waikahalulu and Pohakuloa canyons on the southern slope of Mauna Kea (p. 155, pl. 47A, 47B) have a matrix of lapilli and vitric-crystal ash. Some lithic material also occurs in the matrix but part or all of it was probably derived from the larger blocks by attrition of their surfaces during flight. Most of the blocks are olivine basalt, but in the area near Pohakuloa Gulch blocks of augite-rich picrite-basalt also occur. The matrix of the Makanaka glacial moraine on Mauna Kea closely resembles that of the breccia beds. That is to be expected, however, as much of the debris in the glacial moraines was derived from the numerous easily-eroded cinder cones.

The littoral cones, formed by steam explosion where lava flows entered the sea, are superficially quite similar in composition to many of the cinder cones. They consist largely of vitric ash of sand and silt grades, enclosing irregular lapilli and bombs up to 2 feet across. Many of the bombs show ribbon and spindle shapes. The matrix differs, however, from that typical of cinder cones built by lava fountains at vents. The latter is highly inflated, many of the lapilli are pumice, and the small ash fragments show the typical arcuate shard outlines resulting from fragmentation of pumiceous material. In contrast, the small fragments of the littoral cones are dense or only moderately vesicular. The shards are angular and the arcuate forms are absent or comparatively rare. The difference results from the fact that the gases accompanying lava fountains at vents are of internal origin, the lava undergoing active inflation during the explosion, whereas the steam which atomized the liquid lava in the littoral explosions is of external origin. The difference in grade sizes of the particles less than 32 mm across in a littoral cone in comparison with those in a cinder cone is shown in figure 35.

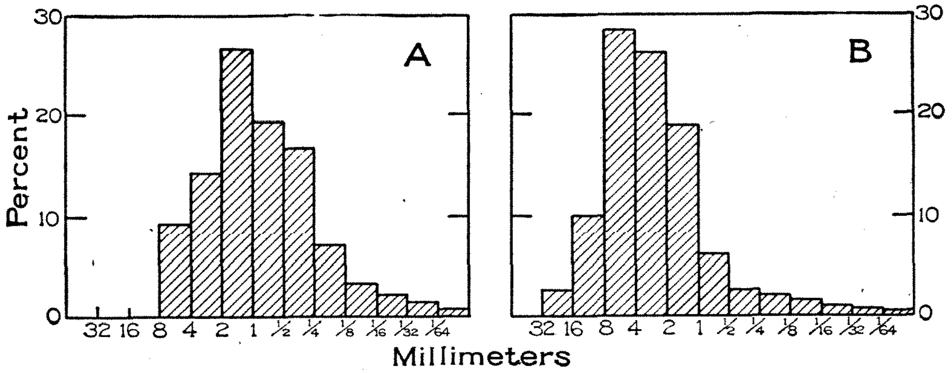


Figure 35. Histograms showing mechanical composition of beds of fine cinder in (A) Kehena littoral cone near Kalapana, and (B) normal basalt cinder cone at the western base of Puu Waawaa (after Wentworth).

CHEMICAL ANALYSES

The accompanying tables contain all of the modern chemical analyses of the lavas of the island of Hawaii. Several older analyses, which are not of the same quality, have been omitted. They may be found in the paper by Cross.[3] In the analyses of Kohala lavas by Lyons the samples were ignited before analysis, thereby increasing the proportion of ferric iron at the expense of ferrous iron. An analysis of "oligoclase basalt", reported by Washington to have come from the City of Refuge at Honaunau,[4] has been omitted from the table because lava from that locality differs greatly from Washington's description, and it seems probable that Washington's specimen was wrongly located.

---

[3] Cross, Whitman, Lavas of Hawaii and their relations: U. S. Geol. Survey Prof. Paper 88, pp. 47–48, 1915.

[4] Washington, H. S., Petrology of the Hawaiian Islands; II. Hualalai and Mauna Loa: Am. Jour. Sci., 5th ser., vol. 6, pp. 114–116, 1923.

Chemical analyses of lavas of Mauna Loa

	Ninole lavas		Kau volcanic series												
			Prehistoric lavas				Historic lavas								Olivine
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	48.60	49.24	45.97	49.24	50.41	52.14	48.57	49.27	51.55	51.82	51.90	52.28	52.30	52.65	40.42
Al_2O_3	10.75	12.72	5.98	13.51	12.37	13.60	10.51	9.38	13.59	13.66	11.69	10.83	11.84	12.12	0.32
Fe_2O_3	3.92	4.27	5.86	3.86	1.94	2.31	2.19	1.28	2.33	1.50	2.24	1.90	2.06	2.19	0.15
FeO	9.38	8.44	7.39	8.88	9.56	8.80	9.45	10.31	9.04	9.68	8.84	9.30	9.03	8.87	11.44
MgO	9.80	7.10	23.55	5.90	7.68	7.26	17.53	17.74	8.02	7.24	7.37	7.69	7.15	7.43	47.08
CaO	10.38	9.74	6.47	10.44	12.56	10.14	8.06	7.46	10.31	10.09	9.87	10.03	10.60	10.12	0.23
Na_2O	2.54	1.87	1.50	2.40	1.68	2.02	1.59	1.80	2.43	2.30	2.07	2.29	2.47	2.25	....
K_2O	0.34	0.28	0.42	0.46	0.40	0.48	0.34	0.42	0.27	0.30	0.41	0.51	0.49	0.35	....
H_2O+	0.22	1.57	0.64	0.70	0.22	0.16	0.37	0.12	0.07	0.11	0.31	0.15	0.15	0.24	....
H_2O-	0.06	1.15	0.04	0.47	none	0.06	0.10	0.06	0.02	0.01	0.04	0.08	0.03	0.07	....
TiO_2	3.37	3.40	1.75	3.70	2.26	2.20	1.48	2.58	1.98	2.07	4.89	4.43	3.98	3.52	0.08
P_2O_5	0.18	0.08	0.21	0.17	0.57	0.29	0.19	0.26	0.24	0.39	0.28	0.32	0.28	0.25	....
MnO	0.05	0.10	0.11	0.12	0.06	0.07	0.16	0.09	0.12	0.13	0.11	0.12	0.10	0.11	0.10
CO_2	none	none	none	none	n.d.	n.d.	none	n.d.	....	....	n.d.	n.d.	n.d.	n.d.	....
Cr_2O_3	n.d.	n.d.	n.d.	n.d.	0.05	0.02	0.10	n.d.	0.08	0.04	n.d.	n.d.	n.d.	n.d.	0.18
NiO	n.d.	n.d.	n.d.	n.d.	0.004	0.005	0.08	n.d.	....	....	n.d.	n.d.	n.d.	n.d.	0.34
Total	99.59	99.96	99.89	99.85	99.76	99.55	100.72	100.77	100.05	99.37	100.02	99.93	100.48	100.17	100.34

1. Olivine basalt, Kaumaikeohu Spring, Kau District. R. K. Bailey, analyst. Washington, H. S., Petrology of the Hawaiian Islands; II. Hualalai and Mauna Loa: Am. Jour. Sci., 5th ser., vol. 6, p. 122, 1923.
2. Hypersthene-bearing basalt, Clover Hill, 0.9 mile northwest of Naalehu, Kau District. R. K. Bailey, analyst. Idem, p. 122.
3. Picrite-basalt, Makanao Valley, 1.5 miles northwest of Hilea, Kau District. R. K. Bailey, analyst. Idem, p. 122.
4. Basalt, 0.7 mile north of Naalehu, Kau District. R. K. Bailey, analyst. Idem, p. 122.
5. Olivine basalt, on Volcano highway at southern boundary of Waiakea Forest Reserve, 1.65 miles northwest of the mill at Olaa, J. J. Fahey, analyst. Powers, H. A., Chemical analyses of Kilauea lavas: Volcano Letter no. 362, p. 2, Dec. 3, 1931.
6. Olivine basalt, reservoir no. 1, Piihonua, near Hilo. J. J. Fahey, analyst. Idem, p. 2.
7. Picrite-basalt, lava flow of 1852. G. Steiger, analyst. Daly, R. A., Magmatic differentiation in Hawaii: Jour. Geology, vol. 19, p. 296, 1911.
8. Picrite-basalt, lava flow of 1868. H. S. Washington, analyst. Washington, H. S., op. cit., p. 115.
9. Basalt, lava flow of 1926, at 1,400 feet altitude near highway. T. A. Jaggar, collector; E. S. Shepherd, analyst. Shepherd, E. S., The gases in rocks and some related problems: Am. Jour. Sci., 5th ser., vol. 35-A, p. 336, 1938.
10. Basalt, lava flow of 1926, pumiceous phase near summit. T. A. Jaggar, collector; E. S. Shepherd, analyst. Idem, p. 335. Total contains S = 0.02, and BaO = tv.
11. Hypersthene-bearing basalt, lava flow of 1887. H. S. Washington, analyst. Idem, p. 113.
12. Basalt, lava flow of 1859. H. S. Washington, analyst. Idem, p. 113.
13. Olivine basalt, lava flow of 1919. H. S. Washington, analyst. Idem, p. 113.
14. Hypersthene-bearing basalt, lava flow of 1881, near Hilo. H. S. Washington, analyst. Idem, p. 113.
15. Olivine phenocryst from 1852 lava. G. Steiger, analyst. Daly, R. A., op. cit., p. 295.

Chemical analyses of prehistoric lavas of Kilauea

	1	2	3	4	5	6	7	8	9	10
SiO_2	46.50	46.59	47.45	50.03	50.46	50.50	50.53	51.06	51.35	51.77
Al_2O_3 ...	9.37	7.69	8.83	12.10	12.75	13.31	13.61	12.91	13.36	13.54
Fe_2O_3 ...	2.47	2.20	1.07	2.10	0.82	1.21	1.69	1.33	1.32	0.75
FeO	10.79	10.46	10.57	9.97	10.68	10.03	9.30	9.63	9.85	9.63
MgO ...	21.00	21.79	19.66	9.57	9.68	6.73	7.01	8.09	7.62	7.33
CaO	6.25	7.41	7.93	10.58	10.43	11.30	10.75	11.03	10.74	10.57
Na_2O ...	1.52	1.33	1.72	2.01	2.42	2.20	2.16	1.92	1.93	2.18
K_2O	0.22	0.28	0.13	0.44	0.51	0.53	0.35	0.43	0.50	0.45
H_2O+ ...	0.14	0.37	0.07	0.32	0.15	0.26	0.27	0.16	0.29	0.16
H_2O- ...	0.03	0.04	0.01	0.16	0.10	0.00	0.07	0.06	none	0.05
TiO_2	1.70	1.83	1.77	2.57	2.14	3.63	3.68	3.59	2.50	4.01
P_2O_5	0.10	0.11	0.37	0.21	0.19	0.47	0.20	0.22	0.28	0.26
MnO	0.11	0.18	[a]0.15	0.16	0.18	0.15	0.13	0.16	0.07	0.15
Cr_2O_3 ...	n.d.	0.13	0.15	n.d.	n.d.	....	n.d.	none	0.03	n.d.
S	n.d.	none	0.02	n.d.	n.d.	0.08	n.d.	none	n.d.	n.d.
NiO ...	n.d.	0.12	....	n.d.	n.d.	....	n.d.	n.d.	0.025	n.d.
BaO	n.d.	none	0.01	n.d.	n.d.	....	n.d.	none	n.d.	n.d.
SrO	n.d.	none	....	n.d.	n.d.	....	n.d.	n.d.	n.d.	n.d.
ZrO_2 ...	n.d.	none	....	n.d.	n.d.	....	n.d.	none	n.d.	n.d.
Cl	n.d.	n.d.	0.03	n.d.	n.d.	0.02	n.d.	n.d.	n.d.	n.d.
Total ...	100.20	100.53	99.94	100.22	100.51	100.42	99.75	100.59	99.86	100.85

[a] Stated in original analysis as $MnO_2 = 0.17$.

1. Picrite-basalt, west of Kamakaia Hills, Kau Desert. H. S. Washington, analyst. Washington, H. S., Petrology of the Hawaiian Islands; III. Kilauea and general petrology of Hawaii: Am. Jour. Sci., 5th ser., vol. 6, pp. 346–347, 1923.
2. Olivine gabbro porphyry, Uwekahuna laccolith, Kilauea Caldera. G. Steiger, analyst. Daly, R. A., Magmatic differentiation in Hawaii: Jour. Geology, vol. 19, p. 293, 1911.
3. Olivine basalt, transitional to picrite-basalt, fragment from wall of conduit ejected during explosion of 1924. E. S. Shepherd, analyst. Piggott, C. S., Radium in rocks: III. The radium content of Hawaiian lavas: Am. Jour. Sci., 5th ser., vol. 22, p. 2, 1931.
4. Olivine basalt, fragment from wall of conduit ejected during explosions of 1790, Collected near Uwekahuna. G. Steiger, analyst. Cross, Whitman, Lavas of Hawaii and their relations: U. S. Geol. Survey Prof. Paper 88, p. 48, 1915.
5. Olivine basalt, fragment from wall of conduit ejected during explosions of 1790, collected southwest of Halemaumau. H. S. Washington, analyst. Washington, H. S., op. cit., pp. 342–343.
6. Basalt(?), aa flow of unknown date in Kilauea Caldera. E. S. Shepherd, anlyst. Shepherd, E. S., The gases in rocks and some related problems: Am. Jour. Sci., 5th ser., vol. 35-A, p. 335, 1938.
7. Basalt, 3-inch apophysis of dike in north wall of Kilauea Caldera (analysis of the dike itself in column 10). H. S. Washington, analyst. Idem, pp. 342–343.
8. Basalt, flow in caldera wall. H. S. Washington, analyst. Idem, pp. 342–343.
9. Olivine basalt, National Park quarry on highway 0.75 mile northeast of Volcano Observatory. J. J. Fahey, analyst. Powers, H. A., Chemical analyses of Kilauea lavas: Volcano Letter no. 362, p. 2, Dec. 3, 1931.
10. Basalt, dike 5 feet thick, in Kilauea Caldera wall just west of the fault blocks below Volcano House. H. S. Washington, analyst. Washington, H. S., op. cit., pp. 342–343.

Chemical analyses of historic lavas of Kilauea

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	47.25	39.54	49.21	49.33	49.42	49.74	50.07	50.14	50.19	50.32	50.37	50.52	50.63	50.85	51.00
Al_2O_3 ...	9.07	0.66	12.93	11.57	11.83	12.36	13.32	13.93	13.34	12.83	14.20	13.85	13.08	15.30	13.03
Fe_2O_3 ...	1.45	1.03	1.76	2.31	3.83	1.64	1.92	0.57	1.23	1.74	1.28	0.98	1.09	0.28	1.83
FeO	10.41	10.87	9.28	9.48	8.08	10.08	9.28	10.07	9.85	9.93	10.10	9.77	10.10	10.42	10.02
MgO	19.96	46.57	7.42	12.41	12.04	8.83	8.01	8.25	7.96	7.39	7.75	7.07	7.44	7.80	6.76
CaO	7.88	tr.	11.27	9.14	9.28	10.88	10.64	11.17	11.65	11.06	11.24	11.33	11.38	11.45	12.40
Na_2O ...	1.38	0.46	2.64	2.20	2.35	2.45	2.16	1.29	2.09	2.38	2.20	1.51	2.36	0.70	2.02
K_2O	0.35	0.15	0.59	0.44	0.59	0.55	0.45	0.41	0.54	0.41	0.56	0.47	0.47	0.58	0.73
H_2O+ ...	0.08	0.18	0.74	0.11	0.16	0.17	0.49	0.03	0.09	0.33	0.06	0.04	0.15	0.18	0.35
H_2O- ...	0.04	0.04	0.08	0.01	0.02	0.05	0.22	none	0.00	0.05	none	none	0.08	tr.	none
TiO_2	1.61	0.09	2.75	2.85	2.42	2.49	2.70	3.20	2.60	3.10	2.33	3.63	3.33	1.55	2.33
P_2O_5	0.21	n.d.	1.21	0.37	0.39	0.41	0.26	0.23	0.41	0.30	0.02	0.22	0.33	0.22	0.14
MnO	0.13	0.13	0.08	0.14	0.14	0.14	0.16	0.06	0.15	0.10	0.14	0.14	0.12	0.10	0.18
Cr_2O_3 ...	0.12	0.13	n.d.	0.08	0.13	0.04	0.05	0.07	....	n.d.	0.05	0.06	n.d.	0.05	[a]0.008
S	n.d.	n.d.	n.d.	0.03	0.01	0.04	0.11	n.d.	0.07	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
NiO	0.09	[b]0.38	n.d.	....	....	0.05	0.04	0.002	....	n.d.	0.008	tr.	n.d.	0.002	tr.
BaO	none	n.d.	n.d.	0.02	0.04	tr.	none	n.d.	....	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
SrO	none	n.d.	n.d.	....	....	0.07	tr.	n.d.	....	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
ZrO_2	none	n.d.	n.d.	....	....	tr.	none	n.d.	....	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cl	n.d.	n.d.	n.d.	0.03	0.02	0.10	0.08	n.d.	0.02	0.04	n.d.	n.d.	n.d.	n.d.	n.d.
V_2O_3	n.d.	n.d.	n.d.	....	....	0.02	none	n.d.	....	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
MoO_3 ...	n.d.	n.d.	n.d.	....	....	0.01	tr.	n.d.	....	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total ...	100.03	100.23	99.96	100.52	100.75	100.12	99.96	99.42	100.19	99.98	100.31	99.59	100.56	99.48	100.80

[a] Quantity of sample insufficient.

[b] Includes CoO.

1. Picrite-basalt, lava flow of 1840, Nanawale Bay. G. Steiger, analyst. Cross, Whitman, Lavas of Hawaii and their relations: U. S. Geol. Survey Prof. Paper 88, p. 44, 1915.
2. Olivine from 1840 lava at Nanawale Bay. M. Aurousseau, analyst. Aurousseau, M., and Merwin, H. E., Olivine; I. From the Hawaiian Islands; II. Pure forsterite: Am. Mineralogist, vol. 13, p. 560, 1928.
3. Pele's hair, collected in 1920, 2.5 miles southwest of Halemaumau. H. S. Washington, analyst. Washington, H. S., Petrology of the Hawaiian Islands; III. Kilauea and general petrology of Hawaii: Am. Jour. Sci., 5th ser., vol. 6, p. 351, 1923.
4. Olivine basalt, lava of 1923, pahoehoe phase, near Makaopuhi Crater. E. S. Shepherd, analyst. Shepherd, E. S., The gases in rocks and some related problems: Am. Jour. Sci., 5th ser., vol. 35-A, p. 335, 1938.
5. Olivine basalt, lava of 1923, aa phase, near Makaopuhi Crater. E. S. Shepherd, analyst. Idem, p. 335.
6. Olivine basalt, dipped from Old Faithful lava fountain by Perret and Shepherd in 1911. J. B. Ferguson, analyst. Day, A. L., and Shepherd, E. S., Water and volcanic activity: Geol. Soc. America Bull., vol. 24, p. 586, 1913.
7. Olivine basalt, lava of 1894(?), floor of caldera. J. B. Ferguson, analyst. Idem, p. 586.
8. Splash from lava lake in Halemaumau, 1917. J. J. Fahey, analyst. Powers, H. A., Chemical analyses of Kilauea lavas: Volcano Letter no. 362, p. 2, Dec. 3, 1931.
9. Olivine basalt, liquid lava collected by T. A. Jaggar in 1919. E. S. Shepherd, analyst. Shepherd, E. S., op. cit., p. 335.
10. Olivine basalt, lava flow of 1920, aa phase, Maunaiki. H. S. Washington, analyst. Washington, H. S., op. cit., p. 351.
11. Olivine basalt, splash from lava lake in Halemaumau during eruption of 1919 lava flow from Mauna Loa. J. J. Fahey, analyst. Powers, H. A., op. cit., p. 2.
12. Olivine basalt, 1919 lava flow at northeast edge of caldera floor. J. J. Fahey, analyst. Idem, p. 2.
13. Olivine basalt, lava flow of 1920, pahoehoe phase, Maunaiki. H. S. Washington, analyst. Washington, H. S., op. cit., p. 351.
14. Olivine basalt, lava flow of 1921, south edge of Kilauea Caldera. L. T. Richardson, analyst. Powers, H. A., op. cit., p. 2.
15. Basalt, scoria from lava fountain in Halemaumau during eruption of July, 1929. R. E. Stevens, analyst. Idem, p. 2.

Piggot has determined the radium content of 13 samples of Hawaiian lavas, including the 1919 lava of Mauna Loa, a lava of Mauna Kea, the trachyte of Puu Anahulu and six lavas of Kilauea. All show approximately the same amount, the average being 0.96 x 10^{-12} gram of radium per gram of sample. The radium content of Hawaiian lavas is about the same as that found in most granites.[5]

MAGMATIC DIFFERENTIATION

All of the other lavas of the volcanoes of the island of Hawaii appear to have been derived from olivine basalt by magmatic differentiation. Because the lavas of Kilauea show less variation than those of the other volcanoes, they are believed to correspond most closely to the parent olivine basalt. Although the transportation of alkalies and other substances in rising volatiles may have played a part, probably the principal factor in the differentiation was the sinking of crystals in the cooling magma. By that process, the materials composing the crystals were removed from the upper part

---

[5] Piggot, C. S., Radium in rocks; III. The radium content of Hawaiian lavas: Am. Jour. Sci., 5th ser., vol. 22, pp. 1–8, 1931.

Chemical analyses of lavas of Hualalai

	1	2	3	4	5	6	7	8
SiO_2	46.01	46.43	46.76	47.69	48.04	48.17	62.02	62.19
Al_2O_3	15.40	10.91	13.78	16.92	15.35	15.45	18.71	17.43
Fe_2O_3	1.22	3.15	1.26	3.69	5.72	3.98	4.30	1.65
FeO	8.15	10.26	10.43	8.83	7.67	8.67	0.10	2.64
MgO	13.25	11.08	11.07	4.02	5.77	3.97	0.40	0.40
CaO	10.74	10.09	10.54	10.73	10.13	11.00	0.86	0.86
Na_2O	2.30	3.16	3.59	2.89	3.26	3.04	6.90	8.28
K_2O	0.67	0.54	0.64	1.17	0.79	0.98	4.93	5.03
TiO_2	1.80	2.59	2.12	2.79	3.13	4.32	0.31	0.37
H_2O+	0.19	0.66	0.10	0.57	0.27	0.25	0.80	0.39
H_2O-	0.07	0.15	0.10	0.09	0.04	0.06	0.31	0.14
ZrO_2	n.d.	none	n.d.	n.d.	n.d.	n.d.	0.06	0.04
P_2O_5	0.62	0.67	0.32	0.67	0.33	0.35	0.24	0.14
SO_3	n.d.	0.07	n.d.	n.d.	n.d.	n.d.	0.02	none
Cr_2O_3	n.d.	none	n.d.	n.d.	n.d.	n.d.	none	tr.
MnO	0.08	0.09	0.08	0.13	0.10	n.d.	0.15	0.32
BaO	n.d.	none	n.d.	n.d.	n.d.	n.d.	0.02	0.03
CO_2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	none	0.02
Cl	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	none	n.d.
Total	100.50	99.85	100.79	100.29	100.60	100.24	100.13	99.93

1. Olivine basalt. "average lava" from an altitude of 7,400 feet on the north slope of Hualalai. R. A. Daly, collector; H. S. Washington, analyst. Washington, H. S., Petrology of the Hawaiian Islands; II. Hualalai and Mauna Loa: Am. Jour. Sci., 5th ser., vol. 6, p. 102, 1923.
2. Olivine basalt, lava of 1801, Hualalai. H. S. Washington, analyst. Idem, p. 102.
3. Olivine basalt, block from pit crater near summit of Hualalai. R. A. Daly, collector; H. S. Washington, analyst. Idem, p. 102.
4. Basalt, block from near summit of Hualalai. H. S. Washington, analyst. Idem, pp. 104–105.
5. Basalt, flow near summit of Hualalai. H. S. Washington, analyst. Idem, pp. 104–105.
6. Gabbro, block from near summit of Hualalai. H. S. Washington, analyst. Idem, pp. 104–105.
7. Soda trachyte, Puu Anahulu. H. S. Washington, analyst. Idem, p. 108.
8. Soda trachyte obsidian, Puu Waawaa. W. F. Hillebrand, analyst. Cross, Whitman, An occurrence of trachyte on the island of Hawaii: Jour. Geology, vol. 12, p. 514, 1904.

Chemical analyses of lavas of Mauna Kea

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	46.43	46.57	47.19	47.32	47.72	47.79	48.42	49.73	50.09	50.68	50.92
Al_2O_3	15.22	7.81	10.95	16.68	16.19	14.80	13.97	16.39	19.49	16.42	17.59
Fe_2O_3	3.79	2.40	3.31	2.63	3.82	2.63	4.17	7.58	0.73	5.79	3.80
FeO	8.19	8.91	10.21	8.67	8.25	10.04	9.57	3.98	8.47	6.22	6.69
MgO	8.40	19.74	10.52	5.43	5.68	6.89	4.61	4.06	4.33	4.25	3.90
CaO	10.37	10.65	9.73	11.27	11.20	11.31	8.86	7.17	6.92	6.47	6.97
Na_2O	2.55	1.70	4.69	3.08	2.80	2.56	3.30	4.12	4.82	4.70	4.28
K_2O	0.99	0.33	0.93	0.79	0.84	0.94	1.29	1.93	1.93	2.16	1.86
H_2O+	0.82	0.11	0.17	0.23	0.51	0.54	0.84	0.54	0.32	0.23	0.79
H_2O-	0.38	0.09	0.07	0.17	0.25	0.09	0.42	0.81	0.08	0.19	0.35
TiO_2	3.03	1.67	2.27	3.09	2.48	1.90	3.25	3.05	2.47	2.64	2.55
ZrO_2	....	....	....	....	....	....	....	0.03	....	....	....
P_2O_5	0.33	0.34	0.55	0.53	0.43	0.26	0.91	0.84	0.78	0.17	0.40
MnO	0.10	0.13	0.16	0.16	0.08	0.14	0.17	0.23	0.15	0.22	0.20
BaO	....	....	....	....	....	....	....	0.03	....	....	....
Cr_2O_3	....	0.23	....	....	....	....	....	none	....	....	none
Total	100.60	100.68	100.75	100.05	100.25	99.89	99.78	100.53	100.58	100.14	100.30

1. Nonporphyritic olivine basalt, Hamakua volcanic series; quarry above Laupahoehoe, at 200 feet altitude. (The locality could not be located.) H. S. Washington, analyst. Washington, H. S., Petrology of the Hawaiian Islands; I. Kohala and Mauna Kea, Hawaii: Am. Jour. Sci., 5th ser., vol. 5, p. 497, 1923.
2. Picrite-basalt, primitive type, Hamakua volcanic series; Kaula Gulch, above Ookala. (No rock corresponding to the description given could be found at that locality.) H. S. Washington, analyst. Idem, p. 500.
3. Andesite(?), Hamakua volcanic series; Kaula Gulch, above Ookala. (No rock the mode of which appears to fit the above analysis has been found at this locality.) H. S. Washington, analyst. Idem, p. 500.
4. Olivine basalt, with feldspar phenocrysts, Hamakua volcanic series; 900 feet altitude in Papalele Gulch. Washington, analyst. Idem, p. 497.
5. Basalt, Hamakua volcanic series; at road north of Nohonaohae Cone. H. S. Washington, analyst. Idem, p. 497.
6. Olivine basalt, nonporphyritic, Hamakua volcanic series; 1,910 feet altitude on highway at Ahualoa, near Honokaa. H. S. Washington, analyst. Idem, p. 497.
7. Andesite, Hamakua volcanic series; 900 feet altitude in Papalele Gulch. H. S. Washington, analyst. Idem, p. 493. Includes Cl = 0.00.
8. Andesite, Laupahoehoe volcanic series; 11,000 feet altitude on the southeast slope of Mauna Kea. G. Steiger, analyst. Daly, R. A., Magmatic differentiation in Hawaii: Jour. Geology, vol. 19, p. 298, 1911. Includes S = 0.00, SrO = 0.00.
9. Andesite, Hamakua volcanic series; 2,700 feet altitude, near Nohonaohae Cone. Washington, analyst. Washington, H. S., op. cit., p. 490.
10. Andesite, Laupahoehoe volcanic series; Laupahoehoe Peninsula, at sea level. H. S. Washington, analyst. Idem, p. 490. A duplicate determination gave 6.25 FeO.
11. Andesite, Laupahoehoe volcanic series; Poliahu Cone, at 13,000 feet altitude near summit of Mauna Kea. G. Steiger, analyst. Daly, R. A., op. cit., p. 301.

Chemical analyses of lavas of Kohala Mountain

	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	45.33	45.79	47.33	47.39	47.98	49.01	49.09	49.14	49.70	51.97	51.99	52.27	58.06
Al_2O_3	16.52	11.67	17.96	16.46	15.32	16.29	15.15	14.64	14.65	12.65	16.30	17.05	18.21
Fe_2O_3	5.60	2.99	12.64	3.75	2.49	7.61	2.95	4.49	1.88	4.60	2.75	3.51	4.87
FeO	6.92	10.32	0.51	8.42	8.86	4.89	10.22	7.17	8.03	7.05	7.44	7.20	2.01
MgO	7.38	8.90	3.97	5.08	6.16	3.62	4.94	3.94	7.80	7.98	3.19	3.13	1.59
CaO	7.89	9.60	6.29	7.37	10.28	9.79	8.47	9.67	12.10	10.59	6.67	5.82	3.29
Na_2O	4.24	2.20	3.67	4.71	3.56	3.82	4.03	4.45	2.09	2.77	5.64	5.40	6.12
K_2O	1.49	0.66	1.10	1.65	1.08	0.80	1.31	1.00	0.52	0.34	2.13	2.22	2.75
H_2O+	0.28	1.85	....	0.28	0.62	....	0.17	0.65	0.22	0.26	0.29	0.44	....
H_2O-	0.05	0.82	....	0.09	0.25	....	0.07	0.14	0.09	0.11	0.07	0.08	....
TiO_2	2.45	5.00	4.84	2.83	3.53	3.93	2.66	4.21	1.92	2.11	3.02	2.13	1.88
P_2O_5	2.32	0.40	1.05	2.22	0.22	0.49	0.80	0.43	0.56	0.25	1.25	0.62	0.65
MnO	0.10	n.d.	0.64	0.09	0.12	0.27	0.09	0.10	0.15	0.16	0.11	0.16	0.36
BaO	n.d.	n.d.	n.d.	0.04	0.06	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.05	n.d.
Cl	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	tr.	n.d.
SO_3	n.d.	n.d.	0.07	0.06	0.02	0.20	n.d.	n.d.	n.d.	n.d.	n.d.	0.13	0.05
ZrO_2	n.d.	n.d.	n.d.	none	none	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	none	n.d.
Cr_2O_3	n.d.	n.d.	n.d.	tr.	none	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total	100.57	100.20	100.29	100.44	100.55	100.84	99.95	100.03	99.71	100.84	100.85	100.21	99.99

1. Oligoclase andesite, Hawi volcanic series; Lahikiola cone, at about 3,000 feet altitude. H. S. Washington, analyst. Washington, H. S., Petrology of the Hawaiian Islands; I. Kohala and Mauna Kea: Am. Jour. Sci., 5th ser., vol. 5, pp. 480–481, 1923.
2. Olivine basalt, Pololu volcanic series; south of Kaala Cone. H. S. Washington, analyst. Idem, p. 487.
3. Oligoclase andesite, Hawi volcanic series; cinder cone on Kohala. A. B. Lyons, analyst. Lyons, A. B., Chemical composition of Hawaiian soils and of the rocks from which they have been derived: Am. Jour. Sci., 4th ser., vol. 2, pp. 422–424, 1896. Includes $S = 0.07$; $CuO = 0.15$.
4. Andesine andesite, Hawi volcanic series; Puu Kawaiwai, at 3,200 feet altitude. H. S. Washington, analyst. Washington, H. S., op. cit., pp. 480–481.
5. Olivine basalt, Pololu volcanic series; 3,400 feet altitude in Kawaihae Gulch, half a mile S. 20° W. of Puu Loa. H. S. Washington, analyst. Idem, p. 483.
6. Olivine(?) basalt, Pololu volcanic series; no locality given. A. B. Lyons, analyst. Lyons, A. B., op. cit., pp. 422–424. Includes $S = 0.02$; $CuO = 0.10$.
7. Oligoclase andesite, Pololu volcanic series; sea level at Mahukona. H. S. Washington, analyst. Washington, H. S., op. cit., pp. 480–481.
8. Olivine basalt, Pololu volcanic series; 2,900 feet altitude in Momoualoa Gulch. H. S. Washington, analyst. Idem, p. 483.
9. Olivine(?) basalt, Pololu volcanic series; first stream west of Waimea on the Waimea-Kohala road (wrongly called Waiaka Stream by Washington). H. S. Washington, analyst. Idem, pp. 485–487.
10. Basalt, Pololu volcanic series; east wall of Waipio Valley. H. S. Washington, analyst. Idem, pp. 493–494.
11. Oligoclase andesite, Hawi volcanic series; 2,900 feet altitude at Momoualoa Gulch. H. S. Washington, analyst. Idem, p. 478.
12. Oligoclase andesite, Hawi volcanic series; 3,600 feet altitude at Puu Makea, half a mile west of Puu Loa. H. S. Washington, analyst. Idem, p. 478.
13. Oligoclase andesite, Hawi volcanic series; near Waimea. A. B. Lyons, analyst. Lyons, A. B., op. cit., pp. 424–425. Includes $S = 0.05$; $CuO = 0.10$.

of the magma body and were added to the lower part. During early stages of the magmatic history, the sinking of olivine crystals resulted in the formation of basalt poor in olivine in the upper part of the magma column and picrite-basalt rich in phenocrysts of olivine at greater depths. At a later period when the temperature of the magma had dropped to a point at which augite and plagioclase were crystallizing, these minerals also were removed from the upper part of the magma, and picrite-basalts rich in phenocrysts of augite, as well as olivine, were formed at lower levels.

Calculations show, however, that formation of andesites and trachytes requires the separation from the parent olivine basalt of calcic plagioclase, diopside, and hypersthene, with comparatively little olivine.[6] The formation of olivine is probably restricted to relatively shallow depths in the magma, greater pressure at greater depths resulting in the formation of hypersthene in place of olivine. Formation of the andesites by removal of calcic plagioclase, diopside, and hypersthene requires crystallization of approximately three quarters of the original mass of magma, and formation of the trachytes requires crystallization of about 90 percent of the magma body. Such extensive crystallization probably does not occur until after the particular magma body involved has been partially or completely isolated from the underlying basaltic substratum which supplied the original injection of olivine basalt. The trachytes are best regarded as the product of differentiation of small lateral intrusive bodies, rather than of the principal magma chamber.

---

[6] Macdonald, G. A., Petrography of the island of Hawaii: U. S. Geol. Survey Prof. Paper (waiting publication).

GROUND-WATER RESOURCES OF THE ISLAND OF HAWAII

CLIMATE[7]

TEMPERATURE, WIND, AND HUMIDITY.—Although the island lies within the tropics, its climate is semitropical and varies greatly from place to place depending upon altitude and position to the leeward or windward of the mountains. January and February are the coldest months with a mean temperature of 68.3° F., and September is the warmest month with a mean of 73.5° F. The temperatures are the means of 23 stations with an average altitude of 1,339 feet. Temperature is chiefly influenced by altitude although slope and exposure to wind affect it slightly. The mean temperature falls about 4° F. in the first thousand feet above sea level and at the rate of about 3° F. for each successive rise of 1,000 feet. Adiabatic cooling accounts for most of the drop in temperature with altitude. As a result of the sunnier and drier climate on the leeward slopes of the mountains, temperatures there are higher and show the greatest range from day to night. Part of the Kona District is an exception as it has a special climate which will be described later. The highest officially recorded temperature, 100° F., occurred April 27, 1931, at Pahala, altitude 850 feet. Frost rarely forms below 4,000 feet. Freezing temperatures occur every night on the summits of Mauna Kea and Mauna Loa,[8] and snow frequently blankets their higher levels, even in midsummer. Temperature records are given in the accompanying table.

Hawaii lies in the belt of northeasterly trade winds which persist throughout most of the year. During the fall and winter months, however, kona or southerly winds blow for a few days at a time. Kona storms are usually accompanied by high winds and heavy rains.

The prevailing winds in most of the Kona District are from the southwest, but they should not be confused with the southerly winds and kona storms just described. The unusual wind direction in the Kona District results from the obstruction of the trade winds by Mauna Loa and Mauna Kea, thereby causing local topographic and heating effects to become operative. In the Kona District, morning

---

[7] This chapter is based chiefly on data and publications of the U. S. Weather Bureau.

[8] Coulter, J. W., Raine, C. T., and Wentworth, C. K., Meteorological reports of the Mauna Kea Expedition, 1935, (I), (II), and (III): Am. Meteor. Soc. Bull., vol. 19, pp. 349–351, 1938; vol. 20, pp. 97–105, 1939.

Mean monthly and annual temperatures at stations on Hawaii, in Fahrenheit degrees, up to and including 1943[1]

Station	Altitude (feet)	Length of record (years)	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Hilo	40	39	70.2	70.2	70.5	71.3	72.8	73.9	74.7	75.3	75.0	74.6	73.1	71.5	72.8
Honokaa	461	39	69.0	69.3	69.9	70.4	72.2	73.6	74.2	74.6	74.7	74.0	72.0	70.1	72.0
Honomu (mauka)	1,000	4	69.6	68.5	67.4	69.3	71.1	71.8	72.8	72.9	74.2	72.9	71.4	69.8	71.0
Kainaliu	1,500	12	66.6	66.3	66.1	66.7	68.6	69.1	69.7	70.7	70.7	70.4	69.1	67.4	68.4
Kiolakaa	1,050	28	68.6	68.8	68.9	69.5	70.6	71.5	72.7	73.0	73.1	72.8	71.6	70.1	70.9
Kohala	309	39	69.8	70.0	70.2	70.7	72.4	73.8	74.6	75.2	75.5	74.7	72.8	71.2	72.6
Kohala Mission	537	39	69.1	69.3	69.7	70.6	72.5	73.8	74.5	75.2	75.2	74.4	72.1	70.3	72.2
Kukuihaele	275	27	69.9	70.0	70.2	70.8	72.1	73.3	74.3	75.3	75.4	74.6	72.8	70.9	72.5
Mahukona	11	31	74.5	74.4	75.0	76.0	77.8	79.3	80.0	80.5	80.3	79.4	78.1	75.7	77.6
Mountain View	1,530	30	64.1	64.4	64.8	65.4	66.6	67.9	68.6	69.3	69.1	68.5	66.8	65.3	67.7
Napoopoo	450	5	71.3	71.1	70.1	71.4	72.5	73.9	74.2	75.6	74.8	74.7	73.6	71.9	72.9
Niulii	85	38	71.0	71.3	71.3	71.8	73.6	74.9	75.5	76.2	76.1	75.6	73.9	72.4	73.6
Olaa	280	39	70.0	70.4	70.8	71.1	72.3	73.5	74.3	74.7	74.7	74.2	72.5	71.2	72.5
Ookala	425	38	70.4	70.2	70.5	70.9	72.4	73.7	74.3	75.1	75.4	75.0	73.2	71.5	72.7
Pahala	850	39	68.6	68.6	68.9	69.9	70.9	72.0	73.3	73.7	73.8	73.1	71.7	70.3	71.2
Pepeekeo	100	38	70.7	70.8	70.8	71.5	72.7	73.7	74.7	75.3	75.5	75.0	73.6	72.0	73.0
Volcano Observatory	3,979	31	57.8	58.4	58.4	59.3	61.1	62.1	63.0	63.7	63.6	63.2	61.0	59.4	60.9
Waimea	2,669	35	61.7	61.8	62.1	62.3	63.7	64.5	64.8	65.9	66.4	66.1	64.7	62.9	63.9
Means	......	....	68.3	68.3	68.5	69.4	71.0	72.0	72.5	73.2	73.5	73.0	71.4	69.8	70.9

[1] Reed, T. R., Climatological Data, Hawaii section: U. S. Dept. Comm., Weather Bur., vol. 39, no. 13, pp. 74 and 80, 1943.

usually dawns clear. Between 8:00 and 10:00 a.m. cool breezes start to blow from the sea to replace the rising warm air over the land. Clouds form at about 2,000 feet and rain begins to fall. The top of the cloud layer rises during the day and usually reaches about 7,000 feet during late afternoon, but the rain falls chiefly below 5,000 feet. During the night the wind stops, the clouds dissipate, and the cool night air flows down the mountain toward the sea. This system of air circulation gives rise to light southwesterly winds nearly every day of the year.

Relative humidity is lowest in July and highest in December. The humidity is less on the leeward than on the windward shore. Uncomfortably high humidity usually accompanies kona storms.

PRECIPITATION.—The mean monthly and mean annual rainfall at 139 stations on Hawaii is given in the succeeding table. The areal distribution of the rainfall and the location of the stations are shown in figure 36. Records are notably lacking from the high mountain slopes. The precipitation is in the form of rain except on the tops of Mauna Kea and Mauna Loa, where snow falls in the winter and sometimes during the summer. Hail falls occasionally during infrequent thunder storms. More rain falls from November to April than from May to October except in the Kona District, where the reverse is true. Some stations at low altitude in very wet areas show a rather uniform monthly distribution.

Most of the rain falls on the eastern side of the island as a result of the cooling of moist trade winds as they rise over the mountains. It increases from sea level to about 1,800 feet and above 3,000 feet decreases again except on Kohala Mountain, where the high sea cliffs and deep canyons cause such an updraft that the maximum rainfall is at 5,500 feet. The rainfall reaches an average maximum of 240 inches above Hilo and more than 200 inches on the summit of Kohala Mountain. The upper parts of Mauna Loa, Mauna Kea, and Hualalai probably receive less than 40 inches annually. Rain in excess of 60 inches annually falls on the southeastern slope of Mauna Loa above Pahala and 100 inches annually on the western slope above Kealakekua.

The lowest annual rainfall ever recorded on Hawaii was 3.62 inches at an altitude of 29 feet at Kalae (South Point) in 1928. The highest annual record is at Upper Kawainui, on Kohala Mountain, where 503.69 inches fell in 1914. The greatest downpour recorded during a single day was 31.95 inches at Honomu on February 20, 1918. Rainfall in excess of 12 inches per day is not rare.

Rain falls more than 300 days a year at several windward stations, in contrast to some stations in the rain shadow of Mauna Kea and Kilauea where it may rain less than 30 days a year. More rain may fall on the leeward coast during a single kona storm than during the rest of the year. Cessation of the trade winds for long periods usually causes droughts on the eastern slopes of the island. Droughts occur every few years and at such times Hilo and other towns, dependent chiefly upon surface streams, are short of water. All plantation ditches lie on the windward slope and they are greatly affected by droughts. Major droughts occur between December and March. The comparative monthly distribution of rainfall in various parts of the island is shown in figure 37. The stations are arranged to show graphically how the maximum rainfall is affected by the configuration of the mountains.

The average annual rainfall computed for Hawaii from the isohyetal map (fig. 36) is 68.2 inches, equivalent to 1,185.2 million

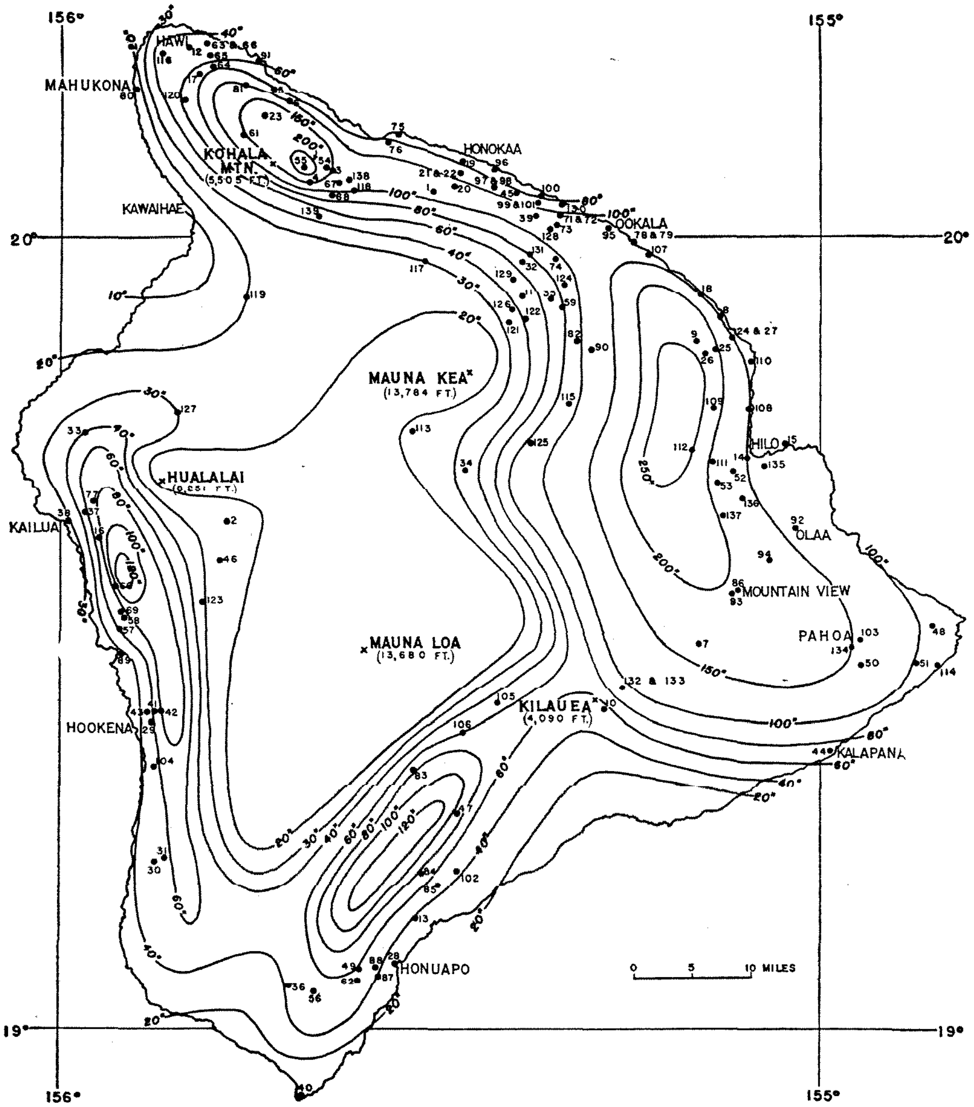


Figure 36. Map of Hawaii showing distribution of rainfall and rain gages. Isohyetal lines by U. S. Weather Bureau, 1942.

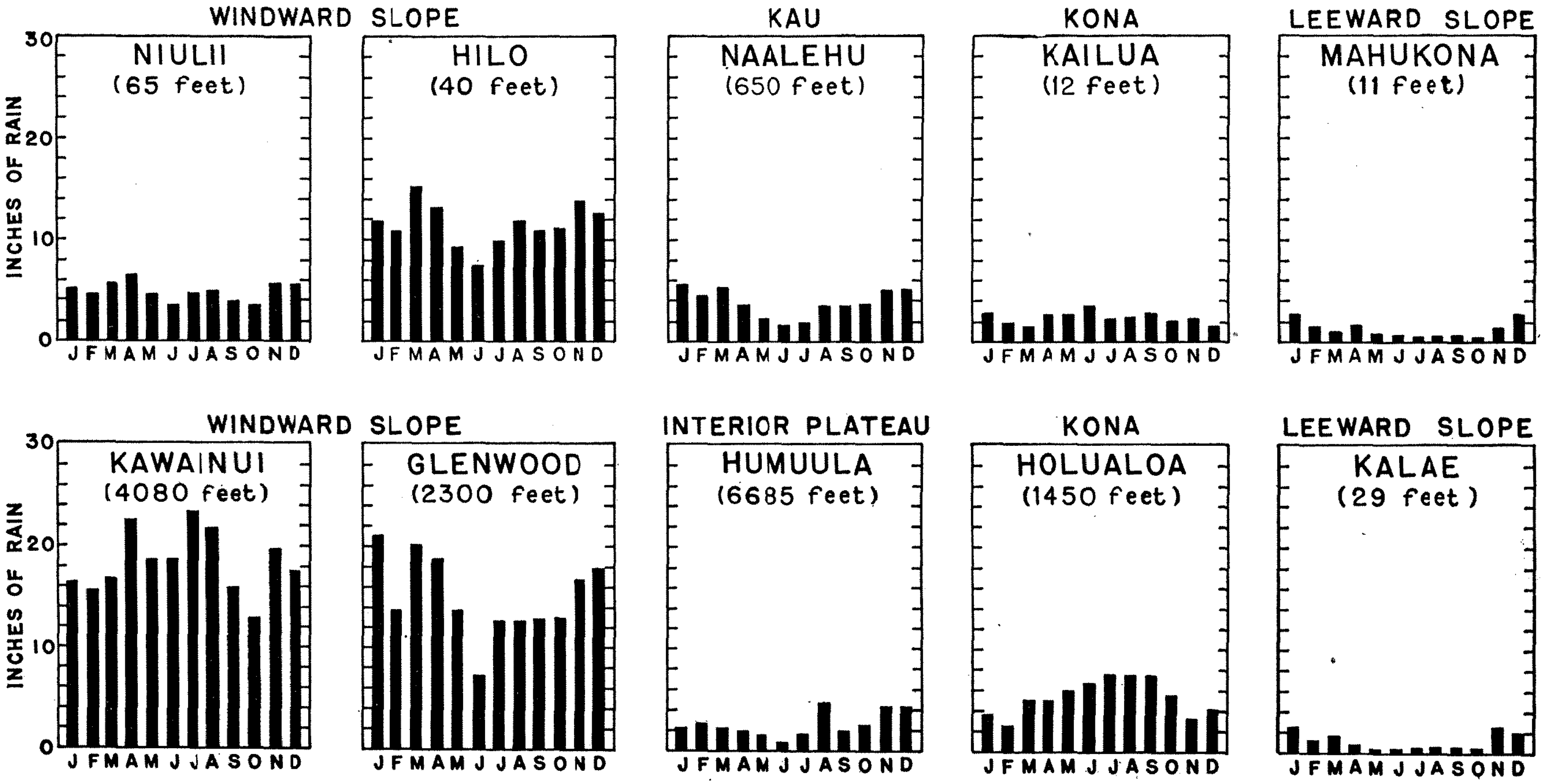


Figure 37. Comparative monthly distribution of rainfall on Hawaii.

