GEOLOGY AND GROUND-WATER RESOURCES OF THE ISLAND OF MAUI, HAWAII

TERRITORY OF HAWAII
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H. T. STEARNS
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Plate 3. Haleakala Crater. A yawning depression, believed to be chiefly erosional, crossed by a line of cinder cones and bordered by steep rocky cliffs broken by side notches. Courtesy of Standard Oil Company of California.

TERRITORY OF HAWAII
INGRAM M. STAINBACK, *Governor*
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DIVISION OF HYDROGRAPHY
MAX H. CARSON, *Chief Hydrographer*

BULLETIN 7

GEOLOGY AND GROUND-WATER RESOURCES
OF THE
ISLAND OF MAUI, HAWAII

(Including Haleakala Section, Hawaii National Park)

BY

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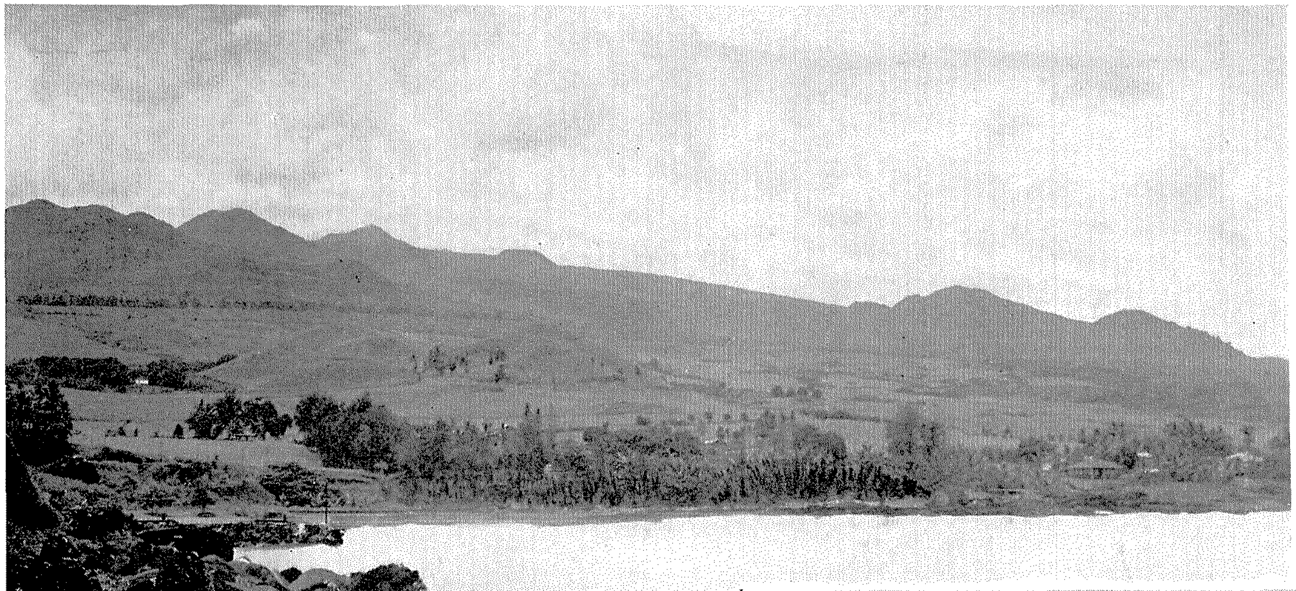
By Harold T. Stearns



Above: Plate 4A. The youth of the cinder cones on the east rift of Haleakala near Hana is concealed under a dense cloak of jungle and sugar cane.

Below: Plate 4B. Looking across the Isthmus to the West Maui Mountains and Iao Valley.

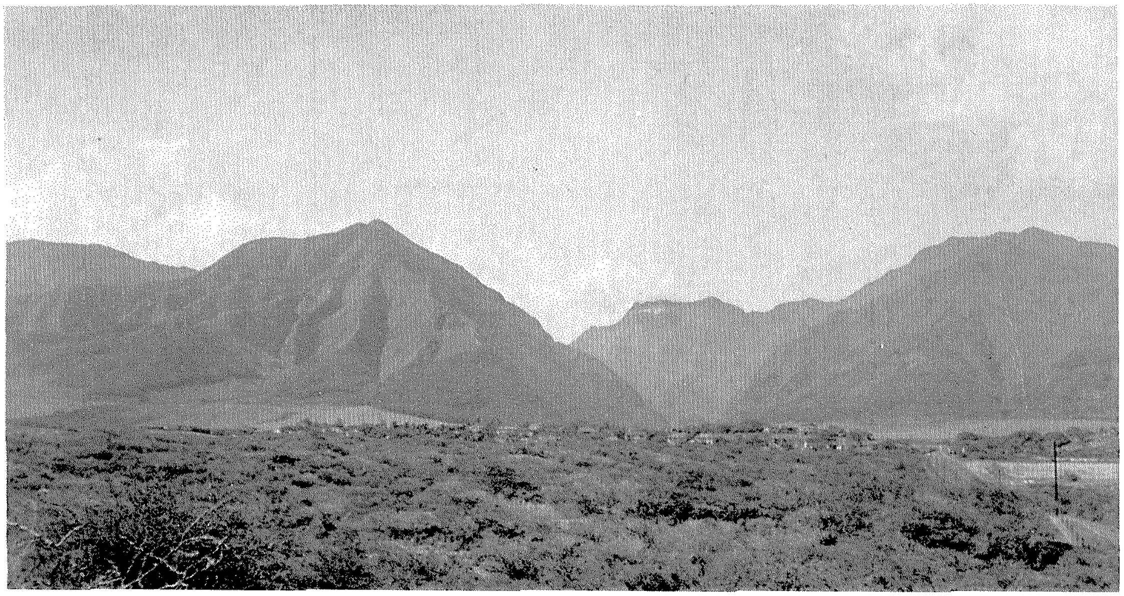