Mean monthly rainfall on Hawaii through 1935

(Data obtained from Territorial Planning Board, 1st Progress Report, 1939)

Station (fig. 36)	Elevation	No. Years Record	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1. Ahualoa Homesteads	2551	24	10.03	9.55	11.26	12.60	7.74	4.35	7.65	7.26	5.08	4.61	13.84	12.85	106.82
2. Ahua Umi	5220	13	1.37	1.66	1.84	2.10	2.41	1.69	1.75	2.57	2.35	2.13	1.33	1.94	23.14
3. Alakahi (Lower)	1030	26	10.73	10.48	11.52	14.34	9.58	7.20	9.55	9.46	6.64	5.77	12.65	12.32	120.24
4. Alakahi (Upper)	3874	23	12.76	11.85	13.52	19.63	14.87	13.09	17.82	16.56	11.54	9.12	16.29	14.97	172.02
5. Awini Ranch	1100	9	5.64	7.32	10.75	10.71	4.95	4.02	9.35	7.83	4.50	6.51	7.88	4.69	84.15
6. Awini	1900	30	12.99	13.41	13.12	19.00	12.14	10.09	13.51	13.91	9.57	7.71	14.32	15.75	155.52
7. Glenwood	2300	14	20.94	13.69	19.88	18.66	13.68	7.11	12.51	12.50	12.72	13.02	16.85	17.88	179.44
8. Hakalau	175	44	12.70	9.97	14.89	13.16	9.40	7.33	9.91	12.21	11.12	10.35	14.01	12.08	137.13
9. Hakalau (Mauka)	1200	30	19.51	17.07	19.86	23.02	16.43	12.64	17.13	18.48	15.40	14.08	22.49	21.98	218.09
10. Halemaumau	3648	6	9.05	7.07	8.22	4.70	2.17	1.41	1.66	4.17	3.14	3.82	4.25	5.08	54.74
11. Halepiula	6000	21	5.44	4.96	6.73	5.24	2.78	0.67	2.20	2.79	2.81	2.72	6.87	5.90	49.11
12. Hawi	600	36	4.98	4.58	4.76	6.34	3.66	3.18	4.02	4.09	3.02	2.85	5.27	5.68	52.43
13. Hilea	330	45	4.36	3.71	4.85	3.18	1.84	1.08	1.52	2.60	2.54	3.22	4.60	4.80	38.30
14. Hilo	40	49	11.77	10.82	15.08	13.06	9.21	7.40	9.89	11.81	10.84	10.97	13.80	12.47	137.12
15. Hilo Breakwater	15	6	10.48	6.36	5.79	12.44	8.68	10.40	9.18	11.60	12.07	11.17	20.10	14.22	132.49
16. Holualoa	1450	26	3.70	2.46	5.00	4.99	5.95	6.74	7.49	7.35	7.30	5.31	3.16	3.97	63.42
17. Homestead Plantation	1350	11	8.13	4.31	4.94	5.92	3.08	2.53	3.93	4.59	2.86	2.51	5.47	7.49	55.76
18. Honohina	300	42	14.24	11.15	17.66	15.14	10.96	7.94	10.47	13.30	11.78	10.69	16.23	13.73	153.29
19. Honokaa	461	46	6.76	6.58	8.95	8.00	4.45	2.71	4.27	5.01	3.35	3.46	7.41	7.52	68.47
20. Honokaa (Miss Rickard)	1900	5	7.54	7.06	17.16	9.58	5.55	2.96	3.45	4.59	1.72	7.96	6.98	4.85	79.40
21. Honokaa (Mauka)	1116	34	9.31	8.92	10.81	12.23	6.51	3.44	5.77	6.80	4.79	3.98	10.46	10.15	93.17
22. Honokaa Village	1100	17	10.08	8.68	10.66	11.21	5.04	2.47	4.88	5.62	4.75	3.78	11.53	8.70	87.40
23. Honokane	1000	30	13.50	13.59	12.85	16.53	10.51	9.49	13.38	12.77	8.98	7.12	14.88	15.59	149.19
24. Honomu	300	8	12.52	10.68	18.52	11.73	7.33	6.38	7.26	10.18	10.00	9.18	12.16	9.84	125.78
25. Honomu	950	6	15.85	13.73	26.54	18.18	6.78	9.88	12.61	13.45	12.64	10.88	16.40	15.18	172.12
26. Honomu	1200	24	22.54	18.84	21.03	22.67	15.88	12.36	16.88	19.04	18.45	14.68	24.54	23.42	230.33
27. Honomu No. 2	350	15	17.95	12.76	13.82	14.99	9.94	7.76	10.85	12.39	12.08	10.91	13.39	16.00	152.84
28. Honuapo	25	12	1.95	3.49	4.48	2.70	1.19	0.61	1.06	3.18	1.58	1.63	4.86	3.00	29.73
29. Hookena	850	3	2.72	3.03	2.61	6.12	6.34	5.80	7.34	5.40	6.50	4.66	3.46	6.22	60.20
30. Hoopuloa (Lower)	1650	9	2.52	4.08	4.31	3.47	5.39	4.45	5.01	5.51	4.76	5.01	2.71	2.45	49.67
31. Hoopuloa (Upper)	2425	9	3.86	3.39	3.45	5.79	5.98	6.09	5.26	7.10	6.18	5.29	2.74	2.98	58.11
32. Hope-a	4000	26	5.95	5.97	7.33	5.23	2.89	0.97	2.05	2.63	1.83	2.65	8.33	7.61	53.44
33. Huehue	2020	32	3.91	2.50	3.59	3.34	3.86	3.35	2.15	2.68	3.01	2.82	2.43	3.38	37.02
34. Humuula	6685	8	2.43	2.89	2.39	2.12	1.85	1.00	1.79	4.73	2.08	2.59	4.22	4.19	32.28
35. Kaala	5500	21	7.46	6.46	7.97	6.03	3.43	1.10	3.52	4.74	3.77	3.99	8.85	7.27	64.59
36. Kahuku Ranch	1680	3	2.77	1.49	3.41	0.62	1.26	1.94	3.23	2.89	2.79	4.75	4.96	3.30	33.41
37. Kailua	950	22	2.65	3.85	3.74	4.11	5.73	5.32	5.73	6.01	5.67	4.59	3.67	3.22	54.29
38. Kailua	12	7	2.79	1.79	1.33	2.62	2.64	3.35	2.18	2.25	2.82	1.98	2.12	1.32	27.19
39. Kainehe	1475	14	9.70	8.63	21.57	16.24	7.18	3.26	6.99	10.23	4.51	6.41	12.26	11.04	118.02
40. Ka Lae	29	11	2.60	1.16	1.81	0.90	0.28	0.31	0.42	0.63	0.61	0.45	2.49	2.03	13.69
41. Kalahiki (Castle)	1500	3	5.02	5.27	4.30	6.74	10.19	6.88	5.68	12.13	7.63	7.76	8.87	6.90	87.37
42. Kalahiki (Castle)	1800	3	1.99	6.49	7.92	6.33	14.91	7.40	11.19	8.35	9.70	6.81	5.84	6.20	93.13
43. Kalahiki (Castle)	750	12	2.18	3.11	3.46	3.88	4.81	3.83	4.37	4.54	4.31	3.90	3.70	3.12	45.21
44. Kalapana (W. E. Wilson)	8	4	6.23	8.23	11.05	2.61	6.18	2.14	2.46	4.31	2.42	9.84	4.64	4.08	64.19
45. Kalopa	900	8	6.59	11.35	10.77	10.97	4.91	3.48	5.58	8.29	5.31	4.65	7.84	12.29	92.03
46. Kanahana	5060	13	1.70	1.64	1.79	2.54	2.69	2.46	2.15	3.11	2.78	2.30	1.56	2.59	27.31

Mean monthly rainfall on Hawaii through 1935
(Data obtained from Territorial Planning Board, 1st Progress Report, 1939—*Con't*)

Station (fig. 36)	Elevation	No. Years Record	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
47. Kapapala Ranch	2150	49	6.90	6.29	7.87	5.01	3.72	1.83	2.57	3.65	3.88	4.84	6.53	6.33	59.42
48. Kapoho	110	44	10.07	8.26	11.30	7.62	5.93	5.34	6.07	7.14	7.71	7.53	9.45	9.93	96.35
49. Kau	1850	9	4.73	4.94	4.93	3.22	4.20	4.36	4.43	5.42	4.76	4.14	7.21	5.40	57.74
50. Kaueleau	1000	10	14.68	11.20	15.89	12.66	12.86	10.02	10.20	8.15	9.13	11.23	14.02	17.29	147.33
51. Kaueleau No. 2	350	9	13.56	9.19	15.42	10.96	5.86	4.75	7.31	7.46	7.28	7.05	8.21	9.43	106.48
52. Kaumana	500	30	15.19	11.41	15.57	15.90	11.87	9.65	12.73	15.52	13.08	11.15	16.03	16.43	164.53
53. Kaumana	1050	12	12.17	10.88	24.27	18.35	14.01	8.73	16.13	23.40	14.81	14.07	18.27	9.76	184.85
54. Kawainui (Lower)	1040	25	13.11	14.19	14.92	19.96	13.18	9.88	13.11	13.05	8.77	7.77	16.65	15.81	160.40
55. Kawainui (Upper)	4080	28	16.42	15.63	16.80	22.40	18.72	18.73	23.18	21.69	15.85	12.78	19.49	17.54	219.23
56. Keaa Homestead	1680	5	3.05	4.02	2.83	2.79	3.34	2.85	3.64	4.37	5.61	3.36	5.81	4.13	46.30
57. Kealakekua	1450	35	3.67	3.09	4.00	4.97	6.44	6.79	6.83	7.00	7.38	5.97	3.74	3.94	63.82
58. Kealakekua (Davis)	1580	25	3.68	3.74	4.00	4.91	6.48	6.89	7.48	7.86	7.84	6.23	4.07	3.23	66.41
59. Keanakolu	5500	7	8.55	10.82	8.56	7.94	4.44	2.27	2.55	7.53	4.85	5.42	10.64	8.07	81.64
60. Keauhou No. 2	1930	8	6.57	5.36	6.09	7.99	11.62	13.05	11.52	12.04	13.98	11.42	9.60	6.30	115.54
61. Kehena	3800	24	16.11	13.19	14.49	17.10	11.34	10.12	13.64	12.81	8.81	7.44	16.93	17.78	159.76
62. Kiolakaa	1000	22	6.63	4.05	5.08	4.56	3.15	2.73	2.54	3.61	3.84	4.51	5.35	6.82	52.87
63. Kohala	309	40	4.88	4.58	5.31	6.42	4.18	3.38	4.55	4.73	3.64	3.16	5.67	5.58	56.08
64. Kohala (Maulili)	960	28	7.57	6.62	6.45	9.66	5.95	4.84	6.37	6.79	4.59	3.92	7.53	8.22	78.51
65. Kohala (Mission)	537	46	5.45	5.04	5.75	6.64	4.21	3.41	4.54	4.83	3.47	3.23	5.65	5.74	57.96
66. Kohala Parsonage	350	11	5.64	4.90	7.01	5.20	4.41	3.39	4.75	4.88	3.01	4.29	4.57	5.12	57.17
67. Koiawe (Lower)	1000	25	8.70	8.63	9.71	13.25	8.52	6.34	9.11	8.50	5.54	5.12	11.13	10.83	105.38
68. Koiawe (Upper)	3355	24	9.62	8.59	10.73	15.04	11.29	9.12	12.65	11.40	8.01	6.61	12.22	11.12	126.40
69. Kona Exp. Station	1500	5	2.59	2.88	4.63	5.97	8.59	7.91	9.91	7.60	8.33	6.64	4.82	2.18	72.05
70. Korean Camp	1750	16	12.79	12.59	15.41	16.01	6.70	3.74	7.20	7.63	6.61	6.88	14.10	11.06	120.72
71. Kukaiau Store	850	16	10.43	10.20	11.91	13.43	5.65	3.24	6.04	7.32	6.04	5.17	11.00	9.66	100.09
72. Kukaiau Pltn. Co.	800	24	9.10	9.24	13.31	13.62	8.66	4.62	7.32	8.12	5.16	5.81	10.94	10.81	106.71
73. Kukaiau (1600)	1600	11	14.01	8.27	24.04	17.62	8.14	3.19	5.94	7.44	2.73	7.18	12.46	9.56	120.58
74. Kukaiau (3400)	3400	11	8.04	5.24	18.22	10.04	2.20	1.24	1.97	3.50	2.99	3.98	6.54	6.88	70.84
75. Kukuihaele	275	45	6.60	6.16	8.44	8.21	4.61	2.69	4.59	5.23	3.68	3.56	7.13	7.01	67.91
76. Kukuihaele (H. I. C.)	950	25	9.76	8.75	9.85	11.63	7.22	4.00	5.94	6.69	4.80	3.71	10.70	9.62	92.67
77. Lanihau	1540	5	2.50	4.67	7.06	4.43	8.99	7.33	6.78	7.87	7.65	7.00	3.06	2.61	69.95
78. Laupahoehoe	30	36	11.76	9.63	18.42	16.00	9.12	6.94	10.78	12.16	8.78	9.75	13.17	13.47	139.98
79. Laupahoehoe (Barnard)	10	5	7.69	9.32	13.24	13.20	6.46	4.91	7.13	8.43	5.81	6.16	7.47	10.69	100.51
80. Mahukona	11	23	2.77	1.39	.99	1.66	.78	.50	.41	.47	.61	.43	1.31	2.78	14.10
81. Makapala	1600	11	9.58	11.16	7.67	14.77	8.38	5.98	7.66	7.21	5.77	3.81	10.06	8.95	101.00
82. Maulua	5400	18	13.79	10.21	15.14	11.04	4.99	3.23	7.68	9.90	8.64	6.43	12.83	12.74	116.62
83. Mauna Anu	6600	6	6.95	5.06	10.29	9.61	2.62	2.24	2.53	6.08	12.54	12.69	4.73	11.74	87.08
84. Moaula (T. C. Wills)	1700	5	4.19	6.75	12.68	3.42	3.70	2.13	3.39	3.40	3.72	6.48	6.02	6.95	62.83
85. Moaula Station	650	16	6.60	3.45	5.86	4.74	1.90	1.16	1.32	2.54	3.44	4.44	4.18	6.76	46.39
86. Mountain View	1530	35	16.99	13.20	18.02	18.58	13.68	11.31	15.42	17.63	15.07	12.87	19.07	16.60	188.44
87. Naalehu	650	45	5.54	4.42	5.19	3.47	2.08	1.52	1.91	3.30	3.27	3.66	4.99	5.05	44.40
88. Naalehu	1250	4	3.39	3.00	9.24	5.12	2.88	1.66	2.26	4.85	2.86	2.15	5.67	4.25	47.33
89. Napoopoo	16	34	2.45	1.77	2.13	2.67	3.63	3.39	3.65	3.77	3.86	3.20	1.94	2.90	35.36
90. Nauhi Gulch	5100	11	13.13	10.17	10.21	12.91	6.98	5.70	9.18	13.14	11.27	6.17	10.45	10.50	119.81
91. Niulii	85	50	4.97	4.48	5.65	6.36	4.52	3.37	4.73	4.93	3.96	3.30	5.59	5.51	57.37
92. Olaa (225)	225	35	12.57	9.95	14.08	13.83	9.15	7.76	10.56	11.83	11.34	10.41	14.90	14.57	140.95
93. Olaa (1650)	1650	8	11.92	12.20	30.99	19.87	14.36	9.26	14.29	17.96	12.17	13.30	18.46	13.61	188.39

Mean monthly rainfall on Hawaii through 1935
(Data obtained from Territorial Planning Board, 1st Progress Report, 1939—*Con't*)

Station (fig. 36)	Elevation	No. Years Record	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
94. Olaa (Kurtistown)	646	22	14.83	11.87	19.37	18.01	10.55	9.23	12.72	15.85	11.41	11.94	16.98	18.45	171.21
95. Ookala	425	45	10.36	9.51	14.15	13.27	7.65	5.27	8.06	9.41	6.93	7.41	11.98	11.05	115.05
96. Paauhau	400	46	6.77	6.42	8.68	7.78	4.55	2.62	4.21	4.89	3.20	3.41	7.22	7.05	66.80
97. Paauhau (Mauka)	1150	6	6.50	6.62	11.58	12.21	5.62	3.79	7.38	9.60	7.62	5.34	5.80	12.63	94.69
98. Paauhau (1200)	1200	11	8.92	7.70	12.13	7.02	4.09	2.86	4.89	4.97	1.76	5.00	6.93	7.37	73.64
99. Paauilo	765	33	9.14	8.86	10.31	13.07	6.73	3.77	6.62	7.02	5.53	4.34	10.07	10.24	95.70
100. Paauilo (Crusher)	269	8	5.46	7.97	7.69	16.41	10.70	3.91	4.09	5.16	1.19	1.94	8.30	11.35	84.17
101. Paauilo (Notley)	750	10	8.06	7.49	13.98	8.02	4.33	2.32	3.52	4.42	2.02	5.76	8.89	6.40	75.21
102. Pahala	850	44	5.34	4.48	5.83	3.27	2.15	1.07	1.24	2.91	2.57	3.41	5.36	5.22	42.85
103. Pahoa	670	26	13.90	11.60	13.24	12.76	10.27	10.01	12.07	11.72	12.13	9.93	13.60	15.20	146.43
104. Pahoehoe	1000	5	3.75	2.99	3.70	3.73	5.43	5.14	5.38	4.51	5.13	7.43	2.80	3.04	53.03
105. Pahuamimi	5140	14	5.89	4.54	6.51	5.70	2.41	1.22	2.35	3.37	7.48	4.39	3.89	5.75	53.50
106. Pakao	5154	7	5.79	4.87	5.99	5.95	4.41	3.09	3.89	5.19	4.84	5.41	4.52	2.40	56.35
107. Papaaloa	260	8	8.23	11.11	12.78	13.13	8.25	8.14	9.68	14.31	11.23	8.19	11.83	12.50	129.38
108. Papaikou	250	37	15.49	11.68	18.44	16.49	12.32	9.38	13.13	15.05	13.71	13.23	17.99	16.24	173.15
109. Papaikou (Mauka)	1400	10	16.29	16.97	14.46	21.30	17.35	13.73	18.20	20.25	19.25	14.40	18.18	26.68	217.06
110. Pepeekeo	100	46	12.30	9.16	14.39	11.43	8.54	6.70	9.57	10.81	10.64	9.96	12.15	12.13	127.78
111. Piihonua	1000	11	12.18	16.01	14.88	17.52	15.18	13.47	17.62	20.23	13.81	13.17	18.63	19.04	191.74
112. Piihonua	1800	11	22.72	15.91	18.06	23.95	19.42	14.90	20.19	23.09	22.03	13.84	19.12	22.80	236.03
113. Pohakuloa	5700	3	1.73	0.40	0.53	4.33	4.13	0.07	....	0.73	2.20	1.40	1.93	14.33	31.78
114. Pohoiki	10	9	8.24	10.00	8.65	5.90	4.62	4.08	5.09	5.79	5.42	10.32	7.39	6.62	82.12
115. Puakala	6350	15	12.66	6.48	9.15	7.86	4.05	4.02	4.90	10.62	8.14	5.98	7.43	7.29	88.58
116. Puakea Ranch	600	32	4.69	3.64	3.59	5.66	2.75	2.68	3.51	3.42	2.51	2.05	4.50	5.59	44.59
117. Punohu Paddock	4200	3	3.90	4.07	7.50	6.57	4.93	2.40	3.80	1.40	1.40	4.00	3.58	9.20	52.75
118. Puu Alala	2800	20	8.51	7.57	9.31	11.28	6.56	4.22	6.47	5.45	4.45	4.50	9.12	10.36	87.80
119. Puuhinei Paddock	1500	3	3.00	1.03	1.47	0.97	2.83	0.43	0.20	1.60	1.53	1.13	1.60	4.00	19.79
120. Puuhue Ranch	1847	6	5.14	5.09	9.02	5.97	3.44	2.42	3.97	5.63	3.25	3.13	4.87	7.08	59.01
121. Puu Kea	8560	17	3.96	2.55	4.10	3.36	1.27	0.51	1.51	2.39	1.78	1.69	4.64	3.19	30.95
122. Puu Kihe	7820	21	4.73	3.57	5.77	4.04	2.11	0.64	2.24	3.59	2.79	2.33	5.81	4.65	42.27
123. Puulehua	4850	13	1.79	1.64	1.76	2.25	2.35	2.61	2.32	2.93	2.53	2.00	1.45	2.47	26.10
124. Puu Loa	2500	16	14.43	14.87	19.55	19.22	7.58	4.49	6.67	8.65	6.65	6.83	13.77	14.79	137.50
125. Puu Oo	6450	24	9.08	6.63	6.54	6.67	5.24	4.24	6.27	8.84	7.13	6.12	8.28	6.70	81.74
126. Puu Ulaula	7020	3	2.59	4.03	4.13	3.55	1.26	0.20	1.02	0.81	1.26	3.28	2.80	1.02	25.95
127. Puu waawaa	2750	32	2.87	2.70	2.76	2.33	2.77	1.67	1.65	2.02	2.93	2.23	1.75	2.43	28.61
128. Station No. 39	1900	15	13.77	13.64	15.62	16.46	7.13	3.80	7.44	7.71	6.89	6.86	14.41	11.16	124.89
129. Stone Corral	5000	22	4.63	4.01	5.50	4.33	2.28	0.58	1.84	2.35	2.00	2.26	6.78	5.00	41.56
130. Sugahara Camp	260	43	8.31	7.86	10.98	11.10	5.72	3.43	5.43	6.14	4.32	4.53	9.67	9.03	86.52
131. Umikoa	3520	42	8.20	8.56	11.96	9.52	4.27	1.40	2.96	4.14	3.10	3.79	10.49	10.84	79.23
132. Volcano Observatory	3979	23	11.75	7.32	10.76	8.87	5.81	4.29	6.20	6.48	6.93	6.42	10.04	10.53	95.40
133. Volcano House	3973	17	6.62	7.22	8.41	7.53	5.58	3.88	5.87	7.63	5.82	6.58	11.36	7.07	83.57
134. Waiakaheula	750	4	12.04	11.75	10.37	12.45	8.98	6.53	8.36	8.42	8.45	8.81	11.50	14.65	122.31
135. Waiakea Mill	50	45	12.32	9.66	14.43	12.84	9.07	7.15	9.67	11.84	10.50	10.79	13.79	12.67	134.73
136. Waiakea Camp No. 6	615	20	18.20	13.12	18.40	18.08	11.88	9.83	13.76	15.56	13.69	12.04	17.03	18.73	180.32
137. Waiakea Camp No. 8	1050	15	21.20	14.50	15.62	20.16	14.10	10.54	14.52	18.10	14.76	11.87	14.21	20.49	190.07
138. Waima (Waipio Valley)	930	23	9.28	8.84	10.41	14.16	8.91	5.78	9.71	9.16	5.96	5.35	12.36	12.09	112.01
139. Waimea	2669	45	4.78	4.27	4.88	4.15	3.01	2.25	2.99	3.18	2.29	2.55	3.76	4.99	43.10

gallons per square mile per year, or 3.25 million gallons per square mile per day. Taking the total area of the island as 4,030 square miles, the average rainfall over the whole island is 13,085 million gallons daily, or 4,776,477 million gallons a year.

SURFACE WATER

The steep permeable terrane and the intensity of the rainfall make all streams flashy. A marked difference exists in the character of the low-water runoff from the ash-covered permeable slopes of Mauna Kea and that from the deeply eroded surface of Kohala Mountain where it is derived from large ground-water bodies. Streams are scarce except on Mauna Kea and Kohala Mountain as shown by the map of ephemeral and perennial streams, figure 38. A summary of the records of stream flow for the island of Hawaii has been published.[9] Daily discharges in Hawaii are published in the annual Surface Water-Supply Papers of the U. S. Geological Survey.[10]

An unusual type of natural stream diversion occurred on March 25, 1937, when a flood caused extensive shifting of bar gravels and other sedimentary deposits along the Wailuku River. It was known that about 50 years ago there had existed a lava tube 25 feet wide and 15 feet high, known as Pukamaui, which led northward from the Wailuku River above Pukamaui Falls (pl. 53C). The Polynesian demigod Maui was said to make this hole his part-time residence. The entrance to this cave had, however, become plugged with flood gravels, and its precise location generally forgotten. The flood of July, 1928, removed the gravel deposit, and the entire flow of the Wailuku River was diverted through the lava tube, emerging in Kokelekele Stream a quarter of a mile to the northeast. The entrance to the tube had to be walled up because it was situated in the intake basin of the Hilo water system, and lowered the water level below that of the intake pipe.

The several large ditch and flume systems that transport water for irrigating and fluming sugar cane are shown in figure 38. The Kohala Ditch Company supplies water to the Kohala Sugar Company plantation. It maintains two large ditch systems. The Kohala ditch diverts water from an altitude of 2,000 feet in Waikaloa Gulch and extends chiefly as a tunnel to the west rim of Pololu Canyon and thence as ditch and tunnel to an altitude of 949 feet, southwest of Hawi, a total length of more than 18 miles. It cost $770,548.

---

[9] Surface water-supply records (1901–1938) Hawaii: Hawaii Terr. Plan. Bd., Summary of Records, pp. 351–411, Honolulu, 1939.

[10] U. S. Geol. Survey Water-Supply Papers 318, 336, 373, 430, 445, 465, 485, 515, 516, 535, 555, 575, 595, 615, 635, 655, 675, 695, 710, 725, 740, 755, 770, 795, 815, 835, 865, 885, 905, 935, 965, 1913–1943; no. 795, pp. 11–12, contains a list of the gaging stations and the years each was in operation.

A 60-kw hydroelectric power plant is operated by the fall in the ditch in Honokane Nui Canyon and a 350-kw plant by the fall at Hawi. The ditch diverts the flow of all streams crossed by it and picks up the flow of 30 water-development tunnels. The capacity of the ditch is 76 m.g.d. and its mean flow from 1928 to 1937 was 23.2 m.g.d. The part of the ditch south of the East Branch of Honokane Nui Canyon is called the Awini ditch.

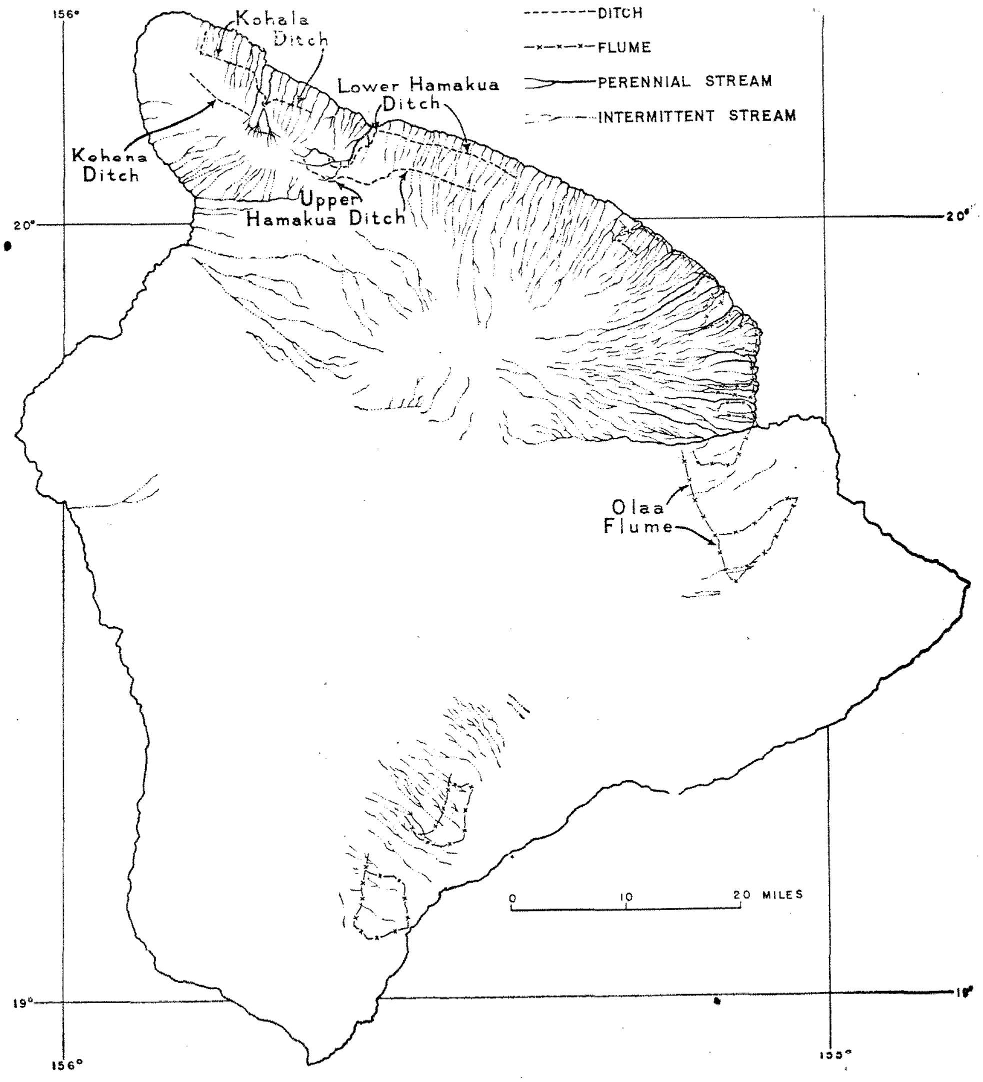


Figure 38. Map of Hawaii showing perennial and intermittent streams and main ditches and flumes.

The Kehena or upper ditch diverts water from an altitude of 4,200 feet from Honokane Nui Stream above the canyon rim. It extends chiefly as a ditch for about 8 miles. It cost $152,503 and its capacity is 86 m.g.d. Its mean flow is 7.75 m.g.d. It goes dry during droughts.

The Hawaiian Irrigation Company maintains two ditches (fig. 38). The lower Hamakua ditch, opened in July, 1910, diverts water from an altitude of 1,037 feet in the Kawainui fork of Waipio Canyon, transports it to the main weir at Kukuihaele at an altitude of 985 feet, and thence 11 miles southeast. It collects the flow of Alakahi, Koiawe, and Waima streams, also. It is chiefly a system of tunnels (pl. 1) and cost $894,795. Its capacity is 60 m.g.d. and its length is 66,484 feet. The low flow drops to 24 m.g.d. occasionally and once it dropped to 19 m.g.d. according to Masaru Matsunami, superintendent of the Hawaiian Irrigation Company. The upper Hamakua ditch, built in 1907, diverts water at an altitude of 4,041 feet from Kawainui Stream above the canyon rim and runs to reservoir no. 4 at an altitude of 2,819 feet. It is 105,874 feet long and cost $387,106. Its capacity is 60 m.g.d. and its average flow from 1913 to 1920 was 9.47 m.g.d. It goes dry in its lower stretches during droughts, but its upper part is said never to completely dry up. From 1933 to 1942 the annual flow of the lower ditch has ranged from a low of 11,302,521,000 gallons in 1935 to a high of 12,952,984,000 gallons in 1942. The upper ditch for the same period ranged from a low of 3,063,131,000 gallons in 1940 to a high of 6,655,135,000 gallons in 1936.

The Olaa Sugar Company maintains the Olaa flume, about 20 miles long with a capacity of 16 m.g.d. (pl. 54B). Its low flow is entirely from perched springs and tunnels. A small gulch contributes surface water in times of floods.

Numerous flumes collect water from streams, springs, and tunnels along the windward slope of Mauna Kea (pl. 54C). Extensive flume systems collect water chiefly from springs and tunnels on the lands of the Hutchinson Sugar Plantation Company and the Hawaiian Agricultural Company, Ltd.

GROUND WATER

SOURCE OF GROUND WATER

Virtually all ground water in the island is derived from rainfall. During eruptions, some magmatic water rises as steam and may add slightly to the ground-water body. The amount is infinitesimal compared with the contributions from rain. It is believed that most of the steam rising from cracks both between and during eruptions is derived from rain water that has percolated to bodies of hot rock.

Rain is dissipated by runoff in streams entering the sea, by transpiration and evaporation from plants, by evaporation from the ground, by percolation into the ground, and by subterranean courses into the sea. The path of percolating water through a highly permeable basalt terrane is shown in figure 39.

Percolation into the ground is the most important factor, as highly permeable lavas from which little or no runoff occurs are exposed over about five-sixths of the surface of the island. No perennial stream is found between the Wailuku River at Hilo and Waiakaukaua Stream east of Upolu Point, by way of South Point, a distance of more than 200 miles. Most of the rain falling on this vast area of about 4,030 square miles percolates to the underlying ground-water body and then slowly moves seaward under the island and discharges at the coast. This fact is very striking when it is remembered that the average rainfall ranges from 40 to 200 inches over a large part of the area of no runoff.

VALUE AND SOURCE OF WATER SUPPLIES

In spite of the unusually favorable conditions for ground-water recharge, potable water cannot be recovered by means of wells or tunnels from 3,500 square miles or 87 percent of the total area of the island (fig. 40). Over much of the area this anomalous condition results from the great depth to the zones of saturation and not from lack of ground water. Under this large area of land lies a vast reservoir of water that would have a profound effect upon the economic development of the island if some feasible means could be found for recovering the water for irrigation. Large tracts of fertile soil on the slopes of Mauna Kea and Kohala Mountain and inland from South Point could be irrigated. Some water is probably confined by dike structures a thousand feet or more above sea level (fig. 42).

The value of ground water is great not only because of the scarcity of surface runoff in large areas but also because satisfactory sites for reservoirs are scarce. The rocks are so permeable that all unlined reservoirs leak heavily and are used chiefly for overnight and storm-water storage. Many leak their capacity every 24 hours. Steep gradients and the great amount of debris carried by the streams during floods make large reservoirs impractical. The floors of a few craters of ancient cinder cones on Kohala Mountain have been sealed sufficiently by soil to make them usable as small reservoirs. Ronald von Holt has made several permanent water holes by placing a feeding trough in damp depressions in the Kahua Ranch. The cattle standing around the trough puddle the ash soil and cause the ground water to collect in the depression where formerly the soil was too porous to retain the water.

During years of normal rainfall moderately sized rain catches and storage tanks meet domestic needs in all except the very dry areas. However, storage tanks large enough to meet shortages in drought years are too expensive to be feasible for the ordinary home owner. These areas have remained unsettled for the most part and are used for grazing (fig. 3). Any water developed in these areas is very valuable. Cattle commonly die in large numbers in the semiarid areas during droughts unless they have cactus (*Opuntia megacantha*) available. During severe droughts, men on the Puu Waawaa Ranch work night and day with blow torches burning the needles from cactus so that cattle will be able to eat it and obtain sufficient water to survive. A few cattle learn to knock down the cactus with their horns and trample the thorns so that they can eat it.

Surface and spring water is abundant along the windward coast except during severe droughts. Basal ground water is also available in large quantities. These areas are covered with sugar cane and forest (fig. 3). Only a small part of the sugar cane is irrigated (fig. 3). Extensive ditch and flume systems collect water along the windward coast and in the Kau District for fluming sugar cane. Improvement in trucks and roads has made flume water less important in the last decade but large areas of many plantations are too steep for the cane to be harvested economically except by fluming.

The new mechanical methods of harvesting sugar cane have increased the demand for water at certain mills. Thus, in 1942 Kaiwiki Sugar Company and Hamakua Mill Company dug deep wells to develop water for washing the dirt from mechanically harvested cane.

Social and economic changes during the next decade or two may create new needs for water, and it may become economically feas-

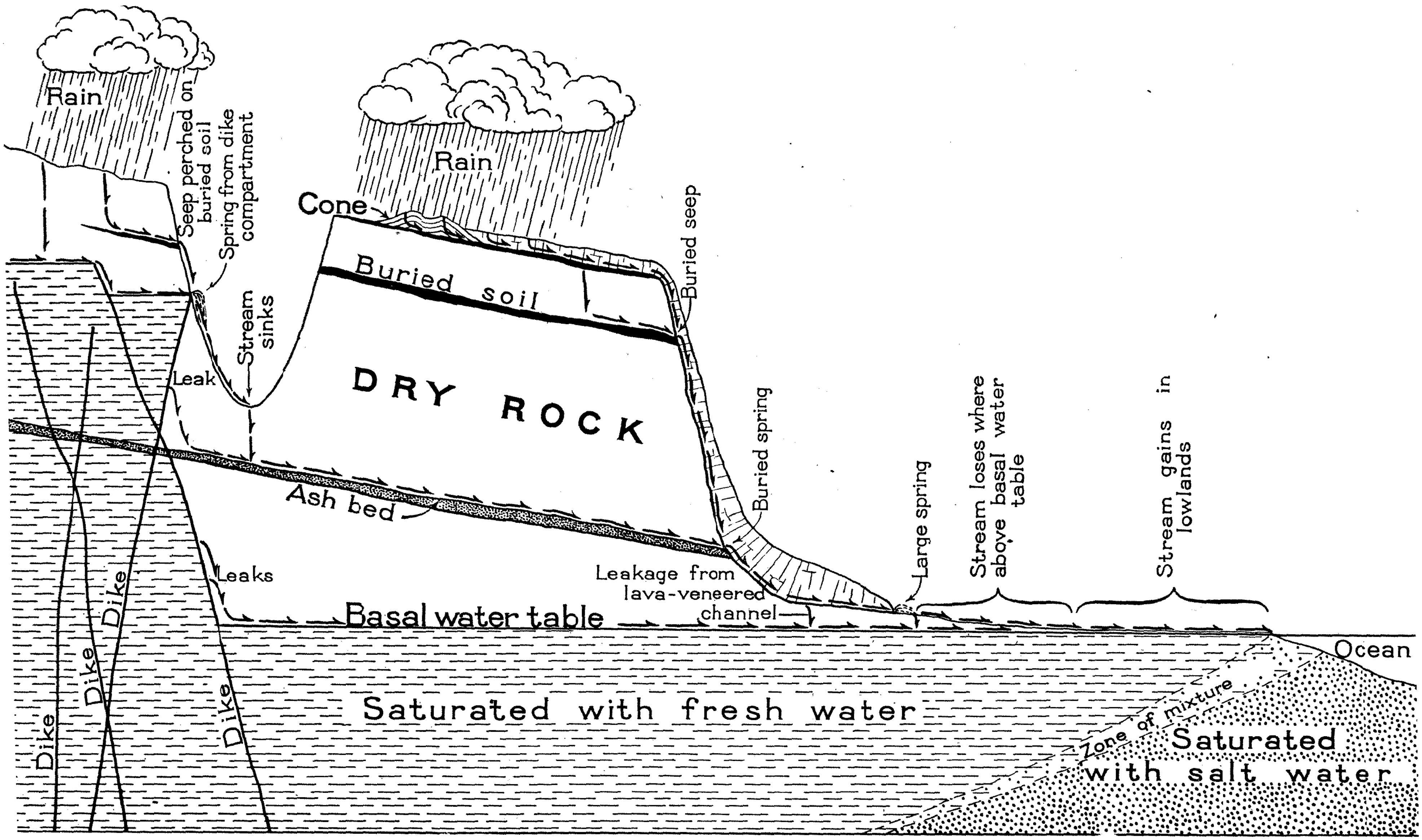

Rain
Seep perched on buried soil
Spring from dike compartment
Stream sinks
Leak
Rain
Cone
Buried soil
Buried seep
DRY ROCK
Ash bed
Buried spring
Large spring
Stream loses where above basal water table
Stream gains in lowlands
Leaks
Leakage from lava-veneered channel
Basal water table
Dike
Dike
Dike
Dike
Ocean
Saturated with fresh water
Zone of mixture
Saturated with salt water

Figure 39. Diagram illustrating the paths of percolating water through a highly permeable basalt terrane containing a dike swarm, interbedded soil and ash beds, and a late valley-filling lava flow.

ible to pump, or to pipe long distances, water supplies now considered too expensive to develop. An example of a new use for water is the washing of sugar cane. New airports and camps of the armed forces require the development of additional water.

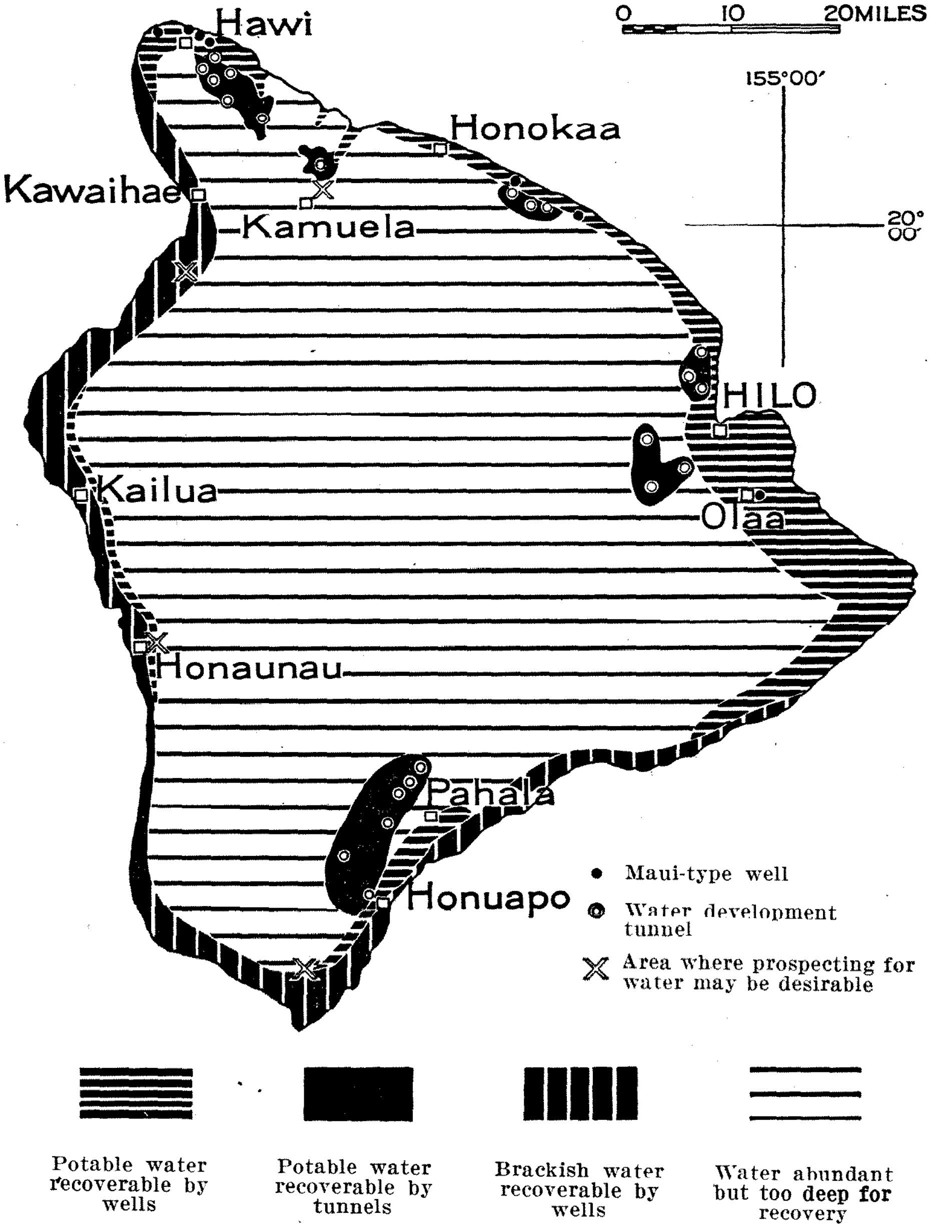


Figure 40. Map of Hawaii showing areas where water can be recovered by wells and tunnels.

During the economic depression of 1932-36 several proposals were made to rehabilitate the coffee farmers in the Kona District by moving them to the leeward slopes of Mauna Kea. Such a move would have increased the plight of the farmers because of the shortage of water. The availability of water supplies should be considered carefully before such rehabilitation plans are undertaken. Ground water is very valuable in the Kona District. Its development and distribution is expensive because the farms and settlements are widely scattered at high altitudes (p. 272).

BASAL GROUND WATER

Definition.—Basal ground water, as distinguished from high-level ground water, is the great body of water that lies below the main water table or upper surface of the zone of saturation in the island.[11] It is the unconfined ground water occurring in the lavas under the entire island except the rift zones. The area of basal water is shown in figure 41. Thus, the term is not used to include the water in the dike complexes (fig. 42).

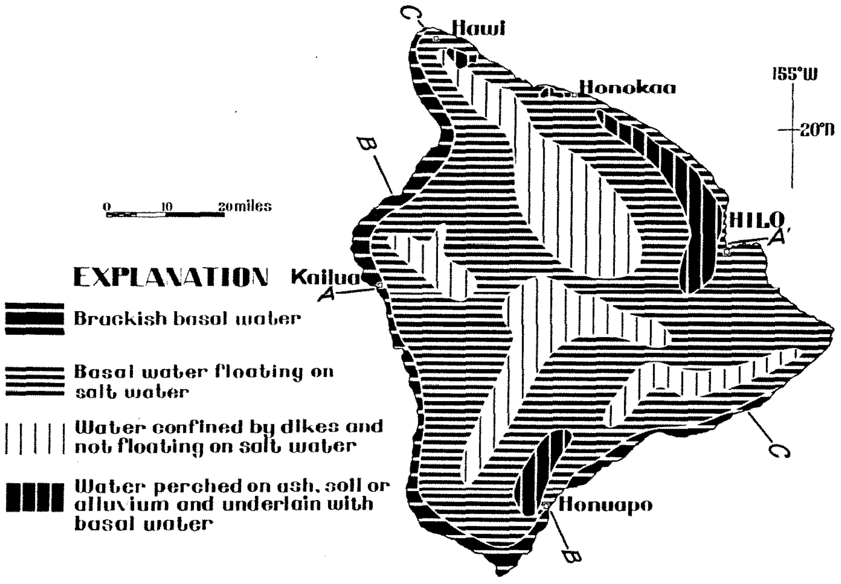


Figure 41. Map of Hawaii showing ground-water areas and location of sections shown in figure 42.

Permeability of lava.—The cavities and crevices within and between the lava flows form a great underground reservoir. In order of potential yield, they are (1) interstitial spaces in clinker, (2) cavities between beds, (3) shrinkage cracks, (4) lava tubes, (5) gas vesicles, (6) fissures produced by faulting and cracking after the flows have cooled, and (7) tree-mold holes.

---

[11] Meinzer, O. E., Ground water in the Hawaiian Islands: U. S. Geol. Survey Water-Supply Paper 616, p. 10, 1930.

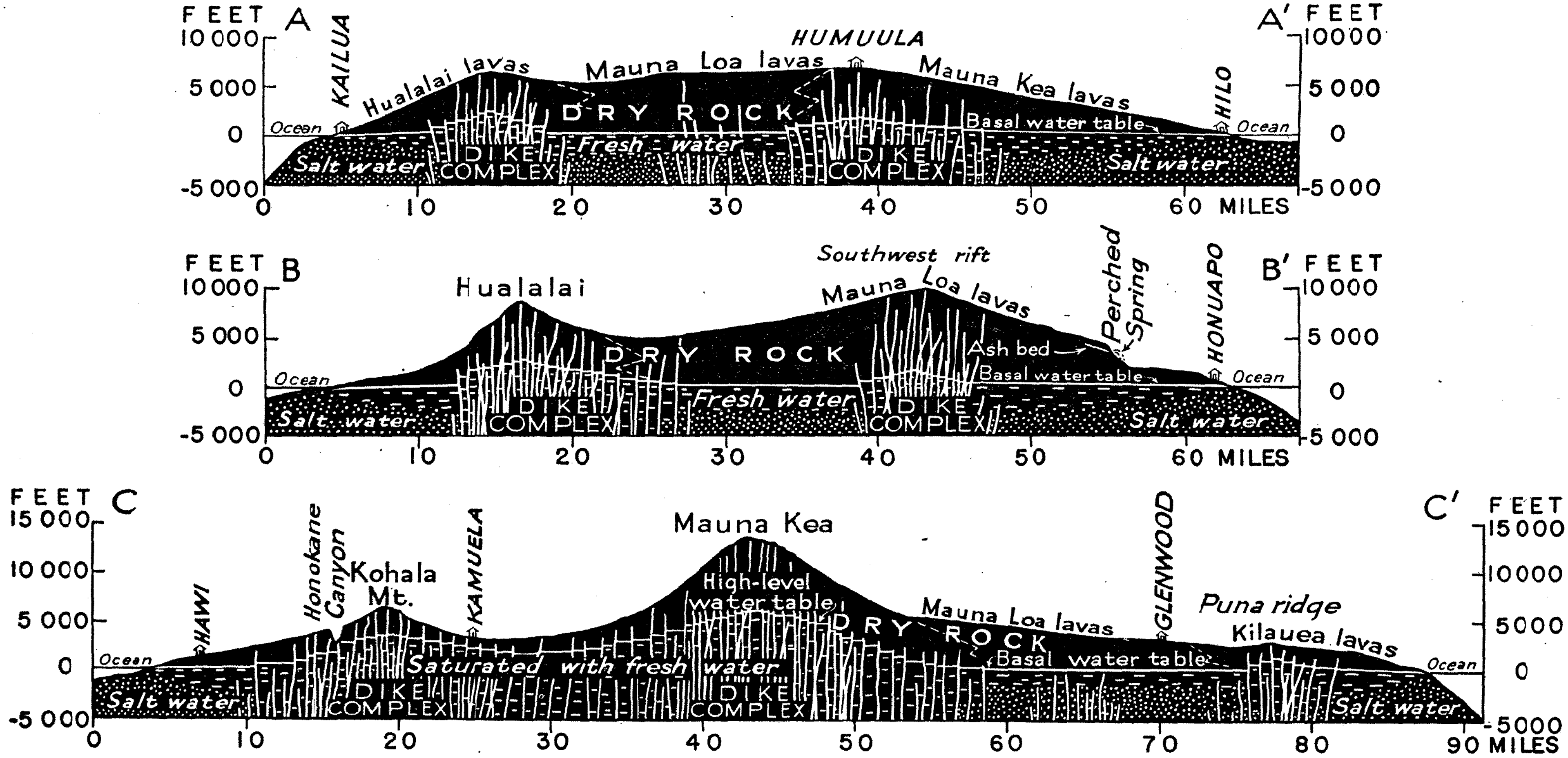


Figure 42. Sections showing ground-water conditions along the lines AA′, BB′, and CC′ in figure 41.

Permeability decreases usually as the thickness of the lava bed increases. Thickness of a flow is determined by its chemical composition, temperature, gas content, and the slope of the terrane over which it flows. The highly gas-charged and fluid lavas erupted near the summit of Mauna Loa form highly scoriaceous beds seldom more than 3 feet thick. Such rocks are extremely permeable. The lavas become less scoriaceous and thicker farther down the slope after some of the gas and heat has been lost, and the rocks are less permeable.

Most lava on Hawaii flows down fairly steep slopes and cools in flow units from a few inches to a few feet thick (pl. 45D). Such lavas are highly permeable as shown by their ability to yield prodigious quantities of water to wells penetrating them. If a branch of such a highly permeable lava flow spills into a crater or other depression, it cools as a massive columnar-jointed mass with relatively low permeability (pl. 14A). Lavas poured down steep slopes contain more tubes than those on gentle slopes. These may range from a few inches to 30 feet or more in diameter and may extend for long distances underground (pl. 12B).

The composition of the lavas profoundly affects their denseness and consequently their permeability. Basalts are usually highly permeable. Andesites are less permeable. The trachyte from Puu Waawaa formed a very dense, impermeable flow more than 900 feet thick with flow units several hundred feet thick on the slope of Hualalai. Basalts laid down on the adjacent slope are only 5 to 20 feet thick and moderately to highly permeable.

Permeability of pyroclastic rocks.—Products of the lava fountains coarser than ash are extremely permeable, and cinder cones and pumice deposits yield water freely in the zone of saturation. Ash is fairly permeable also unless it has been altered by weathering, but altered deposits are relatively impermeable and perch water (p. 263). Coarse pyroclastic deposits resulting from paroxysmal eruptions are fairly permeable before consolidation. After weathering they tend to become impermeable.

HIGH-LEVEL GROUND WATER

High-level ground water is water held at levels above the basal water table by rocks that are relatively impermeable. All types of perching structures known in the Hawaiian Islands are found in Hawaii. In order of importance, they are intrusive rocks, ash beds, dense lava flows, soil, alluvium, and ice. High-level water is valuable because its height above sea level makes pumping unnecessary and salt-water invasion impossible, and because it occurs in places where basal water is too deep to develop economically. However, its total volume is small in comparison with basal water. The highest perched water in the Hawaiian Islands is Lake Waiau on Mauna Kea, altitude 13,007 feet. It is probably perched on ground ice. Upper Waihu Spring, 10,387 feet above sea level on Mauna Kea is perched on ashy hill wash interbedded with lavas.

Ground water confined by dikes occurs in the rift zones of all five mountains but only that in Kohala Mountain (p. 228) is recoverable economically; elsewhere it lies too deep (figs. 40 and 41). Water is perched on ash in many places in the island, the most valuable supplies being in the Kau District. Small volumes of water perched on dense lava sheets occur ubiquitously in the wet slopes of Mauna Kea and in a few places on Kohala Mountain. Water perched on interbedded soils supplies numerous springs and tunnels in Kohala Mountain, the most important horizon lying between the lavas of the Hawi and Pololu volcanic series. Alluvium perches little water due to its scarcity between lava flows. It supports the water in the Bond No. 1 tunnel (no. 10, pl. 1). Perennial ice in cracks in the summit of Mauna Loa provides small quantities of water. It may be that the Waihu Springs on Mauna Kea are supplied in part by melting ground ice.

Perched artesian water, similar to that in the Nahiku area[12] on Maui, has not been found, but the dense sheets of lava on Mauna Kea and Kohala Mountain may form artesian structures locally.

Additional details of perched ground water bodies are given in the succeeding pages.

GROUND WATER IN THE KOHALA AREA

BASAL SUPPLIES

The absence of a cap rock along the coast of the Kohala Mountain causes the basal water table to stand nearly at sea level. The high permeability of the lavas along most of the coast allows ocean water to move freely underground. Large quantities of fresh basal water must run into the sea from the bases of the high cliffs between Kukuihaele and Niulii because of the heavy rainfall inland. Basal springs with an aggregate flow of about 1,000,000 gallons per day discharge from the bottom of the northwest walls of Waipio, Waimanu, and Pololu canyons.

From Niulii to Upolu Point the cliffs are lower and in places weathered rock extends to sea level. The weathered rock is much less permeable than fresh rock, thereby retarding the mixing of sea and fresh water along the coast. Maui-type wells in this area yield an average of 1,440 million gallons per year of water with salt

---

[12] Stearns, H. T., and Macdonald, G. A., Geology and ground-water resources of the island of Maui, Hawaii: Hawaii Div. Hydrography, Bull. 7, p. 258, 1942.

ranging from 8.5 to 152 grains per gallon for irrigating sugar cane (pl. 1). A description of the wells is given on page 286. More water can be developed by Maui-type wells in this area.

From Upolu Point to Kawaihae, cliffs are low or absent and the rock fresh. Rainfall inland is low; hence, only small quantities of basal water move seaward. Dug wells at Mahukona recover brackish water. A well one quarter of a mile south of Mahukona recovered water with 440 grains of salt per gallon (4,572 p.p.m.).[13] The Kahua Ranch dug several wells along the coast between Mahukona and Kawaihae. Some recovered potable water and others water too salty for stock. Their relation to the rock types suggests that the younger clinkery aa flows of the Hawi volcanic series yield brackish water in this stretch and the lavas of the Pololu volcanic series yield potable water. The Hawi lavas form projections through which sea water moves easily.

HIGH-LEVEL SUPPLIES

WATER CONFINED BY DIKES.—The pattern of the dikes has resulted in an area of high-level water, roughly 6 miles wide and 14 miles long, underlying the higher part of Kohala Mountain (fig. 41). The surface of this body of water as indicated by springs rises from an altitude of 300 feet at Hiilawe Spring in Waipio Valley (no. 29, pl. 1) to 1,700 feet at the head of Koiawe Canyon (pl. 52A). In Honokane Nui Canyon springs indicate that the water table is higher than 2,000 feet. It is probably more than 3,000 feet above sea level under the summit. Waimanu and Honokane Nui canyons and Waipio Canyon with its tributaries, cut into this great zone of saturation and serve as open drains to lower the water table. All other perennial streams on the mountain depend on water perched on soil or ash.

Water stored between dikes in the headwaters of Waipio Stream forms a great underground reservoir. Its discharge has been measured daily at the outlet of the lower ditch. Discarding surface run-off, the records indicate that ground-water storage above an altitude of 1,000 feet remains constant with 10 to 12 inches of rain per month regardless of the level of the water in the ground. Rainfalls of 13 to 24 inches per month make the reservoir gain storage until the discharge reaches about 36 m.g.d. The reservoir loses storage at the rate of about 1 m.g.d. per month with rainfalls of 5 to 8 inches. Rainfalls of 3 inches or less per month cause a loss in storage of 2 to 3 m.g.d. The reservoir continues to discharge at the rate of 23 m.g.d. even after several months of less than 4 inches of rain per month. The data indicate that it leaks rapidly above a

---

[13] The term "salt content" as used in this report means the amount of chloride found in the water, expressed in terms of sodium chloride. The abbreviation p.p.m. in parentheses is the amount of the (Cl) radicle in parts per million.

daily discharge of 35 m.g.d. and very slowly below a daily discharge of 25 m.g.d. Rainfalls of less than 5 inches per month are evaporated and transpired. When 20 inches or more rain falls in a few days, much of it runs off, probably because during such wet weather fissures carrying percolating water reach their capacity. Also large leaks in the confining rocks of the reservoir may allow rapid discharge when the water level reaches a certain height. Intense rainfall of short duration in dry spells does not cause an appreciable rise in the ground-water storage as shown by the rapid drop of the discharge to the quantity preceding the rain (fig. 43).

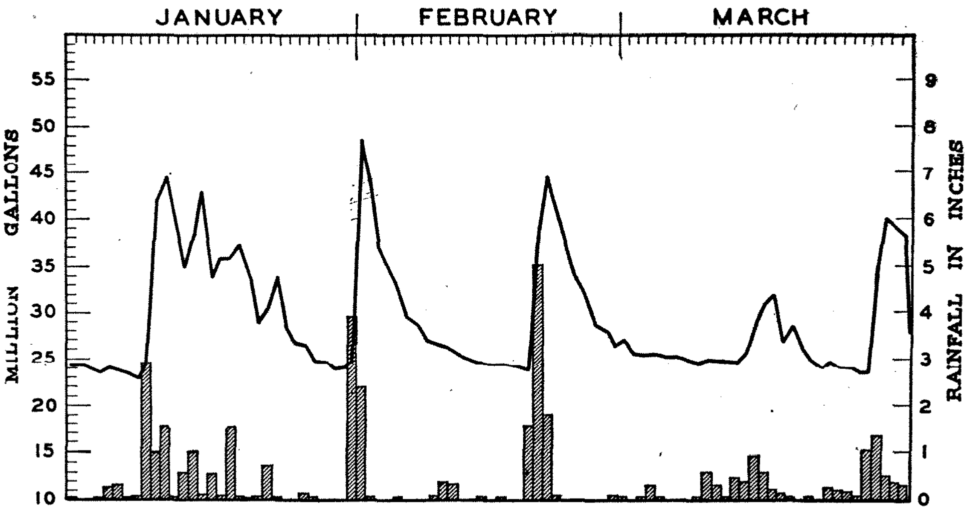


Figure 43. Graph showing the discharge of the lower Hamakua ditch at main weir at Kukuihaele in relation to rainfall at upper Kawainui gage, January to March, 1934.

Tunnel 36 is being driven by the Kohala Ditch Company vertically above a site recommended by the senior author in 1938, to recover water confined by dikes in the East Branch of Honokane Nui. It was 1,200 feet long in February 1944 and had cut 13 dikes. In July 1945 it was yielding 5,000,000 gallons per day. Although a large part of the flow is stored ground water, the drought of 1945 made this water exceedingly valuable. The tunnel was started in the cliff at an altitude of 1,900 feet or 18 feet higher than Awini Falls, the local name of the drop in the ditch on the wall of Honokane Nui Canyon. If this tunnel develops a large dependable supply, a transportation tunnel about 9,000 feet long along the east wall of the canyon would deliver the water to the head of Awini Falls. A large flow combined with the ditch water would make valuable power development possible. The drop at Awini Falls is 840 feet.

From 1,050,000 to 1,350,000 gallons of water per day rises in the floor of the East Branch of Honokane Nui Canyon in the half-mile stretch below the Kohala ditch. Two pumps lift all but 300,000 gallons a day of this quantity up to the ditch. Several dikes cross the canyon in this stretch and the water apparently is held at this high level by them.

The transportation tunnels of the lower Hamakua ditch cut two dikes at the head of Hiilawe Cove but no dikes between there and a point south of the mouth of Waima Stream. The tunnel loses water in this stretch of Pololu lavas. Between this point and the intake in Kawainui Stream the tunnel cuts numerous dikes and gains water. An examination of the tunnel was made in a boat during the investigation. Measurements after four weeks of dry weather follow:

Gain and loss in lower Hamakua ditch

(Measurements made on January 28, 1912, by F. Koelling, W. Payne, and A. Gibb)

	Gallons
Ditch at Kawainui intake	18,572,000
Ditch below Alakahi intake	28,557,000
Ditch above Koiawe intake	29,802,000
Gain in tunnel Alakahi to Koiawe	1,245,000
Ditch below Waima intake	34,870,000
Ditch at main weir	29,892,000
Loss between Waima and weir	[a]4,978,000

[a] The tunnel gains about 1 m.g.d. in the east wall of Waima Canyon, which increases the loss to about 6,000,000 gallons per day.

SPRINGS FROM DIKE STRUCTURES.—Most of the flow of the tributaries of Waipio Stream is from springs issuing from dike swarms which have been cut by erosion (pl. 52A). The number of dikes exposed in these tributaries is given on page 175 and their trends are shown on plate 1. The flow from springs in the tributaries at the confluence with Waipio Stream, after all flow is diverted at 1,000 feet by the lower Hamakua ditch, is estimated as follows:

Estimated ground-water flow of main tributaries of Waipio Stream during dry weather in December 1944

Stream	Diverted by ditch (m.g.d.)	At mouth (m.g.d.)	Total (m.g.d.)
Hiilawe	0.0	8.0	8.0
Waima	0.5	12.0	12.5
Koiawe	6.0	4.0	10.0
Alakahi	7.0	3.5	10.5
Kawainui	18.0	[a]4.0	22.0
	31.5	31.5	63.0

[a] Includes some flow passing under intake dam and possibly some leakage from ditch.

A traverse of Kawainui Stream on December 6, 1943, showed that all except about 2 m.g.d. comes from spring-fed tributaries and Ulu Spring (no. 21) rather than from invisible gain in the bed of the stream. The gage at the lower Hamakua ditch intake at an altitude of 1,037 feet indicated a flow of 18 m.g.d., and an estimate of the flow of tributaries between the intake and Ulu Falls was 15.75 m.g.d. from spring-fed tributaries as shown in the accompanying table. About 1 m.g.d. of the 18 m.g.d. comes from the Upper Kawainui Springs (nos. 22 and 23, pl. 1 and fig. 46), perched on soil or ash; the balance issues from dike structures.

Flow of springs in Kawainui Stream above Hamakua ditch intake

Barometer reading (feet)	Description	Estimated flow (m.g.d.)
1,100	Two springs in N. bank	0.25
1,260	Spring-fed stream from big amphitheater in S. bank (Springs 22 & 23 in this amphitheater)	3.00
1,260	Spring-fed stream from big amphitheater in N. bank	5.00
1,600	Spring-fed stream from the south, 0.75 m.g.d. from base of jointed rock	1.00
1,860	Spring-fed stream from the north	0.50
2,250	Ulu Spring pool (no. 21)	6.00
		15.75

Waimanu (no. 19) and Waihilau (no. 17) springs issue from behind dikes at an altitude of about 425 feet. Their flow was estimated at 5 m.g.d. and 12 m.g.d. respectively on December 22, 1943. Waihilau is the largest spring issuing from dike structures and the largest high-level spring on Hawaii. Near the mouth of Waimanu Stream the flow during dry weather is about 30 m.g.d.,[14] all of which comes from springs.

No springs issue from dike structures between Waimanu and Honokane Nui canyons. Numerous springs issue from the dike swarm in the East Branch of Honokane Nui, some 100 feet or more above the canyon floor. The flow from springs in the canyon is 10.5 to 13.5 m.g.d. in dry weather, including 1.44 m.g.d. which discharges from ash beds below the Awini ditch. A fault plane striking N. 35° W. and dipping 78° SW., yields 25 gallons per minute 1¼ miles above Awini ditch in the west wall of this canyon. The West Branch cuts a dike swarm but yields only about 0.6 m.g.d. in dry weather because most of the water moving underground toward this canyon is intercepted by the East Branch.

Pololu Canyon does not carry high-level spring water probably because Honokane Nui Stream has cut deeper and drained the water that formerly supplied it. The large size of Pololu Canyon indicates that it was formerly supplied by springs.

WATER PERCHED ON ASH BEDS.—Water is known to be perched on ash and tuff beds in four localities, and buried ash beds probably

---

[14] Martin, W. F., and Pierce, C. H., Water resources of Hawaii, 1909–1911: U. S. Geol. Survey Water-Supply Paper 318, p. 333, 1913.

perch water elsewhere in the mountain. The localities are (1) northeast coast, (2) Honokane Nui Canyon, (3) north slope, and (4) slopes above Waimea.

Several thin interbedded vitric tuff beds crop out in the sea cliff between Waimanu and Honopue canyons. Keawewai Spring (no. 16) issues from the west wall about 400 feet above the floor of Waimanu Valley a quarter of a mile from the coast. It yields about 30 gallons per minute and is apparently perched on the eastern extension of the tuff beds. Thirteen gulches are crossed by the trail from Waipio Valley to Waimanu Valley. Seven are perennial, the flow in dry weather ranging from 15,000 gallons per day in the smallest to 30,000 gallons per day in the largest. The aggregate flow is about 180,000 gallons per day. This water is probably derived from springs perched on thin tuff beds as seven tuff beds less than a foot thick are interstratified with the lavas of the Pololu volcanic series in the east side of Waimanu Bay.

The tuff beds in the sea cliff between Waimanu and Honopue canyons cause two spring horizons (fig. 44). The lower one is about 150 feet above the sea, the other about 20 feet higher. In places the beds are only a few inches thick and traced with difficulty. The springs trickle down the face of the cliff, one of the largest (no. 15)

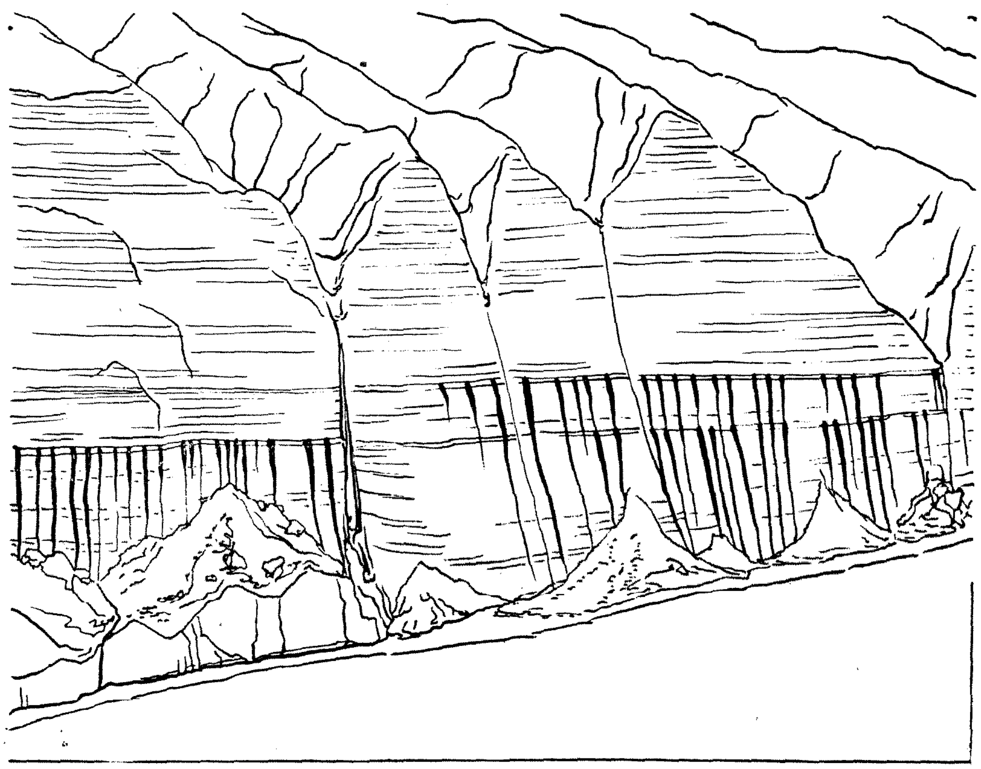


Figure 44. Sketch of sea cliff between Waimanu and Honopue canyons showing perched springs discharging from two thin layers of tuff in the Pololu volcanic series. The cliff is 1,000 feet high.

being behind the landslide known as Laupahoehoe 3 miles northwest of Waimanu Bay. The springs range from a mere trickle to 15 gallons per minute and have an aggregate low flow of about 200 gallons per minute. Northwest of Honopue Canyon, nine tuff streaks are exposed in the sea cliff but they do not yield water.

Three vitric-lithic tuff beds at altitudes of 950 feet, 1,240 feet, and 1,535 feet respectively crop out in the east wall of the East Branch of Honokane Nui Canyon in the Pololu volcanic series. They range from 6 inches to 18 inches in thickness, except one bed which locally thickens to 7 feet. Formerly springs discharged from them but tunnels 33 to 35 have been driven on the tuff beds and have diverted most of the springs. Tunnel 34 is partly a conduit as it delivers the water to Awini Falls. The fall of water from Awini ditch is used to drive turbines which pump water that rises below the ditch up to the intake. The aggregate low flow from these springs and tunnels as reported by the Kohala Ditch Company is 1,440,000 gallons per day. The maximum flow is 2,250,000 gallons per day.

The streams in the deeper gulches between Pololu Valley and Hawi flow even in dry weather. Most of the water discharges from a soil horizon between the lavas of the Pololu and Hawi volcanic series but a few of the springs issue from thin tuff beds interstratified with the Pololu lavas. Some of the water is probably percolating from the adjacent irrigated fields of sugar cane.

Numerous small seeps and springs issue from interstratified ash beds in the slopes on Kohala Mountain above Waimea Plain. They yield from a few gallons to 10,000 gallons per day in dry weather but are mostly too scattered to use except for stock. The low flow of Waiaka, Hauani, and Waikoloa streams is supplied by small springs of this type. The water of Waikoloa Stream is diverted to supply the Waimea area and Kawaihae. The flow is reported by the County Engineer never to drop below 50,000 gallons per day in dry weather. The ash beds are interstratified with the lavas of the Hawi volcanic series. The prospects are poor for developing water by tunneling in this area.

Haloa Falls in Haloa Hill, a large cinder cone at the head of Waima Canyon, is supplied by water perched on a fine-grained bed in the cinder cone. It goes nearly dry in droughts. The aggregate flow of all springs issuing from ash and tuff beds in Kohala Mountain is estimated to be 1,600,000 gallons per day.

WATER PERCHED ON SOIL.—A soil bed ranging from a few inches to 2 feet and commonly overlying 2 to 20 feet of partly decomposed basalt separates the Pololu from the Hawi volcanic series in the north slope of Kohala Mountain. Numerous springs issue from the lavas on top of the soil and 18 tunnels recover perched water from it. The lack of springs on this soil bed along the western slope can be attributed to the low rainfall. It is not exposed in the slopes above Waimea but it gives rise to numerous springs east of Waipio Bay.

The Hawi lavas covered an undulating and slightly eroded terrane in the north slope of the mountain. It was deeply eroded east of Waipio Canyon. The percolating water collects in the swales and gulches buried by the Hawi lavas and discharges at points where these lavas terminate or have been cut by erosion. If conglomerates lie at the contact they may carry water as at Iole Spring (no. 3) or perch water as at Bond No. 1 tunnel (no. 10). The soil bed is fairly continuous in the north slope as shown by the wide distribution of tunnels (pl. 1). Sufficient time intervened between some flows of the Hawi volcanic series for a thin ashy soil to accumulate. A few springs issue from such soil beds stratigraphically above the main soil horizon. In a few places a thin soil accumulated between the upper flows of the Pololu volcanic series so that some water also issues below the main horizon. This condition causes two or three spring horizons one above the other in some gulches. At Watt No. 2 tunnel (no. 16), soils stratigraphically below the main bed cause perched water to issue at the same altitude as the main soil bed due to undulations in the main bed as shown in figure 45. Men driving tunnels at the site of a spring in this area have been puzzled because springs at the same level near by failed to dry up. A careful check of the stratigraphy should be made before tunneling to determine on which soil bed the springs are perched.

Fortunately rocks in this area can usually be differentiated without the aid of the microscope. The Hawi lavas are all andesites, fine grained gray lavas in weathered outcrops. Lindsay tunnel (no. 21) recovers water from a thin soil between two andesites and Waipunalau tunnel (no. 22) from clinker above a dense bed of andesite (fig. 45B). The top flow of the Pololu volcanic series is in most places a porphyry containing green olivine and black augite crystals ⅛ to ¼ inch across. A few contain white feldspar crystals ⅛ to ½ inch across in addition to the olivine and augite. Under the porphyries is a soil a few inches thick in places from which small springs issue. The Dr. Bond tunnel (no. 9) recovers water from such a bed (fig. 45E). Under the porphyries are usually basalts with scattered olivine crystals less than a quarter of an inch across. The absence of augite crystals enables one to identify these rocks with certainty.

The olivine basalts contain thin interbedded ash and ashy soil in some gulches. Hapahapai tunnel (no. 7) collects water from such a bed (fig. 45F). Under the olivine porphyries the rock is commonly nonporphyritic but lacks the light gray color of the andesites.

Some of the water perched on beds below the unconformity may be supplied by leakage from the main soil bed where it was cut by erosion before burial by the Hawi lavas.

The flow of all springs and tunnels derived from the interbedded soils and tributary to the Kohala ditch averages 4,960,000 gallons daily according to data furnished by the Kohala Ditch Company. In dry years the flow drops to 1,000,000 gallons daily.

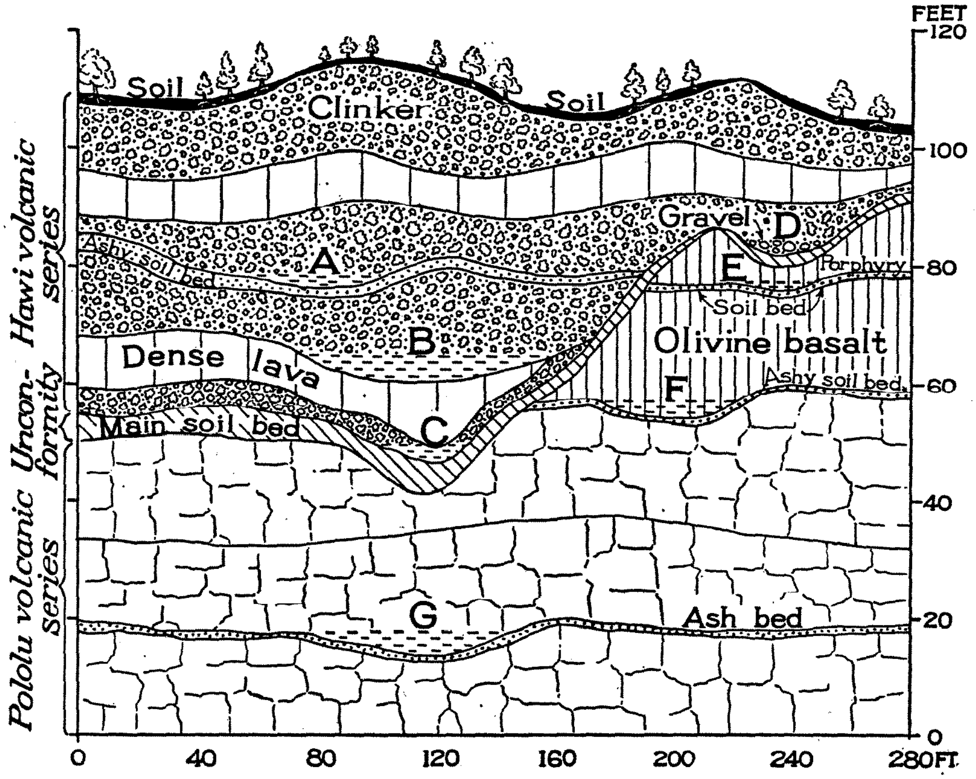


Figure 45. Diagram showing the relation of perching structures to the movement of ground water in the north slope of Kohala Mountain. Water perched on ashy soil interbedded with Hawi lavas, A; on dense lava, B; on main soil at unconformity, C; from bouldery conglomerate on unconformity, D; on soil and ash beds interstratified with the Pololu lavas, E, F, and G.

The water from the tunnels in the north slope is exceedingly valuable as most of it is used for domestic purposes. The tunnels have been driven at springs part way down the slope between Waipunalau and Wainaia streams. These gulches radiate from a small area about 1½ miles across. A tunnel starting at Watt No. 2 (no. 16) and contouring the main soil bed between the Hawi and Pololu volcanic series would capture the flow of most of the springs and tunnels below. The water could then be dropped 750 feet to the Kohala ditch for power before being distributed to camps. Not much new water would be developed because the Hawi lavas terminate on the slope below and water in them not lost by downward percolation must escape there. However, tunneling on the soil bed is relatively cheap because little blasting is necessary.

Recharge must be from rainfall on the wet slopes above and leakage from the Kehena ditch. The flow of such a tunnel might be increased considerably by repairing the abandoned Kahua ditch and turning surplus water from Kehena ditch into it. Kahua ditch always leaked heavily and by building small reservoirs in depressions along it, the leakage could be increased. At present the surplus water in Kehena ditch is lost in the reservoir near Puu o Nale. This water percolates to the basal water table and cannot be recovered by high-level tunnels.

The Upper Kawainui Springs (nos. 22 and 23) discharge about 1,000,000 gallons per day in dry weather from the base of a trachyte flow at an altitude of about 3,550 feet in the southwest rim of Kawainui Canyon. An ashy soil probably perches the spring which issues in the face of a cliff that cannot be examined in detail without the aid of ropes.

UNDEVELOPED HIGH-LEVEL SUPPLIES.—Large quantities of high-level water confined by dikes await development in Kohala Mountain, especially under the summit area. Tunnel 36 should be driven about a mile from the portal to tap water confined by dikes in the northwest rift zone. A large part of this water now escapes underground northward and is lost.

A tunnel driven about a mile southwestward from the head of Alakahi Canyon would tap water confined by dikes in the southeast rift zone (fig. 46, tunnel A). Water from this tunnel would enter the lower Hamakua ditch and could be dropped 1,000 feet into Waipio Valley near the coast to make power. W. O. Clark estimated that a tunnel in this canyon would yield 3.5 million gallons a day.[15] The proposed tunnel would probably divert some of the flow of Koiawe Canyon.

Waihilau (no. 17) and Waimanu (no. 19) springs are held at an altitude of about 425 feet apparently by the same thick dike. A tunnel driven southwestward from Waihilau Spring would probably divert the flow of Waimanu Spring (fig. 46, tunnel B). If successful, the combined flow of both springs would be about 17 m.g.d. which if led 1 mile along the canyon wall in a ditch and then dropped 400 feet to the valley floor, could develop about 680 kw.

About 31 m.g.d. is available in dry weather at an altitude of 500 feet in Waipio Stream. This water has potential value for power. If conducted 1½ miles downstream along the canyon wall it could

---

[15] Letter to Honokaa Sugar Co., dated May 24, 1934, supplementing a manuscript report entitled "Prospects for developing ground water in Waipio Canyon, Hawaii," May 21, 1934.

be dropped 400 feet (fig. 46). Another possibility is to pump some of the water into the lower Hamakua ditch and then drop it 1,000

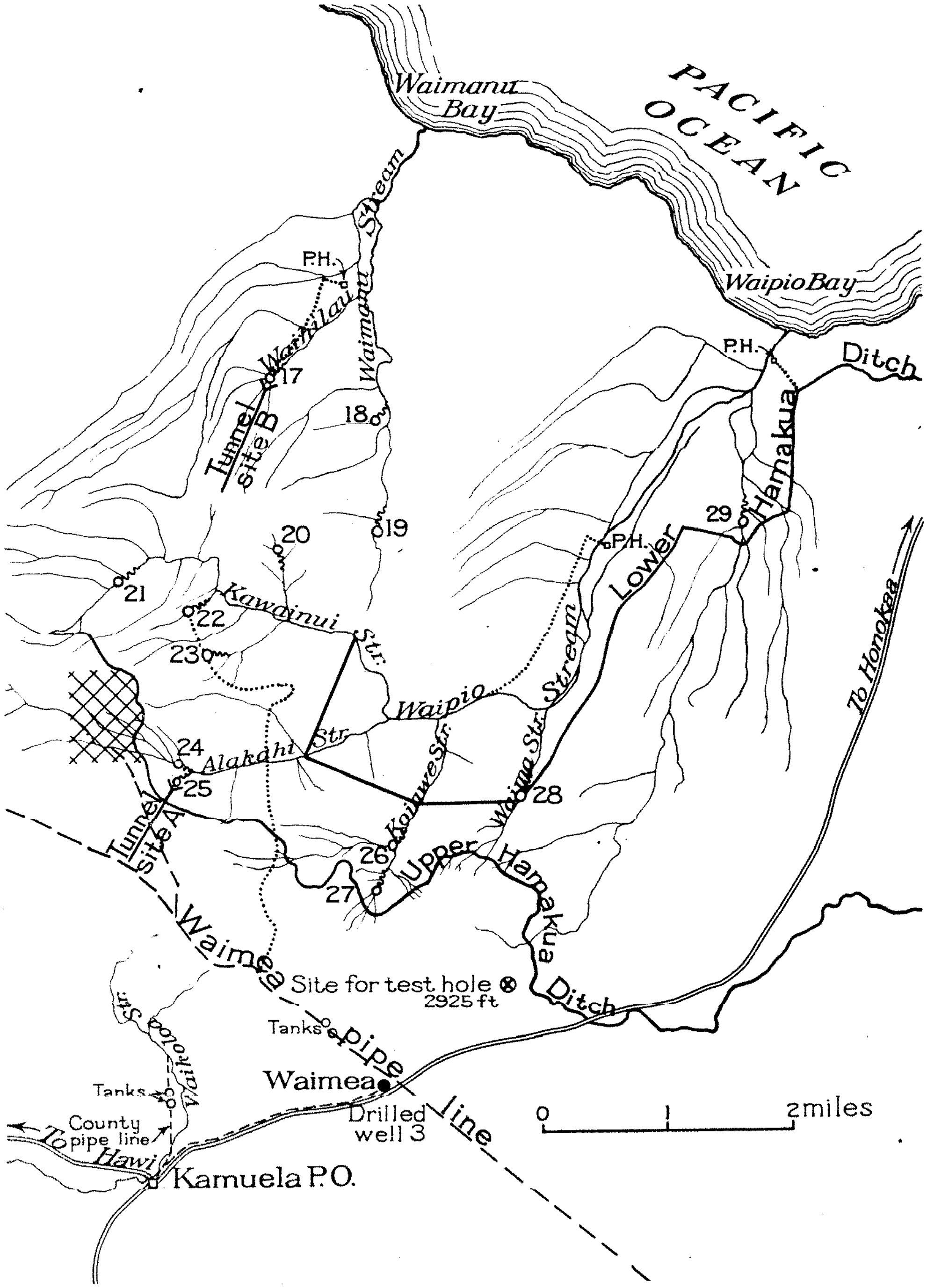


Figure 46. Map of Waipio and Waimanu valleys showing proposed pipe lines and ditches (dotted lines), powerhouse sites (P.H.), tunnel sites A and B, and existing ditches and pipe lines. Springs 17 to 29 are described in the table on page 290. Area worth prospecting for perched ground water is crosshatched.

feet near the coast (fig. 46). A net increase in power would result. The gain from springs 100 feet lower than the intakes in these streams is shown in the following table:

Ground-water gain in Waipio tributaries at weirs 100 feet lower than ditch intakes

(Measurements made on January 28, 1912, by F. Koelling, W. Payne, and A. Gibb)

Stream	Gallons
Kawainui	948,000
Alakahi	727,000
Koiawe	1,144,000
Waima	764,000
	3,583,000

Upper Kawainui Springs (nos. 22 and 23) issue at an altitude of about 3,550 feet and discharge about 1,000,000 gallons per day in dry weather. A pipe line about 3 miles long crossing Alakahi Canyon would lead the flow of these springs by gravity to the Waimea pipe line. This water is moving through the base of late Hawi lavas which cross the upper Hamakua ditch about 0.6 mile to the west. The water supplying these springs might be intercepted by a tunnel or by dug wells along the ditch. Test borings should be made to determine the depth to the water-bearing horizon in the area shown in figure 46.

Any water recovered would make a valuable addition to the Waimea supply. About 500,000 gallons per day could be obtained for this area from the intake end of the upper Hamakua ditch if it were lined with concrete to stop leakage.

The U. S. Marine Corps drilled well 3 into Pololu lavas to a depth of 800 feet in an attempt to encounter confined ground water (fig. 46). The hole should be drilled to a depth of 1,500 feet to fully prospect this area. In times of drought even water that had to be pumped 1,500 feet would be valuable. A better prospect for a test hole is a point 1½ miles northeast of well 3 at an altitude of 2,925 feet, at the site indicated in figure 46. This site lies on the axis of the southeast rift zone where dikes are more numerous than at well 3 and where water should be standing higher in the mountain. The test hole should be drilled to a depth of 1,500 feet before being abandoned, if water is not encountered sooner.

A tunnel contouring the buried soil bed at the base of the Hawi lavas above the Kohala ditch has been described on page 235.

INVENTORY OF GROUND WATER IN KOHALA MOUNTAIN

The following table summarizes the quantity of ground water discharged by wells, tunnels, and springs in Kohala Mountain. The absence of a cap rock along the shore allows large quantities of basal water to waste directly into the sea at this level. This water cannot be measured and is not included. The basal springs listed below are those which issue above tide.

Average daily low-water discharge of ground water, in gallons

Basal water pumped from wells entering basalt		4,000,000
Basal water discharged in springs		1,000,000
Perched water discharged in springs		1,600,000
Perched water discharged from tunnels		3,000,000
Confined water of the dike complex discharged in springs		
Waipio drainage	[a]58,000,000	
Waimanu drainage	30,000,000	
Honokane Nui drainage	[b]7,750,000	
		95,750,000
Confined water of the dike complex discharged from tunnels (Tunnel 36 and tunnels of the lower Hamakua ditch)		8,250,000
		113,600,000

[a] A flow of 1 m.g.d. is deducted for springs 22 & 23 which are perched on soil and an estimated gain of 4 m.g.d. from the dike swarms cut by the lower Hamakua tunnels.

[b] Does not include tunnel 36 listed below.

The average annual quantity of ground water visibly discharged is about 41,464 million gallons.

GROUND WATER IN THE HAMAKUA AND NORTH HILO AREAS

BASAL GROUND WATER

Basal ground water underlies the entire lower slope of Mauna Kea from Hilo to Kukuihaele. Along the coast it is generally brackish, but half a mile inland it is of good quality (fig. 41). Many basal springs issue along the coast, but are unused. Basal water is pumped from two Maui-type wells, one at Ookala, and the other at Paauilo, and brackish basal water formerly was produced from several drilled and dug wells near the coast. Only one dug well, at Kaawalii Gulch, is still in use.[16]

The original Maui-type well at Ookala (no. 6, pl. 1), owned by the Kaiwiki Sugar Company, was completed in 1937. The shaft is 600 feet long, with an inclination of 30° from the horizontal and a bearing of S. 6° E. The portal is on the southeast side of Kaula Gulch 300 feet above sea level. At the bottom of the shaft is a pump chamber 18 feet long, 15 feet wide, and 10 feet high, with a floor about 7 feet above sea level. The water is pumped from a sump with a floor 2 feet below sea level. From the sump a tunnel 15 feet long, at the same depth, leads S. 6° E., to a cross-tunnel 85 feet long. Two reciprocating pumps, each with a capacity of 140 to 160 gallons

---

[16] While this book was in press a new Maui-type well was started at Pepeekeo. The shaft has a slope of about 30°, and starts 250 feet above sea level 0.8 mile S. 58° W. of Pepeekeo Point.

a minute, are powered by 40 hp electric motors. Pumpage at the rate of 400,000 gallons daily results in only slight drawdown. The normal pumpage is about 200,000 gallons daily. The water is used for domestic purposes.

A new unit was completed in 1943 to supply water for a cane laundry. The shaft diverges southwestward from the old shaft 70 feet from the old pump chamber. It is 90 feet long, with a pump chamber 24 feet long, 20 feet wide, and 12 feet high; the floor is 5 feet above sea level. The bottom of the sump is 1 foot above sea level. It is continued S. 6° E. by a tunnel 50 feet long, leading to a cross-tunnel 500 feet long. With the pumps working at a rate of 200,000 gallons daily in the old pump chamber, no drawdown or movement could be detected in the water in the new tunnel, only about 30 feet from the old tunnel. The upper part of the shaft penetrates lavas of the upper member of the Hamakua volcanic series. It is planned to pump about 2.5 million gallons daily from this well.

Water levels in the Maui-type well at Ookala (Kaiwiki shaft) have been published since 1938 in the series of United States Geological Survey Water-Supply Papers on water levels and artesian pressure in observation wells.[17] The recorded variation is between 3.91 and 7.04 feet above sea level. The variation is shown graphically in figure 47. During 1938 and 1939 the salt content of the water ranged from 1.1 to 2.3 grains per gallon (11 to 24 p.p.m.). The infiltration tunnels derive their water from lavas of the lower member of the Hamakua volcanic series, including both pahoehoe and aa, but water appears to enter most freely from the thin-bedded pahoehoe, particularly at and near contacts.

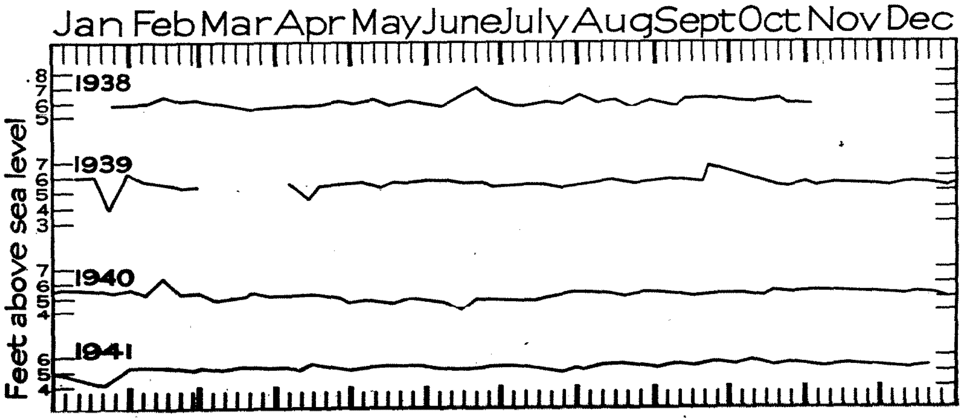


Figure 47. Graph showing fluctuations in the water level in Maui-type well 6 at Ookala.

---

[17] U. S. Geol. Survey Water-Supply Papers 845, p. 64; 886, p. 88; 911, p. 145; 941, p. 178; 949, p. 249; 1938–1942.

The portal of the Maui-type well at Paauilo (no. 5) is situated on the southeast side of Paauilo Gulch at an altitude of 273 feet. The well is in lavas of the upper member of the Hamakua volcanic series. The shaft has a bearing of S. 10° W. and an inclination of 26°, and is 626 feet long. The pump chamber is 22 feet long, 21 feet wide, and 9 feet high. From it a tunnel leads 34 feet S. 10° W. to a cross-tunnel 633 feet long, with its floor 0.5 foot above sea level. On March 21, 1944, the water level was 3.9 feet above sea level, and on September 10, 1944, it was 2.94 feet. The water level fluctuates about 6 inches with the tide. At the time the shaft was completed on March 12, 1943, the salt content was 2.4 grains per gallon (25 p.p.m.). In February 1945, with a static head of approximately 3 feet, pumping about 2.5 million gallons daily resulted in a drawdown of 9 inches, and pumping about 4.5 million gallons daily caused a drawdown of 11 inches. After pumping at the latter rate for 3½ hours, the salt content at the bottom of the sump was 5.6 grains per gallon (58 p.p.m.), that in the cross-tunnel to the southeast of the adit was 6.8 grains per gallon (71 p.p.m.), and that in the cross-tunnel northwest of the adit was 4.5 grains per gallon (47 p.p.m.). Most of the water entered the cross-tunnel northwest of the adit.

Three drilled wells near the coast formerly yielded brackish water, but are no longer used. One of these (no. 6, pl. 1) is located on the northwest side of the site of the former Kukaiau Mill, 450 feet from the shore, 2 miles east of the town of Paauilo. The well is 12 inches in diameter, and was drilled to 20 feet below sea level and cased to the bottom. The total depth is 264.7 feet. On December 29, 1935, the water level was 2.2 feet above sea level, and the salt content was 35.3 grains per gallon (367 p.p.m.) at the top and 36.9 grains per gallon (383 p.p.m.) at the bottom.[18] On May 18, 1939, the salt content was 20.5 grains (213 p.p.m.).

Another drilled well (no. 5, pl. 1) is located within the Paauilo Mill. Like the well near the old Kukaiau Mill site, it formerly was used for mill water and occasionally, during severe droughts, for drinking water. It is 12 inches in diameter and is cased to the bottom. Its depth is 217.1 feet, and its bottom is 1.5 feet below sea level. It is about 500 feet from the shore. On January 25, 1936, the water level was 1.7 feet above sea level, and the salt content was 17.2 grains per gallon (179 p.p.m.).[19] The third drilled well (no. 4, pl. 1), 12 inches in diameter, is located in field 21 of Paauilo Plantation, 500 feet from the shore and 1.2 miles northwest of the Paauilo Mill. It was formerly used for watering cattle. The water

---

[18] Clark, W. O., Unpublished report to T. H. Davies and Company, 1936.

[19] Idem.

is said to have been fresh enough to drink. These two latter wells were drilled by James McCandless in 1894.

An old dug well is situated at Honokaa Landing, in the bottom of the gulch, 300 feet from the shore. At the top, the hole is 15 feet wide and 35 feet long; at water level, it is 15 feet square. A platform about 2 feet above water level on the north side formerly supported the pump. The depth of the hole to water level is 28.5 feet, and to the bottom is 31.5 feet. Water level is probably between 1 and 2 feet above sea level. The hole, when originally dug, was apparently deeper than at present, as it is now partly filled with debris. At low tide on March 9, 1943, the salt content was 15.5 grains per gallon (161 p.p.m.). The water was formerly pumped to the Honokaa Mill when the supply of rain water was insufficient. Mr. W. P. Naquin, former manager of Honokaa Sugar Company, estimates that about 1 m.g.d. was pumped during these periods. According to Judge M. S. Botelho of Honokaa, the water was occasionally used for drinking.

Two dug wells formerly existed near the west side of the bottom of Kahawailiilii Gulch, just northeast of the Paauhau Mill. They are now covered by debris. One, 500 feet from the shore, was used only for mill water during droughts. Mr. J. W. Montgomery, mill superintendent, estimates that the amount of water needed to operate the mill at that time was about 1.5 m.g.d. T. Doi, who pointed out the locations of the wells, says the water in this well was too brackish to drink. The second well was situated a few hundred feet farther south, and was used for drinking water. The supply of water was small, however, and the well frequently went dry when pumped too heavily.

The only dug well now in use is located on the northwest side of Kaawalii Gulch, about 300 feet from the shore. It is a broad sump, about 50 feet long and 40 feet wide at the top, narrowing to about 6 feet at the bottom, and is about 25 feet deep. It is dug in stream-laid alluvium. The well is owned by the Laupahoehoe Sugar Company, and is used to supply water for fluming cane during periods when high-level stream water is insufficient. The amount of water used differs greatly in different years; during 1942, according to Adolph Korte, chief engineer, the amount of water pumped was about 860,000 gallons daily 6 days a week for a period of 6 months. When pumping is at a rate of 1,200 gallons a minute, the drawdown is about 6 feet. The salt content varies with the state of the tide, the amount of rainfall, and the amount of pumping. Before the pump is started the water at the surface is generally fresh enough to drink, but with pumping the salt content increases rapidly to about 250 grains per gallon (2598 p.p.m.).

PERCHED GROUND WATER

Many small perched springs occur on the east and northeast slopes of Mauna Kea (pl. 52B). In size they range from mere seeps of a few gallons a day to fourth magnitude springs[20] with a discharge of about 400,000 gallons a day. Their locations are shown on plate 1. The formation that perches them and their approximate discharge are listed in the table on pages 291-292. Unimportant small springs and seeps have been omitted from the map and table. Many of the springs are used as sources of domestic water; others supply flume water for the transportation of sugar cane. Still others are used to irrigate small patches of water cress, taro, and other vegetables. Few are unused.

The principal types of structure which perch the water are ash beds and the dense central parts of aa lava flows. Beds of rotted aa clinker also perch a few springs. In general, none of these types of perching material is very efficient. Most of the ash beds are only a few inches thick, and the dense aa lava has many fractures which permit water to leak through it. They perch ground water only because the amount of rain water entering the highly permeable surficial lavas is so great that not all of it can pass through these somewhat less permeable beds. By far the greater portion of the ground water, however, passes on down to the basal water table. Although the same structures exist on the leeward side of Mauna Kea, the rainfall and consequent ground water recharge are so small that all the water is able to percolate to the zone of basal water. Another factor contributing to the small size of most of the springs is the absence of any extensively developed buried drainage system on the perching formations, which might concentrate the perched water from a large drainage area.

Several springs on the southern slope of Mauna Kea at altitudes above 8,500 feet (pl. 1) are perched by beds of poorly sorted tuffaceous gravel intercalated with the latest lava flows. Other seeps in the same area are too small to be indicated on plate 1. The gravel was believed by Wentworth and Powers to be buried glacial tillite,[21] but it is now believed to be waterlaid[22] (p. 167). The poorly sorted nature of the hill wash, which consists of all grades of material from clay to boulders, results in its being relatively impermeable. Water entering the overlying lavas sinks to the surface of the hill wash and then runs off along it. Annual precipitation on the upper slopes of Mauna Kea is small, and large

---

[20] Meinzer, O. E., Outline of ground-water hydrology: U. S. Geol. Survey Water-Supply Paper 494, p. 53, 1923.

[21] Wentworth, C. K., and Powers, W. E., Glacial springs on the island of Hawaii: Jour. Geology, vol. 51, pp. 542–547, 1943.

[22] Stearns, H. T., Glaciation of Mauna Kea, Hawaii: Geol. Soc. America Bull., vol. 56, pp. 267–274, 1945.

drainage systems on the upper surface of the hill wash were not developed before burial; therefore, water is not concentrated from any large area. Consequently, the discharge of these springs is small, none of them much exceeding 2,500 gallons daily. Their importance lies in the fact that they are the only source of water supply in that area.

In an effort to increase the yield of springs, or to develop new sources of perched ground water, 26 short tunnels have been driven on the lower windward slopes of Mauna Kea. The location of these is shown on plate 1, and their approximate discharge, length, and geologic setting are listed in the table on page 298. The water-bearing rocks and perching formations are the same as for the springs in this area. None of the tunnels in the northern part of the area succeeded in developing much water, and even in the southern part of the area it appears doubtful if the tunnels notably increased the permanent discharge of the springs at which they were driven.

A large lava tube 2.3 miles S. 10° W. of Kukaiau Post Office constitutes an unusual source of water. Half a mile south of this point a stream disappears underground, apparently flowing into the tube. During heavy rains a large stream of water emerges from the lower end of the tube, but it does not flow in dry weather. A large body of water remains in the tube, however, and is used to supply cattle tanks. About 50,000 gallons is siphoned from the tube every two months, but the tube never has been emptied. A similar situation exists 1.1 miles S. 50° W. of Kauku Hill, where for about half a mile a stream flows underground, apparently through a lava tube.

INVENTORY OF GROUND WATER IN THE HAMAKUA AND NORTH HILO AREAS

The following table summarizes the quantity of ground water known to be discharged by wells, tunnels, and springs along the slopes of Mauna Kea. As in Kohala Mountain, large quantities of basal water escape directly to the sea at tide level. This water, however, cannot be measured, and is not included in the table. The average quantity of ground water visibly discharged is about 2,898 million gallons a year.

Average daily low-water discharge of ground water, in gallons

Basal water pumped from wells in basalt	200,000
Basal water pumped from wells in alluvium	[a]400,000
Perched water discharged from tunnels	140,000
Perched water discharged in springs	7,200,000
	7,940,000

[a] Water is brackish.

PERCHED PONDS

Lake Waiau is a nearly circular pond, 300 feet in diameter, situated on the summit platform of Mauna Kea at an altitude of approximately 13,007 feet (pl. 53A). It is the highest lake within the boundaries of the Pacific Ocean basin. The southern rim of the depression containing the lake is a low segment of a cinder cone, Puu Waiau, on which rests moraine of the latest period of glaciation. The northern rim is the edge of a thick flow of andesite aa which originated at the base of Puu Poliahu and moved westward between Puu Poliahu and Puu Waiau, and southward between Puu Waiau and Goodrich Cone. The lake water is perched on a layer of silt and mud washed into the basin from the sides of the cone and from the glacial moraine. This silt and mud layer is reported to be as much as 8 feet thick.[23]

The lowest point of the rim is on the western side, where the lake water occasionally overflows into the headwaters of Pohakuloa Gulch. On September 27, 1942, the lake level was 3 feet below the lowest point on the rim. At that time Arthur Mitchell, who assisted in the examination of the summit region, swam to the middle of the lake, making several soundings. The greatest depth found was 10 feet. The amount of water in the lake was calculated then to be approximately 1,800,000 gallons. If the lake basin were filled to the overflow point, the volume of water present would be approximately 3,500,000 gallons.

The water is derived entirely from precipitation and runoff from the edges of the basin. The lake water contains abundant organisms, including bacteria, infusoria, algae, and a small crustacean.[24]

The Waikoloa Ponds include several small ponds near the upper stretches of the Wailuku River, 2 miles southeast of the Puu Oo Ranch. None is more than 100 feet across or a few feet in depth. Similar ponds are found near Puu Loe, 10 miles east of Waimea. At both localities the drainage system on the lava of the Laupahoehoe volcanic series is very youthful and the extremely irregular surface of the aa flows results in many undrained hollows, some of which contain quasi-permanent ponds perched by the thin ash cover and the dense interior phase of the flow. The ash cover in the hollows is augmented by wind drift and rainwash, thus increasing its effectiveness in perching water. The water is derived from rainfall and surface runoff from the sides of the small basins. None of the ponds appears to be fed by springs, and if used as a water supply the ponds would probably soon be pumped dry.

---

[23] Gregory, H. E., and Wentworth, C. K., General features and glacial geology of Mauna Kea: Geol. Soc. America Bull., vol. 48, p. 1736, 1937.

[24] Idem, p. 1736.

POSSIBLE FUTURE DEVELOPMENTS

Basal ground water can be secured in large amounts at low levels on the eastern and northeastern slopes of Mauna Kea by the construction of Maui-type wells. Even in the area between Paauilo and Honokaa, where rainfall is comparatively low, large amounts of basal water can be developed if the infiltration tunnels are made sufficiently long and care is taken to avoid excessive drawdown with resultant incursion of sea water. Tunneling for high-level perched water does not appear advisable, as perching structures are in general poor, and no evidence exists of large buried valley systems which might concentrate the subsurface runoff from a large drainage area.

Prospects for the development of important amounts of ground water on the western slope of Mauna Kea are poor, owing to low rainfall and a lack of good perching structures and buried drainage systems. Rain sheds are the most practical solution to the problem (pl. 52C).

On the lower southern slopes of the mountain, the meltwaters of the Pleistocene glacier deposited large alluvial fans and outwash plains, which have in part been buried by later lavas of Mauna Loa. These deposits generally are poorly sorted and consequently have a low permeability. It is possible, however, that some beds are sufficiently well sorted and permeable to constitute aquifers in which water is retained by the enclosing less permeable sediments. It is also possible that lava flows constituting aquifers might be encountered in the poorly sorted alluvium, but no evidence of the existence of such interbedded lava flows has been found. Recharge in this area of low rainfall is so small and intermittent that the prospects appear poor for recovering perched ground water by drilled wells.

GROUND WATER IN THE PUNA AND SOUTH HILO AREAS

BASAL GROUND WATER

The Puna and South Hilo areas comprise the eastern slopes of Kilauea and Mauna Loa. Basal ground water underlies the entire area, with the possible exception of the east rift zone of Kilauea, where water may be impounded at a higher level by dikes (fig. 41). The basal water table probably rises inland at an average rate of 4 or 5 feet a mile. At the Olaa Mill, 3.5 miles from the coast, water stands 17 feet above sea level, indicating an average gradient for the water table of about 5 feet per mile. The water level in drilled wells 7 and 8 near the Hilo airport indicates a similar gradient. Throughout the area from Hilo to the east rift zone of Kilauea, rainfall is high, recharge is great, and ground-water circulation is probably rapid, so that basal water of good quality is abundant. Rough calculations indicate that in this area, below the 4,000-foot contour, the amount of rainfall percolating to the zone of saturation is of the order of 3,500 million gallons a day. Along the southern shore from Kalapana westward, rainfall is so low that the basal water is brackish.

The great supply of basal water is almost unutilized. Drilled wells 7 and 8, 0.2 mile apart, are located at Hilo airport. Drilled wells 9A and 9B and Maui-type well 7 are operated at the Olaa Mill, small dug wells are used at Waiakea, and a few dug wells yield brackish water southwest of Kalapana. A large basal spring supplies water to the Waiakea Mill, and other basal springs are used for watering animals and occasionally for small domestic supplies. Less than 0.1 percent of the estimated available supply of basal ground water in the Puna and South Hilo areas is utilized.

MAUI-TYPE WELL AT OLAA.[25]—Maui-type well 7 is located 100 yards south of the mill of the Olaa Sugar Company at Olaa. The altitude of the shaft collar is 220 feet. A vertical shaft 10 feet in diameter and 203.5 feet deep, equipped with an elevator, is connected with the pump chamber by a tunnel 12 feet long. The pump chamber is 25 feet square and 13 feet high. It is concrete lined, with an arched roof, the spring line of the arch being 6.5 feet above the floor. The floor is 17 feet above sea level. A rise of the water level to 25.86 feet above sea level on March 6, 1939, flooded the pumps and necessitated the construction of a second floor 23.5 feet above sea level. The pump sump is 8 feet wide and 24 feet long, with its floor 2 feet above sea level. It is extended 30 feet in a northerly direction by a tunnel 8 feet wide and about 10 feet high, with its floor 3.25 feet above sea level. Two tunnels, each 6 feet high, 3 feet wide, and 9 feet long, extend southeast and southwest from the southern end of the sump.

Three pumps, with capacities of 3.5, 1.5 and 0.5 million gallons daily permit drafts up to 5.5 million gallons a day. The well is used only to supply water to the mill, and is pumped only when the water supplied to the mill by the cane flumes is insufficient. During the drought in the first three months of 1941 it was pumped 6 days a week at a rate of about 3 million gallons daily. At that rate of draft, drawdown was negligible. However, pumping 7 million gallons daily during construction of the well lowered the water level to an altitude of about 6 feet.

The well penetrates lavas of the Kau and Kahuku volcanic series. The character of the rocks exposed in the shaft is shown in figure 48.

---

[25] U. S. Geol. Survey Water-Supply Paper 817, p. 42, 1937. Duncan, George, The dug well at Olaa Mill: Volcano Letter, no. 477, pp. 1–2, 1942.

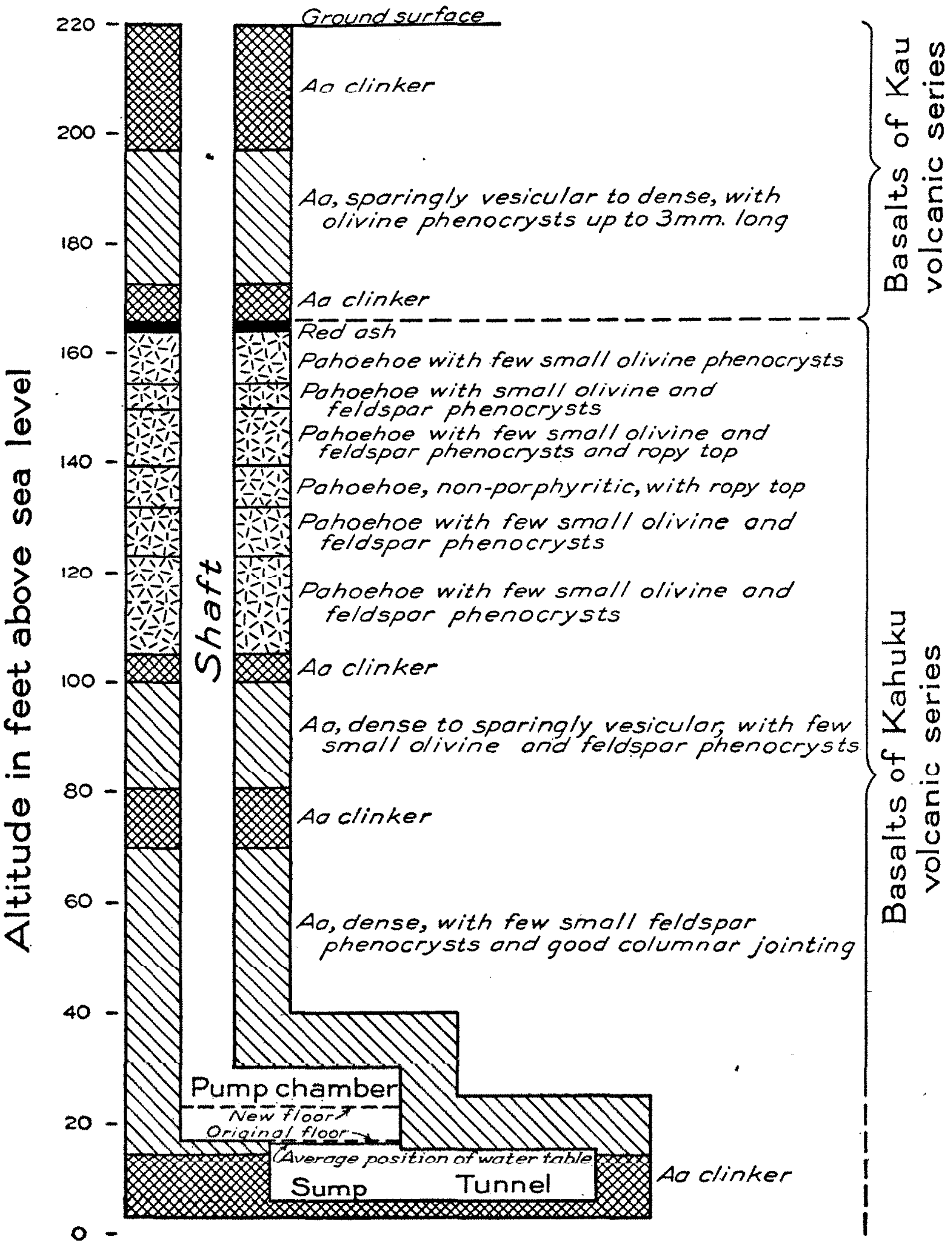


Figure 48. Section of Maui-type well 7 at Olaa.

The basal water table stands normally at an altitude of about 17 feet, but drops as low as 14 feet during droughts. During wet weather the water table rises, and on March 6, 1939, reached the high-level mark of 25.86 feet. The water level shows a diurnal fluctuation of about 1 inch, presumably owing to changes in barometric pressure. Variations in the height of the water table are published annually.[26] Figure 49 shows the fluctuations in water level from May 1936 to December 1943. The sudden rise in April 1938 and March 1939 followed torrential rains in the Olaa area, rainfall in each storm exceeding 12 inches during a single day. The water level in the well reached its peak 3 days after the exceptionally

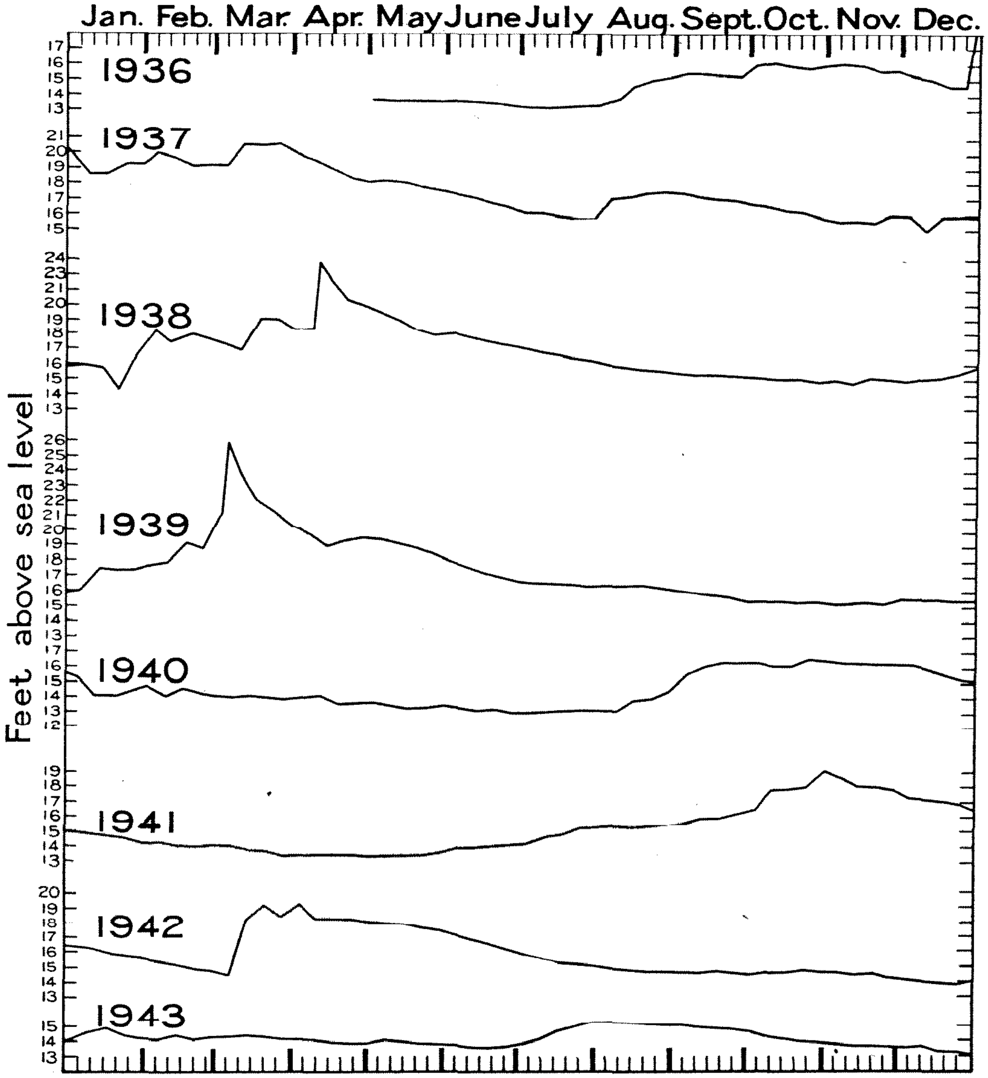


Figure 49. Graph showing fluctuations in water level in Maui-type well 7 at Olaa.

---

[26] Stearns, H. T., Water levels in observation wells in the United States; Hawaii: U. S. Geol. Survey Water-Supply Papers 817, 840, 845, 886, 911, 941, 949, 991, 1937–43.

heavy rainfalls. At other times, when the greatest precipitation accompanying heavy storms is farther up the mountain, the water level in the well rises more slowly. Relation of water level to rainfall during the first part of 1939 is shown in figure 50.

During 1936, and at irregular intervals since then, the Territorial Board of Health has found coliaerogenes organisms in seepage from the shaft walls and also in water from the sump. The contaminating organisms may be carried into the well by persons entering through the shaft, or contamination may be caused by the numerous cesspools in near-by Olaa village and Mill Camp. At any rate, contamination of the basal water at this locality is limited to the uppermost part of the body. Drilled wells 9 and 9A, only about 700 feet to the north, produce from a depth of about 200 feet below sea level, and show no contamination.

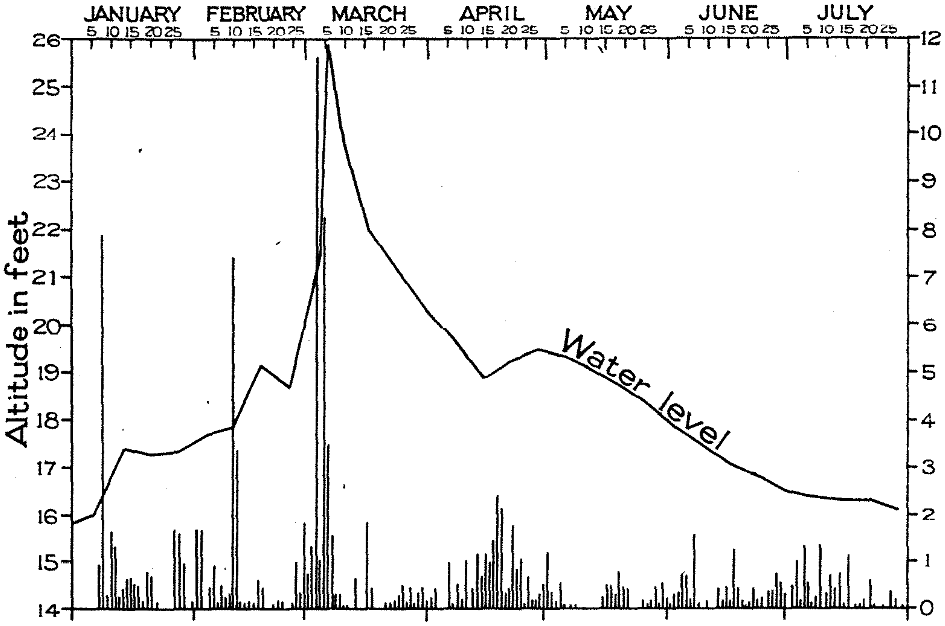


Figure 50. Graph showing fluctuation in water level in Maui-type well 7 and daily rainfall at Olaa, January to July, 1939.

DRILLED WELLS AT OLAA.—On the north side of the Olaa Sugar Company mill, drilled wells 9A and 9B, 12 inches in diameter and 450 feet deep produce basal ground water for domestic supply. The altitude of the ground and height of the water table are the same as at the Maui-type well. The water is free from undesirable bacteria, and has a salt content of only 0.85 grains per gallon (9 p.p.m.). In 1923 the salt content was 0.4 grains per gallon (4 p.p.m.). One well is equipped with a 7-stage deep-well turbine, pumping from near the bottom of the well. It has a theoretical capacity of 1 million gallons a day, but actually will produce nearly 1.25 million gallons a day. The other well is equipped with an air-lift pump designed for a capacity of 500,000 gallons a day with a delivery of 300 cubic feet per minute, but which has produced as much as 700,000 gallons a day.[27]. Normally one of these wells is pumped daily, seven days a week, at a rate of about 500,000 gallons a day.[28] Originally, in 1905, these wells were drilled to a depth of 240 feet, but were deepened to 450 feet in 1921, the drilling in each case being done by James McCandless.

DRILLED WELLS EAST OF HILO.—Two drilled wells (nos. 7 and 8, pl. 1) situated near the Hilo-Keaau road half a mile southeast of the Hilo airport, were drilled in 1944 by the U. S. Navy, using the drilling equipment of the Hawaii Division of Hydrography. They are 16 inches in diameter. Well 7 is 76 feet deep with its bottom 17 feet below sea level and static water level 4 feet above sea level. Pumped at a rate of 900 gallons per minute for 24 hours, the maximum drawdown was 14 feet. Well 8 is 86 feet deep with its bottom 15 feet below sea level and static water level 5 feet above sea level. Pumped at a rate of 1,000 gallons per minute for 24 hours, the maximum drawdown was one foot. The quality of the water is good.

DUG WELLS AT WAIAKEA.—Three shallow dug wells are located in the area of basal springs near the head of the Waiakea estuary. A spring beside the mill of the Waiakea Mill Company has been developed by means of an open sump approximately 10 feet square, with two centrifugal pumps of 100 hp each. According to R. W. Chalmers, engineer of the Waiakea Mill Company, about 4 million gallons is pumped daily, but the drawdown is very small. A water sample on July 28, 1941, when the pumps were idle, contained only 1.6 grains of salt per gallon (17 p.p.m.).

In the grounds of the Hawaiian Cane Products Company, about 150 yards east of the Waiakea Mill Company's spring, a 10-foot-square sump 9 feet deep is equipped with two 40 hp turbine pumps. According to W. F. Goldsmith, manager, these are run at about half capacity, and deliver approximately 2.5 million gallons daily, with no appreciable drawdown, for use in the Canec factory. The water is sweet.

Another small well, about 150 yards to the north, is also in the grounds of the Hawaiian Cane Products Company. It is equipped with a 15 hp horizontal centrifugal pump with a capacity of 1,000 gallons per minute. The water was used to cool condensers at the powerhouse of the Hilo Electric Light Company. It tastes quite sweet at low tide, but is reported to become distinctly brackish at high tide.

---

[27] Duncan, George, A description of the air-lift pump: Hawaiian Planters' Record, vol. 27, pp. 152–163, 1923.

[28] Idem, Letter of Oct. 2, 1941.

A shallow dug well about 10 feet square at the steam plant of the Hilo Electric Light Company, just east of the mouth of Waiakea estuary, yields brackish water for use in condensers.

DUG WELLS SOUTHWEST OF KALAPANA.—A small dug well is located near the Cave of Refuge at the foot of the fault scarp which bounds the north side of the horst along the coast south of Kalapana. The water is used for laundry purposes. It is slightly brackish, and rises and falls with the ocean tides. An ancient Hawaiian well is located 0.5 mile northeast of Ka Lae Kupapau. The water is brackish but drinkable.

A well in a yard just north of the road at Kupaahu is of unusual construction. No digging was necessary. A pipe was inserted in an open crack in basalt which extends about 30 feet to sea level, and a windmill was erected over it. The water stands close to sea level, and contains 69 grains of salt per gallon (717 p.p.m.). It is used for stock.

An abandoned well a mile farther west was formerly equipped with a windmill, but this is now in ruins. The water stands 30 feet below ground or approximately at sea level. The salt content is 74 grains per gallon (769 p.p.m.). A brackish well close to the shore 2½ miles northeast of Ka Lae a Puki is equipped with a windmill and the water is used for cattle.

BASAL SPRINGS.—Several large and many small basal springs issue along the coast. The spring at the head of the Waiakea estuary ranks as a first-order spring[29] and is comparable in size with the largest springs in the continental United States. The Waiakea spring is compound, consisting of a large number of springs and seeps issuing along the banks of the estuary and below water level. Systematic measurements made over a period of 27 hours on June 7 and 8, by J. F. Kunesh, showed the discharge of the Waiakea estuary to be 146 million gallons a day, or 226 second-feet. The estuary is tidal, and the salinity of the water varies with the stage of the tide and with position within the estuary. Analyses of several water samples, made by R. R. Ward, chemist for the Hawaiian Sugar Planters' Association, show that the uncontaminated spring water is soft and contains a relatively small amount of dissolved mineral water. Variation of salt content with depth is indicated by a series of determinations made by chemists of the Hawaiian Sugar Planters' Association. Eleven samples taken 1 foot below the water surface range from 1.1 to 234 grains of salt per gallon, and average 78 grains per gallon (810 p.p.m.). Sixteen samples taken 1 foot above the bottom of the estuary range from 2 to 635 grains per gallon, and average 336 grains per gallon (3,491

---

[29] Meinzer, O. E., Outline of ground-water hydrology: U. S. Geol. Survey Water-Supply Paper 494, p. 53, 1923.

p.p.m.). A sample taken on July 28, 1941, at the spring which supplies the Waiakea Mill had a salt content of 1.6 grains per gallon (2 p.p.m.).

Springs are found along the coast east of Hilo to Leleiwi Point and at the south edge of the South Hilo District. At Leleiwi Point several small springs discharge into a shallow lagoon separated from the ocean by a sand and cobble beach. At low tide the water is only slightly brackish.

Similar conditions exist at Keaau and Haena. At Keaau, at low tide springs bubble up over a large area in a shallow lagoon. The lagoon is separted from the ocean by a beach, which tends to hold back the sea water. At low tide the water is nearly fresh, but at high tide it is slightly brackish. On August 21, 1941, it contained 42 grains of salt per gallon (436 p.p.m.). The discharge of these springs is at least several million gallons daily, but is difficult to estimate, because the springs issue under water at many separate places, and the water escapes by seeping through the sand of the beach.

A large spring, sometimes referred to as the Blue Grotto, occupies a crevice in massive lava flows at the northern base of Kukae cinder cone, near Kapoho. On August 1, 1941, it had a salt content of 98 grains per gallon (1,017 p.p.m.). The temperature at one time was 90° F.,[30] but at present is slightly lower than that of the surrounding air. The former thermal character of the spring probably resulted from hot magma rising in cracks along the rift zone during the eruptions of 1792 and 1840 but which since has cooled.

A large lagoon 0.25 mile northeast of Pohoiki and a fish pond near Mahinaakaka Heiau, 0.5 mile southwest of Pohoiki, are supplied by basal springs and are separated from the ocean by cobble and sand beaches which retard the escape of the fresh water and the incursion of salt water. In both ponds the water is very brackish.

At Kalapana two small ponds are fed by basal springs. They are separated from the ocean by the black sand beach and a strip of dune sand behind it. As at Keaau, the discharge of the springs cannot be estimated with any accuracy, because the water enters beneath the pond at many places, and seeps away through the sand. It must, however, amount to several million gallons a day. A water sample taken from the landward end of the pond at Kalapana Park on July 22, 1941, had a salt content of 88 grains per gallon (913 p.p.m.).

---

[30] Brigham, W. T., Notes on the volcanic phenomena of the Hawaiian Islands with a description of the modern eruptions: Boston Soc. Nat. History Mem., vol. 1, p. 374, 1868. Bird, I. L., The Hawaiian Archipelago, p. 362, London, 1875.

At Punaluu Heiau, 0.5 mile N. 10° E. of Ka Lae Kupapau, a crack in the lavas 50 feet long, 15 feet wide, and 10 feet deep is filled with basal water. The water is brackish and rises and falls a few inches with the ocean tides. A small lagoon 0.25 mile north of Ka Lae Kupapau is supplied by basal springs. The water is brackish.

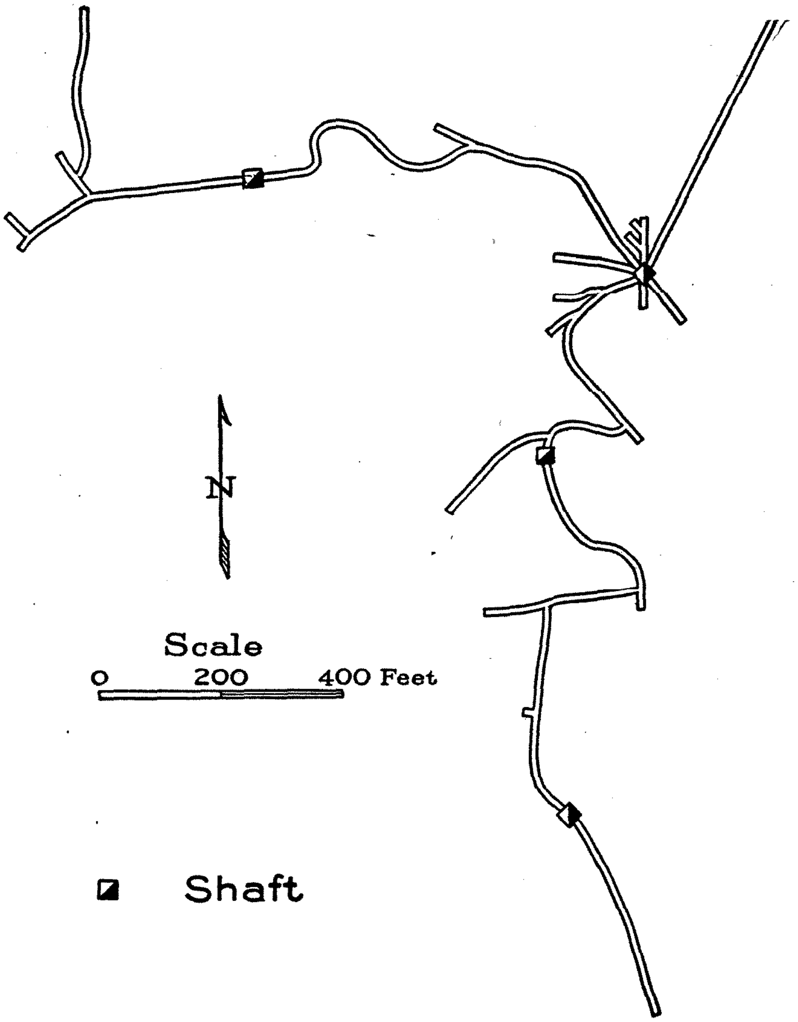


Figure 51. Plan of tunnel 62, Olaa Sugar Company, near Middle Flume House.

PERCHED GROUND WATER

Several perched springs occur on the eastern slope of Mauna Loa near its junction with Mauna Kea. These springs issue from lavas of the Kau volcanic series, which forms a relatively thin layer above the Pahala ash. The Pahala ash in this area ranges from 9 to 20 or more feet thick and is much less permeable than the lavas; hence, some water is perched by it in the overlying rocks. The location of the springs is shown on plate 1, and their approximate average discharge and geologic setting are listed in the table on page 293. Seven tunnels (nos. 58-64) have been driven to recover perched ground water. They are described in the table on page 298, and a plan of tunnel 62 is shown in Figure 51. Elsewhere in the area the ash beds are too thin or too permeable to perch much water. Neither the test borings near Mountain View (figs. 52 and 53) nor the shaft of the Olaa Maui-type well encountered perched water.

The discharge of both the tunnels and the springs in this area is subject to great fluctuation, depending on the weather. In August 1941, during a dry period, the total discharge of springs 138, 139, and 140 and tunnel 60, was only about 135,000 gallons a day, whereas in November 1944, during a period of wet weather, measurements by Raymond Chun and M. H. Carson showed it to be in excess of 8,000,000 gallons daily.

INVENTORY OF GROUND WATER IN THE SOUTH HILO AND PUNA AREAS

The following table summarizes the quantity of ground water known to be discharged by wells, tunnels, and springs along the slopes of Mauna Loa. Large amounts of basal water escape directly to the sea at tide level along the coast from Hilo to Kalapana. Most of these basal springs cannot be measured, and are not included in the table. The average quantity of ground water visibly discharged is about 56,800 million gallons a year.

Average daily low-water discharge of ground water, in gallons

Basal water pumped from wells in basalt	7,700,000
Basal water discharged at Waiakea Springs	146,000,000
Perched water discharged from tunnels	1,700,000
Perched water discharged in springs	4,600,000
	160,000,000

PERCHED PONDS

Green Lake occupies part of the crater of Kapoho Cone. Its surface is said to be approximately 8 feet above sea level. The water is not thermal. On November 11, 1924, when the temperature of the air was 82° F., the lake water had a temperature of 81° F.[31] Its salt content on July 25, 1941, was 6.7 grains per gallon (70 p.p.m.). The water is pumped to the town of Kapoho to supply drinking water for stock. It is probably perched water derived by seepage from the surrounding tuff cone and resting on relatively impermeable late deposits washed into the crater from its walls.

Swamps with small areas of standing water occupy the bottoms of craters at the northeast base of Kulani Cone and 0.9 mile S. 80° E. of Kulani Cone. They are perched on Pahala ash, and are fed principally by runoff from the surrounding ash-covered slopes. If ditched to a depth of 18 feet, the swamp just northeast of Kulani

---

[31] Stearns, H. T., and Clark, W. O., Geology and water resources of the Kau District, Hawaii: U. S. Geol. Survey Water-Supply Paper 616, p. 148, 1930.

Cone would yield approximately 700,000 gallons of stored water. Other swampy areas, not so well defined, exist in the vicinity of Kulani Cone, but most of them, if not all, go dry during droughts.

HILO WATER SUPPLY

Hilo derives its water supply largely from the Wailuku River and its tributaries. The system of intakes and ditches which collects the water is shown in figure 54. A smaller amount of water comes from Kaumana Springs (no. 133). The main ditch extends from the upper intake, at an altitude of 2,060 feet on Kapehu Stream, southward to the Wailuku River 700 feet above Pukamaui, picking up water from Kapehu Spring (no. 114) and the intervening streams. At Pukamaui the Wailuku River is diverted through a pipe line and carried, together with the water of Kahoama Stream, to reservoir 1. During wet weather only a part of these streams is diverted into the Hilo water system, but during droughts the entire flow is used. During 1941 a new ditch and flume were constructed which collect the water of Kokelekele, Kahoama, and Wailuku streams at the junction of Kokelekele Stream with the Wailuku River.

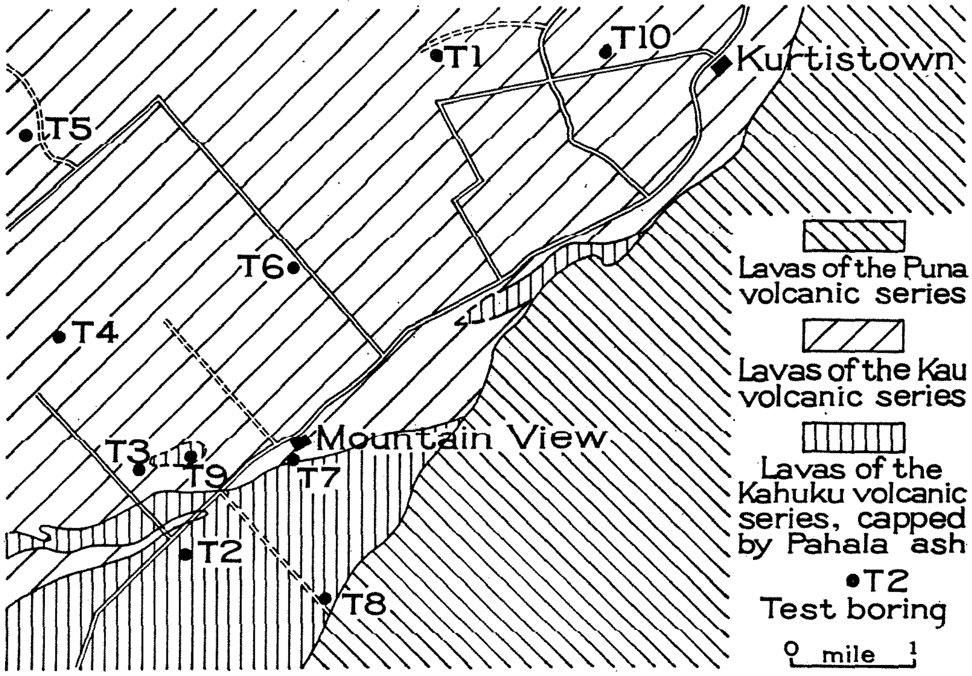


Figure 52. Map showing location of test borings near Mountain View.

The Kapehu gaging station measures the flow of water in the ditch from Kapehu Stream and two of its tributaries, in addition to that from Kapehu Spring (no. 114). The records have been published in the annual Geological Survey reports on Surface-Water

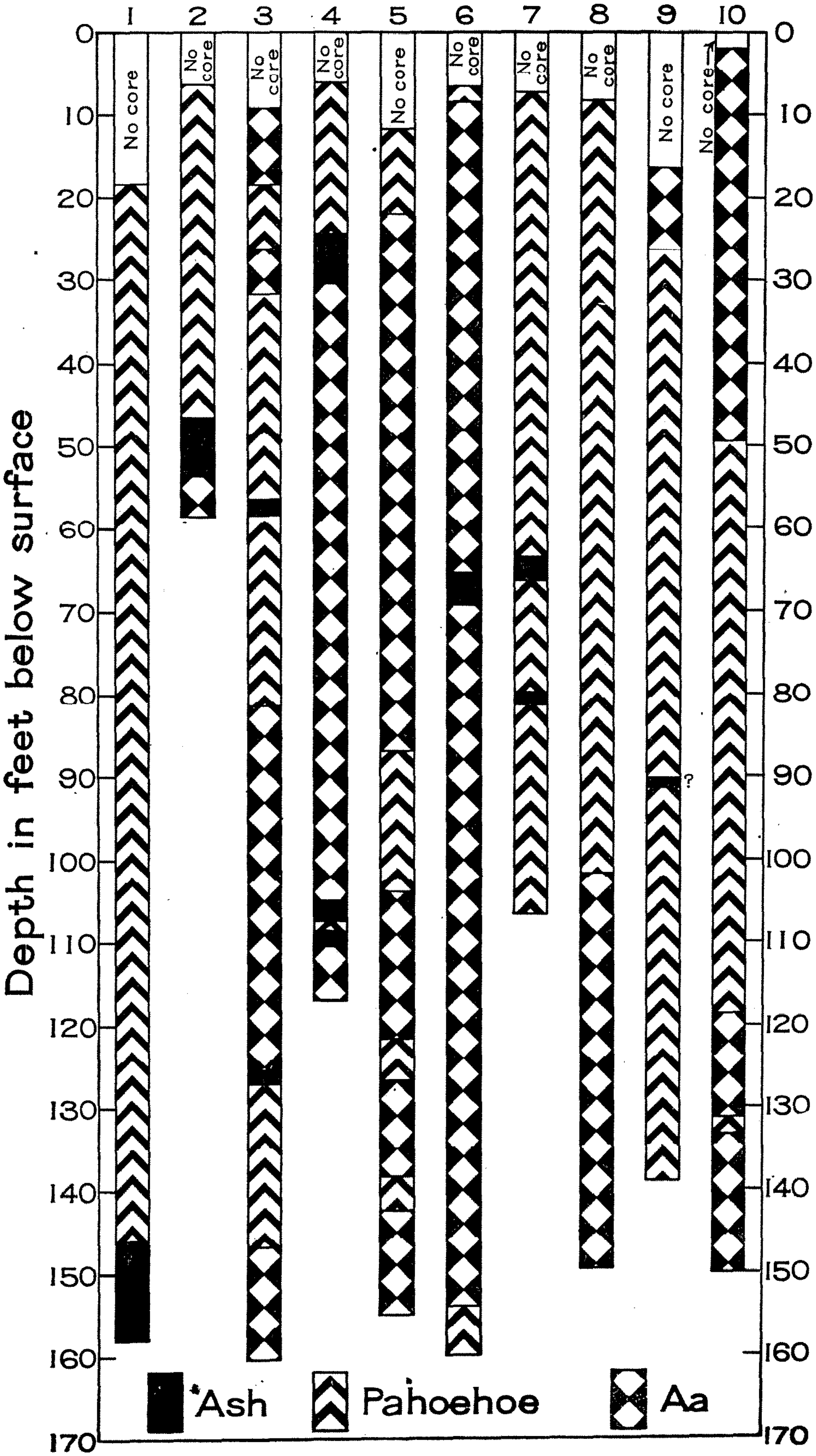


Figure 53. Graphic logs of test borings near Mountain View and Kurtistown.

Supply of Hawaii. Except during low water, Kapehu Stream is allowed to pass the intake, and at a lower level feeds the flumes of the Hilo Sugar Company. Also, during much of the time, water from Kapehu Spring and tributaries of Kapehu Stream is diverted into the ditch of the Hilo Sugar Company just above the Kapehu gaging station.

At present (1944) the average consumption of water by the City of Hilo is about 7.5 million gallons daily. Before the great increase in demand caused by World War II, it was about 5 million gallons daily. Some lessening of demand will probably occur with the end of war activities, but normal growth of the city at the prewar rate will result in a continuous increase in water use. The amount of water available from the Wailuku River and its tributaries generally is more than sufficient to meet the demands. During occasional droughts, however, the total amount of water available from the river and Kaumana Springs falls close to, or even below, the normal needs of the city. The accompanying table shows the total discharge of the river system and Kaumana Spring during the droughts of 1940 and 1941.

Still another menace to Hilo's water supply is the possibility of lava flows from Mauna Loa entering the river system, resulting in contamination of the river water with organic material and partial drying up of the stream. Lava flows burn the vegetation and subsequent leaching of the burned vegetation introduces large amounts of organic material into the stream. It is very probable that in the not far distant future a lava flow may reach the Wailuku River.[32] The flows of 1881, 1899, and 1935 nearly did so. The 1855 lava actually entered some of the tributaries of the river, the water of which was reported to be much discolored by organic matter from the burned vegetation.[33]

Average daily flow, in gallons, of the Wailuku River system and Kaumana Springs (no. 133) during the droughts of 1940 and 1941

	1940			1941
	January	February	March	February
Wailuku River at Pukamaui plus Kahoama Stream	3,843,000	3,168,000	3,682,000	3,367,000
Wailuku River 1,000 feet above Hilo Boarding School ditch	3,220,000	5.370,000	3,550,000	2,480,000
Kaumana Springs	217,400	332,600	430,700	81,700
Total	7,280,400	8,870,600	7,662,700	5,928,700

---

[32] Jaggar, T. A., Preparedness against disaster: Volcano Letter, no. 338, p. 3, 1931.

[33] Coan, Titus, On the recent eruption of Mauna Loa: Am. Jour. Sci., 2d ser., vol. 21, pp. 237–241, 1856.

The desirability of developing additional supplies of ground water for the city of Hilo is apparent. High level perched water would obviously be preferable to basal water because it would not have to be pumped, but the prospects of developing large additional amounts of high-level water are not encouraging. Tunnels driven in the vicinity of certain springs would, during wet weather, yield additional high-level water, but like the springs they would probably go dry during droughts when water is needed. Wells producing from the lens of basal ground water offer the most feasible method for developing an additional reliable supply. The existence of large supplies of basal water in the Hilo area has been apparent on the basis of geological studies for the past several years, and has recently been conclusively demonstrated by drilled wells 7 and 8, of large yield, constructed at the airport. The well water would have to be pumped to the city reservoirs, but if it were so desired the wells could be used only during droughts, and then only to supply the lower parts of the city. Pumping to reservoir 3, at 290 feet altitude, would be sufficient, as there is always sufficient water in the river to supply the higher parts of the city.

Sufficient water would be yielded by one Maui-type well similar to that at the Olaa mill (p. 247), or by a battery of several drilled wells 12 inches or more in diameter. The wells should be so placed as to minimize the danger of contamination from cesspools. Conditions at Olaa appear to indicate that even if the uppermost part of the basal water should prove to be contaminated, water at deeper levels would be free of contamination. For that reason, drilled wells producing from deeper levels, with the upper part of the basal water cased off, are probably preferable to a Maui-type well producing from the uppermost part of the basal water table.

Several possible well sites were suggested by the U. S. Geological Survey[34] in 1942 (fig. 54). That at the Waiakea reservoir was already under consideration by officials of the Hilo Water Works. The site a mile east of the junction of Kilauea Avenue and Lanikaula Street, suggested at that time, has since been essentially proved up by completion of the Navy wells at the airport. Ohrt has recently proposed the construction of a Maui-type well at an altitude of 100 feet on Lanikaula Street.[35] The site would be equally suitable for a drilled well. Figure 54 shows a large area southeast of the center of Hilo in which abundant basal ground water can be obtained by wells. The inland boundary of the area is determined only by increasing altitude of the land surface, making it necessary to drill farther to reach the water table. For a short distance seaward of

---

[34] Macdonald, G. A., Press release, U. S. Dept. Interior, Geol. Survey, Feb. 26, 1942.

[35] Ohrt, Frederick, Report on Hilo water works: Hilo Tribune-Herald, p. 1, July 6, 1944.

the area indicated, fresh water would still be encountered in wells but in less quantity. Near and seaward from the settlement along Kilauea Avenue there must be considered the possibility of contamination of the upper part of the basal water from cesspools. The section least subject to contamination is the Panaewa Forest Reserve. More than 4 miles of pipe line would be required to carry water from the Panaewa Forest to the center of Hilo, but the cost of the pipe would probably be justified by the avoidance of contamination from present or future settled areas.

POSSIBLE FUTURE DEVELOPMENTS

Conditions are unfavorable for the development of any large additional supplies of high-level perched water. Tunneling at Kapehu Spring (no. 114) and spring 121 might increase their yield, but the additional amount of water so gained would probably not be great enough to have any important bearing on the solution of the Hilo water problem. Tunnels at springs 127, 128, and 131 would probably develop more water, but like the springs would go dry during droughts. Such tunnels would be useless, because additional water is not needed except during droughts.

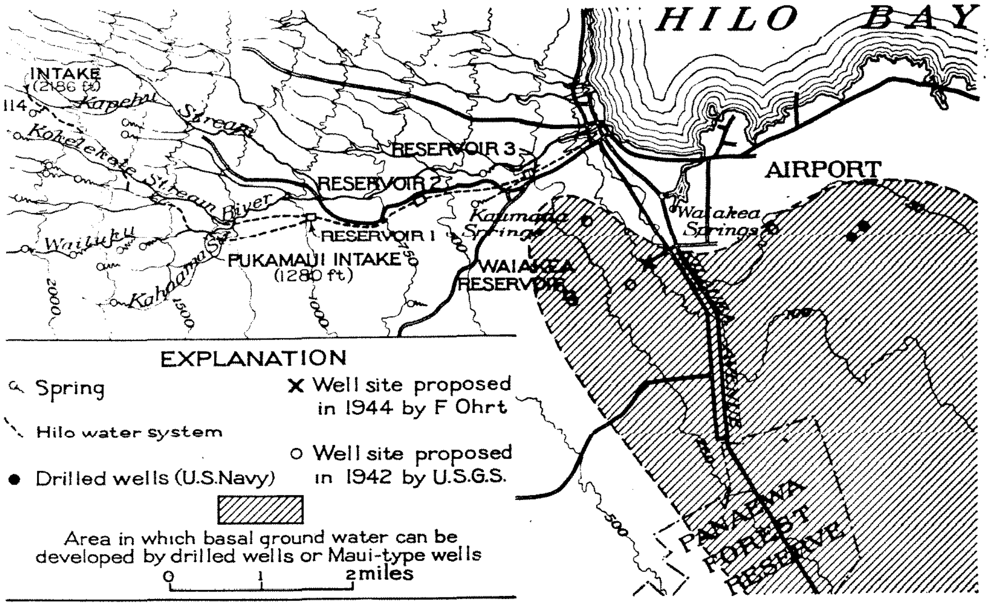


Figure 54. Map of Hilo and vicinity, showing area in which potable water a few feet above sea level can be developed by wells. The inland extent of the area is limited only by the economically practical depth of wells.

Tunnels following the buried ash beds on the east slope of Mauna Loa would probably recover a little perched water. No large subterranean streams could be expected because of the lack of large drainage systems on the buried ash to concentrate the water from many small trickles. Moreover, such prospecting would of necessity be largely random, and in most places long access tunnels to the ash beds would be necessary. Under present conditions it appears doubtful whether the cost of such tunneling would be justified by the amount of water which might be recovered.

Basal water is available throughout the area north of the east rift zone of Kilauea. Maui-type wells a mile or more from the coast would supply large amounts of water. Closer to the coast, however, the altitude of the basal water table is so low that there is danger of encountering brackish water or of the well becoming brackish when pumped. Care should also be taken to locate wells in areas free from danger of pollution by cesspools. The existence of coli-aerogenes organisms in the water of the Maui-type well at Olaa indicates the possibility of contamination of the upper part of the basal water.

Drilled wells reaching the basal water table within the area north of the east rift zone of Kilauea would also yield water, but in smaller amounts than Maui-type wells. Care should be taken to stop the well sufficiently far above the salt water zone to avoid salt water invasion during pumping (section AA′, fig. 42). As with Maui-type wells, care should also be exercised to avoid areas in which danger of bacterial pollution exists. However, if pumping is from a level sufficiently below the top of the water, as in drilled wells 9A and 9B at Olaa, the danger of such pollution is extremely small and could be removed by chlorination.

A well producing basal water appears to be a logical solution to the Hilo water problem (p. 259). So long as the surface water in the Wailuku drainage basin remains of good quality, it might be advisable to pump the well only during droughts, or to use the well water for the part of the city below reservoir no. 3, at 290 feet altitude.

GROUND WATER IN THE KAU AREA

BASAL SUPPLIES

The coast of Kilauea in the Kau District receives little rain and is mostly barren and rocky. Its eastern part lies in the Ainahou Ranch. At Keauhou Beach brackish spring water, satisfactory for stock, issues from the sand. In this area a dug well inland as far as feasible should develop more and fresher water than the springs yield at the beach. The coastal land extending westward lies in Hawaii National Park and Kapapala Ranch. The rocks are extremely permeable along the coast and brackish water issues from a few cracks and locally may extend inland a quarter of a mile or more in cracks and tubes. The water holes sweeten in wet weather.

Considerable basal water discharges along the eastern coast of Mauna Loa in central Kau. Potable ground water could probably be developed by wells at Pahala. The western Kau coast is arid and potable water is obtained with difficulty. Mauna Loa lavas reach the coast at Punaluu where Ninole Spring issues, the second largest basal spring in the island (pl. 53B). Its visible discharge is estimated to be 20 to 25 million gallons per day.[36] Additional water probably discharges below tide. A sample collected at nearly low tide on March 27, 1943, contained 42 grains of salt per gallon (435 p.p.m.). The largest springs issue from lava tubes in a late flow in the Kau volcanic series. It is believed that Ninole Spring is the outlet of the buried drainage system of ancient Ninole Valley which is now partly filled with Kau and Kahuku lavas. The temperature of the spring on July 2, 1924, was 64° F. or about 3° lower than Kawaa Springs described below. The low temperature indicates that the recharge area lies well inland.

Two miles southwestward along the coast are the Kawaa Springs which have a visible discharge of about 10 million gallons a day. More probably discharges beneath the sea. They are the underflow from the partly lava-filled ancient Hilea Valley. The temperature of the water on July 2, 1924, was 67° F. An ancient Hawaiian well near by yields potable water, and a test pit dug in 1941 about half a mile inland yielded water containing only 4.5 (47 p.p.m.) to 5.0 (52 p.p.m.) grains of salt per gallon. Large basal supplies have been developed at Honuapo for mill use. A battery of drilled wells (no. 10) in a sump at the Honuapo Mill formerly supplied 2,000 gallons per minute, but they are now partly filled and their yield is less. The water is slightly brackish.

A basal spring with a temperature of 67° F. on June 23, 1924, discharges at Waikapuna Bay. Potable water exists in an ancient Hawaiian well at this bay.

---

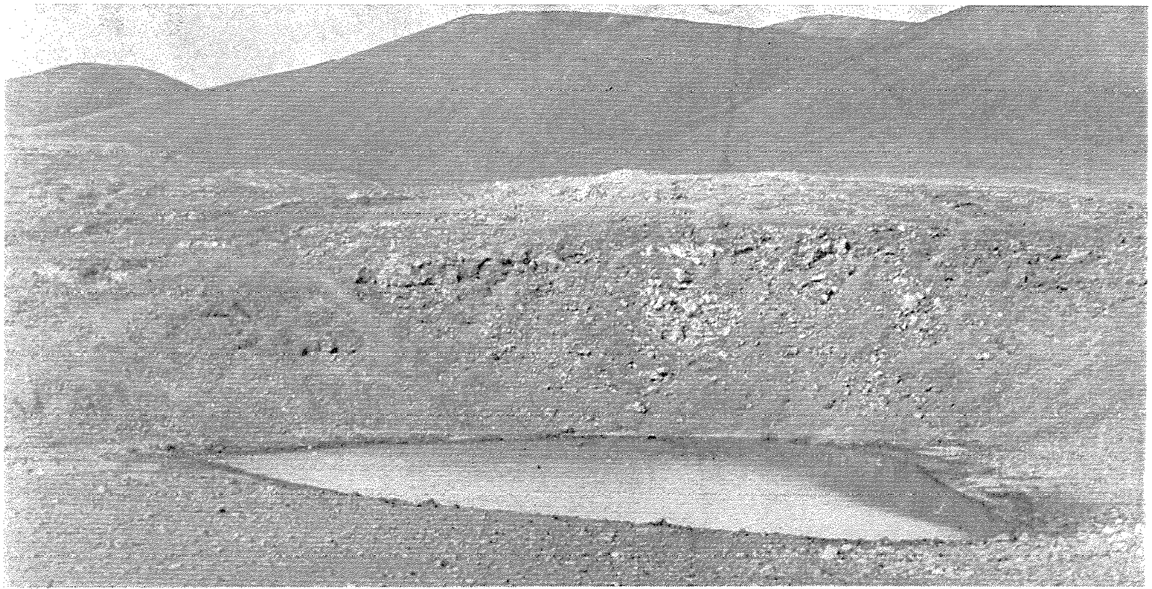
[36] Martin, W. F., and Pierce, C. H., Water resources of Hawaii, 1909–1911: U. S. Geol. Survey Water-Supply Paper 318, p. 335, 1919.

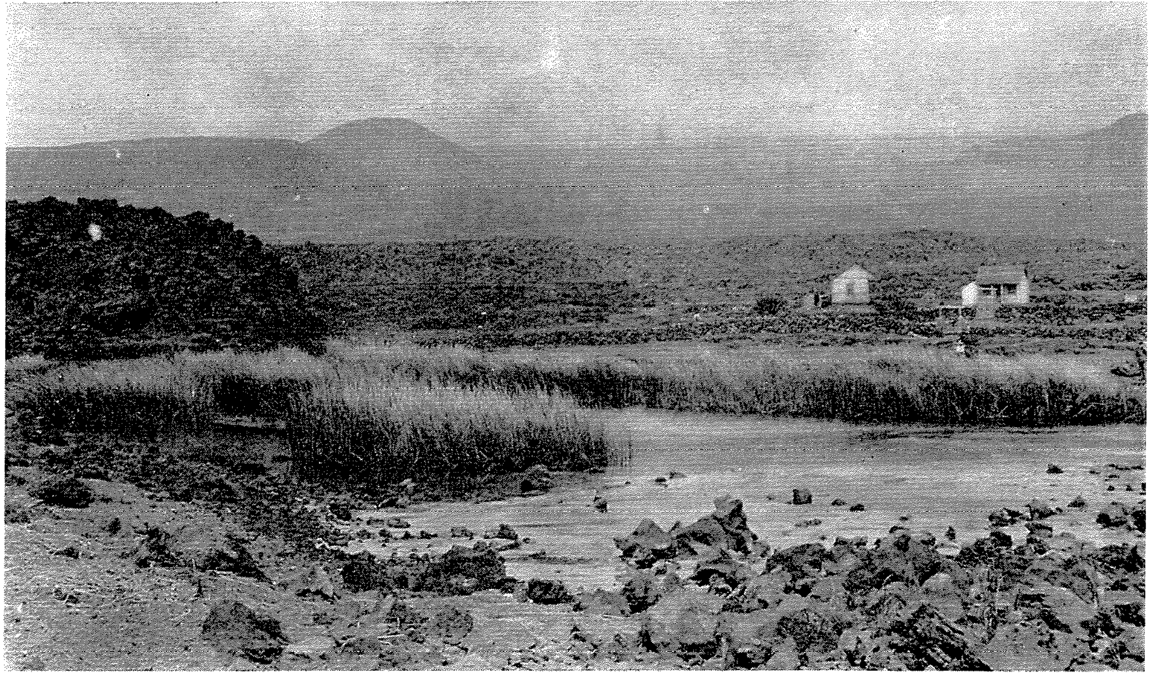
→

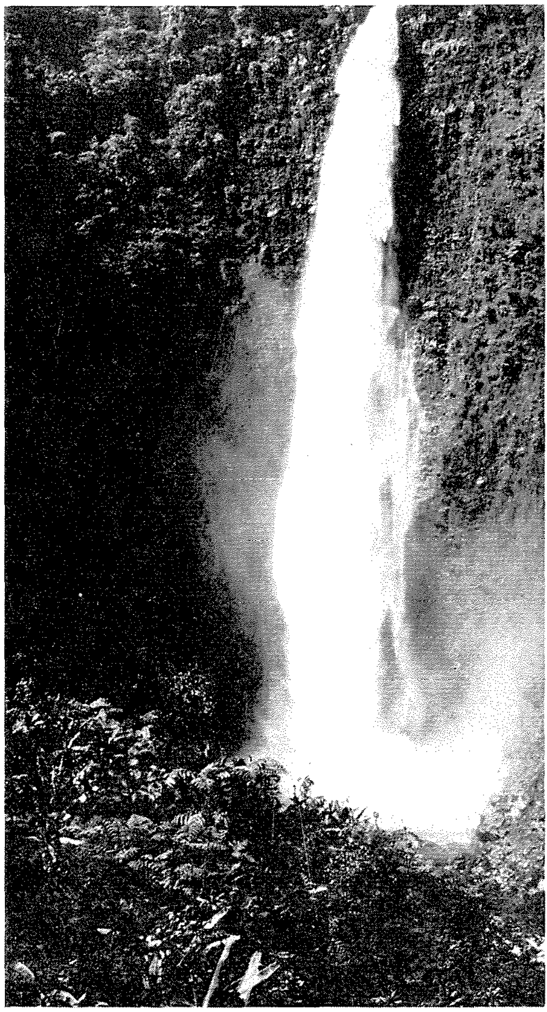
Opposite page, top: Plate 53A. Lake Waiau near the summit of Mauna Kea, probably perched on ground ice. Photo by G. A. Macdonald.

Middle: Plate 53B. Ninole spring at Punaluu, Kau District. Photo by U. S. Geological Survey.

Bottom: Plate 53C. Wailuku River entering Pukamaui, a lava tube. Photo by M. H. Carson.



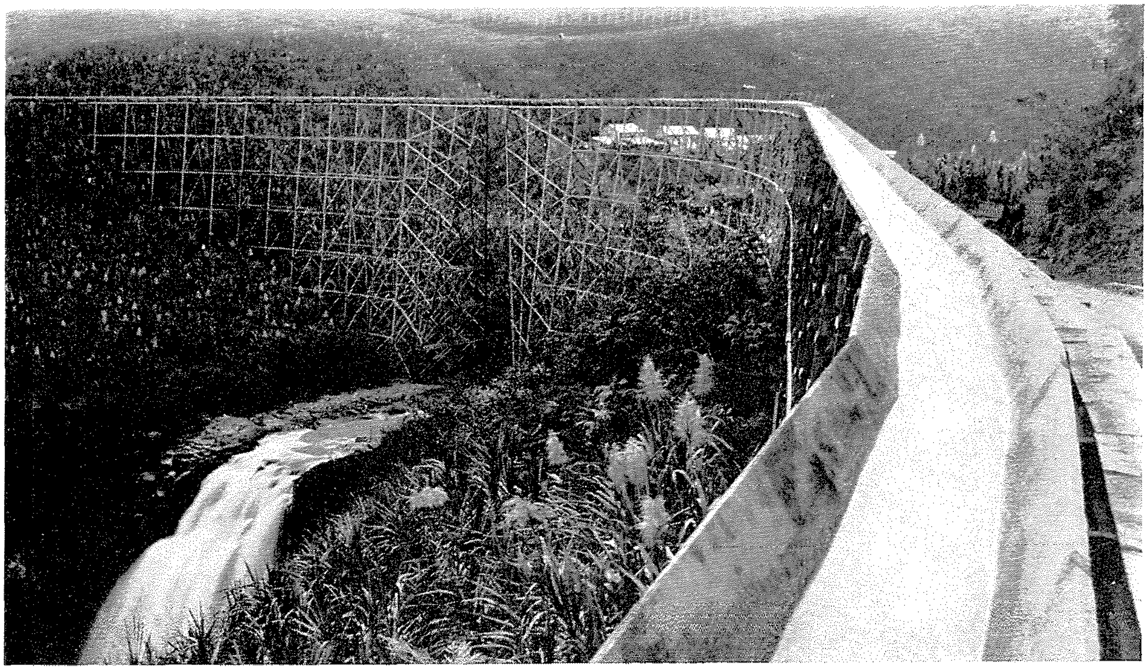




Above, left: Plate 54A. Akaka Falls, in Hamakua lavas, near Honomu, on the windward slope of Mauna Kea. Photo by U. S. Geological Survey.

Above, right: Plate 54B. Olaa flume, in jungle northwest of Mountain View. Photo by U. S. Geological Survey.

Below: Plate 54C. Flume, near Onemea, on the eastern slope of Mauna Kea. Photo by U. S. Geological Survey.



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. It is slightly brackish but has been successfully used for irrigation. On December 1, 1939, water from the Patton well close to the shore at Kaalualu contained 327 grains of salt per gallon (3,400 p.p.m.). Because of almost constant wind, windmills are practical in this area.

The basal water is brackish in the Kalae area (South Point). Well 11, drilled by the U. S. Army in this area, encountered water with 54 to 63 grains of salt per gallon (560 to 655 p.p.m.).

The lavas along the coast northwest of Kalae are youthful and exceedingly permeable allowing sea water to move inland through cracks and crevices. A few water holes along this stretch of coast were used by the ancient Hawaiians but the seaward sides were probably plastered with mud to reduce the ingress of sea water. A test boring at the foot of Kahuku Pali 5 miles north of Kalae has been recommended in connection with the development of a water supply for the South Point airfield.[37]

Work has commenced on a Maui-type well (no. 8) to supply water for mill and possibly domestic use at Pahala. The shaft portal is situated just seaward of the Pahala mill, at an altitude of about 774 feet. The shaft is being driven on an incline of 30 degrees and will be about 1,550 feet long when completed. It is planned to develop about 2.9 million gallons of basal water daily.

PERCHED GROUND WATER

All high-level ground water in the Kau area, so far as is known, is perched. In every observed occurrence, water is in lava rock overlying a bed of volcanic ash and is perched by the ash.

Ash and tuff beds are found in the Ninole, Kahuku, Kau, and Puna volcanic series in Kau. The ash in the Kau and Puna series is too coarse and too loose to perch water. The tuff beds in the Ninole series are more indurated (pl. 25C) and less permeable than the Pahala ash. The beds of ash vary locally in texture, perviousness, and thickness. They also vary in number from place to place. Noguchi No. 2 tunnel (no. 75), one of the most productive in the district, obtains its water from a toe of lava intercalated with the Ninole tuff in the Ninole volcanic series. Noguchi Spring was recovered from the surface of the upper tuff bed by a tunnel driven upward from the lower bed. Two or three bodies of perched water may be above each other in the same cliff as at the head of Wood Valley (fig. 55).

---

[37] Stearns, H. T., Water supply for South Point airfield: Unpubl. rept. to U. S. Army, January, 1940.

The perched water is extremely irregular in its occurrence due to the variation in the physical properties of the ash beds and to their undulating surface. Water usually is recovered from shallow lava-filled gullies in the surface of the ash. The variation in discharge of most of the tunnels and springs is great because the high permeability of the lava rock allows rapid underground drainage following rains (fig. 56). The water occurs in relatively few of the rock openings (fig. 57). Apparently long stretches of the ash beds do not perch water. Where water is present the zone above the ash bed is usually only a few inches thick, although locally its thickness may be 3 or 4 feet. This is in strong contrast to the thick zones of saturation in dike complexes.

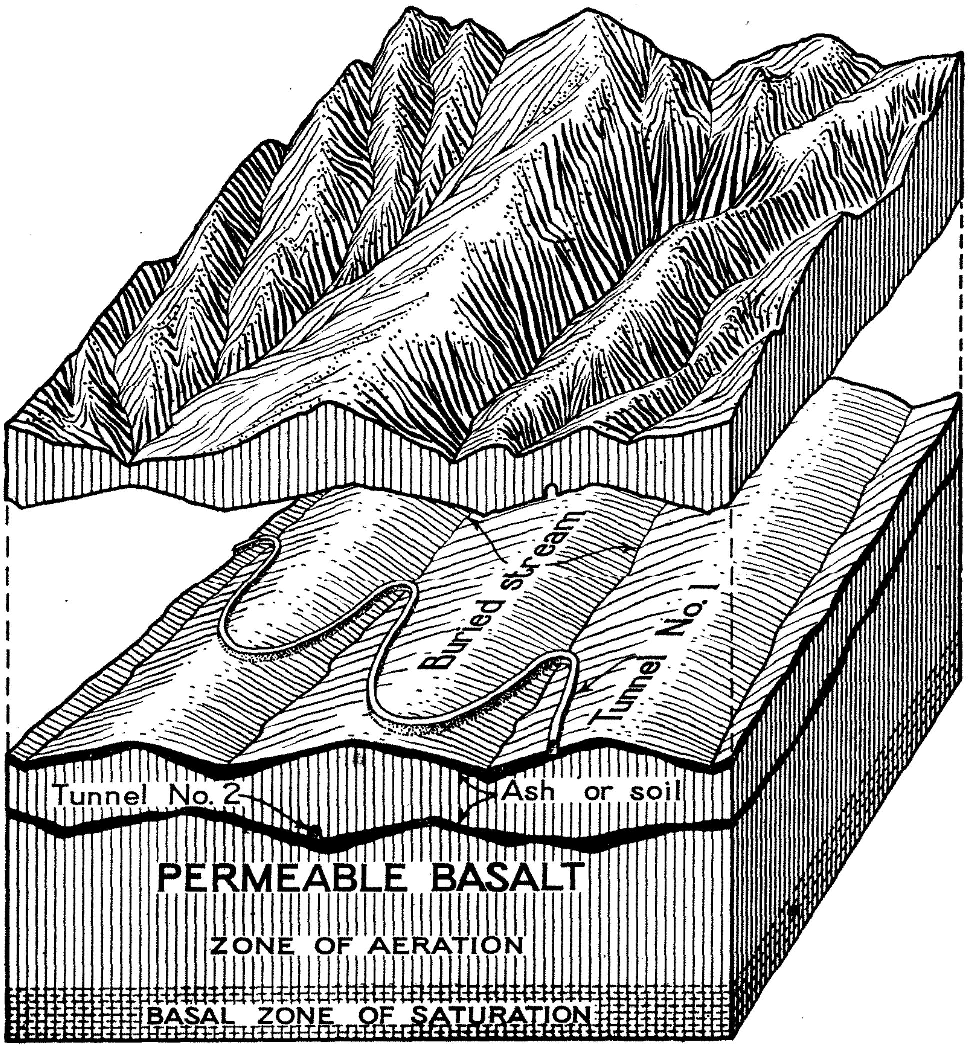


Figure 55. Diagram showing relation of basal water to water perched on two ash beds and tunnels driven to recover it. Most of the perched water is recovered from streams moving down the buried valleys.

Water perched on ash is developed by a tunnel following the buried surface contour of the ash bed. Tunnels are driven at the contact of the ash and the overlying lava, keeping as much of the tunnel in the ash as possible to reduce the cost of excavation. Six inches to a foot of ash should always be left below the floor of the tunnel to prevent leakage, thereby saving concrete lining. Most of the tunnels are not far below the ground surface, the cover usually being less than 100 feet.

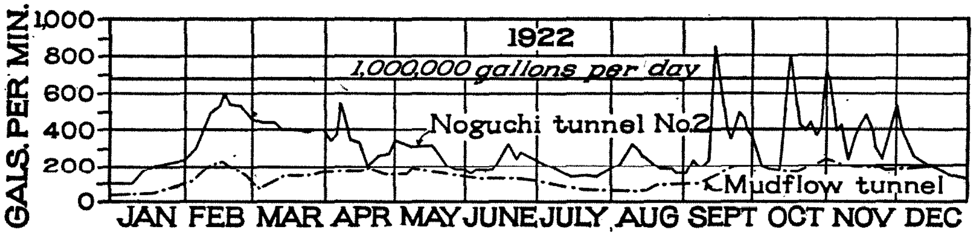


Figure 56. Graph showing discharge of Mudflow (no. 80) and Noguchi No. 2 (no. 75) tunnels for 1922.

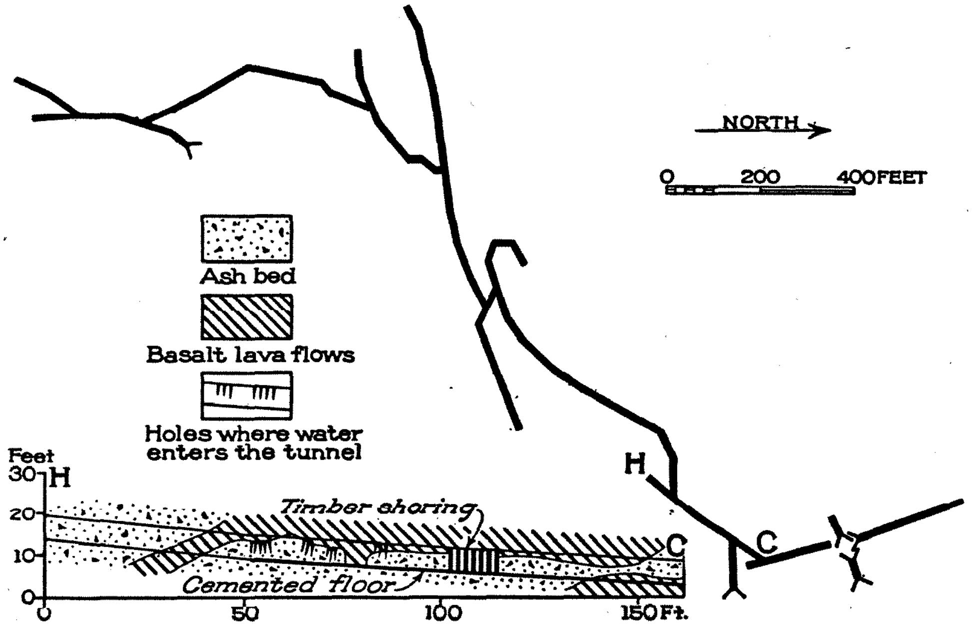


Figure 57. Plan and section CH of Mudflow Tunnel (no. 80) in the Kau District.

New Mountain House tunnel (no. 95) above Naalehu, at an altitude of 3,097 feet, is 7,048 feet long and yields 1,286,000 gallons of water a day. It was driven at the site of a small spring under the direction of W. O. Clark and has the largest yield of any tunnel in Kau. The tunnel recovers water from the surface of several layers of Pahala ash one above the other (fig. 58). One lateral rises above the main tunnel to recover water from a higher ash bed. The water near the portal tumbles from a thin ash bed in the tunnel roof. Not far from the portal the tunnel passes through a lava flow resting on 2 feet of red ash. Under the ash is 2 feet of well-bedded aa clinker ranging from sand-size particles to fragments one inch across and containing well rounded pebbles of red vitric tuff. The deposit apparently was stream laid, but was not transported far or the clinker would be rounded and the tuff pebbles worn away. The north branch of the tunnel derives about 75 percent of its flow from talus interbedded with red vitric ash beds 1½ to 2 feet thick. The talus ranges from 2 to more than 5 feet in thickness and contains blocks reaching 5 feet across. Water issues from the open interstices of the talus in sags in the ash beds.

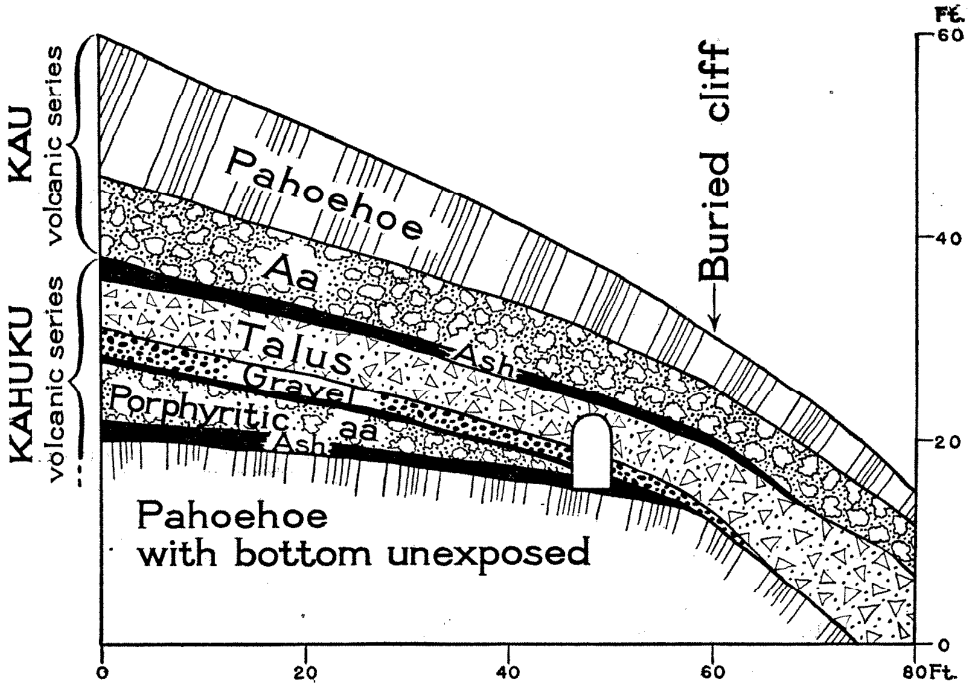


Figure 58. Detailed geologic section near the north end of New Mountain House Tunnel (no. 95) near Honuapo.

The lower ash bed in the tunnel lies on pahoehoe which was bare rock when the ash was deposited. The upper ash bed is overlain with a pahoehoe flow that dips 12° E. The tunnel apparently runs along the face of a lava-veneered spur that projected into the ancestral Kaalaiki Valley between two tributary canyons cut in the Ninole volcanic series. The water may be moving through talus from a buried spring issuing from the surface of a tuff bed in the Ninole volcanic series as shown in figure 59, as most springs with large flows in dry weather issue from tuff beds in this series. Figure 59 also shows the relation of tunnel 95 to the ancestral Kaalaiki Valley cut in the Ninole volcanic series and subsequently partly filled with lavas of the Kahuku and Kau volcanic series. Probably the ancestral valley floor is paved with alluvium which may also carry perched water. The water in tunnel 95 is perched more than 3,000 feet above the basal water table as shown in figure 59.

No prospects for developing perched ground water exist in eastern Kau. Steam could be developed by drilling in the vicinity of Kilauea Caldera, and if a cheap way of condensing it could be found, it would provide a water supply for this area. A small condenser operated north of the caldera in 1944 yielded about 100 gallons a day. Both Kilauea Military Camp and the Volcano House need water during droughts. A few small water holes in the ash exist on Kapapala Ranch where cattle have puddled the ash, but they do not warrant development. The Pahala ash is mostly too coarse and the rainfall too low in eastern Kau for perennial bodies of perched ground water to exist. The Kapapala Ranch is supplied through a pipe line from a spring in the head of Wood Valley.

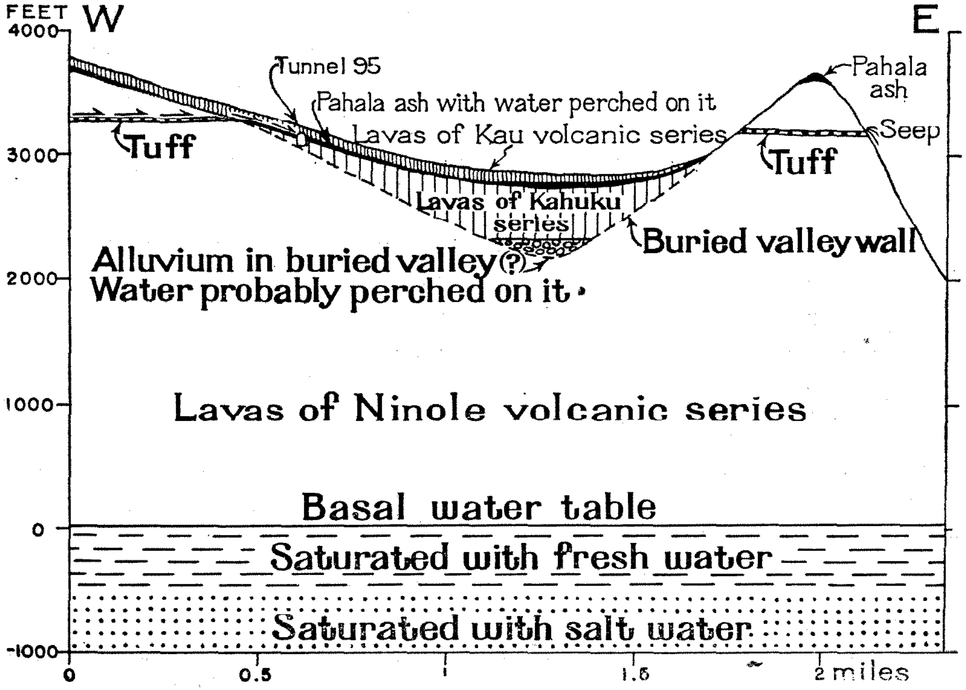


Figure 59. Section through Puu One and New Mountain House Tunnel (no. 95), 6 miles northwest of Honuapo, showing how water in the tunnel may be derived chiefly from ground water moving along a tuff bed in the Ninole volcanic series. The relation of perched water to the basal zone of saturation is also shown.

A great deal of tunneling has been done to develop perched water in central Kau where it is valuable for fluming sugar cane, operating two sugar mills, and domestic use. W. O. Clark, geologist of the Hawaiian Sugar Planters' Association, spent from 1920 to 1930 supervising tunneling in this area and much tunneling had been done prior to his arrival. He found that most of the tunnels had to be driven very crooked in order to follow the contour of the ash beds (fig. 57). Thus if an ancient drainage channel is encountered the tunnel must swing up the ancient drainage channel until it can cross the channel in the ash bed. If the ash bed is eroded away the tunnel is driven through the lava filling the channel in order to reach the ash bed on the other side. Air currents through crevices and tubes in the lava were found in all tunnels so that blowers are not necessary for ventilation. If an ash bed divides into two members it may be necessary to drive one tunnel above the other, as in New Mountain House tunnel (no. 95), to develop the water on both ash beds. Most of the tunnels lie in the rain forest where the construction of roads is impractical. Thus, materials are usually transported over long difficult trails on pack animals or on the backs of men. The trails are so muddy they have to be paved with the trunks of tree ferns.

The record of the tunnels in central Kau is given on page 299. Most were driven where springs formerly discharged; hence, it is difficult to ascertain the amount of water developed by tunneling. The location of the tunnels is shown on plate 1. The tunnels lie chiefly at the head of the buried canyons cut in the Ninole lavas where the Kahuku lavas thin out. Undeveloped perched bodies of ground water probably still exist in this area. If additional water is needed in this area in the future it would be worth while to prospect the base of the Kahuku lavas where they lie as plasters on the cliffs of Ninole lavas 1 mile north of Puu One in Hilea Gulch. New Mountain House tunnel develops much of its flow from talus and ash lying along an unconformity of a similar buried canyon wall.

A possibility exists for developing additional water by tunneling along the ash bed that supplies Haao Springs (no. 146) above Waiohinu. The Pahala ash is overlain by a late lava flow in the Kau volcanic series in which water might be moving seaward. Several thousand feet of tunnel would be necessary to explore this area. Any water developed would be exceedingly valuable for the South Point area, as a pipe line leads from the spring to South Point. At various times the homesteaders in the area west of Waiohinu have agitated for the development of an irrigation supply, but tunneling at Haao Springs would not develop sufficient water for irrigating these homesteads.

No prospect exists for developing water on ash beds in western Kau because of the low recharge and unfavorable geologic structure. Small water holes exist where cattle have puddled ash in kipukas. A small perched spring, called Waiahuli, issues 5 miles northwest of the Kahuku Ranch. Its yield is probably less than 500 gallons daily in dry weather but it is useful for stock. It is probably supplied by seepage following a relatively tight lava channel similar to the small pools in tubes in the Kona area.

THERMAL WATER

No hot springs occur in Kau but steam issues from many cracks around and in the calderas of Kilauea and Mauna Loa. Hot water condensed from steam is used to supply bath houses on the northern rim of Kilauea. Natural steam is used to heat the Volcano House and the National Park headquarters. Numerous hot caves exist on the floor of Kilauea Caldera. Warm water occurs in a crack at Waiwelawela Point, southeast of Pahala. It is probable that if the rocks were less pervious heated water would reach the surface, but with conditions as they exist, both juvenile and meteoric hot waters usually become diluted and cooled at the basal water table and never reach the surface.

ANCIENT HAWAIIAN SUPPLIES

Ancient Hawaiians used brackish water along the coast and carried water in gourds from springs in the mountains. Trees with cavities which caught rain running down the trunk were also used to supplement the supply as shown by the following description:

> "Speaking of trees reminds me that a species of large-bodied tree grows along the road below Waiohinu whose crotch is said to contain tanks of fresh water at all times; the natives suck it out through a hollow weed which always grows near. As no other water exists in that wild neighborhood, within a space of some miles in circumference, it is considered to be a special invention of Providence for the behalf of the natives. I would rather accept the story than the deduction, because the latter is so manifestly but hastily conceived and erroneous. If the happiness of the natives had been the object, the tanks would have been filled with whiskey."[38]

INVENTORY OF GROUND WATER IN THE KAU AREA

As elsewhere along the coast of Hawaii, large unmeasured quantities of basal water escape directly to the sea at tide level. The average quantity of ground water visibly discharged is about 16,800 million gallons a year. The amount of ground water recovered will be increased probably about 1,060 million gallons a year on completion of the Maui-type well at Pahala.

Approximate average daily discharge of ground water, in gallons

Basal water pumped from wells	3,000,000
Basal water discharged at Ninole and Kawaa Springs	35,000,000
Perched water discharged from tunnels	7,000,000
Perched water discharged in springs	1,000,000
	46,000,000

---

[38] Twain, Mark, Letters from the Sandwich Islands; June 1866, The cistern tree, p. 202, Stanford Univ. Press, Calif., 1938.

GROUND WATER IN THE KONA AREA

BASAL SUPPLIES

Numerous wells and springs along the Kona coast are supplied by basal water. The largest spring is at Honaunau, and is used by some residents for cooking. The water issues from crevices in a pahoehoe lava flow of the Kau volcanic series. At high tide the spring is submerged but at low tide water can be seen welling from numerous crevices. The flow in the cove north of the ancient City of Refuge at Honaunau was estimated to be about 250 gallons per minute at low tide on October 13, 1939, and the salt content was determined as 295.1 grains per gallon (3,067 p.p.m.). It is suspected that a lava tube conducts the water to the spring, possibly from a buried drainage system farther inland. A tube about 1,000 feet from the shore at Kailua is 30 feet in diameter and contains brackish water suitable for cooking. Such tubes allow sea water to penetrate farther inland than on a coast free from tubes. This tube has the usual lava stalactites and congealed shore lines formed as the molten river of lava subsided at the end of the eruption. It is reported that Lorrin Thurston explored the tube for a distance of 1,200 feet.[38a]

The salt content of dug wells, water holes, and springs, along the coast of the Kona area are given in the table on page 287. The salt content increases appreciably southward toward Kau because the tributary recharge area becomes progressively drier. A water hole at Milolii contained water with a salt content of 352.2 grains per gallon (3,653 p.p.m.). The springs and wells at Napoopoo are too brackish for human consumption but are used for cooking, washing, and stock. Two brackish springs with a combined yield of about 75 gallons per minute at low tide issue at Keauhou Bay. The salt content of wells and springs along the shore from Keauhou Bay northward to Kaupulehu Springs (pl. 1) ranges from 96.9 grains per gallon (1,007 p.p.m.) to about 350 grains per gallon (3,636 p.p.m.). Kaupulehu Springs discharge at the rate of about 50 gallons per minute during low tide chiefly through the lava around the southern end of the beach rock. Additional water escapes under the beach rock and discharges below sea level. The beach rock serves as a dam to prevent sea water and ground water from mixing freely at Kaupulehu. A pool of water just east of Stillman's beach cottage at Kikaua Point on the northeast side of Kakapa Bay, was fresh when tasted on September 21, 1939, but it may become brackish in dry weather. It is probably the most potable water on the coast of Hualalai.

Water fairly low in salt issues from the lavas of Mauna Kea along the coast of the South Kohala District (pl. 1). Camp Drewes,

---

[38a] A new spring appeared on the floor of Kailua Bay, during the seismic sea wave of April 1, 1946. It is fed by a small lava tube, which may connect inland with the Thurston tube. The water, which bubbles up strongly at low tide, is brackish.

U.S.M.C., obtained from a well dug in beach sand at Hapuna Bay, 15,000 gallons per day with a salt content of 54 grains per gallon (561 p.p.m.), based on a sample collected on April 12, 1944. Considerable water was pumped at Puako Bay when sugar was produced near by, but how much the basal water was freshened at that time because mountain water was flumed there from Waikoloa Stream cannot now be ascertained.

During this investigation a test hole (drilled well 12, pl. 1) was drilled to the basal water table from an altitude of 595 feet at a point 2 miles southeast of Kailua on the road from the beach to Holualoa. It encountered basal water two feet above mean sea level with a salt content of 50 grains per gallon (519 p.p.m.). It indicates that water suitable for nearly all purposes except drinking can be recovered from wells about 1½ miles from shore. Although the hole is only 6 inches in diameter, it could be equipped with a deep-well pump and used to supplement the supply of Kailua and the adjacent beach lots.

Contracts were let with two Honolulu companies to sink diamond drill holes at altitudes of 638 and 245 feet east-northeast of Keikiwaha Point near Kealakekua, but both companies failed to drill more than 80 feet. The men were inexperienced in drilling in loose cavernous rock such as typifies the Kau volcanic series in this place.

HIGH-LEVEL SUPPLIES

The only ground water that occurs at high level is found in pools in lava tubes and in bogs in depressions in pahoehoe. The pools were used formerly for drinking water as shown by the following quotation:

> "The drinking water of the people was very brackish, from numerous caves which reached below the sea level. The white people, and some chiefs had their water from up the mountain where were numerous depressions in the lava, full of clear, sweet rain water. There were also many tunnel-caves, the channels of former lava-streams. Sometimes the fine rootlets of ohia-trees penetrating from above, festooned the ceilings of these dark lava-ducts as with immense spider webs. If in a dry season, water was lacking on the open ground, it could always be found higher up on the mountain in such caves. Twice a week one of our ohuas or native dependents went up the mountain with two huewai, or calabash bottles, suspended by nets from the ends of his mamaki or yoke, similar to those used by Chinese vegetable venders. These he filled with sweet water and brought home, having first covered the bottles with fresh ferns, to attest his having been well inland. The contents of the two bottles filled a five-gallon demijohn twice a week."[39]

A few pumping tests show that some of the water holes would yield from 5,000 to 50,000 gallons before going dry. They are supplied by seepage along the floor of the tubes, the water collecting

---

[39] Bishop, Sereno E., Reminiscences of life in old Hawaii, pp. 14–15, Honolulu, 1916.

near the mouth where soil has been washed into them and more or less sealed the fissures in the floor, thereby making natural tanks. Commonly the lavas are underlain by thin ash deposits which may increase percolation to them. If bailed out in dry weather they do not fill again. Kimble estimated that about 50 water holes exist in the area with an aggregate capacity of not more than 500,000 gallons.[40]

Outcrops of relatively fine grained ash beds such as perch water in Kau were not found in Kona. They may exist in the mountain but exploration for them by drilling is not recommended because of the high cost of such drilling in Hawaii, the problem of recovering ash in the cores, and the difficulty of ascertaining in such small holes whether perched water, if found, is present in sufficient quantities to justify tunneling. A few dikes were seen in pit crater walls in Hualalai but water confined by dikes in Kona is believed to be too deep to be recovered economically at present.

EXISTING WATER SUPPLIES

Brackish wells are used along the coast for all purposes except drinking. Farther inland public and domestic supplies are derived entirely from roofs and stored in wood or metal tanks. The average roof area per capita is about 100 square feet and the average per capita consumption about 10 gallons per day.[41] Kona Inn, Huehue Ranch, and Puu Waawaa Ranch divert water from Waiaha Stream when it flows and store it in tanks. Five other intermittent streams cross the highway in Kona. Kiilae Stream, just south of Keokea, is the only one which has been measured,[42] and it usually sinks at an altitude of 2,000 feet. The Captain Cook Coffee Company utilizes flat rock areas on the uplands as rain catches. They mix this water with brackish water pumped from a well. During the coffee season about 6,000 gallons per day is used for washing the beans. Most ranches, including those mentioned above, have rain sheds to catch water for their livestock. During droughts, which occur every few years, public and domestic supplies become exhausted and much hardship ensues. The need for additional water in Kona is acute every dry spell, but the problem is one of distribution as well as development. The houses and villages lie scattered above and below the main highway which ranges in altitude from 927 feet near Kealia to 1,572 feet at Kealakekua. The main settlements stretch for 17 miles along the road with no village containing more than a few hundred people. The total population of North and South Kona districts in 1940 was only 7,948.

---

[40] Kimble, Howard, North and South Kona, Hawaii, water investigation: Hawaii Div. Hydrography Spec. Rept., p. 34, 1915.

[41] Idem, p. 10.

[42] Idem, table III. Altitude of weir was at 2,840 feet.

PROPOSED WATER SYSTEMS

Kimble[43] reached the conclusion in 1915 that storage of surface water from Kiilae Stream was uneconomical. He proposed 9 sheet iron rain sheds near the 9 centers of population with individual storage tanks and distribution systems at an estimated cost of $351,000. The cost would be several times greater now (1945).

Test well 12 encountered water with 50 grains of salt per gallon (520 p.p.m.), or 330 grains less than in dug wells along the nearest coast 1.5 miles away. It has 150 grains less than wells at Kailua. The salt content of basal water under the highway 1 mile farther inland should be low enough for domestic use. The water table rises only 1.3 feet per mile from the coast; hence, the depth to water under any point along the highway is nearly equal to the altitude of the point. Thus, the depth of wells far enough inland to recover potable water would range from 1,100 to 1,500 feet. Such wells are costly, but water is pumped from wells this deep in certain localities in the United States for municipal use.

The water in wells at Keauhou Bay averages about 100 grains of salt per gallon (1,039 p.p.m.), less than at any other place along the Kona coast. A well 1,150 feet deep at Keauhou School 1½ miles inland might encounter potable water.

Three deep wells are proposed to supply the main settlements as shown in figure 60. Water from well A, 1,500 feet deep at Waiaha Stream, would be pumped to tanks at an altitude of 1,600 feet and piped northward 4½ miles to Honokohau and southward 3 miles to a point on the highway and thence to the coast and Keauhou. Another line 3 miles long would lead the water to Kailua. Water from well B, 1,600 feet deep at Kealakekua would be pumped to tanks at an altitude of 1,650 feet near by and distributed northward for 3½ miles and southward along the highway 6½ miles to the junction of the southern road to Napoopoo, with a branch line from Captain Cook to Napoopoo via Napoopoo School. Water from well C, 1,100 feet deep at the junction of the highway and the southern road to Napoopoo would be pumped to tanks at 1,200 feet near by and be piped southward for 3 miles to Kealia and the Hookena area with a branch line to Honaunau. Large existing tanks, such as those at the Kealakekua Hospital could be used for distribution where available. The advantage of wells would be the dependability of the supply. The pipes can be reduced in size as their distance from the three distributing tanks increase. Water from wells A, B, and C would have to be pumped 1,600 feet, 1,650 feet, and 1,200 feet respectively according to this plan, whereas the Kimble plan of rain sheds has the advantage of gravity distribution. Water is

---

[43] Idem, p. 18.

being lifted 1,140 feet for domestic use to supply Lanai City, Lanai, and 1,024 feet at the U. S. Naval radio station at Wahiawa, Oahu.

Any pipe-line distribution system to supply water to Kona residents based on sales of water would not be economically sound at present, except along the beaches where the pumping lift is small. The coffee industry in Kona is precarious and commonly unprofitable, depending upon the world price of coffee. At times it would be nearly impossible for the water users in Kona to buy water based on cost. Agitation for rehabilitation is common in periods when the price of coffee is low.

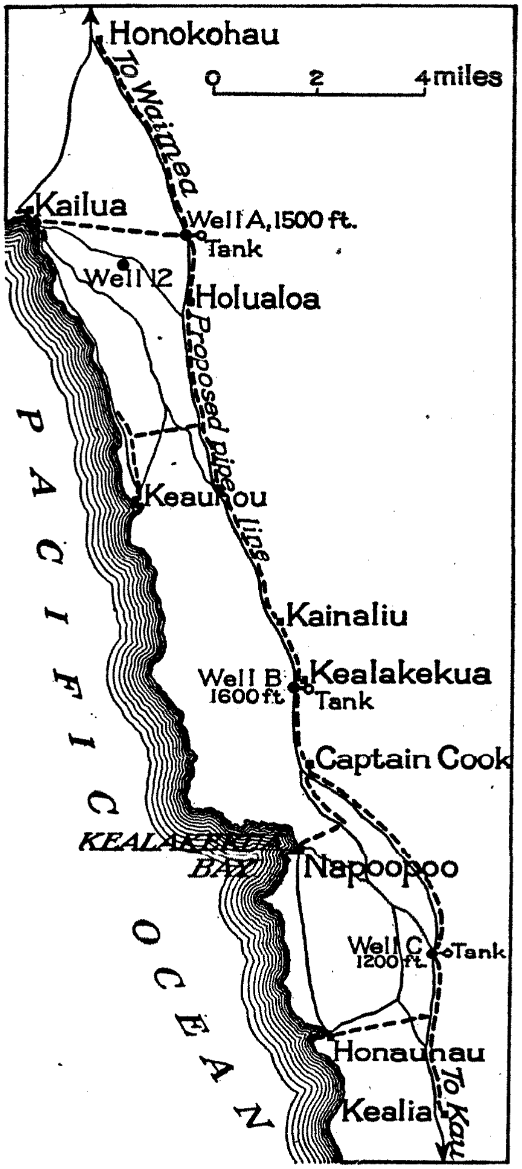


Figure 60. Map showing proposed deep wells and pipe lines for a public water supply for the Kona District.

If, however, the water project were built by the United States Government, the Territory, or the County of Hawaii, and the cost of installation charged as a rehabilitation measure, the maintenance thereafter might be feasible from the sale of water. The value of land in Kona would be greatly enhanced by a dependable water system. The most economically feasible method would be to pump water to tanks on the roads adjacent to the proposed wells and not build the expensive distribution systems. Water would then be available to those wishing to haul it in times of need. The County might even maintain tank trucks which would haul water and pump it into private tanks during droughts for a fixed price per 100 gallons.

Well 12 indicates that water suitable for irrigation can be obtained in the Kona District. Tomatoes are at present (1945) yielding sufficient profit to justify a pumping lift of 600 feet. The high permeability of the soil will require sprinkling rather than surface irrigation.

INVENTORY OF GROUND WATER IN THE KONA AREA

The amount of water discharged at sea level by the numerous small basal springs in the Kona District is unknown. Likewise unknown is the quantity of brackish water pumped from shallow wells along the coast for cattle and domestic purposes other than drinking. The two largest brackish springs are at Honaunau and Kaupulehu; they discharge respectively about 350,000 and 70,000 gallons daily. The brackish well at Camp Drewes yields about 15,000 gallons a day. Thus the known discharge from the Honaunau and Kaupulehu springs and the Camp Drewes well is about 435,000 gallons daily, or 158,775,000 gallons a year.

GROUND WATER IN THE INTERIOR PLATEAU

Ground water lies too deep under the Interior Plateau to justify developing. Pohakuloa Camp is supplied by Waihu Springs (nos. 112 and 113). A few natural rock tanks carry perennial water in the eastern part of the plateau but they are too small to have value except to the hiker. The possible occurrence of water in alluvial fans along the southern base of Mauna Kea is discussed on page 246.

CHEMICAL ANALYSES OF WATER

The table on page 289 lists chemical analyses of water from various wells, springs, tunnels, and streams on the island of Hawaii, and from the adjacent ocean. It expresses in general the chemical quality of waters of the island of Hawaii.

All the springs and tunnels listed in the table yield perched water. The streams listed in the table are to a large degree spring-fed; hence, their water is very similar in composition to that of the springs and tunnels. They are, however, somewhat poorer in silica than most of the springs and tunnels.

The water of Lake Waiau is much like that of the streams in its content of inorganic matter, but it is remarkable for the great abundance of micro-organisms, which give it a distinct yellowish-green color. A sample of the water was examined in 1921 by H. L. Lyon, who reports: "The water of Lake Waiau is a veritable infusion. Bacteria are extremely numerous and probably the chief factor in causing the turbidity of the water. A small ciliate is also present in enormous numbers, while a larger infusorian, *Stylonchia sp.*, is present in large numbers. I also find a few diatoms and numerous dead bodies of a crustacean, *Daphnia sp.*, which are being consumed by a fish mold, *Achlya sp.*"[44]

Along much of the coast of southern Puna, Kau, Kona, and western Kohala, the basal water close to the coast is brackish (fig. 41). The salt content of water of many basal springs and wells has already been given. The dug well at the steam plant of the Hilo Electric Light Company, just east of the mouth of Waiakea estuary (pl. 1), is situated very close to the shore, and its water is brackish as a result of admixture with sea water. The chemical composition of water from this well is shown in the table, as well as that of water from the open Pacific Ocean. The analyses indicate that sea water and fresh basal water have mixed in nearly equal proportions.

INVENTORY OF GROUND WATER IN HAWAII

The accompanying table summarizes the known discharge of ground water on the island of Hawaii. In addition, huge unmeasured amounts of water discharge from basal springs at sea level all around the island and particularly along the rainy northeastern and eastern coasts. The water discharged from the basal springs is almost entirely unused. Rainfall over the entire island averages about 13,085 million gallons daily. The total yield of water from springs and tunnels on perching structures, tunnels recovering water from the dike complex in Kohala Mountain, and wells producing from the basal water zone is about 145.5 million gallons daily, or approximately 1.1 percent of the rainfall, as compared with 11 percent on the island of Maui,[45] and 20.5 percent on the island of Oahu.[46] If the visible discharge of basal springs is included, the total is about 328 million gallons daily, or approximately 2.5 percent of the rainfall, as compared with about 25.6 percent on the island of Oahu.

---

[44] Gregory, H. E., and Wentworth, C. K., General features and glacial geology of Mauna Kea, Hawaii: Geol. Soc. America Bull., vol. 48, p. 1726, 1937.

[45] Stearns, H. T., and Macdonald, G. A., Geology and ground-water resources of the island of Maui, Hawaii: Hawaii Div. Hydrography, Bull. 7, p. 202, 1942.

[46] Stearns, H. T., and Vaksvik, K. N., Geology and ground-water resources of the island of Oahu, Hawaii: Idem, Bull. 1, p. 442, 1935.

Average discharge of ground water, in gallons per day, from rock structures in Hawaii

Area	Perched water		Water in dike complex		Basal water		Total
	Springs	Tunnels	Springs	Tunnels	Wells	Visible springs[a]	
Kohala	1,600,000	3,000,000	95,750,000	8,250,000	4,000,000	1,000,000	113,600,000
Hamakua and North Hilo	7,200,000	140,000	0	0	600,000	0	7,940,000
South Hilo and Puna	4,600,000	1,700,000	0	0	7,700,000	146,000,000	160,000,000
Kau	1,000,000	7,000,000	0	0	3,000,000	35,000,000	46,000,000
Kona	0	0	0	0	15,000	420,000	435,000
Total	14,400,000	11,840,000	95,750,000	8,250,000	15,315,000	182,420,000	327,975,000

[a] Large quantities of water must be discharged into the sea by invisible basal springs all along the coast, particularly in the wet areas.

SUMMARY OF UNDEVELOPED GROUND-WATER SUPPLIES IN HAWAII

Large quantities of high-level ground water await development between Waipio and Honokane Nui canyons in Kohala Mountain. The rough character of the terrane makes development of the water and its utilization difficult. Vast quantities of potable basal water escape daily into the sea along the Hamakua, Hilo, and Puna coasts. During the last 5 years several wells of large capacity have been sunk but they recover only a small fraction of the water available.

During the last twenty years large sums of money have been spent developing high-level ground water in central Kau. More high-level water awaits development, but the cost of geologic exploration and tunneling is large in proportion to the quantity recovered. Considerable basal water is available but the point of use requires high-lift pumping. The remaining part of the Kau District will long remain dependent upon rain sheds.

The high salt content of basal water along the Kona coast makes shallow wells useless for domestic supplies. Only deep wells several miles inland will recover potable water. The point of use is chiefly above an altitude of 1,200 feet which makes pumping costly.

Details regarding undeveloped ground-water resources of the island and methods for recovery are described under the chapters dealing with the separate areas.

GROUND-WATER STATISTICS

Water supplies of towns and villages on Hawaii

(Data compiled from county, plantation, and original surveys)

Place	Population	Source of water
Kohala area		
Kohala Sugar Co.:[a]		
Niulii (3 camps)	192	Tunnel 28
Makapala	84	Tunnel 25
Halawa	116	Tunnel 22
Camp 17 (Kohala)	28	Tunnels 10, 11, 12, and 15
Kohala	960	
Union Mill	372	Tunnel 2 and Kohala ditch
Hawi	628	Tunnels 6 and 7
Camp 5 (Hawi)	56	
Camp 17 (Hawi)	116	
Hoea	100	Kohala ditch
Stephens	20	
Homestead (Kokoiki)	64	
Mahukona	60	Do.[b]
North Kohala Water Works:[c]		
Kapaau-Honomakau[d]	475	Spring 1 and Kohala ditch
Kokoiki	130	Kohala ditch[e]
Hawi	65	Kohala Sugar Co. pipe to Hawi[f]
Kaauhuhu	130	Kehena ditch[g]
Waimea Water Works:[c]		
Waimea	170	Waikoloa Stream
Kawaihae	1,200	
Camp Tarawa	......	Do., and upper Hamakua ditch
Waipio	[h]50	Hiilawe Stream
Kahua Ranch	......	Kehena ditch, Puu Ahia Stream, pond on Puu Pili and adjacent springs, and Hooleipalaoa Gulch
Lindsay's Ranch	......	Keawewai Stream
Parker Ranch:		
Kohala Division (Puu Hue Ranch)	......	Waipuhi Stream and Kehena ditch
Kawaihae-Uka Division	......	Keawewai Stream
All other divisions	......	Alakahi and Kohakohau streams
Ahualoa Homesteads	......	Rainwater
Ahualoa School	......	
Hamakua and North Hilo areas		
Honokaa Sugar Co.:[i]		
Kukuihaele Section:		
Camp 101	6	Lower Hamakua ditch
Camp 102	54	
Camp 103	2	
Camp 104	69	Spring 30
Camp 105	150	
Camp 106	10	Lower Hamakua ditch
Camp 107	10	
Camp 108	22	
Camp 109	78	
Camp 110	10	
Camp 112	84	
Kapulena Village	77	
Camp 113	73	
Kapulena School	......	

Honokaa Section:		
Camp 1	118	Lower Hamakua ditch
Camp 2	96	
Camp 3	13	
Camp 4	163	
Camp 5	299	
Camp 6	42	
Camp 7	88	Do. (County system)
Camp 8	117	
Camp 9	47	Lower Hamakua ditch
Camp 10	101	
Camp 11	3	
Camp 12	37	
Camp 13	62	
Two houses in Kalahai area	10	Spring 33
Honokaa Water Works:		
Honokaa	[c]950	Lower Hamakua ditch
Honokaa School	......	
Hanaipoe Ranch	......	Rain water
Paauhau Sugar Plantation Co.:[j]		
Village 1	584	Lower Hamakua ditch
Village 2	178	
Village 3	195	
Mauka Camp	57	
Paauhau School	......	
Paauhou Hospital	......	
Kukaiau Ranch	......	Rain water
Kaapahu School (Kalopa)	......	
Hamakua Mill Co.:		
Japanese Camp	491	Lower Hamakua ditch and tunnel 41
Filipino Old Camp	311	Do., and tunnels 39 and 42
Gibo Camp	15	Do.
Stable Camp	28	Do., and tunnel 41
Nakalei Village[k]	125	Do., and spring 41
Big Kukaiau Camp	91	Puumaile Stream, lower Hamakua ditch and tunnel 44
Small Kukaiau Camp	20	Puumaile Stream and tunnels 45 and 45A
Paauilo Hospital	......	Lower Hamakua ditch
Paauilo School	......	Do.
Kaiwiki Sugar Co.:		
Naukane Camp	25	Maui-type well 6. Spring 45 contributes some water to the western part of the system.
Niu Camp	33	
Kukui Camp	129	
Machida Camp	57	
Mill Camp	142	
Boarding House Camp	38	
Store Camp	75	
Salvino Camp	72	
Chinese Camp	37	
Sato Camp	29	
Akosaki Camp	41	
Fujioshi Camp	32	
Segundo Camp	39	
Ramon Camp	21	
Korean Camp	28	
Niupea Mauka Camp	5	
Ishikawa Camp	16	
Ookala Hospital	......	
Ookala School	......	Maui-type well 6

Laupahoehoe Sugar Co.:		
Camp 1 (Kahinano)	16	Spring 66
Camp 2 (Kaiaakea)	152	Spring 65
Camp 3 (Maulua)	72	Spring 63
Camp 4 (Uiki)	25	Spring 60
Camp 5 (Kapehu)	197	Spring 59
Camp 6 (Kapehu Mauka)	35	Spring 58
Camp 7 (Kapehu Stable)	11	
Camp 9 (Oshiro)	50	Spring 54
Camp 10 (Kekoa)	188	Spring 56
Camp 11 (Papaaloa)	109	
Camp 12 (Mill)	43	Spring 52
Camp 13 (Kihalani)	155	
Camp 14 (Kilau)	75	Spring 50
Camp 16 (Waipunalei)	142	Do. (through County pipe line)
Camp 17 (Waipunalei Mauka)	9	
Papaaloa Hospital	......	Spring 51
Laupahoehoe Water Works:		
Laupahoehoe (upper village)	450	Spring 50
Laupahoehoe (lower village)	......	Spring 49
Laupahoehoe School	......	
Kapehu School	......	Spring 59
John M. Ross School	......	Spring 72
Hakalau Sugar Co.:		
Chin Chuck Stable Camp[1]	136	Spring 86
Chin Chuck Genjiro Camp	106	
Hakalau Village	567	Springs 86 and 81
Wailea Camp	97	Spring 84
Korean Camp	47	Spring 79
Sugimoto Camp	55	
Kamaee Mauka Camp	169	Spring 78
Honohina Village	295	Spring 73
Kahuku Camp	86	Spring 71
Yamagata Camp	77	Spring 67
Moi Place Camp	15	Spring 74
Ah Ling Camp	46	Spring 76
Honohina Stable Camp	79	Spring 68
Hata Camp	25	Spring 70
Gus Camp	12	
Yogogawa Camp	14	Spring 68
Umauma Village	40	Spring 77
Taro House Camp	12	Spring 82
Hakalau School	......	Spring 84
Wailea Milling Co.:		
Wailea Village	130	Spring 83
Chin Chuck houses	3	Spring 87
Honomu Sugar Co.:		
Camps 1 to 11	1,141	Spring 88
Honomu Water Works:		
Honomu	[c]370	Spring 88
Honomu School	......	
Pepeekeo Sugar Co.:		
Maukaloa Camp	225	Spring 94
Andrade Camp	203	
Hospital Camp	22	
Mill Camp	691	
Store Camp	20	
Kaupakuea Camp	42	
Pepeekeo Hospital	......	
Pepeekeo Water Works:		
Pepeekeo	135	Spring 94
Pepeekeo School	......	

Onomea Sugar Co.:		
Paukaa Camp	108	Tunnel 57
Paukaa Mauka Camp	14	Flume, from Honolii Stream
Piinau Camp	61	Tunnel 56
Papaikou Camps	1,093	Tunnel 55 and springs 101 and 103
Kalaoa Camp	168	Spring 99
Kainole Camp	106	Spring 96
Onomea Camp	401	Tunnel 54
Papaikou Water Works:		
Papaikou	[c]325	Paihaaloa Stream, intake at about 500 feet altitude
Kalanianaole School	......	
Hilo Sugar Co.:		
Amauulu Camp 1	302	Pukihae Stream
Amauulu Camp 3	29	Wailuku River
Amauulu Camp 4	193	Awehi Stream
Amauulu Camp 5	11	
Wainaku Camp 1	255	Pukihae Stream
Wainaku Camp 2	589	
Wainaku Camp 3	28	
Wainaku Camp 4	23	
Piihonua Camp	350	Rain water and tributary of Wailuku River
Kaiwiki School	......	Rain water
South Hilo and Puna areas		
Hilo Water Works:		
City of Hilo	[m]16,576	Wailuku River and its tributaries and spring 133[n]
Schools and hospitals in the Hilo area	......	
Hilo Airport	......	Do., and drilled wells 11 and 12
Kaumana	600	Rain water and spring 131 via flume
Kaumana School	......	
Piihonua	500	Rain water and Wailuku River
Piihonua School	......	Wailuku River
Waiakea Mill Co.:		
Mill Camp	......	Hilo Water Works
Other camps	......	Springs 138, 139, 140, 141, and tunnels 59, 60
Olaa Sugar Co.:[a]		
Mill camps	740	Drilled wells 1 and 1A
Olaa Village	1,416	Rain water
Kurtistown	412	
Iwasaki Camp	196	
Kukui Camp	302	Tunnels 58, 61, 62
Mountain View	859	
Pahoa	949	Rain water
Kapoho	541	
Opihikao area	250	
Kalapana	......	
Glenwood	......	
Volcano district	......	
Kilauea Military Camp	......	
Kau area		
Kapapala Ranch	[o]45	Tunnel 65
Hawaiian Agricultural Co.:[o,p]		
Wood Valley	425	Tunnels 70, 71, 72, 74, 75
Kapapala		
Kapapala homesteads		

Meyer	1,321	Tunnel 85
Whitney		
Keaiwa		
Pahala (part)		
Pahala (part)	706	Tunnel 91
Moaula		
Higashi		
Hutchinson Plantation Co.	1,276	Tunnels 93, 95, and springs 145, 146
Hilea		
Honuapo		
Naalehu		
Waiohinu Water Works (County)	150	Spring 146
South Point Airport	500	Tunnel 95
Kamaoa Homesteads (County)	50	Spring 146
Kahuku Ranch	......	Rain sheds, water holes, and spring 146
	Kona area	
Milolii	......	Roofs and brackish water holes
Hoopuloa	......	Roofs
Hookena	......	Roofs and brackish well
Kealia	......	Roofs
Keokea	......	
Honaunau	......	Roofs and Honaunau spring
Napoopoo	......	Roofs and brackish wells
Captain Cook	......	Roofs
Kealakekua	......	
Konawaena School	......	
Kainaliu	......	
Keauhou	......	Roofs and brackish wells
Holualoa	......	Roofs
Kailua	......	Roofs and brackish wells
Kona Inn	......	Waiaha Stream
Honokohau	......	Roofs
Kalaoa	......	
Huehue Ranch	......	Waiaha Stream and rain sheds
Puu Waawaa Ranch	......	
Camp Drewes	500	Dug well
Camp Hayes	250	
Pohakuloa Camp	......	Springs 112 and 113

---

[a] Population figures are from plantation census, 1943.

[b] Filtered.

[c] Population is estimated as 5 times the number of consumers.

[d] Contract with Kohala Ditch Co. allows county 141,000 gallons daily in return for rights of way. Water is filtered and stored in two concrete reservoirs, capacity 300,000 gallons and 46,800 gallons respectively. The spring goes dry in dry weather. The charge is a flat rate of $1.50 per month if not metered; if metered, 10 cents per 1,000 gallons for first 25,000 gallons and reduced rate thereafter.

[e] Water bought from Kohala Ditch Co., at rate of $10.00 per million gallons; it is not filtered.

[f] Water is purchased from Kohala Sugar Co., for $75.00 per year.

[g] Water is purchased from Kohala Ditch Co., for $100.00 per year but often no water is available. Reservoir capacity 130,000 gallons.

[h] Estimated.

[i] Plantation census, 1942.

[j] Total domestic water consumption of Paauhau Sugar Plantation Co., is approximately 20,000,000 gallons per month.

[k] Includes Mill Camp.

[l] Includes Chin Chuck Mauka Camp and Porto Rican Camp.

[m] Census of 1940.

[n] See page 294 for discharge records.

[o] Plantation census, 1941.

[p] During droughts water is used from any available source.

Records of drilled wells in Hawaii

Number (pl. 1)	Location	Owner	Date completed	Driller	Diameter (inches)	Depth (feet)	Altitude of ground surface (feet above sea level)	Average altitude of water table (feet above sea level)	Average salt content (gr/gal)	Average pumpage (m.g.d.)	Use and remarks
1	Hawi	Kohala Sugar Co.	1898(?)	McCandless Bros.(?)	..	200(?)	500	Dry	....	....	Bit reported lost
2	Union Mill (Hawi)	do.	1898(?)	McCandless Bros.(?)	4	425±	400±	....	....	0	Abandoned
3	Waimea	U. S. Government	1944	U. S. Marine Corps	8	890	2,855±	Dry	....	0	Not completed
4	Paauilo (1.2 miles NW of mill)	Hamakua Mill Co.	1894	McCandless Bros.	12	....	175±	....	....	0	Abandoned
5	Paauilo Mill	do.	1894	do.	12	217.1	215.6	1.7	17	0	do.
6	Kukaiau (old mill site)	do.	....	....	12	264.7	244.7	2	30±	0	do.
7	Hilo Airport	U. S. Navy	1944	U. S. Navy	16	76	59	4	....	....	Domestic[a]
8	Do.	do.	1944	do.	16	86	71	5	....	....	do.[a]
9A	Olaa Mill	Olaa Sugar Co.	1921	McCandless Bros.	12	450	220	17	0.85	0.25	Domestic
9B	Do.	do.	1921	do.	12	450	220	17	0.85	0.25	do.
[b]10	Honuapo Mill	Hutchinson Sugar Plantation Co.	....	Capt. Bruns.	(b)	(?)	22	0	9.5	3.0	Industrial
11	South Point Airport	U. S. Army	1941	W. M. Mullin	6	63.5	51±	0	57	[d]0	Unused
12	Kailua	U.S.G.S. and T.H.	1944	U.S.G.S.	6	615	595	2	[e]50	0	do.
[c]13	Mahukona	Hawaii R.R. Co.	1881	McCandless Bros.	..	800	25±	0.5±	Salty	0	Abandoned

[a] Not yet in use at date of writing.

[b] Nine drilled holes, each 3 inches in diameter, only 3 of the holes open, in the bottom of a pit 20 feet deep which extends a little below sea level. The holes are partly backfilled, thus considerably reducing their yield, which was originally about 2,000 gallons a minute.

[c] McCandless, J. S., A brief history of the McCandless brothers and their part in the development of artesian well water in the Hawaiian Islands, 1880–1936, pp. 16, 66, and 71, Honolulu, 1936. Exact location unknown.

[d] Pumping test in May 1941 at rate of 30 g.p.m. for 2 hrs. increased the salt content from 50 to 60 gr.p.gal. Water level 53.5 ft. below top of well casing which is 21.5 feet long.

[e] Salt content on March 24, 1945, was 45 grains per gallon.

Records of Maui-type wells in Hawaii

(Data furnished by owners)

U.S.G.S. number (See pl. 1)	Name of plant	Owner	Date installed	Altitude collar of shaft (ft.)	Length of shaft (ft.)	Number of tunnels	Length of tunnels (ft.)	Number of pumps	Capacity (m.g.d.)	Number of hp of each motor	Number of booster pumps	Hp of booster pumps	Maximum pumping lift (ft.)	Average altitude of static water level (ft.)	Average draw-down (ft.)	Salt content while pumping (gr.p.g.)		Chief aquifer
																Min.	Max.	
1	Waikane	Kohala Sugar Co.	[a]1920	26	42	2	690	1	3.0	200	0	..	220	+ 0.5	1.0	57.80	152.0	Polulu basalt
2	Hoea	do.	[b]1900	52	61	6	1,612	1	8.0	250	1 2 2	150 75 40	155	+ 2.0	2.5	29.60	58.2	do.
3	Alaalae[c]	do.	[d]1900	75	84	1	10	..	...	...	..	..	..	+ 2.0	..	...	...	do.
4	Kohala	do.	[b]1900	123	135	4	673	3	5.0 2.5 2.5	300 150 100	0	..	275	+ 7.0	2.0	8.50	42.4	do.
5	Paauilo	Hamakua Mill Co.	1944	273	623	2	667	[e]1	3.6	250	0	..	300	+ 3.4	..	2.40	6.8	Hamakua basalt
6	Ookala	Kaiwiki Sugar Co.	[f]1937	300	600	2	650	3	0.2 0.2 3.1	40 40 300	0	..	810	+ 6.0	0	0.70	1.4	do.
7	Olaa	Olaa Sugar Co.	1936	220	203	1	35	3	3.5 1.5 0.5	150 75 25	0	..	207	+17.0	0	0.85	0.85	Kau basalt
8	Pahala	Hawaiian Agricultural Co.	[g]....	774	1550	..	...	..	2.9	...	..	..	..	..	..	...	...	......

[a] Remodeled 1943.

[b] Steam-driven pumps installed about 1900 and replaced by electric-driven pumps in 1933.

[c] Abandoned.

[d] Completed about 1900.

[e] Pumping equipment not yet operating.

[f] A second infiltration tunnel was driven in 1944.

[g] Under construction; length of shaft and pumping capacity are proposed figures.

Salt content of dug wells, springs, and water holes, Kona coast, Hawaii

Name	Owner	Location	Date	Salt[a] (gr.p.g.)	Chloride (p.p.m.)
Camp Drewes well	U. S. Marine Corps	Hapuna Bay	Apr. 12, 1944	54	558
Kaupulehu Spring[b]	Bishop Estate	Beach at Kaupulehu	Sept. 21, 1939	122	1,263
Kaupulehu pool[b]	do.	100 feet from shore, Kaupulehu	Sept. 22, 1939	154	1,599
Hawaiian well[b]	do.	Kaupulehu	do.	169	1,757
Kaupulehu water hole[b]	do.	50 feet inland of well, Kaupulehu	do.	165	1,712
Ancient Hawaiian well[b]	do.	In Kaupulehu lava flow of 1801	do.	168	1,745
Kaupulehu water hole[b]	do.	At Lolu palms, Kaupulehu	do.	144	1,498
Cave spring[b]	do.	Makalawena	June 2, 1944	192	2,000
Stillman well[b]	Huehue Ranch	Kikaua, 2½ miles NW. of Makalawena	do.	275	2,860
Old spring[b]	A. K. Magoon	Mahaiula, near coconut trees	do.	179	1,860
Factors well	American Factors	Kailua	Apr. 26, 1944	685	7,100
Court House well	County of Hawaii	do.	Sept. 26, 1939	206	2,142
Manuel Gomes well	Manuel Reis	85 feet from shore and ½ mile S. of Kailua	July 20, 1939	[c]206	2,150
Frank Gouveia well	Manuel Gomes	900 feet from shore and 1⅜ miles S. of Kailua	do.	[c]384	4,000
A. C. Amorino well	J. C. Pacheco	250 feet from shore and 2⅛ miles S. of Kailua	do.	[c]312	3,250
Hind stock well	Thomas Gouveia	200 feet from shore and 2¼ miles S. of Kailua	do.	[c]912	9,500
J. Pacheco well	T. Gouveia, et al.	175 feet from shore and 2⅜ miles S. of Kailua	do.	[c]293	3,050
T. Yamanaka well	Kimura, et al.	225 feet from shore and 2⅝ miles from Kailua	do.	[c]173	1,800
J. Pacheco well	J. Pacheco	175 feet from shore and 2⅝ miles from Kailua	do.	[c]178	1,850
Geo. Carr well	F. Silva	2⅞ miles S. of Kailua	Sept. 27, 1939	219	2,278
Old Hawaiian well	T. C. White	3 miles S. of Kailua	do.	234	2,435
Do.	do.	do.	do.	234	2,435
F. Silva well	Frank Silva	300 feet from shore and 3 miles from Kailua	July 20, 1939	[b]178	1,850
Old Hawaiian well	Frank Greenwell	15 feet from shore and 3⅛ miles from Kailua	Sept. 27, 1939	236	2,413
J. Pacheco well	do.	150 feet from shore and 3¼ miles from Kailua	July 20, 1939	[c]221	2,300
Stock well	Manuel De Guair	3⅜ miles S. of Kailua	Sept. 27, 1939	250	2,593
Hawaiian well	K. Leleiwi Estate	3½ miles S. of Kailua	do.	428	4,442
Hugo well	Daniel Hugo	do.	July 20, 1939	[c]278	2,900
Joyce well	Horace Joyce	4 miles S. of Kailua	Sept. 27, 1939	228	2,368
Stock well	H. P. Ching	35 feet from shore and 4 miles S. of Kailua	July 20, 1939	[c]226	2,350

Salt content of dug wells, springs, and water holes, Kona coast, Hawaii (continued)

Name	Owner	Locality	Rate	Salt[a] (gr.p.g.)	Chloride (p.p.m.)
Church well	Catholic Church	50 feet from shore, Kahaluu Bay	Sept. 27, 1939	156	1,624
Hind well	Bishop Estate	725 feet from shore, Kahaluu Bay	July 20, 1939	[c]113	1,175
House well	do.	350 feet from shore, Kahaluu Bay	do.	[c]115	1,200
Fishpond[d]	C. K. Nahale	Kahaluu Bay	Sept. 27, 1939	137	1,421
Well[d]	T. C. White	Keauhou	do.	110	1,139
White well[d]	Bishop Estate	do.	do.	97	1,007
Kahoee cave	....	100 feet from shore and ¾ mile S. of Keauhou	Sept. 28, 1939	194	2,007
Stock well	Wm. Paris	40 feet from shore and 1⅜ miles S. of Keauhou	do.	217	2,255
Do.	Wm. Roy	2 miles S. of Keauhou	do.	221	2,300
Do.[d]	Wm. Paris	2⅞ miles S. of Keauhou	do.	195	2,030
Do.	Walter Ackerman	3 miles S. of Keauhou	do.	177	1,849
Nawawa cave	....	3⅜ miles S. of Keauhou	do.	258	2,683
Stock well	Henry Greenwell	60 feet from shore and 4 miles S. of Keauhou	do.	241	2,503
Do.[e]	Maude Greenwell	Cook's monument	do.	286	2,977
Old McCandless well	Hawaii Coffee Mill	Napoopoo	Oct. 17, 1939	122	1,263
Well	Capt. Cook Coffee Co.	Half a mile S. of Napoopoo	do.	191	1,984
Stock well	McCandless Ranch	2,000 feet from shore and 1½ miles S. of Napoopoo	Oct. 13, 1939	143	1,488
Honaunau Spring	....	Honaunau	do.	295	3,067
Well	Albert Waiau	Hookena	do.	234	2,435
Well	Eaton Magoon	Pahoehoe, 2.6 miles S. of Hookena	July 7, 1944	289	3,000
Water hole	Kala Pilipo	Milolii	Oct. 13, 1939	353	3,653

[a] Titrated in US.G.S. laboratory, Honolulu, unless otherwise indicated.
[b] Collected at low tide.
[c] Data furnished by T. H. Board of Health.
[d] Collected at half tide.
[e] Collected at nearly high tide.

Chemical analyses of spring, tunnel, well, stream, and ocean water (in parts per million)

	Silica (SiO_2)	$Fe_2O_3 + Al_2O_3$	Calcium (Ca)	Magnesium (Mg)	Sodium (Na) or sodium and potassium (Na + K)	Loss on ignition	Sulfate radicle (SO_4)	Chloride radicle (Cl) and nitrate radicle (NO_3)	Carbonate radicle (CO_3)	Total solids	Total hardness (calculated)	Date of analysis	Analyst[a]
Spring 30 (Kukuihaele)	20.0	11.0	14.0	5.6	15.0	2.2	4.9	28.0	27	128	58	5/13/10	D
Spring 41 (Paauilo)	3.6	2.0	8.0	2.9	8.6	1.7	2.8	7.1	23	60	32	6/21/40	D
Spring 83 (Wailea)	11.0	12.0	15.0	3.1	22.0	5.7	6.5	50.0	14	139	50	1/21/36	D
Spring 137	11.0	0.2	2.6	trace	4.7	13.0	1.7	5.0	. .	41	7	6/5/42	T
Spring 138	10.0	0.2	2.6	trace	4.9	15.0	2.0	5.0	. .	38	7	6/5/42	T
Spring 139	11.0	0.2	2.9	trace	4.7	14.0	1.5	5.0	. .	39	8	6/5/42	T
Spring 140	10.0	0.2	2.6	trace	4.6	16.0	2.1	5.0	. .	39	7	6/5/42	T
Tunnel 59	12.0	0.2	2.9	trace	5.0	13.0	2.0	5.0	. .	41	8	6/5/42	T
Tunnel 60	10.0	0.2	2.9	trace	4.7	13.0	1.7	5.0	. .	41	8	6/5/42	T
Tunnel 2	11.0	5.2	8.4	3.8	11.5	1.7	1.6	18.0	21	82	37	6/16/09	D
Tunnels near Pahala (composite sample)	8.0	1.2	7.2	2.6	7.4	2.8	9.0	11.0	12	61	29	12/24/40	D
Tunnels and perched springs near Naalehu (composite sample)	8.0	0.8	8.7	4.2	8.3	4.4	13.0	8.9	19	75	39	12/27/40	D
Papaaloa Stream	4.8	1.6	8.7	3.7	15.0	0.1	4.6	20.0	22	80	37	6/16/09	D
Kihalani Stream	3.9	1.0	7.8	4.1	18.0	0.4	5.2	11.0	18	70	36	6/16/09	D
Lower Hamakua Ditch at Paauhau	20.0	14.0	13.0	3.4	26.0	1.5	trace	14.0	50	142	46	7/19/27	D
Hilo City Supply (largely Wailuku River)	1.7	1.1	4.9	3.1	51.0	. . .	2.4	7.1	20	68	25	8/26/40	H
Do.	4.4	0.4	7.7	1.1	7.7	3.4	2.8	5.3	18	51	24	12/27/40	D
Lake Waiau	4.0	1.2	18.0	3.9	19.0	. . .	23.0	13.0	37	110	61	12/30/29	D
Drilled well 9 (Olaa)	12.0	0.8	1.6	4.3	14.0	2.5	6.1	14.0	16	72	22	3/23/34	D
Dug well at Hilo Electric Light Co. steam plant	2.6	2.4	170.0	617.0	5,167	. . .	1,223	9,006	65	18,748	2,955	8/26/40	H
Pacific Ocean, half way between Hawaii and Maui[b]	7.0	1.3	405.0	1,305	10,960	. . .	2,620	19,120	66	34,470	6,363	. . . .	B

---

[a] Analysts: D, Dearborn Chemical Co.; H, Hawaiian Sugar Planters Association; T, Board of Health, Territory of Hawaii; B, L. T. Bryson, Honolulu Board of Water Supply.

[b] Wentworth, C. K., The specific gravity of sea water and the Ghyben-Herzberg ratio at Honolulu: Hawaii Univ. Bull., vol. 18, no. 8, pp. 9–10, 1939.

Perched springs on Hawaii

(Only those numbered on plate 1)

No. (pl.1)	Valley or name	Approximate altitude (feet)	Daily discharge (gallons)	Water-bearing formation	Perching structure
	Perched springs in the Kohala area				
1	County Spring in E. bank of Hapahapai Gulch	900	[a]10,000	Hawi lava	Soil at base of series
2	Kohala Seminary Spring in Pali Akamoa Gulch	625	[a]Dry	do. (?)	do. (?)
3	Iole Springs in W. bank of Wainaia Gulch	650	[b]50,000	do.	do.
4	Maulili Spring in small branch of Waiakauaua Gulch	1,030	[c]20,000	do.	do.
5	Olding Spring in W. branch of Wainaia Gulch	1,600	[a]25,000	Hawi clinker	do.
6	Waipuhi Spring in Waiakauaua Gulch	2,000	[a]20,000	Hawi lava	Dense aa (?)
7	Halawa Gulch, W. branch	1,200	[a]150,000	Boulders	Soil in Pololu series (?)
8	Halawa Gulch, E. branch	850	[a]7,200	Hawi lava	Soil at base of series
9	Waipunalau Gulch	1,600	[a]45,000	do.	Dense aa
10	Murphy Spring in E. branch of Waikani Gulch	1,250	[a]25,000	do.	Soil at base of series (?)
11	Mau Spring in small fork of Waikama Gulch	900	[a]Dry	do.	do.
12A	Spring rising in floor of E. Honokane Nui Canyon below Kohala ditch	900	1,250,000	Pololu lava	Dikes
12B	E. wall of E. branch of Honokane Nui Canyon	950	650,000	do.	Ash bed
13	Do.	1,400	500,000	do.	do. (?)
14	Apua Springs in sea cliff mouth of Oniu Stream	150	40,000	do.	Ash beds
15	Laupoehoe Springs in sea cliff near mouth of Paopao Stream	150	75,000	do.	do.
16	Keawewai Spring in W. wall of Waimanu Valley	400	40,000	do.	do. (?)
17	Waihilau Spring tributary to Waimanu Stream	425	12,000,000	do.	Dikes
18	W. bank of Waimanu Stream	175	500,000	Talus	do. (?)
19	Waimanu Spring, Waimanu Valley	425	5,000,000	Pololu lava	do.
20	N. branch of Kawainui Stream	3,000	5,000,000	do.	do.
21	Plunge pool foot of Ulu Falls, Kawainui Stream	2,250	6,000,000	do.	do.
22	Northern Upper Kawainui Springs	3,550	500,000	Hawi lava	Soil at base of series (?)
23	Southern Upper Kawainui Springs	3,550	500,000	do.	do.
24	Plunge pool head of Alakahi Canyon	1,475	1,000,000	Pololu lava	Dikes
25	Springs in S. bank 50 feet above Alakahi Stream	1,425	3,000,000	do.	do.
26	Pool 25 feet above Koiawe Stream in W. wall	1,200	200,000	do.	do.
27	In falls at head of Koiawe Canyon	1,650	2,000,000	do.	do.
28	E. wall of Waima Canyon just below intake of ditch	850	1,000,000	do.	do.
29	Pool at foot of Hiilawe Falls	300	8,000,000	do.	do.
30	Kukuihaele	900	250,000	Hamakua aa	Soil between lavas
31	Waiulili	600	250,000	do.	Soil at basal unconformity

Perched Springs on Hawaii (Continued)

No. (pl.1)	Valley or name	Approximate altitude (feet)	Daily discharge (gallons)	Water-bearing formation	Perching structure
Perched springs in the Hamakua and North Hilo areas					
32	Kapulena Stream	1,650	[d]250	Laupahoehoe aa	Dense aa
33	Ahualoa Stream	1,450	1,000	Hamakua aa	do. (?)
34	Waikomakapo Spring in Kahaupu Gulch	4,275	[e]1,000	Laupahoehoe aa	Pahala ash
35	Palikau Spring in Kalopa Gulch	3,850	[e]10,000	do.	do.
36	Papalele Gulch	1,800	500	Hamakua aa	Dense aa
37	W. fork of Manienie Gulch	2,250	500	Laupahoehoe aa	do.
38	Gulch west of Manienie Gulch	1,510	50	do.	do.
39	Do.	1,050	[e]50	do.	do.
40	Sea cliff 0.4 mile NW. of Manienie Gulch	15	5,000	Hamakua lava	do. (?)
41	Paauilo Gulch	730	10,000	Hamakua aa clinker	do.
41A	Do.	700	100	do.	do.
41B	Do.	675	100	do.	do.
42	Branch of Kawaiili Stream	2,025	[e]100	Laupahoehoe aa	do.
43	Kalapahapuu Gulch	3,075	[e]40,000	do.	do.
44	Keehia Stream	2,000	[e]250	Hamakua aa	do.
45	Kupapaulua Stream	1,100	1,000	do.	Ash bed (?)
46	Kaahaoha Stream	450	[e]4,000	do.	Soil bed
47	Kaawalii Spring in E. fork of Kaawalii Gulch	380	150,000	do.	do.
48	Sea cliff just west of Kilau Stream	330	20,000	Hamakua lava	do.
49	Laupahoehoe Spring in sea cliff 0.25 mile SE. of Kilau Stream	320	[f]50,000	Hamakua lava	Soil beds
50	Manowaiopae Stream	1,100	100,000	Hamakua aa	Ashy soil
51	Kihalani Stream	700	20,000	Hamakua pahoehoe	Ash bed (?)
52	Do.	500	40,000	do.	Soil bed
53	Sea cliff, just W. of Kaiwilahilahi Stream	150	100,000	Hamakua aa	Ash bed
54	Kaiwilahilahi Stream	1,200	20,000	Alluvium[g]	Soil bed (?)
55	Kaiwilahilahi Gulch, NW. side	750	15,000	Hamakua pahoehoe	Ash bed
56	Do.	700	40,000	do.	do. (?)
57	Pahale Stream	1,575	[e]1,000	Hamakua aa	Dense aa
58	Kapehu Stream	750	3,500	Hamakua aa clinker	do.
59	Do.	525	25,000	do.	do.
60	Paeohe Stream	1,100	2,500	Hamakua pahoehoe	do. (?)
61	Stream S. of Paeohe Stream	1,000	40,000	do.	Ash bed (?)
62	Weloka Stream, N. fork	400	8,000	Hamakua lava	Ashy soil bed
63	Weloka Stream, S. fork	400	5,000	do.	do.
64	Sea cliff at Weloka Stream, in railroad cut	200	5,000	do.	do.
65	Huliilii Stream	650	18,000	Laupahoehoe aa	Ash bed (?)
66	Poupou Stream	350	5,000	Hamakua pahoehoe	Ash bed
67	SW. of Ninole Village 0.1 mile	300	100,000	Laupahoehoe aa	do.
68	Nanue Gulch, N. side	1,500	25,000	do.	Ashy soil bed
69	Do., S. side	1,450	[e]5,000	Hamakua aa clinker	do.
69A	Do., N. side	1,450	[e]10,000	Hamakua pahoehoe	Ash bed (?)
70	Waiehu Stream (just N. of Nanue Stream)	1,050	8,000	do.	Rotted clinker
71	Waiehu Stream	300	12,000	do.	Ash bed
72	Nanue Gulch, N. side	450	10,000	do.	do.
73	Opea Gulch (reaches sea at Nahaku Point), N. side	450	15,000	do.	Rotted clinker
73A	Do., 300 feet farther NE.	450	15,000	do.	do.
74	Branch of Umauma Stream	1,150	10,000	Hamakua aa clinker	Dense aa
75	Peleau Stream	960	2,000	Hamakua pahoehoe	Dense lava (?)
76	Do.	880	30,000	do.	do.
77	Lujan Spring in Peleau Stream	600	20,000	do.	do.
78	Kamaee Stream	1,300	35,000	Laupahoehoe aa	Rotted aa clinker
79	Hanapueo Stream	775	12,000	do.	Ashy soil

Perched Springs on Hawaii (Continued)

No. (pl.1)	Valley or name	Approximate altitude (feet)	Daily discharge (gallons)	Water-bearing formation	Perching structure
80	Highway cut, N. side of Hakalau Gulch	200	5,000	Hamakua pahoehoe	do.
81	Hakalau Gulch, S. side	270	35,000	do.	Dense underlying lavas
82	Waawaa Stream	800	5,000	Laupahoehoe aa	Ash bed (?)
82A	Do.	775	3,000	do.	do.
83	W. of Hakalau school 0.25 mile	325	60,000	Pahala ash	Fine Pahala ash (?)
84	Duhrsen Spring 0.1 mile W. of Hakalau School	250	20,000	Hamakua pahoehoe	Ash bed
85	Kolekole Gulch, NW. side	150	10,000	do.	Dense lava (?)
86	Hakalau Iki Spring in branch of Kaahakini Stream	1,300	46,000	Laupahoehoe aa	Ash bed
87	Do.	1,250	500	do.	do.
88	Akaka Spring in Kalakaoo Stream, at head of Akaka Falls, S. side	1,250	140,000	Hamakua pahoehoe	Rotted aa clinker
89	Branch of Paheehee Stream	1,000	100,000	Hamakua aa clinker	Dense aa
90	Honomu Gulch, NW. side	300	1,000	Hamakua pahoehoe	Dense lava (?)
91	Branch of Honomu Stream	1,500	100,000	Laupahoehoe aa	Ash bed
92	Honomu Stream	1,200	5,000	do.	Rotted clinker
93	Luiz Spring in branch of Alia Stream	950	200,000	Hamakua aa	Ash bed
94	Branch of Alia Stream	950	400,000	do.	do.
95	Branch of Kawainui Stream	2,050	2,000	Hamakua pahoehoe	Dense lava (?)
96	Do.	1,330	15,000	Laupahoehoe aa	Ash bed
97	Kalaoa Stream	1,250	300,000	do.	do.
98	Kaieie Stream	1,250	300,000	do.	do. (?)
99	Branch of Kaieie Stream	550	17,000	Pahala ash (?)	Fine ash bed (?)
100	Branch of Pahoehoe Stream	750	50,000	do. (?)	do. (?)
101	Branch of Kapue Stream	1,225	45,000	Laupahoehoe aa	Ash bed
102	Kapue Gulch, N. side	1,050	10,000	Hamakua lavas	do. (?)
103	Small stream N. of Kapue Stream	425	25,000	Pahala ash	Fine ash bed (?)
104	Honolii Gulch, N. side	600	10,000	Hamakua aa	Ash bed
105	Branch of Maili Stream	700	20,000	Hamakua pahoehoe	Dense lava (?)
106	Do.	2,350	500	Pahala ash	Fine ash bed (?)
107	Waiokaumalo Stream at Spring Water Camp	5,100	15,000	Laupahoehoe aa clinker	Dense aa
108	Nauhi Spring in Nauhi Stream, N. branch	5,150	15,000	Pahala ash	Fine ash bed (?)
109	Nauhi Stream, S. branch	5,250	200,000	Pahala ash and Waiau aa clinker	do.
110	Kanakaleonui Spring in Nauhi Stream	8,000	[e]5,000	Laupahoehoe ash	Ashy soil bed
111	Waikahalulu Gulch	11,000	2,000	Laupahoehoe aa	Poorly sorted gravel (?)
112	Waihu Spring in Pohakuloa Gulch, W. branch; several small springs and seeps	10,390	39,000	do.	Poorly sorted gravel
112A	Do.	10,140	[h]1,500	do.	do.
112B	Do.	10,090	[h]1,500	do.	do.
112C	Do.	9,990	[h]2,000	do.	do.
112D	Do.	9,825	[h]2,500	do.	do.
112E	Do.	9,575	[h]2,500	do.	do.
112F	Do., in E. branch	10,500	[h]1,500	do.	do.
113	Small gulch W. of Pohakuloa Gulch	8,935	[h]1,500	do.	do.
114	Kapehu Spring in tributary of Kapehu Stream	2,150	2,000,000	Hamakua aa	Rotted aa clinker (?)
115	Kalamana Stream (tributary of Wailuku River)	2,160	500,000	do.	do. (?)
116	Tributary of Wailuku River	1,800	100,000	Hamakua aa clinker	Dense underlying lava
117	Do., 0.2 mile S. of Spring 116	1,800	100,000	do.	do.
118	N. fork, Kahena Stream	1,990	[e]300,000	do.	do. (?)
119	S. fork, Kahena Stream	1,990	[e]300,000	do.	do. (?)
120	Kahena Stream	1,880	[e]400,000	do.	do. (?)
121	Kalohewahewa Stream, N. bank	2,100	1,000,000	Hamakua aa	Rotted aa clinker
122	Kahoama Gulch	1,200	400,000	Hamakua pahoehoe	do.

Perched Springs on Hawaii (Continued)

No. (pl.1)	Valley or name	Approximate altitude (feet)	Daily discharge (gallons)	Water-bearing formation	Perching structure
Perched springs in the South Hilo area					
123	Wailuku River	2,400	[i]500,000	Kau lava	Pahala ash (?)
124	Do.	2,000	250,000	do.	do.
125	Do., at Poakana Falls	1,975	500,000	do.	do.
126	Tributary of Wailuku River	1,700	[j]1,000,000	Kau pahoehoe	Ash bed
127	Do.	1,750	[j]2,500,000	do.	do.
128	Do.	1,570	[j]1,500,000	do.	do.
129	Kipuka just S. of Hilo-Humuula road	2,725	15,000	do.	Pahala ash (?)
130	Kipuka just N. of Hilo-Humuula road	2,370	[f]500,000	do.	do.
131	Kahoama Stream[k]	1,700	[j]1,000,000	do.	do.
131A	Do., 50 feet N. of Spring 132	1,700	2,500,000	do.	do.
132	Wailuku River at Rainbow Falls	375	100,000	Kau aa[l]	Partly rotted Waiau lavas
133	Kaumana Spring in tributary of Wailuku River	400	[m]1,500,000	Kau pahoehoe	Pahala ash
134	Tributary of Waipahoehoe Stream	725	100,000	do.	do. (?)
135	S. edge of 1881 lava flow	1,775	10,000	1881 lava of Mauna Loa	do.
136	Do.	1,825	50,000	do.	do.
137	Upper Waiakea Homesteads[n]	1,500	20,000	Kau pahoehoe	do.
138	Do.	1,600	[h]25,000	do.	do.
139	Do.	1,620	[h]40,000	Tube in do.	do.
140	Do.	1,675	[h]15,000	Kau pahoehoe	do.
Perched springs in the Kau area					
141	Plantation Spring in Hilea area	3,650	(o)	Ninole lava	Ninole tuff
142	Mountain House Spring	3,400	(p)	Pahala lava	Ash bed
143	Makanau Ridge	1,750	(q)	Ninole lava	Ninole tuff
144	W. of Hilea	1,550	....	do. (?)	do. (?)
145	Portuguese Spring N. of Waiohīnu	2,650	[r]250,000	Kau lava	Pahala ash (?)
146	Haao (Waiohinu) Springs, N. of Waiohinu	2,300	600,000	do.	Pahala ash

---

[a] Estimated during one visit in dry weather in January 1944.

[b] The flow of these springs ranged between 250,000 and 1,000,000 g.p.d. but has been largely diverted by tunnel 10.

[c] Flow over weir January 19, 1944.

[d] The flow of most springs in the Hamakua and North Hilo areas was estimated on the basis of a single visit in 1943, made mostly during weather wetter than usual; hence, the recorded flow may be greater than the average for many of these springs.

[e] Goes dry during dry weather.

[f] Several springs close together.

[g] Probably derived from Hamakua aa.

[h] Low water flow; discharge increases greatly in wet weather.

[i] The flow of springs in the South Hilo area was estimated largely on the basis of a single visit during 1941.

[j] Decreases greatly or dries up completely during droughts.

[k] Supplies Hilo Sugar Company flume.

[l] Water issues from the base of the lava flow which filled the ancient valley of the Wailuku River.

[m] Decreased to an average of 24,733 in November 1939.

[n] Supplies Waiakea Mill Company flume.

[o] Included with discharge of tunnel 93.

[p] Included with discharge of tunnel 95.

[q] Included with discharge of tunnel 99.

[r] Estimated in flume below spring.

Average discharge of Kaumana Spring (no 133), Hilo, in million gallons daily[a]

(Data furnished by County of Hawaii, Bureau of Water Works and Sewers)

Month	1930	1931	1932	1933	1934	1935	1936	1937	1938	1939	1940	1941	1942	1943	Average
Jan.	....	1.629	2.014	2.661	1.010	1.822	1.534	1.508	1.634	1.745	.217	.917	1.003	2.706	1.569
Feb.	....	.673	1.961	2.658	1.346	1.671	1.122	1.516	1.638	1.748	.333	.082	.562	3.250	1.428
Mar.	....	1.560	1.777	2.535	1.358	1.920	1.701	1.597	1.646	1.764	.431	.241	1.371	3.049	1.611
Apr.	....	.735	....	2.501	1.512	1.976	2.442	1.599	1.391	1.807	.037	.681	.908	3.017	1.558
May	....	1.088	1.252	2.853	2.204	2.004	1.983	1.695	1.369	1.896	.058	.296	.643	3.162	1.577
June	[b]2.772	.190	2.159	2.239	2.180	1.213	2.084	1.753	1.668	1.493	.109	.119	.524	3.314	1.558
July	2.656	.797	2.414	2.040	1.749	1.117	2.139	1.704	1.721	.954	.482	.451	.464	3.411	1.578
Aug.	3.208	1.965	1.977	1.085	1.535	1.304	2.056	1.719	1.747	1.279	1.697	.470	1.076	3.304	1.744
Sept. ...	3.132	2.245	1.145	.865	1.488	1.223	2.154	1.729	1.725	1.308	.643	.466	1.447	2.621	1.585
Oct.	2.922	2.585	1.136	.904	1.549	1.712	1.596	1.716	1.676	.431	0.55	.463	2.348	2.790	1.563
Nov.	2.534	2.529	.503	.160	1.595	1.795	1.758	1.723	1.676	.025	.345	1.340	2.110	2,346	1.460
Dec.	2.215	2.088	2.061	.058	1.868	2.009	1.783	1.669	[b]1.448	.025	.933	1.607	1.392	2.709	1.562
Average	2.778	1.507	1.673	1.713	1.616	1.647	1.863	1.661	1.611	1.206	.445	.594	1.154	2.973	1.567

[a] Measured by Venturi meter at Kaumana Springs chlorinator.

[b] Record incomplete.

Discharge of Haao (Waiohinu) Springs (no. 146)[a]
December 1917 to June 1918

Month	Daily discharge (million gallons per day)			Total monthly discharge (million gallons)
	Maximum	Minimum	Average	
December	0.62	0.17	0.326	10.1
January	1.22	0.17	0.473	14.6
February	1.82	.51	.922	25.8
March	1.17	.54	.787	24.4
April	.86	.47	.643	19.3
May	....	....	.603	18.7
June	.70	.47	.586	17.6

---

[a] Data from U. S. Geol. Survey Water-Supply Paper 485, p. 161, 1919.

Tunnels driven for high-level ground water in Hawaii

Water-development tunnels in the Kohala area

(Owned or leased by Kohala Sugar Co.)

No. (pl. 1)	Date dug	Valley or name	Approximate altitude (feet)	Approximate length (feet)	Yield			Geologic structure and perching formation
					Maximum (g.d.)	Minimum (g.d.)	Average (g.d.)	
1	1934	Kaala	1,025	30	....	Seep	....	Soil bed in Pololu series.
2	Old	Union	900	180	50,000	2,000	....	Apparently seepage from gulch.
3	Old	Cowpea (west 1)[a]	1,700	700+	360,000	[b]1,500	....	Soil between Hawi and Pololu series.
4	Old	Cowpea (west 2)[a]	1,740	360	640,000	....	....	No perching structure. In Hawi series.
5	Old	Cowpea (east and west 3)[a]	1,740	250	....	....	....	Do.
6	Old	Watt No. 1	1,750	1,230	2,500,000	175,000	1,250,000	Soil between Hawi and Pololu series; gravel at contact in one place.
7	1935	Hapahapai[c]	1,350	1,076	1,500,000	45,000	500,000	Decomposed layer in Pololu series.
8	1939	Pahei	1,000	395	[b]20,000	[b]500	[b]15,000	Soil between Hawi and Pololu series.
9	Old	Dr. Bond	968	712	[b]50,000	[b]10,000	....	Decomposed clinker in the Pololu series.
10	1937–39	Bond No. 1 (Relief)[d]	978	1,038	4,175,000	200,000	1,265,000	Conglomerate between Hawi and Pololu series.
11	Old	Iole, Bond Estate	650	30	....	(e)	....	Soil at contact of Hawi and Pololu series.
12	1934	Bond No. 2 (K. D. Bond)	1,450	700	53,000	5,000	30,000	Starts at contact of Hawi and Pololu series, but 30 feet from portal enters Pololu lavas.
13	Old	Olding	1,600	930	1,500,000	10,000	35,000	Spring overflow to irrigation. Soil between Hawi and Pololu series.
14	1935	J. D. Bond	1,500	260	[b]25,000	0	....	Decomposed zone in Pololu series.
15	1937	Koelling	1,600	255	35,000	5,000	20,000	Soil between Hawi and Pololu series.
16	1936	Watt No. 2[f]	1,700	1,658	500,000	8,000	250,000	Do.
17	Old	Kay	1,700	400	....	[b]6,000	....	Do.
18	Old	McGill 1	2,000	100	....	[g]18,000	....	(Blocked) Probably soil between Hawi and Pololu series.
19	1932	McGill 3	2,040	400	....	[g]45,000	....	Water issues from Hawi series, but is probably perched by soil on Pololu series.
20	1932	McGill 2[c]	2,060	170	....	[g]45,000	....	Soil between Hawi and Pololu series.
21	1933	Lindsay	2,150	300	166,000	93,000	130,000	Thin soil between two andesite flows of Hawi series.
22	1934	Waipunalau	1,600	155	1,500,000	150,000	250,000	Clinker bed on dense lava of Hawi series.
23	1938	Halawa[h]	1,000	380	....	40,000	100,000	Soil between Hawi and Pololu series.

24	1939	Paa	1,200	25	....	[b]25,000	....	Water issues from Hawi series; probably perched on Pololu series.
25	1937	Puu Mimi	1,200	246	400,000	10,000	75,000	Soil between Hawi and Pololu series.
26	1939	Maulua	750	[i]150	100,000	33,000	70,000	Do.
27	1939	Amau	1,000	30	....	[b]3,000	10,000	Do.
28	Old	Waikani	1,500	.....	....	[b]20,000	....	Hawi series (caved in).
29	Old	Murphy	1,250	300	....	70,000	250,000	Hawi series, but soil on Pololu series probably not far below.
30	1934	Opaepilau No. 1	1,100	100	....	[b]3,000	[b]30,000	Hawi series (covered).
31	1934	Opaepilau No. 2	1,182	132	....	[b]5,000	[b]40,000	Hawi series.
32	1937	Pae	720	25	....	1,000	10,000	Soil between Hawi and Pololu series.
33	1932	E. Honokane Nui[j] Upper	1,535	289	250,000	145,000	200,000	Vitric-lithic tuff bed in Pololu series.
34		Middle	1,229	546	750,000	435,000	600,000	
35		Lower	950	254	500,000	325,000	400,000	
36	1941	E. Honokane Nui	1,900	[k]1,200	....	....	[k]4,250,000	Dike swarm in Pololu series.

---

[a] The Cowpen tunnels, driven about 1900, provided the main water supply of the former Hawi Mill. They yield a maximum of 1,000,000 gallons daily in wet weather but go dry in droughts. It is suspected that Watt No. 1 intercepted their flow as it was driven a little above them.

[b] Estimated.

[c] Driven by F. Koelling with the geologic advice of W. O. Clark.

[d] Decreased the flow or dried up all the Iole Springs except one.

[e] Dry when visited January 28, 1944, but yields water in wet weather.

[f] Consists of three development tunnels, A, B, and C, connected with a transportation tunnel. Tunnels B and C are in the Pololu series. Tunnel C is dry, but has a lower adit that develops 1 gallon per minute.

[g] Estimated for individual tunnels. Measured minimum for all three tunnels is 108,000 gallons daily.

[h] The old Halawa tunnel, 30 feet long, driven in 1918 or earlier, is connected to the new tunnel, 350 feet long, driven under the direction of W. O. Clark.

[i] Driven by William Sproat. Length reported by him.

[j] Springs formerly issued from these tuff beds.

[k] Length in February 1945. About half of the flow is water that formerly contributed to the flow of the East Branch of Honokane Nui Canyon; a part of the flow is also being drawn from storage in the ground.

Tunnels driven for high-level ground water in Hawaii—*continued*

No. (pl.1)	Owner	Name or location	Approximate altitude (feet)	Approximate length (feet)	Yield[a] (g.d.)	Geologic structure and perching formation
Water-development tunnels in the Hamakua and Hilo areas						
37	....	SE. branch of Lalakea Gulch	2,200	580	0	Hamakua lava.
38	Hamakua Mill Co	Manienie Gulch, W. side	700	[b]100+	1,500	Hamakua aa clinker on dense center of lava flow.
39	Do.	Paauilo Stream	1,060	50	[c]50	do.
40	Do.	Paauilo Stream, E. bank	700	25	100	do.
41	Do.	Kanui Gulch, E. bank (first gulch SE. of Paauilo Gulch)	1,350	[b]100+	200	Hamakua pahoehoe perched by ash bed.
42	Do.	Paauilo Gulch, E. bank	1,540	225	0	Hamakua aa clinker.
42A	Do.	Paauilo Gulch	1,580	100	100	Hamakua aa clinker perched by ash bed.
43	Do.	E. branch of Kawaiili Stream	1,500	[b]100+	[c]50	Laupahoehoe aa on ash bed(?).
44	Do.	E. branch of Kainehe Stream	1,200	190	[c]50	Hamakua aa clinker on dense center of lava flow.
45	Do.	Puumaile Stream, NW. bank	1,075	35	100	do.
45A	Do.	do., SE. bank	1,075	30	50	do.
46	Do.	do., NW. bank	850	40	50	do.
47	Do.	do., SE. bank	800	30	300	Hamakua aa on ash bed.
48	Kaiwiki Sugar Co.	Kaula Gulch	1,200	15	[d]0	Hamakua aa clinker on dense lava.
48A	Do.	do., NW. bank, 25 feet N. of 48	1,200	30	[d]0	do. (?)
48B	Do.	do., 50 feet N. of 48A	1,200	80	[d]0	do.
49	Do.	do., NW. bank on road cut	640	450	[d]0	Hamakua aa on ash bed.
50	Do.	Small gulch, 0.45 mile SE. of Kaula Gulch	1,600	[b]400	0	Hamakua aa at heading; pahoehoe at portal.
51	Do.	Branch of Kaawalii Gulch	2,000	150	0	Hamakua aa.
51A	Do.	do., 60 feet SE. of 50	2,010	20	0	do.
52	Do.	Kaawalii Gulch, NW. bank	2,000	90	0	do.
53	Laupahoehoe Sugar Co.	Branch of Kapili Stream	2,075	[b]100	[c]100	Hamakua aa on ash bed.
54	Onomea Sugar Co.	Branch of Kawainui Stream	600	75	60,000	Hamakua pahoehoe on ash bed(?).
55	Do.	Branch of Kapue Stream	1,275	100	50,000	Laupahoehoe aa on Pahala ash.
56	Do.	Pahoehoe Stream, S. bank	900	10	7,000	Hamakua aa on rotted aa clinker.
57	Do.	Small stream 0.15 mile N. of Honolii Stream	575	25	20,000	Hamakua pahoehoe on ash bed(?).
58	Hawaiian Evangelical Assoc.	2.9 miles N. 75° W. of Kaumana, at head of Olaa flume	2,000	2,000	[e]5,000,000	Kau pahoehoe; Pahala ash not exposed but probably present at small depth.
59	Waiakea Mill Co.	2.65 miles S. 10° W. of Kaumana	1,550	300	[f]100,000	Kau lavas on Pahala ash.

60	Do.	3 miles S. 12° W. of Kaumana	1,560	170	[f]50,000	do.
61	Olaa Sugar Co.	4.35 miles S. 33° W. of Kaumana	2,100	1,027	[e]200,000	Kau lavas; Pahala ash not exposed but probably present at small depth.
62	Do.	4.3 miles S. 32° W. of Kaumana	2,050	4,860	[e]3,000,000	Kau lavas on Pahala ash.
63	Do.	4.5 miles S. 35° W. of Kaumana	2,150	51	[c]100	Kau lavas on dense lava.
64	Do.	do.	2,150	82	[c]100	do.

Water-development tunnels in the Kau area[a]

65	Hawaiian Agricultural Co.	Makakupu (13)[g]	3,700	5,798	505,000	Kahuku lava on 6± feet of Pahala ash.
66	Do.	....	3,600	.....	....	Kahuku lava on ash bed.
67	Do.	Mauka of ranch (18)	4,300	98	[h]0	do.
68	Do.	Weda 2 (9)	3,750	198	....	do.
69	Do.	Weda 1 (8)	3,700	344	....	do.
70	Do.	Weda (7)	3,600	1,627	149,000	do.
71	Do.	Weda 3 (10)	3,400	599	90,000	do.
72	Do.	Heio (5)	3,600	1,799	214,000	do.
73	Do.	Fault (6)	3,500	138	[h]0	do.
74	Do.	Noguchi mauka (4)	3,600	1,128	86,000	Ninole lava on ash bed.
75	Do.	Noguchi 2 (19)	3,450	2,480	236,000	do.
76	Do.	Noguchi 1	3,400	.....	689,000	do.
77	Do.	....	4,150	.....	....	Kahuku lava on ash bed.
78	Do.	....	3,900	.....	....	do.
79	Do.	Double Arch (11)	3,700	1,479	595,000	do.
80	Do.	Mudflow (Clark) (2)	3,500	2,611	444,000	do.
81	Do.	Mudflow 3 (3)	3.500	333	....	do.
82	Do.	....	3,400	.....	....	do.
83	Do.	....	3,250	.....	....	do.
84	Do.	Ipuu Ridge (14)	2,600	435	....	Ninole lava on ash bed.
85	Do.	Alili (15)	2,900	3,839	713,000	Kau lava on Pahala ash.
86	Do.	Shirakura (20)	3,700	1,750	297,000	Kahuku lava on ash bed.
87	Do.	Moaula Gulch (17)	3,500	1,716	247,000	do.
88	Do.	....	3,100	.....	....	Kau lava on 20± feet of Pahala ash.
89	Do.	Fukuda (12)	3,000	1,844	203,000	Kau lava on 18± feet of Pahala ash.
90	Do.	Kaumaikeohu (1)	2,900	2,093	210,000	Ninole lava on ash bed.
91	Do.	Domestic supply (16)	2,750	2,574	345,000	do.
92	Do.	Horita	4,150	1,500	[i]29,000	Kahuku lava on ash bed.
93	Hutchinson Sugar Plantation Co.	Plantation Spring	3,650	3,097	199,000	Ninole lava on ash bed.
94	Do.	Vischer	2,150	.....	0	None.[j]
95	Do.	New Mountain House	3,400	7,048	1,175,000	Kahuku lava and talus on ash.
96	Do.	Old Mountain House	3,070	.....	....	Kahuku lava on ash bed.

Tunnels driven for high-level ground water in Hawaii—*continued*

97	Do.	Kahilipali	2,250	359	[k]279,000	do.
98	Do.	Kapuna	1,900	.....	....	do.
99	Do.	Makanau 1	1,750	.....	....	Ninole lava on ash bed.
100	Do.	Makanau 2	1,500	.....	....	do.
101	Do.	Haao	2,300	.....	[l]25,000	Early Kau porphyritic olivine basalt overlying 6 feet of red vitric ash.
102	Do.	Tanaka	2,100	715	[k,m]1,000	Kahuku lava on ash bed.

[a] In the Hamakua and Hilo areas, yield is largely estimated on the basis of a single visit, some during weather wetter than usual; hence, the recorded flow may be greater for some tunnels than the average. In the Kau area, the figures represent average yield as recorded in the tables of monthly discharge on a later page.

[b] Tunnel now partly or completely blocked and inaccessible.

[c] Goes dry in dry weather.

[d] Flows only during very wet weather.

[e] Yield decreases greatly in dry weather, in some dropping to as little as one-tenth that shown in the table.

[f] Low-water flow; discharge increases greatly in wet weather.

[g] Numbers in parentheses are owner's number.

[h] Abandoned.

[i] Low water yield in 1931.

[j] Driven in Kau basalt by a Mr. Vischer, the site determined with a "doodle bug."

[k] Average combined discharge of tunnels 97 and 102, during 1924, was 279,700 gallons daily.

[l] Estimated flow on December 2, 1939. Tunnel dug prior to 1920. The basalt is either early Kau or late Kahuku lava.

[m] Reported to go dry a month after rains cease. Six to eight feet of transported soil overlying the aquifer; hence, the basalt is either late Kahuku or early Kau lava.

Average flow of Waiakea Stream near Middle Flume House, in million gallons a day; low flow is entirely from tunnels 61 and 62; high flow includes surface runoff.

(Data from U. S. Geological Survey)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1930	....	....	....	....	....	....	....	....	5.49	4.06	4.21	1.81	3.89
1931	0.842	1.49	1.41	0.425	0.431	0.20	3.02	5.78	7.42	7.43	8.24	3.14	3.32
1932	10.1	8.67	4.69	7.67	7.00	4.61	4.32	3.13	2.32	0.496	1.45	5.20	4.97
1933	9.03	5.70	6.20	4.20	7.17	3.88	1.95	1.53	1.74	1.27	0.602	0.112	3.62
1934	4.46	6.10	2.18	3.51	10.1	4.91	6.36	5.58	6.92	6.95	10.9	10.3	6.52
1935	14.2	6.91	10.1	14.7	4.22	3.77	6.39	5.76	6.94	3.93	4.78	7.87	7.46
1936	0.997	0.269	6.03	9.45	9.81	4.91	8.58	17.1	9.52	10.6	5.98	15.1	8.20
1937	24.9	21.5	15.7	7.88	13.3	5.31	10.3	17.5	3.80	6.38	11.1	6.37	12.0
1938	12.7	11.2	13.5	15.9	11.2	9.20	6.81	5.66	4.67	5.31	10.0	13.6	9.98
1939	16.8	15.1	18.3	12.0	6.10	5.82	11.0	5.22	5.82	5.83	8.70	4.25	9.55
1940	0.379	0.274	0.330	1.19	2.32	1.57	6.22	13.8	10.7	7.36	9.98	2.19	4.70
1941	1.14	0.082	2.25	4.79	8.59	6.97	9.19	8.69	18.5	20.4	8.05	11.7	8.42
1942	2.46	1.17	31.7	20.6	16.1	6.34	5.14	2.99	8.62	8.39	4.39	0.918	9.11
1943	8.39	7.02	6.48	9.84	7.91	11.2	....	....	....	....	....	....	....

Average discharge of tunnel 58, measured in Olaa flume at Kaumana, in million gallons daily

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1917	....	....	....	.....	....	....	....	....	....	....	....	3.57
1918	7.15	14.0	11.7	12.5	12.0	11.0	11.5	10.8	10.5	6.72	7.88	10.5
1919	8.4	5.86	9.44	5.27	6.64	4.15	3.99	10.9	8.76	[a]6.32	....	....
1920	....	....	5.36	[a]11.3	....	....	.....	....	....	....	....	....

[a] Record incomplete.

MONTHLY DISCHARGE, IN GALLONS, OF TUNNELS IN THE KAU DISTRICT, HAWAII

Discharge of Tunnel 65 (Makakupu Tunnel)

(Data from C. Brewer and Co., Ltd., and Hawaiian Agricultural Co., Ltd.)

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1925[a]				
January	125,000	73,000	97,000	3,000,000
February	....	60,000	75,000	2,100,000
March	151,000	63,000	97,000	3,000,000
April	138,000	111,000	113,000	3,400,000
May	700,000	122,000	352,000	10,900,000
June	743,000	278,000	433,000	13,000,000
July	289,000	216,000	235,000	7,300,000
August	269,000	223,000	229,000	7,100,000
September	465,000	193,000	310,000	9,300,000
October	808,000	629,000	713,000	22,100,000
November	808,000	409,000	653,000	19,600,000
December	390,000	164,000	255,000	7,900,000
The year	808,000	60,000	299,000	108,700,000
1926[a]				
January	112,000	79,000	100,000	3,100,000
February	68,000	49,000	54,000	1,500,000
March	89,000	58,000	71,000	2,200,000
April	225,000	69,000	143,000	4,300,000
May	354,000	223,000	303,000	9,400,000
June	759,000	238,000	460,000	13,800,000
July	1,004,000	505,000	661,000	20,500,000
August	1,757,000	526,000	913,000	28,300,000
September	1,184,000	831,000	1,003,000	30,100,000
October	936,000	490,000	648,000	20,100,000
November	792,000	451,000	687,000	20,600,000
December	1,099,000	340,000	655,000	20,300,000
The year	1,757,000	49,000	477,000	174,200,000
1927[a]				
January	769,000	272,000	548,000	17,000,000
February	288,000	240,000	257,000	7,200,000
March	395,000	240,000	332,000	10,300,000
April	....	451,000	857,000	25,700,000
May	1,557,000	451,000	848,000	26,300,000
June	769,000	469,000	640,000	19,200,000
July	413,000	180,000	268,000	8,300,000
August	166,000	79,000	116,000	3,600,000
September	1,166,000	140,000	810,000	24,300,000
October	1,194,000	864,000	1,071,000	33,300,000
November	887,000	592,000	820,000	24,600,000
December	1,446,000	550,000	1,168,000	36,200,000
The year	1,557,000	79,000	647,000	236,000,000
1928[a]				
January	1,921,000	323,000	1,023,000	31,700,000
February	323,000	127,000	207,000	6,000,000
March	166,000	108,000	135,000	4,200,000
April	864,000	102,000	403,000	12,100,000
May	792,000	413,000	655,000	20,300,000
June	376,000	305,000	320,000	9,600,000
July	1,377,000	323,000	655,000	20,600,000
August	592,000	206,000	281,000	8,700,000
September	706,000	458,000	623,000	18,700,000
October	642,000	369,000	484,000	15,000,000
November	432,000	229,000	350,000	10,500,000
December	187,000	120,000	152,000	4,700,000
The year	1,921,000	102,000	443,000	162,100,000

Discharge of Tunnel 65 (Makakupu Tunnel)—continued

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1929[a]				
January	151,000	112,000	139,000	4,300,000
February	520,000	151,000	306,000	8,600,000
March	714,000	575,000	642,000	19,900,000
April	831,000	700,000	713,000	21,400,000
May	449,000	302,000	387,000	12,000,000
June	356,000	281,000	320,000	9,600,000
July	370,000	196,000	268,000	8,300,000
August	662,000	347,000	503,000	15,600,000
September	653,000	513,000	597,000	17,900,000
October	733,000	481,000	568,000	17,600,000
November	1,130,000	857,000	1,013,000	30,400,000
December	1,760,000	842,000	1,094,000	33,900,000
The year	1,760,000	112,000	546,000	199,500,000
1930				
July	363,000	209,000	292,000	9,100,000
August	1,512,000	372,000	995,000	30,800,000
September	1,670,000	389,000	1,159,000	34,800,000
October	1,498,000	729,000	1,104,000	34,300,000
November	778,000	554,000	644,000	19,300,000
December	495,000	246,000	343,000	10,600,000
The period	1,670,000	209,000	756,000	138,900,000
1931				
January	233,000	107,000	145,000	4,500,000
February	105,000	58,000	79,000	2,200,000
March	58,000	43,000	50,000	1,500,000
April	85,000	43,000	53,000	1,600,000
May	439,000	87,000	168,000	5,200,000
June	526,000	302,000	426,000	12,800,000
July	821,000	238,000	370,000	11,500,000
August	864,000	576,000	757,000	23,500,000
September	740,000	432,000	550,000	16,500,000
October	950,000	723,000	828,000	25,600,000
November	723,000	302,000	528,000	15,800,000
December	294,000	138,000	207,000	6,400,000
The year	950,000	43,000	347,000	127,100,000
1932				
January	629,000	130,000	285,000	8,800,000
February	936,000	634,000	793,000	23,000,000
March	778,000	389,000	622,000	19,200,000
April	374,000	216,000	276,000	8,300,000
May	474,000	245,000	320,000	9,900,000
June	734,000	487,000	631,000	18,900,000
July	713,000	327,000	518,000	16,000,000
August	317,000	181,000	245,000	7,600,000
September	518,000	166,000	323,000	9,700,000
October	422,000	245,000	347,000	10,700,000
November	590,000	216,000	372,000	11,100,000
December	641,000	392,000	533,000	16,500,000
The year	936,000	130,000	439,000	159,700,000

Discharge of Tunnel 65 (Makakupu Tunnel)—continued

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1933				
January	691,000	360,000	520,000	16,100,000
February	605,000	504,000	553,000	15,500,000
March	994,000	608,000	814,000	25,200,000
April	979,000	576,000	827,000	24,800,000
May	950,000	562,000	814,000	25,200,000
June	1,022,000	537,000	791,000	23,700,000
July	530,000	223,000	372,000	11,500,000
August	217,000	124,000	158,000	4,900,000
September	122,000	72,000	86,000	2,600,000
October	135,000	72,000	94,000	2,900,000
November	230,000	141,000	199,000	6,000,000
December	202,000	154,000	180,000	5,600,000
The year	1,022,000	72,000	451,000	164,000,000
1934				
January	168,000	130,000	148,000	4,600,000
February	194,000	144,000	176,000	4,900,000
March	213,000	153,000	186,000	5,800,000
April	821,000	214,000	455,000	13,600,000
May	1,207,000	706,000	844,000	26,100,000
June	1,469,000	789,000	1,140,000	34,200,000
July	762,000	599,000	657,000	20,300,000
August	835,000	518,000	668,000	20,600,000
September	878,000	576,000	714,000	21,400,000
October	804,000	490,000	622,000	19,200,000
November	749,000	562,000	628,000	18,800,000
December	562,000	353,000	452,000	14,000,000
The year	1,469,000	130,000	558,000	203,500,000
1935				
January	347,000	295,000	328,000	10,100,000
February	325,000	281,000	302,000	8,500,000
March	852,000	472,000	783,000	24,200,000
April	878,000	734,000	802,000	24,000,000
May	734,000	598,000	680,000	21,000,000
June	850,000	490,000	644,000	19,300,000
July	472,000	302,000	425,000	13,100,000
August	670,000	395,000	481,000	14,900,000
September	1,008,000	662,000	791,000	23,700,000
October	821,000	609,000	765,000	23,600,000
November	599,000	487,000	546,000	16,300,000
The period	1,008,000	281,000	595,000	198,700,000

---

[a] Tunnel under construction.

Discharge of Tunnel 70 (Weda Tunnel)

(Data from C. Brewer and Co., Ltd., and Hawaiian Agricultural Co., Ltd.)

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1925				
January	43,000	....	29,000	900,000
February	....	22,000	25,000	700,000
March	101,000	24,000	61,000	1,900,000
April	58,000	40,000	53,000	1,600,000
May	253,000	101,000	148,000	4,600,000
June	....	35,000	100,000	3,000,000
July	68,000	....	65,000	2,000,000
August	89,000	68,000	81,000	2,500,000
September	253,000	68,000	130,000	3,900,000
October	372,000	320,000	345,000	10,700,000
November	320,000	79,000	180,000	5,400,000
December	68,000	32,000	45,000	1,400,000
The year	372,000	22,000	106,000	38,600,000
1927				
January	180,000	49,000	106,000	3,300,000
February	69,000	49,000	68,000	1,900,000
March	127,000	69,000	116,000	3,600,000
April	510,000	323,000	373,000	11,200,000
May	180,000	79,000	129,000	4,000,000
June	288,000	91,000	143,000	4,300,000
July	69,000	43,000	58,000	1,800,000
August	69,000	32,000	45,000	1,400,000
September	530,000	59,000	253,000	7,600,000
October	395,000	114,000	229,000	7,100,000
November	225,000	69,000	133,000	4,000,000
December	657,000	59,000	361,000	11,200,000
The year	657,000	32,000	168,000	61,400,000
1928				
January	288,000	24,000	123,000	3,800,000
February	49,000	17,000	31,000	900,000
March	59,000	36,000	42,000	1,300,000
April	413,000	40,000	193,000	5,800,000
May	240,000	180,000	216,000	6,700,000
June	166,000	86,000	127,000	3,800,000
July	592,000	79,000	210,000	6,500,000
August	209,000	91,000	116,000	3,600,000
September	288,000	91,000	200,000	6,000,000
October	357,000	153,000	229,000	7,100,000
November	180,000	69,000	120,000	3,600,000
December	59,000	40,000	45,000	1,400,000
The year	592,000	17,000	138,000	50,400,000

Discharge of Tunnel 70 (Weda Tunnel)—continued

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1929				
January	102,000	29,000	45,000	1,400,000
February	340,000	114,000	175,000	4,900,000
March	432,000	194,000	294,000	9,100,000
April	635,000	91,000	337,000	10,100,000
May	240,000	79,000	145,000	4,500,000
June	166,000	69,000	113,000	3,400,000
July	102,000	43,000	87,000	2,700,000
August	340,000	140,000	223,000	6,900,000
September	272,000	140,000	193,000	5,800,000
October	323.000	91,000	187,000	5,800,000
November	1,089,000	140,000	500,000	15,000,000
December	340,000	180,000	268,000	8,300,000
The year	1,089,000	29,000	213,000	77,900,000
1930				
July	79,000	69,000	72,000	2,200,000
August	962,000	91,000	383,000	11,900,000
September	469,000	166,000	281,000	8,400,000
October	592,000	102,000	274,000	8,500,000
November	305,000	79,000	158,000	4,700,000
December	79,000	40,000	53,000	1,600,000
The period	962,000	40,000	204,000	37,300,000
1931				
January	32,000	24,000	30,000	900,000
February	17,000	17,000	17,000	500,000
March	17,000	11,000	14,000	400,000
April	59,000	32,000	39,000	1,200,000
May	59,000	127,000	101,000	3,100,000
June	376,000	49,000	143,000	4,300,000
July	209,000	59,000	105,000	3,300,000
August	288,000	127,000	158,000	4,900,000
September	127,000	49,000	91,000	2,700,000
October	490,000	114,000	253,000	7,800,000
November	153,000	69,000	101,000	3,000,000
December	49,000	24,000	40,000	1,200,000
The year	490,000	11,000	91,000	33,300,000
1932				
January	180,000	32,000	94,000	2,900,000
February	288,000	166,000	210,000	6,100,000
March	240,000	69,000	134,000	4,200,000
April	114,000	49,000	65,000	1,900,000
May	194,000	79,000	138,000	4,300,000
June	166,000	127,000	150,000	4,500,000
July	91,000	59,000	79,000	2,500,000
August	69,000	49,000	59,000	1,800,000
September	166,000	79,000	135,000	4,100,000
October	140,000	69,000	108,000	3,400,000
November	240,000	69,000	147,000	4,400,000
December	240,000	91,000	148,000	4,600,000
The year	288,000	32,000	122,000	44,700,000

Discharge of Tunnel 70 (Weda Tunnel)—continued

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1933				
January	225,000	69,000	135,000	4,200,000
February	180,000	140,000	145,000	4,100,000
March	340,000	114,000	187,000	5,800,000
April	340,000	102,000	210,000	6,300,000
May	256,000	114,000	199,000	6,200,000
June	490,000	91,000	233,000	7,000,000
July	79,000	40,000	56,000	1,700,000
August	40,000	32,000	36,000	1,100,000
September	32,000	24,000	26,000	800,000
October	69,000	24,000	35,000	1,100,000
November	79,000	59,000	69,000	2,100,000
December	79,000	49,000	68,000	2,100,000
The year	490,000	24,000	117,000	42,500,000
1934				
January	65,000	49,000	59,000	1,800,000
February	69,000	59,000	65,000	1,800,000
March	122,000	69,000	91,000	2,800,000
April	256,000	127,000	167,000	5,000,000
May	305,000	140,000	265,000	8,200,000
June	469,000	153,000	292,000	8,800,000
July	357,000	140,000	232,000	7,200,000
August	323,000	140,000	215,000	6,700,000
September	256,000	180,000	212,000	6,400,000
October	153,000	79,000	121,000	3,700,000
November	194,000	102,000	138,000	4,100,000
December	127,000	79,000	95,000	2,900,000
The year	469,000	49,000	163,000	59,400,000
1935				
January	127,000	59,000	86,000	2,800,000
February	102,000	59,000	85,000	2,400,000
March	323,000	170,000	248,000	7,700,000
April	240,000	166,000	210,000	6,300,000
May	209,000	140,000	190,000	5,900,000
June	357,000	144,000	225,000	6,700,000
July	144,000	69,000	127,000	3,900,000
August	153,000	114,000	128,000	4,000,000
September	272,000	140,000	177,000	5,300,000
October	305,000	127,000	207,000	6,400,000
November	194,000	127,000	153,000	4,600,000
The period	357,000	59,000	167,000	56,000,000

Discharge of Tunnel 71 (Weda No. 3 Tunnel)

(Data from C. Brewer and Co., Ltd., and Hawaiian Agricultural Co., Ltd.)

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1925				
January	24,000	17,000	23,000	700,000
February	....	9,000	14,000	400,000
March	32,000	9,000	23,000	700,000
April	49,000	17,000	30,000	900,000
May	193,000	58,000	94,000	2,900,000
June	112,000	....	47,000	1,400,000
July	49,000	24,000	29,000	900,000
August	49,000	32,000	39,000	1,200,000
September	79,000	24,000	47,000	1,400,000
October	288,000	223,000	242,000	7,500,000
November	243,000	49,000	137,000	4,100,000
December	40,000	14,000	29,000	900,000
The year........	288,000	9,000	62,000	22,800,000
1927				
January	127,000	24,000	65,000	2,000,000
February	49,000	29,000	36,000	1,000,000
March	91,000	43,000	81,000	2,500,000
April	395,000	166,000	277,000	8,300,000
May	127,000	40,000	87,000	2,700,000
June	240,000	49,000	103,000	3,100,000
July	....	24,000	35,000	1,100,000
August	40,000	17,000	29,000	900,000
September	323,000	40,000	133,000	4,000,000
October	272,000	49,000	129,000	4,000,000
November	180,000	32,000	90,000	2,700,000
December	432,000	32,000	239,000	7,400,000
The year........	432,000	17,000	109,000	39,700,000
1928				
January	209,000	12,000	87,000	2,700,000
February	32,000	6,000	7,000	200,000
March	32,000	17,000	23,000	700,000
April	340,000	22,000	157,000	4,700,000
May	180,000	140,000	165,000	5,100,000
June	127,000	59,000	90,000	2,700,000
July	451,000	49,000	158,000	4,900,000
August	166,000	40,000	81,000	2,500,000
September	225,000	69,000	157,000	4,700,000
October	288,000	114,000	171,000	5,300,000
November	140,000	32,000	83,000	2,500,000
December	29,000	17,000	23,000	700,000
The year........	451,000	6,000	100,000	36,700,000
1929				
January	69,000	12,000	29,000	900,000
February	272,000	79,000	107,000	3,000,000
March	340,000	127,000	232,000	7,200,000
April	550,000	49,000	283,000	8,500,000
May	180,000	59,000	110,000	3,400,000
June	140,000	49,000	90,000	2,700,000
July	69,000	24,000	52,000	1,600,000
August	272,000	114,000	174,000	5,400,000
September	225,000	91,000	150,000	4,500,000
October	272,000	69,000	145,000	4,500,000
November	746,000	114,000	337,000	10,100,000
December	305,000	153,000	223,000	6,900,000
The year........	746,000	12,000	161,000	58,700,000

Discharge of Tunnel 71 (Weda No. 3 Tunnel)—continued

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1930				
July	17,000	12,000	13,000	400,000
August	357,000	14,000	168,000	5,200,000
September	272,000	59,000	145,000	4,400,000
October	210,000	32,000	117,000	3,600,000
November	127,000	17,000	63,000	1,900,000
December	24,000	6,000	13,000	400,000
The period	357,000	6,000	86,000	15,900,000
1931				
January	22,000	6,000	12,000	400,000
February	....	....	....	....
March	....	....	....	....
April	....	....	....	....
May	49,000	6,000	30,000	900,000
June	167,000	32,000	76,000	2,300,000
July	140,000	24,000	59,000	1,800,000
August	194,000	69,000	98,000	3,000,000
September	91,000	24,000	59,000	1,800,000
October	272,000	69,000	158,000	4,900,000
November	91,000	24,000	52,000	1,600,000
December	23,000	6,000	13,000	400,000
The period	272,000	6,000	62,000	17,100,000
1932				
January	140,000	6,000	53,000	1,600,000
February	180,000	91,000	132,000	3,800,000
March	140,000	40,000	75,000	2,300,000
April	33,000	17,000	24,000	700,000
May	140,000	49,000	85,000	2,600,000
June	130,000	62,000	89,000	2,700,000
July	62,000	18,000	30,000	900,000
August	40,000	17,000	23,000	700,000
September	91,000	32,000	69,000	2,100,000
October	72,000	32,000	52,000	1,600,000
November	102,000	24,000	63,000	1,900,000
December	140,000	35,000	78,000	2,400,000
The year	180,000	6,000	64,000	23,300,000
1933				
January	127,000	32,000	71,000	2,200,000
February	127,000	55,000	89,000	2,500,000
March	209,000	39,000	109,000	3,400,000
April	240,000	32,000	141,000	4,200,000
May	180,000	59,000	121,000	3,700,000
June	225,000	40,000	104,000	3,100,000
July	40,000	17,000	27,000	800,000
August	17,000	6,000	10,000	300,000
September	6,000	6,000	6,000	200,000
October	24,000	6,000	10,000	300,000
November	24,000	17,000	23,000	700,000
December	49,000	17,000	32,000	1,000,000
The year	240,000	6,000	62,000	22,400,000

Discharge of Tunnel 71 (Weda No. 3 Tunnel)—continued

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1934				
January	35,000	24,000	26,000	800,000
February	40,000	24,000	30,000	800,000
March	84,000	24,000	50,000	1,500,000
April	153,000	79,000	105,000	3,100,000
May	209,000	102,000	170,000	5,300,000
June	240,000	89,000	163,000	4,900,000
July	194,000	79,000	132,000	4,100,000
August	166,000	69,000	115,000	3,600,000
September	145,000	114,000	122,000	3,700,000
October	105,000	40,000	66,000	2,000,000
November	140,000	59,000	95,000	2,900,000
December	79,000	40,000	50,000	1,600,000
The year	240,000	24,000	94,000	34,300,000
1935				
January	69,000	24,000	48,000	1,500,000
February	49,000	32,000	42,000	1,200,000
March	153,000	109,000	135,000	4,200,000
April	153,000	114,000	131,000	3,900,000
May	127,000	79,000	111,000	3,400,000
June	194,000	86,000	121,000	3,600,000
July	86,000	32,000	68,000	2,100,000
August	102,000	59,000	76,000	2,400,000
September	153,000	91,000	114,000	3,400,000
October	166,000	91,000	121,000	3,700,000
November	114,000	59,000	82,000	2,500,000
December	....	....	....	....
The period	194,000	24,000	95,000	31,900,000

Discharge of Tunnel 72 (Heio Tunnel)

(Data from C. Brewer and Co., Ltd.)

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1925				
January	43,000	....	35,000	1,100,000
February	40,000	24,000	32,000	900,000
March	94,000	29,000	68,000	2,100,000
April	86,000	40,000	70,000	2,100,000
May	432,000	138,000	258,000	8,000,000
June	158,000	79,000	120,000	3,600,000
July	86,000	....	68,000	2,100,000
August	130,000	79,000	103,000	3,200,000
September	317,000	94,000	153,000	4,600,000
October	648,000	518,000	548,000	17,000,000
November	662,000	94,000	300,000	9,000,000
December	86,000	50,000	65,000	2,000,000
The year	662,000	24,000	154,000	56,000,000
1927				
January	202,000	58,000	123,000	3,800,000
February	94,000	58,000	86,000	2,400,000
March	130,000	86,000	113,000	3,600,000
April	950,000	374,000	610,000	18,300,000
May	346,000	102,000	203,000	6,300,000
June	346,000	122,000	187,000	5,600,000
July	94,000	58,000	77,000	2,400,000
August	86,000	43,000	81,000	2,500,000
September	864,000	86,000	470,000	14,100,000
October	821,000	259,000	474,000	14,700,000
November	317,000	115,000	217,000	6,500,000
December	864,000	79,000	510,000	15,800,000
The year	950,000	43,000	263,000	96,000,000
1928				
January	376,000	49,000	158,000	4,900,000
February	86,000	24,000	55,000	1,600,000
March	79,000	50,000	77,000	2,400,000
April	518,000	58,000	240,000	7,200,000
May	389,000	216,000	326,000	10,100,000
June	202,000	130,000	170,000	5,100,000
July	677,000	94,000	245,000	7,600,000
August	259,000	86,000	152,000	4,700,000
September	346,000	130,000	247,000	7,400,000
October	432,000	173,000	268,000	8,300,000
November	274,000	79,000	163,000	4,900,000
December	65,000	43,000	58,000	1,800,000
The year	677,000	24,000	181,000	66,100,000
1929				
January	115,000	32,000	51,000	1,600,000
February	432,000	130,000	282,000	7,900,000
March	511,000	216,000	351,000	10,900,000
April	720,000	127,000	393,000	11,800,000
May	288,000	101,000	174,000	5,400,000
June	230,000	86,000	140,000	4,200,000
July	122,000	50,000	106,000	3,300,000
August	403,000	153,000	232,000	7,200,000
September	305,000	130,000	223,000	6,700,000
October	376,000	115,000	222,000	6,900,000
November	1,557,000	166,000	640,000	19,200,000
December	396,000	209,000	309,000	9,600,000
The year	1,557,000	32,000	260,000	94,700,000

Discharge of Tunnel 74 (Noguchi Mauka Tunnel)

(Data from C. Brewer and Co., Ltd.)

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1925				
January	....	20,000	23,000	700,000
February	....	16,000	25,000	700,000
March	50,000	20,000	29,000	900,000
April	35,000	24,000	30,000	900,000
May	151,000	63,000	97,000	3,000,000
June	68,000	40,000	60,000	1,800,000
July	45,000	33,000	39,000	1,200,000
August	63,000	33,000	52,000	1,600,000
September	108,000	39,000	70,000	2,100,000
October	232,000	137,000	190,000	5,900,000
November	243,000	45,000	137,000	4,100,000
December	40,000	16,000	29,000	900,000
The year	243,000	16,000	65,000	23,800,000
1927				
January	112,000	24,000	65,000	2,000,000
February	40,000	24,000	36,000	1,000,000
March	58,000	35,000	45,000	1,400,000
April	373,000	206,000	247,000	7,400,000
May	170,000	56,000	106,000	3,300,000
June	98,000	63,000	80,000	2,400,000
July	....	29,000	68,000	2,100,000
August	....	24,000	29,000	900,000
September	265,000	29,000	180,000	5,400,000
October	265,000	84,000	158,000	4,900,000
November	121,000	46,000	83,000	2,500,000
December	245,000	40,000	187,000	5,800,000
The year	373,000	24,000	107,000	39,100,000
1928				
January	206,000	20,000	87,000	2,700,000
February	24,000	6,000	14,000	400,000
March	20,000	13,000	16,000	500,000
April	197,000	13,000	90,000	2,700,000
May	153,000	89,000	129,000	4,000,000
June	69,000	45,000	60,000	1,800,000
July	179,000	39,000	94,000	2,900,000
August	91,000	35,000	58,000	1,800,000
September	105,000	56,000	83,000	2,500,000
October	137,000	76,000	106,000	3,300,000
November	112,000	29,000	67,000	2,000,000
December	24,000	20,000	23,000	700,000
The year	206,000	6,000	69,000	25,300,000
1929				
January	50,000	14,000	23,000	700,000
February	144,000	58,000	100,000	2,800,000
March	144,000	63,000	116,000	3,600,000
April	170,000	52,000	110,000	3,300,000
May	144,000	45,000	94,000	2,900,000
June	96,000	39,000	67,000	2,000,000
July	50,000	24,000	42,000	1,300,000
August	179,000	76,000	100,000	3,100,000
September	120,000	63,000	73,000	2,200,000
October	153,000	50,000	87,000	2,700,000
November	531,000	96,000	270,000	8,100,000
December	245,000	140,000	187,000	5,800,000
The year	531,000	14,000	105,000	38,500,000

Discharge of Tunnel 75 (Noguchi No. 2 Tunnel)

(Data from C. Brewer and Co., Ltd., and Hawaiian Agricultural Co., Ltd.)

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1925				
January	86,000	58,000	68,000	2,100,000
February	43,000	29,000	39,000	1,100,000
March	69,000	29,000	58,000	1,800,000
April	86,000	58,000	70,000	2,100,000
May	245,000	115,000	161,000	5,000,000
June	259,000	187,000	227,000	6,800,000
July	180,000	173,000	168,000	5,200,000
August	202,000	173,000	190,000	5,900,000
September	274,000	187,000	203,000	6,100,000
October	619,000	403,000	471,000	14,600,000
November	485,000	166,000	317,000	9,500,000
December	137,000	43,000	94,000	2,900,000
The year	619,000	29,000	173,000	63,100,000
1926				
January	72,000	65,000	71,000	2,200,000
February	58,000	....	50,000	1,400,000
March	43,000	40,000	42,000	1,300,000
April	130,000	50,000	97,000	2,900,000
May	194,000	130,000	171,000	5,300,000
June	317,000	158,000	230,000	6,900,000
July	360,000	259,000	310,000	9,600,000
August	576,000	245,000	390,000	12,100,000
September	490,000	389,000	447,000	13,400,000
October	360,000	245,000	310,000	9,600,000
November	374,000	245,000	327,000	9,800,000
December	475,000	187,000	319,000	9,900,000
The year	576,000	40,000	231,000	84,400,000
1927				
January	389,000	187,000	268,000	8,300,000
February	....	158,000	161,000	4,500,000
March	202,000	144,000	174,000	5,400,000
April	490,000	317,000	367,000	11,000,000
May	461,000	245,000	345,000	10,700,000
June	360,000	245,000	313,000	9,400,000
July	202,000	144,000	171,000	5,300,000
August	122,000	72,000	87,000	2,700,000
September	749,000	79,000	530,000	15,900,000
October	475,000	432,000	448,000	13,900,000
November	....	331,000	350,000	10,500,000
December	446,000	382,000	416,000	12,900,000
The year	749,000	72,000	303,000	110,500,000

Discharge of Tunnel 76 (Noguchi No. 1 Tunnel)

(Data from C. Brewer and Co., Ltd., and Hawaiian Agricultural Co., Ltd.)

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1925				
January	454,000	403,000	419,000	13,000,000
February	374,000	324,000	364,000	10,200,000
March	346,000	302,000	306,000	9,500,000
April	432,000	396,000	403,000	12,100,000
May	706,000	432,000	616,000	19,100,000
June	792,000	612,000	653,000	19,600,000
July	598,000	576,000	442,000	13,700,000
August	605,000	576,000	448,000	13,900,000
September	698,000	576,000	607,000	18,200,000
October	1,123,000	893,000	916,000	28,400,000
November	1,224,000	792,000	940,000	28,200,000
December	691,000	504,000	587,000	18,200,000
The year	1,224,000	302,000	559,000	204,100,000
1926				
January	468,000	418,000	426,000	13,200,000
February	374,000	360,000	369,000	10,300,000
March	....	338,000	355,000	11,000,000
April	475,000	346,000	417,000	12,500,000
May	612,000	504,000	555,000	17,200,000
June	821,000	554,000	620,000	18,600,000
July	1,051,000	749,000	842,000	26,100,000
August	1,512,000	749,000	1,039,000	32,200,000
September	1,224,000	1,109,000	1,200,000	36,000,000
October	1,022,000	734,000	887,000	27,500,000
November	979,000	763,000	910,000	27,300,000
December	1,195,000	619,000	806,000	25,000,000
The year	1,512,000	338,000	705,000	257,300,000
1927[a]				
January	1,138,000	634,000	819,000	25,400,000
February	576,000	547,000	575,000	16,100,000
March	648,000	533,000	590,000	18,300,000
April	1,253,000	792,000	947,000	28,400,000
May	1,440,000	778,000	1,016,000	31,500,000
June	1,037,000	706,000	857,000	25,700,000
July	677,000	554,000	613,000	19,000,000
August	526,000	454,000	481,000	14,900,000
September	1,195,000	884,000	907,000	27,200,000
October	1,296,000	1,008,000	1,161,000	36,000,000
November	893,000	734,000	850,000	25,500,000
December	1,994,000	677,000	1,129,000	35,000,000
The year	1,994,000	454,000	830,000	303,000,000

---

[a] Tunnel under construction.

Combined discharge, Tunnel 75 (Noguchi No. 2 Tunnel) and Tunnel 76 (Noguchi No. 1 Tunnel)

(Data from C. Brewer and Co., Ltd.)

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1928				
January	2,609,000	973,000	1,613,000	50,000,000
February	854,000	613,000	710,000	20,600,000
March	664,000	592,000	635,000	19,700,000
April	994,000	562,000	783,000	23,500,000
May	1,397,000	1,122,000	1,348,000	41,800,000
June	1,152,000	979,000	1,063,000	31,900,000
July	1,858,000	929,000	1,384,000	42,900,000
August	1,210,000	857,000	935,000	29,000,000
September	1,476,000	1,159,000	1,287,000	38,600,000
October	1,404,000	1,210,000	1,303,000	40,400,000
November	1,397,000	1,051,000	1,237,000	37,100,000
December	871,000	605,000	758,000	23,500,000
The year	2,609,000	562,000	1,090,000	399,000,000
1929				
January	634,000	504,000	555,000	17,200,000
February	1,354,000	605,000	868,000	24,300,000
March	2,023,000	1,310,000	1,619,000	50,200,000
April	2,131,000	1,224,000	1,740,000	52,200,000
May	1,368,000	986,000	1,210,000	37,500,000
June	1,152,000	828,000	1,020,000	30,600,000
July	1,008,000	763,000	842,000	26,100,000
August	1,728,000	1,066,000	1,348,000	42,900,000
September	1,613,000	1,267,000	1,407,000	42,200,000
October	1,642,000	1,267,000	1,413,000	43,800,000
November	2,765,000	1,613,000	1,937,000	58,100,000
December	2,592,000	1,584,000	1,990,000	61,700,000
The year	2,765,000	504,000	1,334,000	486,800,000
1930				
July	1,094,000	950,000	1,035,000	32,000,000
August	3,024,000	1,194,000	2,163,000	67,200,000
September	2,880,000	2,131,000	2,307,000	69,300,000
October	2,822,000	1,540,000	2,344,000	72,700,000
November	1,613,000	1,195,000	1,411,000	42,300,000
December	1,195,000	677,000	876,000	27,200,000
The period	3,024,000	677,000	1,689,000	310,700,000
1931				
January	677,000	468,000	553,000	17,100,000
February	468,000	360,000	409,000	11,400,000
March	360,000	288,000	308,000	9,600,000
April	488,000	288,000	337,000	10,100,000
May	897,000	498,000	599,000	18,600,000
June	1,397,000	864,000	1,092,000	32,900,000
July	1,728,000	691,000	939,000	29,000,000
August	1,786,000	1,143,000	1,532,000	47,600,000
September	1,506,000	950,000	1,136,000	34,100,000
October	2,160,000	1,397,000	1,796,000	55,800,000
November	1,391,000	835,000	1,145,000	34,300,000
December	818,000	521,000	654,000	20,200,000
The year	2,160,000	288,000	875,000	320,700,000

Combined discharge of Tunnels 75 and 76—continued

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1932				
January	1,522,000	461,000	727,000	22,500,000
February	2,131,000	1,584,000	1,856,000	53,900,000
March	1,872,000	948,000	1,431,000	44,400,000
April	927,000	634,000	747,000	22,400,000
May	1,296,000	733,000	935,000	28,900,000
June	1,642,000	1,325,000	1,544,000	46,400,000
July	1,469,000	819,000	1,135,000	35,200,000
August	835,000	691,000	734,000	22,700,000
September	1,181,000	720,000	958,000	28,700,000
October	1,166,000	749,000	971,000	30,000,000
November	1,282,000	706,000	996,000	29,800,000
December	1,411,000	924,000	1,233,000	38,300,000
The year	2,131,000	461,000	1,106,000	403,200,000
1933				
January	1,368,000	864,000	1,162,000	36,100,000
February	1,368,000	1,120,000	1,227,000	34,400,000
March	1,944,000	1,221,000	1,577,000	48,900,000
April	1,843,000	1,152,000	1,506,000	45,500,000
May	2,074,000	1,354,000	1,731,000	53,800,000
June	2,160,000	1,181,000	1,692,000	50,800,000
July	1,152,000	619,000	835,000	25,800,000
August	609,000	389,000	481,000	14,900,000
September	403,000	374,000	395,000	11,800,000
October	475,000	389,000	413,000	12,800,000
November	648,000	490,000	609,000	18,200,000
December	619,000	576,000	593,000	18,400,000
The year	2,160,000	374,000	1,018,000	371,400,000
1934				
January	655,000	490,000	569,000	17,600,000
February	763,000	626,000	696,000	19,400,000
March	1,030,000	605,000	786,000	24,300,000
April	1,526,000	979,000	1,077,000	32,300,000
May	2,527,000	1,267,000	1,751,000	54,300,000
June	3,024,000	1,716,000	2,480,000	74,600,000
July	1,621,000	1,267,000	1,381,000	42,900,000
August	1,606,000	1,066,000	1,305,000	40,500,000
September	1,843,000	1,555,000	1,659,000	49,800,000
October	1,734,000	922,000	1,395,000	43,300,000
November	1,584,000	1,097,000	1,284,000	38,600,000
December	1,077,000	825,000	956,000	29,600,000
The year	3,024,000	490,000	1,278,000	467,200,000
1935				
January	864,000	720,000	791,000	24,400,000
February	841,000	763,000	792,000	22,100,000
March	1,920,000	901,000	1,652,000	51,300,000
April	2,045,000	1,555,000	1,768,000	53,100,000
May	1,539,000	1,325,000	1,423,000	44,200,000
June	1,512,000	1,129,000	1,305,000	39,200,000
July	1,109,000	864,000	1,035,000	32,200,000
August	1,757,000	1,041,000	1,352,000	42,000,000
September	1,987,000	1,411,000	1,721,000	51,700,000
October	1,958,000	1,411,000	1,669,000	51,800,000
November	1,492,000	1,210,000	1,326,000	39,800,000
The period	2,045,000	720,000	1,348,000	451,800,000

Combined discharge of Tunnels 75 and 76—continued

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1932				
January	1,522,000	461,000	727,000	22,500,000
February	2,131,000	1,584,000	1,856,000	53,900,000
March	1,872,000	948,000	1,431,000	44,400,000
April	927,000	634,000	747,000	22,400,000
May	1,296,000	733,000	935,000	28,900,000
June	1,642,000	1,325,000	1,544,000	46,400,000
July	1,469,000	819,000	1,135,000	35,200,000
August	835,000	691,000	734,000	22,700,000
September	1,181,000	720,000	958,000	28,700,000
October	1,166,000	749,000	971,000	30,000,000
November	1,282,000	706,000	996,000	29,800,000
December	1,411,000	924,000	1,233,000	38,300,000
The year	2,131,000	461,000	1,106,000	403,200,000
1933				
January	1,368,000	864,000	1,162,000	36,100,000
February	1,368,000	1,120,000	1,227,000	34,400,000
March	1,944,000	1,221,000	1,577,000	48,900,000
April	1,843,000	1,152,000	1,506,000	45,500,000
May	2,074,000	1,354,000	1,731,000	53,800,000
June	2,160,000	1,181,000	1,692,000	50,800,000
July	1,152,000	619,000	835,000	25,800,000
August	609,000	389,000	481,000	14,900,000
September	403,000	374,000	395,000	11,800,000
October	475,000	389,000	413,000	12,800,000
November	648,000	490,000	609,000	18,200,000
December	619,000	576,000	593,000	18,400,000
The year	2,160,000	374,000	1,018,000	371,400,000
1934				
January	655,000	490,000	569,000	17,600,000
February	763,000	626,000	696,000	19,400,000
March	1,030,000	605,000	786,000	24,300,000
April	1,526,000	979,000	1,077,000	32,300,000
May	2,527,000	1,267,000	1,751,000	54,300,000
June	3,024,000	1,716,000	2,480,000	74,600,000
July	1,621,000	1,267,000	1,381,000	42,900,000
August	1,606,000	1,066,000	1,305,000	40,500,000
September	1,843,000	1,555,000	1,659,000	49,800,000
October	1,734,000	922,000	1,395,000	43,300,000
November	1,584,000	1,097,000	1,284,000	38,600,000
December	1,077,000	825,000	956,000	29,600,000
The year	3,024,000	490,000	1,278,000	467,200,000
1935				
January	864,000	720,000	791,000	24,400,000
February	841,000	763,000	792,000	22,100,000
March	1,920,000	901,000	1,652,000	51,300,000
April	2,045,000	1,555,000	1,768,000	53,100,000
May	1,539,000	1,325,000	1,423,000	44,200,000
June	1,512,000	1,129,000	1,305,000	39,200,000
July	1,109,000	864,000	1,035,000	32,200,000
August	1,757,000	1,041,000	1,352,000	42,000,000
September	1,987,000	1,411,000	1,721,000	51,700,000
October	1,958,000	1,411,000	1,669,000	51,800,000
November	1,492,000	1,210,000	1,326,000	39,800,000
The period	2,045,000	720,000	1,348,000	451,800,000

Combined discharge of Tunnels 75 and 76—continued

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1937				
January	1,570,000	432,000	766,000	23,700,000
February	2,477,000	1,584,000	2,104,000	59,100,000
March	1,950,000	1,526,000	1,788,000	55,500,000
April	1,958,000	1,195,000	1,521,000	45,700,000
May	2,304,000	1,325,000	1,860,000	57,700,000
June	1,318,000	919,000	1,126,000	33,800,000
The period	2,477,000	432,000	1,528,000	275,500,000
1942				
February	311,000	230,000	256,000	7,200,000
March	314,000	230,000	255,000	7,900,000
April	662,000	317,000	582,000	17,400,000
May	1,210,000	605,000	913,000	28,200,000
June	1,152,000	985,000	1,066,000	32,000,000
July	968,000	691,000	780,000	24,200,000
August	1,094,000	605,000	900,000	27,800,000
September	2,592,000	619,000	1,512,000	45,500,000
October	2,030,000	1,382,000	1,535,000	47,700,000
November	1,431,000	1,002,000	1,228,000	36,900,000
December	985,000	835,000	891,000	27,600,000
The period	2,592,000	230,000	902,000	302,400,000

Discharge of Tunnel 79 (Double Arch Tunnel)

(Data from C. Brewer and Co., Ltd., and Hawaiian Agricultural Co., Ltd.)

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1925				
January	58,000	40,000	45,000	1,400,000
February	....	32,000	50,000	1,400,000
March	526,000	40,000	329,000	10,200,000
April	193,000	60,000	130,000	3,900,000
May	1,263,000	253,000	697,000	21,600,000
June	428,000	158,000	380,000	11,400,000
July	427,000	122,000	213,000	6,600,000
August	324,000	230,000	255,000	7,900,000
September	2,131,000	203,000	760,000	22,800,000
October	2,304,000	1,153,000	1,732,000	53,700,000
November	1,642,000	193,000	523,000	15,700,000
December	151,000	40,000	81,000	2,500,000
The year	2,304,000	32,000	436,000	159,100,000
1927				
January	323,000	180,000	245,000	7,600,000
February	305,000	127,000	200,000	5,600,000
March	524,000	140,000	426,000	13,200,000
April	1,814,000	657,000	1,237,000	37,100,000
May	605,000	317,000	532,000	16,500,000
June	1,296,000	202,000	560,000	16,800,000
July	259,000	58,000	139,000	4,300,000
August	216,000	43,000	152,000	4,700,000
September	3,168,000	317,000	1,357,000	40,700,000
October	3,168,000	374,000	1,348,000	41,800,000
November	864,000	202,000	590,000	17,700,000
December	3,024,000	346,000	1,655,000	51,300,000
The year	3,168,000	43,000	705,000	257,300,000
1928				
January	576,000	72,000	223,000	6,900,000
February	432,000	29,000	124,000	3,600,000
March	....	86,000	116,000	3,600,000
April	2,304,000	216,000	1,057,000	31,700,000
May	1,354,000	547,000	1,065,000	33,000,000
June	576,000	317,000	520,000	15,600,000
July	3,168,000	202,000	913,000	28,300,000
August	648,000	187,000	448,000	13,900,000
September	1,152,000	418,000	880,000	26,400,000
October	2,592,000	432,000	1,065,000	33,000,000
November	1,123,000	130,000	470,000	14,100,000
December	115,000	65,000	81,000	2,500,000
The year	3,168,000	29,000	581,000	212,600,000
1929				
January	720,000	58,000	210,000	6,500,000
February	2,102,000	230,000	443,000	12,400,000
March	2,390,000	490,000	1,216,000	37,700,000
April	3,024,000	317,000	1,093,000	32,800,000
May	922,000	173,000	519,000	16,100,000
June	1,296,000	151,000	627,000	18,800,000
July	605,000	144,000	448,000	13,900,000
August	3,024,000	432,000	1,484,000	46,000,000
September	864,000	317,000	557,000	16,700,000
October	1,008,000	187,000	584,000	18,100,000
November	3,744,000	605,000	1,993,000	59,800,000
December	2,016,000	1,210,000	1,584,000	49,100,000
The year	3,744,000	58,000	898,000	327,900,000

Discharge of Tunnel 79 (Double Arch Tunnel)—continued

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1930				
July	446,000	288,000	384,000	11,900,000
August	3,888,000	634,000	1,485,000	46,000,000
September	2,102,000	662,000	1,158,000	34,700,000
October	3,456,000	259,000	1,462,000	45,300,000
November	763,000	230,000	438,000	13,100,000
December	259,000	86,000	140,000	43,400,000
The period	3.888,000	86,000	844,000	194,400,000
1931				
January	78,000	43,000	58,000	1,700,000
February	43,000	20,000	35,000	1,000,000
March	130,000	14,000	45,000	1,400,000
April	446,000	144,000	235,000	7,000,000
May	1,022,000	115,000	380,000	11,800,000
June	1,210,000	72,000	413,000	12,400,000
July	1,008,000	72,000	523,000	16,200,000
August	1,325,000	187,000	684,000	21,200,000
September	1,152,000	144,000	567,000	17,000,000
October	1,728,000	374,000	868,000	26,900,000
November	878,000	101,000	271,000	8,100,000
December	101,000	50,000	65,000	2,000,000
The year	1,728,000	14,000	345,000	126,700,000
1932				
January	1,037,000	43,000	570,000	17,700,000
February	1,152,000	490,000	779,000	22,600,000
March	1,152,000	144,000	382,000	11,800,000
April	1,080,000	130,000	256,000	7,700,000
May	1,526,000	245,000	788,000	24,400,000
June	1,526,000	403,000	680,000	20,400,000
July	461,000	230,000	324,000	10,000,000
August	374,000	158,000	261,000	8,100,000
September	1,469,000	173,000	628,000	18,900,000
October	346,000	144,000	269,000	8,300,000
November	1,037,000	187,000	626,000	18,800,000
December	1,699,000	173,000	567,000	17,600,000
The year	1,699,000	43,000	511,000	186,300,000
1933				
January	1,238,000	158,000	516,000	16,000,000
February	835,000	288,000	518,000	14,500,000
March	2.016,000	302,000	778,000	24,100,000
April	2,448,000	259,000	1,165,000	35,000,000
May	1,152,000	216,000	847,000	26,200,000
June	2,966,000	187,000	876,000	26,200,000
July	158,000	43,000	109,000	3,400,000
August	490,000	29,000	130,000	4,000,000
September	300,000	48,000	134,000	4,000,000
October	288,000	43,000	154,000	4,800,000
November	281,000	101,000	203,000	6,100,000
December	432,000	86,000	265,000	8,200,000
The year	2,966,000	29,000	475,000	172,500,000

Discharge of Tunnel 79 (Double Arch Tunnel)—continued

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1934				
January	749,000	260,000	504,000	15,600,000
February	475,000	86,000	207,000	5,800,000
March	285,000	202,000	240,000	7,400,000
April	907,000	288,000	570,000	17,100,000
May	1,642,000	230,000	1,070,000	33,200,000
June	2,102,000	230,000	1,119,000	33,600,000
July	2,016,000	202,000	922,000	28,600,000
August	1,584,000	375,000	904,000	28,000,000
September	1,152,000	634,000	806,000	24,200,000
October	341,000	144,000	300,000	9,300,000
November	403,000	202,000	340,000	10,200,000
December	662,000	144,000	240,000	7,400,000
The year	2,102,000	86,000	602,000	220,400,000
1935				
January	576,000	144,000	248,000	7,700,000
February	302,000	86,000	259,000	7,200,000
March	2,362,000	216,000	818,000	25,400,000
April	576,000	274,000	416,000	12,500,000
May	720,000	259,000	528,000	16,400,000
June	1,123,000	247,000	668,000	20,000,000
July	642,000	187,000	557,000	17,300,000
August	1,152,000	259,000	649,000	20,100,000
September	1,526,000	461,000	763,000	22,900,000
October	1,411,000	377,000	816,000	25,300,000
November	533,000	220,000	350,000	10,500,000
December	....	....	....	....
The period	2,362,000	86,000	552,000	185,300,000

Discharge of Tunnel 80 (Mudflow Tunnel)

(Data from C. Brewer and Co., Ltd.)

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1925				
January	101,000	86,000	103,000	3,200,000
February	....	65,000	96,000	2,700,000
March	504,000	72,000	248,000	7,700,000
April	202,000	108,000	137,000	4,100,000
May	1,152,000	288,000	632,000	19,600,000
June	....	144,000	273,000	8,200,000
July	288,000	194,000	226,000	7,000,000
August	418,000	216,000	294,000	9,100,000
September	893,000	202,000	457,000	13,700,000
October	1,656,000	1,188,000	1,439,000	44,600,000
November	1,742,000	202,000	620,000	18,600,000
December	173,000	86,000	132,000	4,100,000
The year	1,742,000	65,000	391,000	142,600,000
1926				
January	130,000	101,000	135,000	4,200,000
February	166,000	115,000	138,000	3,900,000
March	230,000	115,000	152,000	4,700,000
April	360,000	223,000	350,000	10,500,000
May	590,000	259,000	426,000	13,200,000
June	1,915,000	158,000	783,000	23,500,000
July	878,000	331,000	584,000	18,100,000
August	2,002,000	274,000	877,000	27,200,000
September	1,512,000	504,000	827,000	24,800,000
October	590,000	331,000	448,000	13,900,000
November	936,000	216,000	527,000	15,800,000
December	1,900,000	173,000	771,000	23,900,000
The year	2,002,000	101,000	503,000	183,700,000
1927				
January	346,000	187,000	258,000	8,000,000
February	403,000	245,000	282,000	7,900,000
March	432,000	202,000	352,000	10,900,000
April	1,656,000	720,000	1,052,000	31,500,000
May	504,000	259,000	416,000	12,900,000
June	806,000	302,000	477,000	14,300,000
July	238,000	122,000	181,000	5,600,000
August	187,000	101,000	145,000	4,500,000
September	1,584,000	238,000	907,000	27,200,000
October	1,224,000	360,000	706,000	21,900,000
November	634,000	216,000	453,000	13,600,000
December	1,872,000	274,000	942,000	29,200,000
The year	1,872,000	101,000	514,000	187,500,000
1928				
January	724,000	140,000	323,000	10,000,000
February	240,000	102,000	145,000	4,200,000
March	153,000	114,000	152,000	4,700,000
April	864,000	114,000	513,000	15,400,000
May	613,000	395,000	519,000	16,100,000
June	490,000	288,000	440,000	13,200,000
July	2,376,000	209,000	645,000	20,000,000
August	531,000	209,000	352,000	10,900,000
September	613,000	305,000	497,000	14,900,000
October	887,000	340,000	510,000	15,800,000
November	550,000	194,000	327,000	9,800,000
December	153,000	114,000	135,000	4,200,000
The year	2.376,000	102,000	380,000	139,200,000

Discharge of Tunnel 80 (Mudflow Tunnel)—continued

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1929				
January	550,000	91,000	200,000	6,200,000
February	510,000	323,000	417,000	11,700,000
March	864,000	305,000	512,000	15,900,000
April	1,676,000	209,000	816,000	24,500,000
May	613,000	209,000	396,000	12,300,000
June	701,000	194,000	373,000	11,200,000
July	510,000	153,000	338,000	10,500,000
August	1,858,000	357,000	754,000	23,400,000
September	572,000	288,000	463,000	13,900,000
October	572,000	225,000	454,000	14,100,000
November	2,484,000	395,000	1,153,000	34,600,000
December	769,000	413,000	597,000	18,500,000
The year	2,484,000	91,000	539,000	196,800,000
1930				
July	240,000	225,000	239,000	7,400,000
August	3,604,000	357,000	1,208,000	37,400,000
September	1,705,000	340,000	808,000	24,200,000
October	1,585,000	272,000	750,000	23,300,000
November	451,000	209,000	312,000	9,400,000
December	194,000	102,000	148,000	4,600,000
The period	3,604,000	102,000	578,000	106,300,000
1931				
January	91,000	79,000	88,000	2,700,000
February	69,000	59,000	63,000	1,800,000
March	127,000	49,000	71,000	2,200,000
April	413,000	166,000	252,000	7,600,000
May	490,000	194,000	347,000	10,800,000
June	873,000	153,000	383,000	11,500,000
July	816,000	180,000	396,000	12,300,000
August	469,000	413,000	419,000	13,000,000
September	873,000	209,000	472,000	14,200,000
October	1,274,000	357,000	661,000	20,500,000
November	530,000	139,000	294,000	8,800,000
December	127,000	90,000	105,000	3,300,000
The year	1,274,000	49,000	296,000	108,700,000
1932				
January	613,000	79,000	320,000	9,900,000
February	724,000	413,000	537,000	15,600,000
March	510,000	165,000	297,000	9,200,000
April	153,000	140,000	187,000	5,600,000
May	839,000	240,000	425,000	13,200,000
June	469,000	394,000	456,000	13,700,000
July	357,000	180,000	353,000	10,900,000
August	413,000	153,000	255,000	7,900,000
September	550,000	240,000	458,000	13,700,000
October	432,000	180,000	302,000	9,400,000
November	769,000	209,000	550,000	16,500,000
December	1,089,000	240,000	478,000	14,800,000
The year	1,089,000	79,000	385,000	140,400,000

Discharge of Tunnel 80 (Mudflow Tunnel)—continued

1933				
January	1,011,000	180,000	467,000	14,500,000
February	724,000	357,000	494,000	13,800,000
March	1,329,000	272,000	554,000	17,200,000
April	1,414,000	224,000	720,000	21,600,000
May	873,000	288,000	582,000	18,000,000
June	1,274,000	288,000	546,000	16,400,000
July	240,000	126,000	177,000	5,500,000
August	114,000	91,000	107,000	3,300,000
September	126,000	91,000	107,000	3,200,000
October	340,000	91,000	161,000	5,000,000
November	323,000	194,000	264,000	7,900,000
December	376,000	166,000	258,000	8,000,000
The year	1,414,000	91,000	370,000	134,400,000
1934				
January	288,000	165,000	264,000	8,200,000
February	272,000	153,000	216,000	6,000,000
March	225,000	360,000	275,000	8,500,000
April	724,000	357,000	481,000	14,400,000
May	1,063,000	323,000	675,000	20,900,000
June	1,358,000	322,000	772,000	23,200,000
July	701,000	305,000	409,000	12,700,000
August	936,000	256,000	533,000	16,500,000
September	724,000	451,000	585,000	17,500,000
October	340,000	225,000	328,000	10,200,000
November	530,000	305,000	393,000	11,800,000
December	340,000	256,000	284,000	8,800,000
The year	1,358,000	153,000	435,000	158,700,000
1935				
January	510,000	225,000	307,000	9,500,000
February	272,000	225,000	262,000	7,300,000
March	792,000	340,000	635,000	19,700,000
April	550,000	376,000	441,000	13,200,000
May	769,000	376,000	544,000	16,900,000
June	1,011,000	435,000	641,000	19,200,000
July	209,000	194,000	397,000	12,300,000
August	613,000	305,000	441,000	13,700,000
September	864,000	376,000	560,000	16,800,000
October	1,089,000	413,000	704,000	21,800,000
November	510,000	357,000	455,000	13,700,000
December	....	....	....	....
The year	1,089,000	194,000	490,000	164,100,000

Discharge of Tunnel 85 (Alili Tunnel)

(Data from C. Brewer and Co., Ltd., and Hawaiian Agricultural Co., Ltd.)

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1925[a]				
October	337,000	166,000	219,000	6,800,000
November	320,000	24,000	173,000	5,200,000
December	17,000	4,000	13,000	400,000
The period	337,000	4,000	135,000	12,400,000
1926[a]				
April	12,000	0	7,000	200,000
May	49,000	32,000	45,000	1,400,000
June	428,000	58,000	240,000	7,200,000
July	759,000	269,000	468,000	14,500,000
August	1,616,000	127,000	661,000	20,500,000
September	880,000	302,000	543,000	16,300,000
October	323,000	166,000	226,000	7,100,000
November	530,000	140,000	313,000	9,400,000
December	887,000	127,000	419,000	13,000,000
The period	1,616,000	0	245,000	89,600,000
1927[a]				
January	395,000	91,000	261,000	8,100,000
February	153,000	59,000	100,000	2,800,000
March	395,000	140,000	274,000	8,500,000
April	2,246,000	592,000	1,323,000	39,700,000
May	1,499,000	288,000	626,000	19,400,000
June	1,441,000	288,000	707,000	21,200,000
July	272,000	102,000	171,000	5,300,000
August	194,000	79,000	116,000	3,600,000
September	2,182,000	194,000	1,407,000	42,200,000
October	1,166,000	572,000	935,000	29,000,000
November	657,000	272,000	477,000	14,300,000
December	2,182,000	225,000	1,161,000	36,000,000
The Year	2,246,000	59,000	630,000	230,100,000
1928[a]				
January	1,037,000	240,000	700,000	21,700,000
February	153,000	91,000	124,000	3,600,000
March	166,000	102,000	139,000	4,300,000
April	1,899,000	127,000	677,000	20,300,000
May	1,194,000	912,000	981,000	30,400,000
June	864,000	572,000	737,000	22,100,000
July	1,646,000	530,000	865,000	26,800,000
August	1,441,000	413,000	648,000	20,100,000
September	1,080,000	724,000	893,000	26,800,000
October	1,414,000	635,000	942,000	29,200,000
November	746,000	256,000	490,000	14,700,000
December	209,000	114,000	145,000	4,500,000
The Year	1,889,000	91,000	613,000	224,500,000

Discharge of Tunnel 85 (Alili Tunnel)—continued

1929				
January	194,000	102,000	164,000	5,100,000
February	1,951,000	469,000	1,042,000	29,200,000
March	1,557,000	840,000	1,283,000	39,800,000
April	1,470,000	451,000	1,050,000	31.500,000
May	840,000	530,000	648,000	20,100,000
June	816,000	106,000	640,000	19,200,000
July	887,000	240,000	567,000	17,600,000
August	2,484,000	680,000	1,261,000	39,100,000
September	2,448,000	550,000	1,280,000	38,400,000
October	2,376,000	530,000	929,000	28,800,000
November	....	840,000	1,420,000	42,600,000
December	1,765,000	550,000	1,038,000	32,200,000
The year	2,484,000	102,000	941,000	343,600,000
1930				
July	724,000	469,000	641,000	19,800,000
August	2,015,000	560,000	1,418,000	44,000,000
September	2,510,000	1,063,000	1,597,000	47,900,000
October	1,857,000	494,000	1,128,000	35,000,000
November	1,557,000	393,000	806,000	24.100,000
December	357,000	154,000	236,000	7,300,000
The period	2,510,000	154,000	971,000	178,100,000
1931				
January	161,000	105,000	122,000	3,800,000
February	104,000	62,000	81,000	2,800,000
March	108,000	49,000	63,000	2,000,000
April	490,000	147,000	382,000	11,400,000
May	2,006,000	376,000	844,000	26,100,000
June	2,111,000	363,000	1,081,000	32,400,000
July	2,510,000	288,000	785,000	24,300,000
August	1,666,000	451,000	946,000	29,200,000
September	1,335,000	340,000	632,000	18,900,000
October	2,177,000	840,000	1,509,000	46,800,000
November	887,000	312,000	556,000	16,600,000
December	305,000	150,000	222,000	6,900,000
The year	2,510,000	49,000	602,000	220,700,000
1932				
January	1,610,000	140,000	641,000	19,800,000
February	1,925,000	962,000	1,358,000	37,000,000
March	2,015,000	334,000	870,000	26,900,000
April	323,000	209,000	253,000	7,600,000
May	1,166,000	346,000	575,000	17,800,000
June	1,557,000	1,140,000	1,397,000	41,900,000
July	1,194,000	396,000	773,000	24,900,000
August	490,000	376,000	410,000	12,700,000
September	1,220,000	413,000	786,000	23,600,000
October	706,000	301,000	492,000	15,200,000
November	1,115,000	272,000	618,000	18,500,000
December	1,358,000	428,000	818,000	25,300,000
The year	2,015,000	140,000	749,000	271,200,000

Discharge of Tunnel 85 (Alili Tunnel)—continued

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1933				
January	1,089,000	413,000	756,000	23,400,000
February	1,063,000	743,000	1,007,000	28,200,000
March	1,858,000	510,000	1,076,000	33,300,000
April	1,646,000	842,000	1,254,000	37,600,000
May	1,286,000	840,000	1,440,000	44,600,000
June	2,177,000	490,000	1,202,000	36,100,000
July	469,000	156,000	279,000	8,700,000
August	212,000	114,000	140,000	4,400,000
September	256,000	202,000	235,000	7,100,000
October	288,000	166,000	204,000	6,300,000
November	395,000	298,000	359,000	10,700,000
December	314,000	187,000	225,000	7,000,000
The year	2,177,000	114,000	681,000	247,400,000
1934				
January	237,000	166,000	192,000	6,000,000
February	272,000	194,000	238,000	6,700,000
March	592,000	274,000	454,000	14,000,000
April	1,083,000	451,000	616,000	18,400,000
May	1,901,000	724,000	1,093,000	33,900,000
June	2,310,000	680,000	1,616,000	48,500,000
July	1,274,000	657,000	973,000	30,100,000
August	1,247,000	357,000	772,000	23,900,000
September	1,247,000	701,000	936,000	28,000,000
October	1,115,000	530,000	825,000	25,600,000
November	1,414,000	662,000	1,007,000	30,200,000
December	662,000	320,000	504,000	15,600,000
The year	2,310,000	166,000	769,000	280,900,000
1935				
January	469,000	256,000	334,000	10,300,000
February	449,000	225,000	302,000	8,500,000
March	1,564,000	546,000	1,260,000	39,100,000
April	1,705,000	635,000	1,089,000	32,700,000
May	816,000	472,000	624,000	19,300,000
June	1,414,000	432,000	899,000	27,000,000
July	550,000	288,000	405,000	12,500,000
August	1,302,000	323,000	936,000	29,000,000
September	1,797,000	701,000	1,246,000	37,400,000
October	1,921,000	651,000	1,276,000	39,600,000
November	704,000	469,000	576,000	17,200,000
The period	1,921,000	225,000	813,000	272,600,000
1942				
February	92,000	59,000	68,000	1,900,000
March	96,000	40,000	66,000	2,000,000
April	393,000	96,000	258,000	7,800,000
May	962,000	340,000	662,000	20,500,000
June	1,166,000	769,000	907,000	27,200,000
July	870,000	346,000	544,000	16,800,000
August	1,414,000	583,000	1,179,000	36,500,000
September	2,592,000	490,000	1,509,000	45,300,000
October	1,646,000	657,000	1,171,000	36,300,000
November	924,000	469,000	714,000	21,400,000
December	1,813,000	413,000	802,000	24,800,000
The period	2,592,000	40,000	716,000	240,500,000

Discharge of Tunnel 85 (Alili Tunnel)—continued

1943				
January	2,592,000	514,000	1,433,000	44,400,000
February	482,000	197,000	317,000	8,900,000
March	962,000	180,000	576,000	17,800,000
April	769,000	490,000	622,000	18,600,000
May	1,765,000	490,000	1,342,000	41,600,000
June	1,655,000	530,000	952,000	28,500,000
July	1,705,000	544,000	1,250,000	38,800,000
August	1,152,000	530,000	871,000	27,000,000
September	1,119,000	635,000	887,000	26,600,000
October	1,765,000	468,000	1,045,000	32,400,000
November	441,000	265,000	346,000	10,400,000
December	262,000	153,000	209,000	6,500,000
The year	2,592,000	153,000	821,000	301,500,000
1944				
January	151,000	114,000	135,000	4,200,000
February	840,000	91,000	174,000	5,100,000
March	1,166,000	634,000	971,000	30,000,000
April	724,000	382,000	566,000	17,000,000
May	2,448,000	305,000	1,153,000	35,700,000
June	1,644,000	965,000	1,395,000	41,800,000
July	1,358,000	530,000	926,000	28,600,000
August	1,223,000	340,000	599,000	18,600,000
September	962,000	361,000	677,000	20,300,000
October	867,000	413,000	628,000	19,400,000
November	806,000	504,000	641,000	19,200,000
The period	2,448,000	91,000	715,000	239,900,000

[a] Tunnel under construction.

Discharge of Tunnel 86 (Shirakura Tunnel)

(Data from C. Brewer and Co., Ltd., and Hawaiian Agricultural Co., Ltd.)

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1929[a]				
May	395,000	225,000	274,000	8,500,000
June	256,000	79,000	150,000	4,500,000
July	323,000	166,000	287,000	8,900,000
August	680,000	225,000	455,000	14,100,000
September	572,000	166,000	350,000	10,500,000
October	550,000	256,000	445,000	13,800,000
November	613,000	288,000	440,000	13,200,000
December	550,000	166,000	352,000	10,900,000
The period	680,000	79,000	344,000	84,400,000
1930				
July	510,000	166,000	328,000	10,000,000
August	962,000	258,000	570,000	17,600,000
September	832,000	340,000	550,000	16,500,000
October	510,000	75,000	112,000	9,700,000
November	288,000	66,000	164,000	4,900,000
December	63,000	32,000	43,000	1,300,000
The period	962,000	32,000	328,000	60,000,000
1931				
January	69,000	24,000	36,000	1,100,000
February	209,000	17,000	40,000	1,100,000
March	96,000	24,000	52,000	1,600,000
April	395,000	49,000	207,000	6,200,000
May	370,000	49,000	180,000	5,600,000
June	451,000	32,000	184,000	5,500,000
July	769,000	143,000	563,000	17,400,000
August	746,000	253,000	556,000	17,200,000
September	816,000	153,000	621,000	18,300,000
October	694,000	127,000	315,000	9,800,000
November	124,000	73,000	99,000	3,000,000
December	71,000	17,000	35,000	1,100,000
The year	816,000	17,000	241,000	87,900,000
1932				
January	816,000	17,000	366,000	11,300,000
February	792,000	114,000	452,000	13,100,000
March	240,000	69,000	130,000	4,000,000
April	288,000	49,000	132,000	4,000,000
May	799,000	187,000	488,000	15,100,000
June	840,000	240,000	472,000	14,100,000
July	451,000	153,000	255,000	7,900,000
August	194,000	98,000	174,000	5,400,000
September	490,000	59,000	281,000	8,400,000
October	225,000	49,000	122,000	3,800,000
November	657,000	17,000	256,000	7,700,000
December	724,000	49,000	183,000	5,700,000
The year	840,000	17,000	276,000	100,500,000

Discharge of Tunnel 86 (Shirakura Tunnel)—continued

1933				
January	769,000	40,000	314,000	9,800,000
February	619,000	40,000	225,000	6,300,000
March	792,000	100,000	410,000	12,700,000
April	657,000	91,000	348,000	10,400,000
May	613,000	91,000	341,000	10,500,000
June	572,000	60,000	236,000	7,100,000
July	59,000	24,000	39,000	1,200,000
August	323,000	24,000	153,000	4,800,000
September	194,000	69,000	137,000	4,100,000
October	194,000	32,000	99,000	3,100,000
November	127,000	26,000	73,000	2,200,000
December	26,000	12,000	20,000	600,000
The year	792,000	12,000	283,000	72,800,000
1934				
January	240,000	12,000	96,000	3,000,000
February	206,000	32,000	122,000	3,400,000
March	469,000	114,000	284,000	8,800,000
April	701,000	127,000	262,000	7,900,000
May	693,000	140,000	477,000	14,800,000
June	724,000	340,000	474,000	14,200,000
July	613,000	180,000	376,000	11,600,000
August	510,000	232,000	344,000	10,600,000
September	432,000	166,000	291,000	8,700,000
October	482,000	166,000	300,000	9,300,000
November	530,000	207,000	360,000	10,800,000
December	194,000	32,000	95,000	2,900,000
The year	724,000	12,000	290,000	106,000,000
1935				
January	395,000	89,000	183,000	5,700,000
February	305,000	69,000	186,000	5,200,000
March	657,000	194,000	353,000	10,900,000
April	701,000	225,000	416,000	12,400,000
May	406,000	49,000	190,000	5,900,000
June	469,000	265,000	377,000	11,300,000
July	469,000	194,000	386,000	11,900,000
August	724,000	194,000	523,000	16,200,000
September	816,000	127,000	400,000	12,000,000
October	769,000	127,000	334,000	10,300,000
November	240,000	114,000	166,000	5,000,000
The period	816,000	49,000	319,000	106,800,000

[a] Tunnel under construction.

Discharge of Tunnel 87 (Moaula Gulch Tunnel)

(Data from C. Brewer and Co., Ltd., and Hawaiian Agricultural Co., Ltd.)

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1929				
April	550,000	180,000	300,000	6,000,000
May	451,000	127,000	268,000	8,300,000
June	305,000	127,000	217,000	6,500,000
July	572,000	140,000	332,000	10,300,000
August	432,000	209,000	316,000	9,800,000
September	305,000	194,000	253,000	7,600,000
October	413,000	256,000	310,000	9,600,000
November	413,000	256,000	327,000	9,800,000
December	413,000	209,000	332,000	10,300,000
The period	572,000	127,000	295,000	78,200,000
1930				
July	323,000	166,000	249,000	7,700,000
August	432,000	203,000	298,000	9,300,000
September	357,000	256,000	324,000	9,700,000
October	272,000	143,000	223,000	6,900,000
November	240,000	140,000	183,000	5,500,000
December	147,000	78,000	102,000	3,200,000
The period	432,000	78,000	230,000	42,300,000
1931				
January	75,000	59,000	69,000	2,100,000
February	58,000	40,000	49,000	1,400,000
March	160,000	49,000	78,000	2,400,000
April	357,000	180,000	226,000	6,800,000
May	298,000	127,000	222,000	6,900,000
June	357,000	127,000	213,000	6,400,000
July	413,000	153,000	344,000	10,600,000
August	413,000	213,000	333,000	10,300,000
September	451,000	180,000	336,000	10,100,000
October	348,000	225,000	282,000	8,800,000
November	220,000	158,000	181,000	5,400,000
December	156,000	79,000	111,000	3,400,000
The year	451,000	40,000	204,000	74,600,000
1932				
January	510,000	79,000	281,000	8,700,000
February	510,000	140,000	334,000	9,700,000
March	288,000	127,000	180,000	5,600,000
April	209,000	127,000	174,000	5,200,000
May	376,000	209,000	288,000	8,900,000
June	351,000	216,000	266,000	8,000,000
July	256,000	166,000	207,000	6,400,000
August	209,000	157,000	196,000	6,100,000
September	240,000	140,000	196,000	5,900,000
October	194,000	114,000	150,000	4,700,000
November	357,000	114,000	233,000	7,000,000
December	395,000	140,000	213,000	6,700,000
The year	510,000	79,000	226,000	82,900,000

Discharge of Tunnel 87 (Moaula Gulch Tunnel)—continued

1933				
January	550,000	150,000	287,000	8,900,000
February	422,000	140,000	223,000	6,300,000
March	530,000	134,000	304,000	9,400,000
April	490,000	127,000	282,000	8,500,000
May	471,000	153,000	287,000	8,900,000
June	395,000	141,000	233,000	7,000,000
July	140,000	102,000	122,000	3,800,000
August	240,000	91,000	176,000	5,500,000
September	209,000	153,000	187,000	5,600,000
October	240,000	140,000	181,000	5,600,000
November	194,000	97,000	153,000	4,600,000
December	94,000	79,000	89,000	2,800,000
The year	550,000	79,000	210,000	76,900,000
1934				
January	272,000	69,000	151,000	4,700,000
February	240,000	127,000	192,000	5,400,000
March	357,000	194,000	274,000	8,500,000
April	510,000	194,000	246,000	7,400,000
May	521,000	180,000	379,000	11,700,000
June	550,000	209,000	363,000	10,900,000
July	490,000	240,000	327,000	10,100,000
August	432,000	272,000	325,000	10,100,000
September	376,000	256,000	314,000	9,400,000
October	356,000	209,000	255,000	7,900,000
November	395,000	240,000	302,000	9,100,000
December	256,000	127,000	174,000	5,400,000
The year	550,000	69,000	275,000	100,600,000
1935				
January	256,000	127,000	171,000	5,300,000
February	225,000	114,000	190,000	5,300,000
March	323,000	209,000	262,000	8,100,000
April	395,000	225,000	305,000	9,200,000
May	312,000	180,000	233,000	7,200,000
June	451,000	288,000	354,000	10,600,000
July	323,000	256,000	311,000	9,700,000
August	469,000	256,000	379,000	11,700,000
September	550,000	194,000	359,000	10,800,000
October	613,000	261,000	357,000	10,700,000
November	259,000	194,000	235,000	7,100,000
The period	613,000	114,000	287,000	95,700,000

Discharge of Tunnel 89 (Fukuda Tunnel)

(Data from C. Brewer and Co., Ltd., and Hawaiian Agricultural Co., Ltd.)

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1925				
January	49,000	45,000	39,000	1,200,000
February	....	42,000	43,000	1,200,000
March	269,000	49,000	155,000	4,800,000
April	207,000	58,000	100,000	3,000,000
May	288,000	193,000	242,000	7,500,000
June	320,000	151,000	227,000	6,800,000
July	138,000	89,000	145,000	4,500,000
August	238,000	144,000	161,000	5,000,000
September	547,000	171,000	317,000	9,500,000
October	808,000	207,000	390,000	12,100,000
November	320,000	89,000	173,000	5,200,000
December	68,000	22,000	45,000	1,400,000
The year	808,000	22,000	170,000	62,200,000
1927				
January	127,000	69,000	110,000	3,400,000
February	127,000	79,000	107,000	3,000,000
March	180,000	79,000	135,000	4,200,000
April	376,000	194,000	277,000	8,300,000
May	238,000	127,000	187,000	5,800,000
June	272,000	166,000	217,000	6,500,000
July	114,000	49,000	71,000	2,200,000
August	395,000	49,000	158,000	4,900,000
September	510,000	272,000	373,000	11,200,000
October	323,000	180,000	245,000	7,600,000
November	240,000	102,000	177,000	5,300,000
December	986,000	102,000	590,000	18,300,000
The year	986,000	49,000	221,000	80,700,000
1928				
January	153,000	59,000	165,000	5,100,000
February	225,000	91,000	145,000	4,200,000
March	114,000	49,000	71,000	2,200,000
April	724,000	91,000	320,000	9,600,000
May	376,000	240,000	294,000	9,100,000
June	576,000	127,000	357,000	10,700,000
July	395,000	225,000	323,000	10,000,000
August	680,000	127,000	355,000	11,000,000
September	323,000	194,000	267,000	8,000,000
October	256,000	127,000	194,000	6,000,000
November	272,000	102,000	163,000	4,900,000
December	91,000	59,000	71,000	2,200,000
The year	724,000	49,000	227,000	83,000,000
1929				
January	209,000	69,000	129,000	4,000,000
February	305,000	272,000	300,000	8,400,000
March	746,000	209,000	455,000	14,100,000
April	635,000	127,000	307,000	9,200,000
May	395,000	140,000	252,000	7,800,000
June	272,000	79,000	177,000	5,300,000
July	635,000	166,000	474,000	14,700,000
August	635,000	180,000	484,000	15,000,000
September	357,000	225,000	277,000	8,300,000
October	305,000	240,000	303,000	9,400,000
November	572,000	240,000	337,000	10,100,000
December	376,000	194,000	281,000	8,700,000
The year	746,000	69,000	315,000	115,000,000

Discharge of Tunnel 89 (Fukuda Tunnel)—continued

1930				
July	225,000	166,000	200,000	6,200,000
August	357,000	153,000	252,000	7,800,000
September	305,000	240,000	289,000	8,700,000
October	256,000	130,000	206,000	6,400,000
November	225,000	108,000	157,000	4,700,000
December	108,000	45,000	62,000	1,900,000
The period	357,000	45,000	194,000	35,700,000
1931				
January	45,000	24,000	37,000	1,200,000
February	32,000	17,000	20,000	600,000
March	163,000	24,000	63,000	2,000,000
April	305,000	163,000	210,000	6,300,000
May	242,000	102,000	181,000	5,600,000
June	288,000	91,000	180,000	5,400,000
July	305,000	102,000	249,000	7,700,000
August	256,000	127,000	194,000	6,000,000
September	288,000	79,000	174,000	5,200,000
October	252,000	180,000	216,000	6,700,000
November	323,000	114,000	181,000	5,400,000
December	144,000	32,000	56,000	1,700,000
The year	323,000	17,000	147,000	53,800,000
1932				
January	357,000	32,000	206,000	6,400,000
February	340,000	127,000	249,000	7,200,000
March	256,000	69,000	140,000	4,300,000
April	127,000	59,000	85,000	2,500,000
May	313,000	150,000	229,000	7,100,000
June	294,000	157,000	199,000	6,000,000
July	194,000	114,000	157,000	4,900,000
August	209,000	145,000	187,000	5,800,000
September	272,000	127,000	180,000	5,400,000
October	166,000	59,000	114,000	3,500,000
November	323,000	79,000	215,000	6,400,000
December	288,000	102,000	174,000	5,400,000
The year	357,000	32,000	178,000	64,900,000
1933				
January	340,000	91,000	196,000	6,100,000
February	298,000	105,000	173,000	4,800,000
March	376,000	98,000	223,000	6,900,000
April	323,000	91,000	207,000	6,200,000
May	284,000	114,000	206,000	6,400,000
June	340,000	94,000	184,000	5,500,000
July	91,000	46,000	72,000	2,200,000
August	153,000	40,000	118,000	3,700,000
September	153,000	79,000	122,000	3,700,000
October	120,000	91,000	105,000	3,300,000
November	153,000	72,000	118,000	3,500,000
December	71,000	49,000	59,000	1,800,000
The year	376,000	40,000	149,000	54,100,000

Discharge of Tunnel 89 (Fukuda Tunnel)—continued

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1934				
January	166,000	40,000	92,000	2,900,000
February	145,000	91,000	124,000	3,500,000
March	194,000	151,000	177,000	5,500,000
April	395,000	114,000	193,000	5,800,000
May	360,000	166,000	297,000	9,200,000
June	376,000	180,000	278,000	8,300,000
July	357,000	225,000	265,000	8,200,000
August	340,000	233,000	271,000	8,400,000
September	305,000	225,000	259,000	7,800,000
October	271,000	194,000	220,000	6,800,000
November	272,000	180,000	228,000	6,800,000
December	240,000	102,000	154,000	4,800,000
The year	395,000	40,000	213,000	78,000,000
1935				
January	127,000	69,000	105,000	3,300,000
February	127,000	91,000	124,000	3,500,000
March	272,000	206,000	239,000	7,400,000
April	288,000	194,000	240,000	7,200,000
May	225,000	153,000	186,000	5,800,000
June	305,000	240,000	248,000	7,400,000
July	264,000	180,000	215,000	6,700,000
August	376,000	194,000	308,000	9,600,000
September	432,000	153,000	285,000	8,500,000
October	357,000	166,000	243,000	7,500,000
November	272,000	140,000	186,000	5,600,000
December	....	....	....	....
The year	432,000	69,000	216,000	72,500,000

Discharge of Tunnel 90 (Kaumaikeohu Tunnel)

(Data from C. Brewer and Co., Ltd., and Hawaiian Agricultural Co., Ltd.)

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1925				
January	138,000	32,000	65,000	2,000,000
February	....	22,000	32,000	900,000
March	355,000	32,000	168,000	5,200,000
April	127,000	40,000	83,000	2,500,000
May	390,000	....	265,000	8,200,000
June	1,263,000	164,000	423,000	12,700,000
July	....	164,000	368,000	11,400,000
August	180,000	115,000	161,000	5,000,000
September	720,000	138,000	403,000	12,100,000
October	1,004,000	223,000	523,000	16,200,000
November	485,000	79,000	237,000	7,100,000
December	58,000	32,000	45,000	1,400,000
The year	1,263,000	22,000	232,000	84,700,000
1927				
January	153,000	79,000	123,000	3,800,000
February	114,000	69,000	86,000	2,400,000
March	209,000	91,000	139,000	4,300,000
April	256,000	194,000	237,000	7,100,000
May	207,000	127,000	171,000	5,300,000
June	305,000	153,000	207,000	6,200,000
July	256,000	32,000	100,000	3,100,000
August	469,000	49,000	174,000	5,400,000
September	635,000	256,000	400,000	12,000,000
October	305,000	194,000	245,000	7,600,000
November	256,000	91,000	177,000	5,300,000
December	1,302,000	114,000	719,000	22,300,000
The year	1,302,000	32,000	232,000	84,800,000
1928				
January	....	59,000	194,000	6,000,000
February	240,000	69,000	138,000	4,000,000
March	102,000	49,000	77,000	2,400,000
April	1,011,000	114,000	410,000	12,300,000
May	451,000	240,000	332,000	10,300,000
June	1,089,000	127,000	463,000	13,900,000
July	469,000	209,000	355,000	11,000,000
August	1,104,000	127,000	526,000	16,300,000
September	395,000	209,000	333,000	10,000,000
October	256,000	127,000	203,000	6,300,000
November	305,000	79,000	187,000	5,600,000
December	79,000	59,000	71,000	2,200,000
The year	1,104,000	49,000	274,000	100,300,000
1929				
January	240,000	59,000	139,000	4,300,000
February	635,000	288,000	500,000	14,000,000
March	1,274,000	225,000	619,000	19,200,000
April	1,274,000	102,000	490,000	14,700,000
May	657,000	140,000	309,000	9,600,000
June	288,000	79,000	180,000	5,400,000
July	1,274,000	180,000	706,000	21,900,000
August	864,000	127,000	642,000	19,900,000
September	357,000	194,000	237,000	7,100,000
October	....	194,000	245,000	7,600,000
November	550,000	209,000	297,000	8,900,000
December	288,000	166,000	245,000	7,600,000
The year	1,274,000	59,000	384,000	140,200,000

Discharge of Tunnel 90 (Kaumaikeohu Tunnel)—continued

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1930				
July	194,000	153,000	180,000	5,600,000
August	209,000	166,000	186,000	5,700,000
September	209,000	180,000	193,000	5,800,000
October	194,000	166,000	170,000	5,200,000
November	240,000	79,000	138,000	4,200,000
December	69,000	40,000	58,000	1,800,000
The period	240,000	40,000	154,000	28,300,000
1931				
January	59,000	24,000	37,000	1,200,000
February	24,000	17,000	19,000	500,000
March	59,000	24,000	52,000	1,600,000
April	225,000	180,000	191,000	5,700,000
May	209,000	102,000	170,000	5,200,000
June	272,000	69,000	167,000	5,000,000
July	272,000	91,000	222,000	6,900,000
August	240,000	166,000	191,000	5,900,000
September	288,000	102,000	223,000	6,700,000
October	256,000	166,000	206,000	6,400,000
November	194,000	102,000	143,000	4,300,000
December	79,000	31,000	55,000	1,700,000
The year	288,000	17,000	140,000	51,100,000
1932				
January	288,000	24,000	176,000	5,400,000
February	305,000	114,000	228,000	6,600,000
March	225,000	91,000	130,000	4,000,000
April	127,000	59,000	88,000	2,600,000
May	305,000	166,000	219,000	6,800,000
June	225,000	180,000	199,000	6,000,000
July	194,000	102,000	148,000	4,600,000
August	194,000	166,000	174,000	5,400,000
September	240,000	114,000	168,000	5,000,000
October	140,000	69,000	104,000	3,200,000
November	288,000	69,000	204,000	6,100,000
December	225,000	91,000	156,000	4,800,000
The year	305,000	24,000	166,000	60,500,000
1933				
January	272,000	102,000	177,000	5,500,000
February	180,000	127,000	148,000	4,100,000
March	305,000	127,000	196,000	6,100,000
April	272,000	91,000	189,000	5,700,000
May	256,000	91,000	193,000	6,000,000
June	256,000	102,000	171,000	5,100,000
July	69,000	48,000	60,000	1,900,000
August	127,000	40,000	101,000	3,100,000
September	166,000	91,000	117,000	3,500,000
October	114,000	79,000	94,000	2,900,000
November	114,000	79,000	101,000	3,000,000
December	69,000	59,000	62,000	1,900,000
The year	305,000	40,000	134,000	48,800,000

Discharge of Tunnel 90 (Kaumaikeohu Tunnel)—continued

1934				
January	127,000	40,000	79,000	2,500,000
February	91,000	91,000	105,000	2,900,000
March	209,000	153,000	166,000	5,100,000
April	340,000	127,000	184,000	5,500,000
May	272,000	140,000	246,000	7,600,000
June	305,000	180,000	246,000	7,400,000
July	288,000	166,000	219,000	6,800,000
August	323,000	194,000	236,000	7,300,000
September	272,000	209,000	239,000	7,200,000
October	225,000	140,000	192,000	5,900,000
November	256,000	180,000	207,000	6,200,000
December	209,000	114,000	141,000	4,400,000
The year........	340,000	40,000	188,000	68,800,000
1935				
January	127,000	91,000	102,000	3,200,000
February	153,000	59,000	115,000	3,200,000
March	256,000	194,000	223,000	6,900,000
April	288,000	166,000	230,000	6,900,000
May	209,000	153,000	179,000	5,500,000
June	272,000	224,000	222,000	6,700,000
July	194,000	153,000	183,000	5,700,000
August	288,000	180,000	253,000	7,800,000
September	305,000	153,000	229,000	6,900,000
October	305,000	194,000	200,000	6,200,000
November	225,000	153,000	180,000	5,400,000
December	....	....	....	....
The year........	305,000	59,000	192,000	64,400,000

Discharge of Tunnel 91 (Domestic Supply Tunnel)

(Data from C. Brewer and Co., Ltd., and Hawaiian Agricultural Co., Ltd.)

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1925[a]				
February[b]	50,000	....	39,000	[c]1,100,000
March	119,000	....	94,000	2,900,000
April	96,000	63,000	83,000	2,500,000
May	135,000	69,000	110,000	3,400,000
June	112,000	86,000	107,000	3,200,000
July	89,000	76,000	87,000	2,700,000
August	....	82,000	97,000	3,000,000
September	151,000	103,000	120,000	3,600,000
October	372,000	168,000	212,000	6,600,000
November	356,000	202,000	257,000	7,700,000
December	151,000	79,000	116,000	3,600,000
The period	372,000	48,000	124,000	40,300,000
1926[a]				
January	207,000	68,000	116,000	3,600,000
February	193,000	89,000	146,000	4,100,000
March	101,000	79,000	100,000	3,100,000
April	225,000	114,000	127,000	3,800,000
May	320,000	207,000	261,000	8,100,000
June	900,000	138,000	507,000	15,200,000
July	1,128,000	390,000	677,000	21,000,000
August	1,771,000	302,000	800,000	24,800,000
September	1,128,000	465,000	760,000	22,800,000
October	490,000	372,000	432,000	13,400,000
November	592,000	209,000	430,000	12,900,000
December	912,000	166,000	468,000	14,500,000
The year	1,771,000	68,000	404,000	147,300,000
1927[a]				
January	395,000	166,000	294,000	9,100,000
February	180,000	166,000	161,000	4,500,000
March	272,000	127,000	229,000	7,100,000
April	1,302,000	413,000	797,000	23,900,000
May	510,000	323,000	455,000	14,100,000
June	635,000	305,000	423,000	12,700,000
July	225,000	114,000	181,000	5,600,000
August	395,000	91,000	194,000	6,000,000
September	1,274,000	340,000	847,000	25,400,000
October	816,000	357,000	648,000	20,100,000
November	395,000	288,000	333,000	10,000,000
December	1,889,000	166,000	1,065,000	33,000,000
The year	1,889,000	91,000	470,000	171,500,000
1928[a]				
January	592,000	194,000	455,000	14,100,000
February	225,000	91,000	162,000	4,700,000
March	272,000	108,000	171,000	5,300,000
April	1,195.000	140,000	567,000	17,000,000
May	572,000	469,000	519,000	16,100,000
June	592,000	376,000	483,000	14,500,000
July	635,000	323,000	448,000	13,900,000
August	864,000	223,000	390,000	12,100,000
September	572,000	395,000	530,000	15,900,000
October	1,274,000	323,000	584,000	18,100,000
November	550,000	241,000	373,000	11,200,000
December	240,000	134,000	174,000	5,400,000
The year	1,274,000	91,000	405,000	148,300,000

Discharge of Tunnel 91 (Domestic Supply Tunnel)—continued

1929				
January	209,000	127.000	174.000	5,400.000
February	451.000	209.000	339.000	9.800.000
March	680.000	357,000	548,000	17,000.000
April	680.000	240.000	463,000	13,900.000
May	357.000	272.000	326.000	10.100.000
June	510,000	272,000	363,000	10.900.000
July	550,000	153.000	355.000	11,000.000
August	657,000	323,000	539,000	16.700,000
September	887,000	323.000	550,000	16,500.000
October	864.000	166,000	410,000	12,700,000
November	1,089,000	451,000	783,000	23,500,000
December	746,000	272,000	481,000	14.900.000
The year	1.069.000	127.000	444.000	162,400.000
1930				
July	357,000	305,000	331,000	10,200,000
August	816.000	387,000	608,000	18,800,000
September	769,000	490,000	588,000	17,600,000
October	510,000	287,000	442,000	13,700,000
November	357.000	186,000	282,000	8,500,000
December	194,000	94,000	141,000	4,400.000
The period	816.000	94.000	399,000	73,200.000
1931				
January	89,000	46,000	66.000	2,000,000
February	43,000	24,000	30,000	800,000
March	164,000	17,000	52,000	1,600,000
April	550,000	226,000	361,000	10,800,000
May	592,000	194.000	413,000	12,800,000
June	510,000	160,000	357,000	10,700.000
July	490,000	127,000	264,000	8,200,000
August	420,000	225,000	308,000	9,600,000
September	579,000	194,000	304,000	9,100,000
October	701,000	323,000	513,000	15,900,000
November	312,000	132,000	203,000	6,100,000
December	130,000	52.000	89,000	2,700,000
The year	701.000	17.000	247.000	90.300.000
1932				
January	936,000	49,000	356,000	11,000,000
February	724,000	395,000	567,000	16,400,000
March	550,000	156,000	314,000	9,800,000
April	154,000	102,000	124,000	3,700,000
May	330,000	180,000	222,000	6,900,000
June	376,000	288,000	325.000	9,800,000
July	340,000	180,000	255,000	7,900.000
August	262,000	180,000	216,000	6,700,000
September	572,000	264,000	357,000	10,700,000
October	272,000	166,000	223,000	6,900,000
November	613,000	166,000	387,000	11,600,000
December	530,000	180,000	356,000	11,000,000
The year	936,000	49.000	308.000	112.400.000

Discharge of Tunnel 91 (Domestic Supply Tunnel)—continued

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1933				
January	510,000	288,000	369,000	11,400,000
February	459,000	294,000	366,000	10,200,000
March	550,000	216,000	380,000	11,800,000
April	572,000	180,000	384,000	11,500,000
May	507,000	288,000	413,000	12,800,000
June	550,000	207,000	367,000	11,000,000
July	194,000	114,000	153,000	4,700,000
August	209,000	102,000	156,000	4,800,000
September	209,000	127,000	164,000	4,900,000
October	171,000	114,000	135,000	4,200,000
November	225,000	180,000	194,000	5,800,000
December	161,000	114,000	135,000	4,200,000
The year	572,000	102,000	268,000	97,300,000
1934				
January	288,000	114,000	187,000	5,800,000
February	269,000	209,000	230,000	6,500,000
March	357,000	169,000	321,000	10,000,000
April	451,000	256,000	312,000	9,400,000
May	539,000	323,000	420,000	13,000,000
June	550,000	323,000	412,000	12,400,000
July	530,000	268,000	397,000	12,300,000
August	592,000	256,000	400,000	12,400,000
September	550,000	340,000	431,000	12,900,000
October	530,000	272,000	354,000	11,000,000
November	680,000	301,000	516,000	15,400,000
December	340,000	242,000	294,000	9,100,000
The year	680,000	114,000	356,000	130,200,000
1935				
January	323,000	194,000	259,000	8,000,000
February	291,000	180,000	238,000	6,700,000
March	550,000	302,000	472,000	14,600,000
April	592,000	323,000	422,000	12,700,000
May	340,000	256,000	293,000	9,100,000
June	490,000	305,000	387,000	11,600,000
July	324,000	240,000	288,000	9,000,000
August	530,000	305,000	416,000	12,900,000
September	613,000	357,000	471,000	14,100,000
October	724,000	316,000	527,000	16,300,000
November	340,000	256,000	304,000	9,100,000
The period	724,000	180,000	371,000	124,100,000

[a] Tunnel under construction.

[b] Through August, the water is that of the old spring at which the tunnel was driven. A drought in December resulted in drying up of most of new water, while the flow of the old spring continued nearly constant.

[c] Beginning February 10.

Discharge of Tunnel 93 (Plantation Spring Tunnel)[a]

(Data from Hutchinson Sugar Plantation Co. and C. Brewer and Co., Ltd.)

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1925[b]				
January	68,000	40,000	45,000	1,400,000
February	49,000	36,000	43,000	1,200,000
March	69,000	60,000	68,000	2,100,000
April	82,000	....	63,000	1,900,000
May	196,000	76,000	113,000	3,500,000
June	196,000	112,000	150,000	4,500,000
July	135,000	96,000	106,000	3,300,000
August	148,000	122,000	139,000	4,300,000
September	158,000	122,000	140,000	4,200,000
October	268,000	230,000	232,000	7,200,000
November	206,000	151,000	180,000	5,400,000
December	137,000	89,000	110,000	3,400,000
The year	268,000	36,000	116,000	42,400,000
1926[b]				
January	372,000	223,000	281,000	8,700,000
February	372,000	278,000	293,000	8,200,000
March	390,000	253,000	310,000	9,600,000
April	372,000	253,000	333,000	10,000,000
May	785,000	409,000	590,000	18,300,000
June	855,000	505,000	663,000	19,900,000
July	1,800,000	723,000	1,087,000	33,700,000
August	2,808,000	1,051,000	1,781,000	55,200,000
September	2,785,000	1,011,000	1,677,000	50,300,000
October	1,642,000	662,000	1,058,000	32,800,000
November	1,066,000	518,000	723,000	21,700,000
December	1,354,000	432,000	800,000	24,800,000
The year	2,808,000	223,000	803,000	293,200,000
1927[b]				
January	180,000	166,000	181,000	5,600,000
February	180,000	127,000	150,000	4,200,000
March	140,000	127,000	135,000	4,200,000
April	194,000	180,000	187,000	5,600,000
May	272,000	225,000	232,000	7,200,000
June	272,000	194,000	240,000	7,200,000
July	180,000	166,000	174,000	5,400,000
August	194,000	180,000	187,000	5,800,000
September	272,000	225,000	230,000	6,900,000
October	288,000	240,000	252,000	7,800,000
November	209,000	153,000	187,000	5,600,000
December	272,000	180,000	210,000	6,500,000
The year	288,000	127,000	197,000	72,000,000
1928[b]				
January	256,000	140,000	194,000	6,000,000
February	140,000	140,000	140,000	4,000,000
March	127,000	114,000	123,000	3,800,000
April	194,000	127,000	150,000	4,500,000
May	225,000	194,000	203,000	6,300,000
June	256,000	194,000	223,000	6,700,000
July	272,000	209,000	229,000	7,100,000
August	209,000	194,000	203,000	6,300,000
September	209,000	180,000	200,000	6,000,000
October	....	166,000	181,000	5,600,000
November	180,000	153,000	177,000	5,300,000
December	153,000	153,000	153,000	5,100,000
The year	256,000	114,000	182,000	66,700,000

Discharge of Tunnel 93 (Plantation Spring Tunnel)—continued

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1929				
July	166,000	140,000	161,000	4,978,000
August	166,000	166,000	166,000	5,134,000
September	166,000	166,000	166,000	4,968,000
October	166,000	166,000	166,000	5,134,000
November	180,000	180,000	180,000	5,400,000
December	180,000	180,000	180,000	5,580,000
The period	180,000	140,000	170,000	31,194,000
1930				
January	180,000	180,000	180,000	5,580,000
February	180,000	180,000	180,000	5,040,000
March	180,000	153,000	174,000	5,388,000
April	180,000	180,000	180,000	5,400,000
May	194,000	180,000	192,000	5,954,000
June	194,000	194,000	194,000	5,820,000
July	194,000	194,000	194,000	6,026,000
August	225,000	194,000	204,000	6,309,000
September	225,000	225,000	225,000	6,739,000
October	225,000	180,000	213,000	6,596,000
November	166,000	153,000	164,000	4,928,000
December	140,000	140,000	140,000	4,330,000
The year	225,000	140,000	187,000	68,110,000
1931				
January	140,000	140,000	140,000	4,330,000
February	140,000	127,000	134,000	3,756,000
March	127,000	114,000	117,000	3,630,000
April	140,000	140,000	140,000	4,190,000
May	140,000	140,000	140,000	4,330,000
June	140,000	140,000	140,000	4,190,000
July	166,000	140,000	162,000	5,017,000
August	194,000	166,000	190,000	5,897,000
September	194,000	180,000	192,000	5,767,000
October	225,000	194,000	213,000	6,616,000
November	194,000	180,000	192,000	5,764,000
December	166,000	127,000	141,000	4,385,000
The year	225,000	114,000	158,000	58,872,000
1932				
January	....	....	....	....
February	153,000	153,000	153,000	4,427,000
March	153,000	153,000	153,000	4,732,000
April	153,000	140,000	150,000	4,488,000
May	153,000	153,000	153,000	4,732,000
June	153,000	153,000	153,000	4,579,000
July	153,000	140,000	144,000	4,473,000
August	140,000	140,000	140,000	4,330,000
September	153,000	140,000	145,000	4,352,000
October	140,000	127,000	130,000	4,045,000
November	140,000	127,000	136,000	4,093,000
December	140,000	140,000	140,000	4,330,000
The year	153,000	127,000	145,000	....

Discharge of Tunnel 93 (Plantation Spring Tunnel)—continued

1933				
January	140,000	140,000	140,000	4,330,000
February	140,000	140,000	140,000	3,911,000
March	140,000	140,000	140,000	4,330,000
April	153,000	140,000	142,000	4,255,000
May	153,000	153,000	153,000	4,743,000
June	153,000	153,000	153,000	4,579,000
July	153,000	153,000	153,000	4,743,000
August	153,000	140,000	152,000	4,698,000
September	140,000	140,000	140,000	4,200,000
October	140,000	127,000	134,000	4,152,000
November	127,000	114,000	120,000	3,596,000
December	114,000	91,000	101,000	3,144,000
The year	153,000	91,000	139,000	50,681,000
1934				
January	102,000	91,000	97,000	2,997,000
February	102,000	102,000	102,000	2,856,000
March	102,000	102,000	102,000	3,162,000
April	102,000	102,000	102,000	3,060,000
May	140,000	102,000	118,000	3,670,000
June	194,000	153,000	168,000	5,041,000
July	153,000	153,000	153,000	4,743,000
August	153,000	153,000	153,000	4,743,000
September	153,000	153,000	153,000	4,590,000
October	155,000	153,000	154,000	4,782,000
November	166,000	153,000	155,000	4,649,000
December	153,000	153,000	153,000	4,743,000
The year	194,000	91,000	134,000	49,036,000
1935				
January	153,000	140,000	152,000	4,698,000
February	140,000	127,000	136,000	3,797,000
March	127,000	127,000	127,000	3,937,000
April	140,000	127,000	133,000	3,999,000
May	140,000	140,000	140,000	4,340,000
June	140,000	140,000	140,000	4,200,000
July	140,000	140,000	140,000	4,340,000
August	140,000	140,000	140,000	4,340,000
September	140,000	140,000	140,000	4,200,000
October	140,000	140,000	140,000	4,340,000
November	140,000	114,000	137,000	4,096,000
December	140,000	114,000	132,000	4,093,000
The year	153,000	114,000	138,000	50,380,000
1936				
January	114,000	114,000	114,000	3,534,000
February	114,000	114,000	114,000	3,306,000
March	114,000	114,000	114,000	3,534,000
April	114,000	114,000	114,000	3,420,000
May	114,000	114,000	114,000	3,534,000
June	114,000	114,000	114,000	3,420,000
July	140,000	114,000	129,000	3,989,000
August	140,000	140,000	140,000	4,340,000
September	140,000	140,000	140,000	4,200,000
October	140,000	140,000	140,000	4,340,000
November	140,000	102,000	123,000	3,687,000
December	140,000	91,000	104,000	3,218,000
The year	140,000	91,000	122,000	44,522,000

Discharge of Tunnel 93 (Plantation Spring Tunnel)—continued

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1937				
January	140,000	102,000	120,000	3,705,000
February	140,000	140,000	140,000	3,920,000
March	140,000	140,000	140,000	4,340,000
April	140,000	127,000	132,000	3,960,000
May	153,000	140,000	152,000	4,711,000
June	153,000	127,000	144,000	4,317,000
July	140,000	127,000	135,000	4,197,000
August	153,000	140,000	150,000	4,659,000
September	153,000	153,000	153,000	4,590,000
October	153,000	153,000	153,000	4,743,000
November	153,000	127,000	133,000	3,979,000
December	127,000	127,000	127,000	3,937,000
The year	153,000	102,000	140,000	51,100,000
1938				
January	127,000	127,000	127,000	3,937,000
February	153,000	140,000	148,000	4,154,000
March	140,000	140,000	140,000	4,340,000
April	140,000	140,000	140,000	4,200,000
May	153,000	140,000	145,000	4,496,000
June	153,000	153,000	153,000	4,590,000
The period	153,000	127,000	142,000	25,717,000

[a] Weir read about 5 times a month from 1929 on.

[b] Tunnel under construction.

Discharge of Tunnel 95 (New Mountain House Tunnel)[a]

(Data from Hutchinson Sugar Plantation Co. and C. Brewer and Co., Ltd.)

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1924[b]				
January	....	....	413,000	12,800,000
February	....	....	145,000	4,200,000
March	....	....	232,000	7,200,000
April	....	....	667,000	20,000,000
May	....	....	916,000	28,400,000
June	....	....	810,000	24,300,000
July	....	....	671,000	20,800,000
August	....	....	774,000	24,000,000
September	....	....	717,000	21,500,000
October	....	....	1,300,000	40,300,000
November	....	....	690,000	20,700,000
December	....	....	368,000	11,400,000
The year	....	....	642,000	235,600,000
1925[b]				
January	287,000	207,000	248,000	7,700,000
February	215,000	193,000	214,000	6,000,000
March	485,000	193,000	365,000	11,300,000
April	785,000	377,000	433,000	13,000,000
May	1,263,000	785,000	1,052,000	32,600,000
June	1,857,000	906,000	1,337,000	40,100,000
July	1,231,000	546,000	774,000	24,000,000
August	1,220,000	588,000	781,000	24,200,000
September	1,735,000	670,000	1,007,000	30,200,000
October	1,705,000	550,000	977,000	30,300,000
November	1,385,000	490,000	760,000	22,800,000
December	490,000	256,000	361,000	11,200,000
The year	1,857,000	193,000	694,000	253,400,000
1926[b]				
January	372,000	223,000	281,000	8,700,000
February	372,000	238,000	293,000	8,200,000
March	390,000	253,000	310,000	9,600,000
April	372,000	253,000	333,000	10,000,000
May	785,000	409,000	590,000	18,300,000
June	855,000	505,000	663,000	19,900,000
July	1,800,000	723,000	1,087,000	33,700,000
August	2,808,000	1,051,000	1,781,000	55,200,000
September	2,785,000	1,011,000	1,677,000	50,300,000
October	1,642,000	662,000	1,058,000	32,800,000
November	1,066,000	518,000	723,000	21,700,000
December	1,354,000	432,000	800,000	24,800,000
The year	2,808,000	223,000	803,000	293,200,000
1927[b]				
January	1,185,000	513,000	729,000	22,000,000
February	611,000	389,000	500,000	14,000,000
March	825,000	362,000	497,000	15,400,000
April	1,403,000	752,000	967,000	29,000,000
May	1,824,000	901,000	1,326,000	41,100,000
June	4,113,000	645,000	1,727,000	51,800,000
July	611,000	481,000	548,000	17,000,000
August	1,228,000	449,000	913,000	28,300,000
September	2,464,000	1,228,000	1,853,000	55,600,000
October	1,728,000	1,143,000	1,477,000	45,800,000
November	1,185,000	449,000	810,000	24,300,000
December	3,149,000	481,000	2,045,000	63,400,000
The year	4,113,000	362,000	1,119,000	408,300,000

Discharge from Tunnel 95 (New Mountain House Tunnel)—continued

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1928[b]				
June	1.922,000	752,000	1.377,000	41,300,000
July	1,584,000	901,000	1.197,000	37,100,000
August	2,742,000	1,447,000	1,806,000	56,000,000
September	2,229,000	1,102,000	1.473,000	44,200,000
October	2,282,000	1,102,000	1,565,000	48,500,000
November	1,539,000	752,000	1.050,000	31,500,000
December	716,000	611,000	626,000	19,400,000
The period	2,282,000	611,000	1,299,000	278.000.000
1929				
July	1,725,000	937,000	1.260,000	39,073,000
August	2,023,000	1,448,000	1,736,000	53,803,000
September	1,920,000	1,099,000	1,457,000	43,695,000
October	1,920,000	1,312,000	1,550,000	48,061,000
November	....	....	....	....
December	2,546,000	827,000	1.270,000	39,370,000
The period	2.546,000	827.000	1,455.000	....
1930				
January	827,000	543,000	714,000	22,136,000
February	575,000	511,000	537,000	15,028,000
March	827,000	446,000	595,000	18,431,000
April	1,448,000	750,000	1.165,000	34,959,000
May	1,777,000	1,099,000	1,424,000	44,159,000
June	2,281,000	1,312,000	2,020,000	60,589,000
July	2,281,000	1,228,000	1,534,000	47,539,000
August	3,115,000	1,273,000	2,384,000	73,914,000
September	2,715,000	1,726,000	2,221,000	66,636,000
October	2,824,000	982,000	1,780,000	55,168,000
November	982,000	717,000	771,000	23,142,000
December	717,000	478,000	576,000	17,866,000
The year	3.115,000	446,000	1.310,000	479,567,000
1931				
January	478,000	330,000	407,000	12,623,000
February	388,000	304,000	360,000	10,079,000
March	330,000	252,000	288,000	8,927,000
April	1,273,000	252,000	697,000	20,922,000
May	1,273,000	788,000	999,000	30,984,000
June	1,357,000	788,000	1,066,000	31,965,000
July	2,656,000	788,000	1,839,000	57,023,000
August	2,715,000	1,312,000	2,191,000	67,932,000
September	2,656,000	1,099,000	1,491,000	44,719,000
October	2,656,000	1,312,000	2,048,000	63,475,000
November	1,228,000	717,000	931,000	27,924,000
December	1,021,000	511,000	679,000	21,061,000
The year	2,715,000	252,000	1,083,000	397,634,000

Discharge from Tunnel 95 (New Mountain House Tunnel)—continued

1932				
January	2,126,000	478,000	1,111,000	34,452,000
February	2,126,000	1,228,000	1,682,000	48,781,000
March	1,777,000	750,000	1,183,000	36,688,000
April	1,162,000	652,000	883,000	26,479,000
May	3,089,000	971,000	1,610,000	49,918,000
June	3,496,000	1,489,000	2,141,000	64,241,000
July	1,529,000	1,045,000	1,236,000	38,323,000
August	1,241,000	1,045,000	1,160,000	35,963,000
September	1,881,000	971,000	1,432,000	42,958,000
October	1,045,000	652,000	804,000	24,919,000
November	1,659,000	685,000	1,196,000	35,880,000
December	2,110,000	824,000	1,424,000	44,153,000
The year	3,496,000	478,000	1,322,000	482,755,000
1933				
January	1,446,000	824,000	1,291,000	40,018,000
February	1,572,000	1,282,000	1,402,000	39,266,000
March	1,572,000	789,000	1,311,000	40,651,000
April	1,881,000	720,000	1,017,000	30,522,000
May	2,831,000	1,241,000	2,016,000	62,495,000
June	2,110,000	933,000	1,582,000	47,445,000
July	1,162,000	789,000	990,000	30,699,000
August	1,084,000	720,000	905,000	28,066,000
September	1,123,000	1,045,000	1,070,000	32,102,000
October	1,084,000	933,000	1,012,000	31,365,000
November	1,084,000	524,000	833,000	24,987,000
December	512,000	389,000	426,000	13,219,000
The year	2,831,000	389,000	1,155,000	420,835,000
1934				
January	825,000	389,000	536,000	16,629,000
February	825,000	544,000	635,000	17,767,000
March	611,000	544,000	562,000	17,437,000
April	611,000	513,000	571,000	17,139,000
May	1,824,000	611,000	1,163,000	36,062,000
June	4,254,000	1,680,000	2,979,000	89,361,000
July	2,282,000	1,539,000	2,007,000	62,215,000
August	1,539,000	979,000	1,223,000	37,905,000
September	1,776,000	1,315,000	1,474,000	44,214,000
October	1,539,000	1,185,000	1,270,000	39,385,000
November	1,776,000	1,270,000	1,579,000	47,383,000
December	1,270,000	611,000	883,000	27,366,000
The year	4,254,000	389,000	1,240,000	452,863,000
1935				
January	1,358,000	577,000	882,000	27,344,000
February	979,000	513,000	640,000	17,937,000
March	1,185,000	513,000	992,000	30,750,000
April	1,680,000	1,020,000	1,344,000	40,316,000
May	1,680,000	1,102,000	1,302,000	40,337,000
June	2,177,000	1,102,000	1,691,000	50,740,000
July	2,177,000	1,270,000	1,783,000	55,261,000
August	3,149,000	1,447,000	2,329,000	72,192,000
September	3,149,000	1,447,000	2,265,000	67,951,000
October	1,776,000	1,102,000	1,498,000	46,423,000
November	1,143,000	788,000	974,000	29,231,000
December	979,000	611,000	814,000	25,236,000
The year	3,149,000	513,000	1,376,000	503,715,000

Discharge from Tunnel 95 (New Mountain House Tunnel)—continued

Month	Daily discharge (gallons)			Total discharge (gallons)
	Maximum	Minimum	Average	
1936				
January	611,000	481,000	529,000	16,396,000
February	979,000	481,000	687,000	19,932,000
March	1,228,000	481,000	733,000	22,735,000
April	1,143,000	752,000	859,000	25,776,000
May	901,000	716,000	785,000	24,327,000
June	1,539,000	752,000	1,158,000	34,731,000
July	6,450,000	611,000	1,819,000	56,382,000
August	5,021,000	2,282,000	2,936,000	91,020,000
September	2,023,000	1,633,000	1,819,000	54,559,000
October	2,177,000	1,539,000	1,914,000	59,327,000
November	1,176,000	716,000	1,614,000	34,924,000
December	645,000	333,000	465,000	14,409,000
The year	6,450,000	333,000	1,276,500	454,518,000
1937				
January	2,125,000	333,000	878,000	27,219,000
February	2,464,000	1,020,000	1,885,000	52,770,000
March	1,824,000	752,000	1,241,000	38,485,000
April	2,177,000	788,000	1,324,000	39,705,000
May	3,776,000	1,447,000	2,257,000	69,965,000
June	1,873,000	901,000	1,509,000	45,278,000
July	1,680,000	863,000	1,204,000	37,322,000
August	2,854,000	1,102,000	2,048,000	63,482,000
September	2,573,000	901,000	1,932,000	57,951,000
October	2,177,000	1,358,000	1,786,000	55,368,000
November	1,315,000	611,000	904,000	27,131,000
December	1,102,000	513,000	619,000	19,191,000
The year	3,776,000	333,000	1,466,000	533,867,000
1938				
January	1,102,000	645,000	784,000	24,313,000
February	3,776,000	645,000	2,222,000	62,202,000
March	1,102,000	544,000	788,000	24,422,000
April	1,228,000	1,020,000	1,150,000	34,504,000
May	2,388,000	752,000	1,318,000	40,860,000
June	2,388,000	1,403,000	1,899,000	56,961,000
July	3,716,000	1,228,000	2,248,000	69,686,000
August	2,604,000	1,538,000	2,069,000	64,133,000
September	2,178,000	1,583,000	1,913,000	57,381,000
October	1,583,000	898,000	1,367,000	42,383,000
November	2,178,000	898,000	1,318,000	39,541,000
December	937,000	329,000	561,000	17,380,000
The year	3,776,000	329,000	1,470,000	533,766,000
1939				
January	1,312,000	542,000	932,000	28,899,000
February	2,824,000	1,312,000	1,970,000	55,147,000
March	3,115,000	1,182,000	2,100,000	65,111,000
April	2,022,000	1,147,000	1,618,000	48,525,000
May	1,628,000	678,000	1,085,000	33,631,000
June	2,546,000	646,000	1,573,000	47,179,000
July	2,546,000	1,312,000	1,795,000	55,650,000
August	2,126,000	1,059,000	1,522,000	47,180,000
September	1,874,000	1,098,000	1,418,000	42,529,000
October	1,273,000	827,000	1,035,000	32,093,000
November	1,273,000	827,000	1,081,000	32,419,000
December	827,000	575,000	676,000	20,942,000
The year	3,115,000	542,000	1,400,000	509,305,000

Discharge from Tunnel 95 (New Mountain House Tunnel)—continued

1940				
January	542,000	361,000	461,000	14,287,000
February	361,000	226,000	277,000	8,034,000
March	420,000	226,000	330,000	10,238,000
April	749,000	420,000	549,000	16,467,000
May	2,022,000	717,000	1,272,000	39,420,000
June	2,022,000	788,000	1,421,000	42,621,000
July	2,022,000	937,000	1,266,000	39,262,000
August	3,716,000	1,021,000	2,289,000	70,967,000
September	3,115,000	1,143,000	2,181,000	65,426,000
October	2,229,000	1,098,000	1,782,000	55,255,000
November	2,126,000	749,000	1,256,000	37,665,000
December	1,770,000	387,000	1,003,000	31,103,000
The year	3,716,000	226,000	1,174,000	430,294,000
1941				
January	387,000	277,000	308,000	9,546,000
February	303,000	226,000	243,000	6,792,000
March	788,000	226,000	323,000	10,016,000
April	982,000	717,000	804,000	24,136,000
May	2,281,000	1,059,000	1,865,000	57,829,000
June	2,126,000	827,000	1,236,000	37,085,000
July	1,680,000	1,273,000	1,294,000	40,106,000
The period	2,281,000	226,000	868,000	185,510,000

[a] Weir read daily.
[b] Tunnel under construction.

Combined discharge of Tunnel 97 (Kahilipali Tunnel) and Tunnel 102 (Tanaka Tunnel)

(Data from C. Brewer and Co., Ltd.)

Month	Average daily discharge (gallons)	Total discharge (gallons)
1924		
February	138,000	2,900,000
March	116,000	3,600,000
April	490,000	14,700,000
May	352,000	10,900,000
June	220,000	6,600,000
July	232,000	7,200,000
August	252,000	7,800,000
September	147,000	4,400,000
October	500,000	15,500,000
November	340,000	10,200,000
December	290,000	9,000,000
The period	279,700	92,800,000

Miscellaneous discharge measurements in gallons per day

(Data from Hawaiian Agricultural Co., Ltd.)

Date	Discharge	Date	Discharge	Date	Discharge
Tunnel 65 (Makakupu Tunnel)					
Dec. 2, 1935	461,000	Apr. 14, 1942	274,000	Apr. 21, 1943	288,000
Oct. 9, 1936	972,000	Apr. 25, 1942	223,000	May 1, 1943	720,000
Oct. 10, 1936	972,000	May 8, 1942	180,000	May 13, 1943	1,008,000
Oct. 26, 1936	979,000	May 23, 1942	634,000	June 18, 1943	432,000
Nov. 2, 1936	922,000	May 29, 1942	547,000	June 30, 1943	950,000
Nov. 9, 1936	792,000	June 6, 1942	677,000	Aug. 21, 1943	346,000
Nov. 23, 1936	468,000	June 20, 1942	619,000	Aug. 31, 1943	720,000
Nov. 30, 1936	360,000	July 11, 1942	461,000	Sept. 1, 1943	648,000
Dec. 14, 1936	209,000	July 23, 1942	288,000	Sept. 30, 1943	432,000
Dec. 21, 1936	166,000	July 30, 1942	245,000	Oct. 7, 1943	749,000
Jan. 9, 1937	202,000	Aug. 7, 1942	432,000	Oct. 28, 1943	403,000
Jan. 26, 1937	202,000	Aug. 19, 1942	432,000	Nov. 1, 1943	403,000
Feb. 15, 1937	720,000	Aug. 30, 1942	288,000	Nov. 30, 1943	158,000
Mar. 30, 1937	1,066,000	Sept. 12, 1942	245,000	Dec. 31, 1943	86,000
May 17, 1937	1,080,000	Sept. 19, 1942	979,000	Jan. 31, 1944	58,000
May 29, 1937	792,000	Sept. 26, 1942	993,000	Feb. 5, 1944	39,000
June 8, 1937	619,000	Oct. 1, 1942	864,000	Feb. 29, 1944	331,000
Jan. 24, 1942	86,000	Oct. 10, 1942	662,000	Mar. 2, 1944	576,000
Jan. 31, 1942	72,000	Oct. 25, 1942	792,000	Mar. 31, 1944	518,000
Feb. 5, 1942	65,000	Nov. 6, 1942	669,000	Apr. 30, 1944	216,000
Feb. 14, 1942	65,000	Nov. 13, 1942	662,000	May 31, 1944	1,080,000
Feb. 21, 1942	50,000	Dec. 5, 1942	432,000	June 30, 1944	576,000
Feb. 28, 1942	50,000	Dec. 31, 1942	288,000	July 31, 1944	576,000
Mar. 7, 1942	43,000	Jan. 4, 1943	1,296,000	Aug. 30, 1944	173,000
Mar. 18, 1942	58,000	Jan. 30, 1943	432,000	Sept. 30, 1944	432,000
Mar. 27, 1942	58,000	Feb. 2, 1943	1,296,000	Oct. 31, 1944	216,000
Apr. 2, 1942	79,000	Feb. 28, 1943	259,000	Nov. 30, 1944	259,000
Apr. 6, 1942	94,000	Apr. 1, 1943	432,000		
Tunnel 70 (Weda Tunnel)					
Dec. 2, 1935	140,000	Nov. 23, 1936	96,000	Feb. 15, 1937	130,000
Oct. 9, 1936	469,000	Nov. 30, 1936	58,000	Mar. 8, 1937	94,000
Oct. 19, 1936	451,000	Dec. 14, 1936	49,000	Apr. 6, 1937	193,000
Oct. 26, 1936	240,000	Jan. 4, 1937	32,000	Apr. 20, 1937	223,000
Nov. 2, 1936	272,000	Jan. 25, 1937	490,000	Feb. 5, 1942	14,000
Nov. 9, 1936	166,000	Jan. 28, 1937	130,000	Sept. 12, 1942	69,000
Tunnel 71 (Weda No. 3 Tunnel)					
Dec. 2, 1935	59,000	Nov. 23, 1936	94,000	Mar. 8, 1937	43,000
Nov. 2, 1936	145,000	Nov. 30, 1936	36,000	Feb. 5, 1942	1,000
Nov. 9, 1936	94,000	Feb. 15, 1937	58,000	Sept. 12, 1942	14,000
Tunnels 75 and 76 (Noguchi No. 2 and No. 1 Tunnels)					
Dec. 2, 1935	1,354,000	Jan. 4, 1943	2,938,000	Oct. 7, 1943	1,454,000
Oct. 9, 1936	2,304,000	Jan. 30, 1943	1,152,000	Oct. 28, 1943	1,123,000
Oct. 19, 1936	2,765,000	Feb. 2, 1943	1,584,000	Nov. 1, 1943	1,123,000
Oct. 26, 1936	2,275,000	Feb. 28, 1943	576,000	Nov. 30, 1943	749,000
Nov. 2, 1936	1,987,000	Mar. 3, 1943	634,000	Dec. 31, 1943	490,000
Nov. 9, 1936	1,800,000	Mar. 23, 1943	1,354,000	Jan. 31, 1944	346,000
Nov. 20, 1936	1,354,000	Apr. 14, 1943	864,000	Feb. 8, 1944	317,000
Nov. 23, 1936	1,102,000	Apr. 30, 1943	749,000	Feb. 29, 1944	835,000
Nov. 30, 1936	893,000	May 13, 1943	2,160,000	Mar. 2, 1944	1,152,000
Dec. 6, 1936	778,000	May 29, 1943	1,584,000	Mar. 31, 1944	1,080,000
Dec. 14, 1936	677,000	June 18, 1943	936,000	Apr. 30, 1944	749,000
Dec. 21, 1936	605,000	June 30, 1943	1,901,000	May 31, 1944	2,592,000
Dec. 28, 1936	533,000	July 16, 1943	1,872,000	June 30, 1944	1,598,000
July 6, 1937	778,000	July 31, 1943	1,224,000	July 31, 1944	1,296,000
July 10, 1937	662,000	Aug. 21, 1943	1,008,000	Aug. 30, 1944	662,000
Jan. 10, 1942	403,000	Aug. 31, 1943	1,872,000	Sept. 30, 1944	1,296,000
Jan. 24, 1942	346,000	Sept. 1, 1943	1,440,000	Oct. 31, 1944	806,000
Jan. 31, 1942	317,000	Sept. 30, 1943	1,152,000	Nov. 30, 1944	922,000

Miscellaneous discharge measurements in gallons per day—continued

Date	Discharge	Date	Discharge	Date	Discharge
Tunnel 79 (Double Arch Tunnel)					
Dec. 2, 1935	187,000	Dec. 14, 1936	23,000	May 3, 1937	2,707,000
Oct. 9, 1936	1,267,000	Dec. 21, 1936	23,000	May 17, 1937	461,000
Oct. 12, 1936	1,800,000	Jan. 4, 1937	58,000	June 5, 1937	778,000
Oct. 19, 1936	1,901,000	Jan. 18, 1937	333,000	June 18, 1937	135,000
Oct. 26, 1936	720,000	Jan. 25, 1937	1,570,000	July 6, 1937	72,000
Nov. 2, 1936	1,411,000	Feb. 8, 1937	390,000	Mar. 27, 1942	281,000
Nov. 9, 1936	389,000	Apr. 1, 1937	677,000	July 3, 1942	144,000
Nov. 23, 1936	72,000	Apr. 2, 1937	547,000	July 16, 1942	91,000
Nov. 30, 1936	65,000	Apr. 21, 1937	2,088,000		
Tunnel 80 (Mudflow Tunnel)					
Dec. 2, 1935	305,000	Apr. 20, 1937	360,000	Mar. 27, 1942	376,000
Feb. 8, 1937	485,000	May 3, 1937	1,557,000	July 17, 1942	180,000
Apr. 5, 1937	374,000	Feb. 3, 1942	340,000	Nov. 18, 1942	340,000
Tunnel 85 (Alili Tunnel)					
Dec. 4, 1935	404,000	Mar. 13, 1937	465,000	July 9, 1937	465,000
Oct. 10, 1936	2,542,000	Mar. 19, 1937	390,000	June 4, 1940	550,000
Oct. 21, 1936	2,160,000	Mar. 26, 1937	1,858,000	Jan. 24, 1942	36,000
Nov. 28, 1936	288,000	Apr. 3, 1937	1,263,000	Jan. 31, 1942	96,000
Dec. 13, 1936	193,000	Apr. 8, 1937	808,000	Dec. 15, 1944	484,000
Dec. 21, 1936	151,000	Apr. 24, 1937	1,263,000	Dec. 22, 1944	272,000
Dec. 28, 1936	127,000	May 14, 1937	1,735,000	Dec. 29, 1944	1,528,000
Jan. 9, 1937	112,000	May 20, 1937	808,000		
Jan. 16, 1937	193,000	June 4, 1937	1,102,000		
Tunnel 86 (Shirakura Tunnel)					
Dec. 7, 1935	91,000	Nov. 7, 1936	166,000	Dec. 28, 1936	194,000
Oct. 10, 1936	962,000	Nov. 21, 1936	69,000	Mar. 3, 1937	120,000
Oct. 24, 1936	451,000	Dec. 5, 1936	40,000	July 2, 1937	102,000
Oct. 31, 1936	592,000	Dec. 13, 1936	40,000	Feb. 6, 1942	17,000
Tunnel 87 (Moaula Gulch Tunnel)					
Dec. 7, 1935	194,000	Nov. 21, 1936	121,000	Mar. 6, 1937	144,000
Oct. 10, 1936	413,000	Dec. 5, 1936	89,000	June 11, 1937	253,000
Oct. 17, 1936	323,000	Dec. 13, 1936	79,000	July 2, 1937	144,000
Oct. 24, 1936	272,000	Dec. 19, 1936	68,000	Feb. 6, 1942	40,000
Oct. 31, 1936	340,000	Dec. 28, 1936	193,000	July 15, 1942	151,000
Nov. 7, 1936	209,000	Mar. 3, 1937	158,000		
Tunnel 89 (Fukuda Tunnel)					
Dec. 7, 1935	166,000	Nov. 21, 1936	84,000	Mar. 13, 1937	78,000
Oct. 10, 1936	680,000	Dec. 13, 1936	43,000	June 11, 1937	158,000
Oct. 17, 1936	451,000	Dec. 19, 1936	39,000	Feb. 6, 1942	17,000
Oct. 31, 1936	490,000	Jan. 9, 1937	78,000	July 15, 1942	49,000
Tunnel 90 (Kaumaikeohu Tunnel)					
Dec. 7, 1935	166,000	Oct. 17, 1936	240,000	Dec. 13, 1936	24,000
Oct. 10, 1936	272,000	Nov. 21, 1936	59,000	Dec. 19, 1936	24,000

Date	Discharge	Date	Discharge	Date	Discharge
Tunnel 91 (Domestic Supply Tunnel)					
Dec. 7, 1935	256,000	Aug. 14, 1942	769,000	Oct. 19, 1943	360,000
Oct. 26, 1936	746,000	Aug. 21, 1942	340,000	Oct. 27, 1943	288,000
Nov. 7, 1936	572,000	Aug. 29, 1942	374,000	Nov. 2, 1943	216,000
Nov. 28, 1936	144,000	Sept. 8, 1942	451,000	Nov. 15, 1943	166,000
Dec. 13, 1936	98,000	Sept. 21, 1942	1,440,000	Nov. 25, 1943	153,000
Dec. 21, 1936	69,000	Sept. 28, 1942	1,166,000	Nov. 30, 1943	108,000
Dec. 28, 1936	79,000	Oct. 8, 1942	680,000	Dec. 22, 1943	130,000
Jan. 9, 1937	69,000	Oct. 20, 1942	357,000	Dec. 30, 1943	108,000
Jan. 24, 1942	36,000	Oct. 23, 1942	1,140,000	Jan. 16, 1944	94,000
Jan. 31, 1942	33,000	Oct. 31, 1942	490,000	Jan. 31, 1944	72,000
Feb. 6, 1942	33,000	Nov. 24, 1942	225,000	Feb. 12, 1944	49,000
Feb. 14, 1942	36,000	Dec. 15, 1942	887,000	Feb. 22, 1944	72,000
Feb. 21, 1942	32,000	Jan. 6, 1943	1,440,000	Mar. 1, 1944	360,000
Feb. 28, 1942	32,000	Jan. 28, 1943	490,000	Mar. 31, 1944	323,000
Mar. 7, 1942	27,000	Feb. 11, 1943	180,000	Apr. 4, 1944	360,000
Mar. 19, 1942	91,000	Feb. 26, 1943	180,000	Apr. 10, 1944	328,000
Mar. 28, 1942	91,000	Mar. 2, 1943	180,000	Apr. 26, 1944	240,000
Apr. 6, 1942	91,000	Mar. 12, 1943	413,000	May 6, 1944	158,000
Apr. 12, 1942	376,000	Mar. 19, 1943	592,000	May 13, 1944	576,000
Apr. 20, 1942	187,000	Mar. 27, 1943	413,000	May 17, 1944	451,000
Apr. 30, 1942	225,000	Apr. 6, 1943	240,000	June 28, 1944	680,000
May 8, 1942	236,000	Apr. 20, 1943	510,000	July 12, 1944	225,000
May 15, 1942	432,000	May 6, 1943	360,000	Aug. 3, 1944	533,000
May 23, 1942	592,000	June 15, 1943	274,000	Aug. 9, 1944	305,000
May 31, 1942	510,000	July 28, 1943	274,000	Aug. 19, 1944	202,000
June 8, 1942	701,000	Aug. 11, 1943	346,000	Aug. 31, 1944	173,000
June 15, 1942	864,000	Sept. 1, 1943	504,000	Sept. 13, 1944	317,000
June 29, 1942	816,000	Sept. 21, 1943	572,000	Sept. 25, 1944	504,000
July 7, 1942	272,000	Sept. 28, 1943	288,000	Oct. 5, 1944	403,000
July 14, 1942	180,000	Oct. 7, 1943	1,440,000	Oct. 17, 1944	317,000
Aug. 7, 1942	769,000	Oct. 12, 1943	864,000	Oct. 22, 1944	274,000

INDEX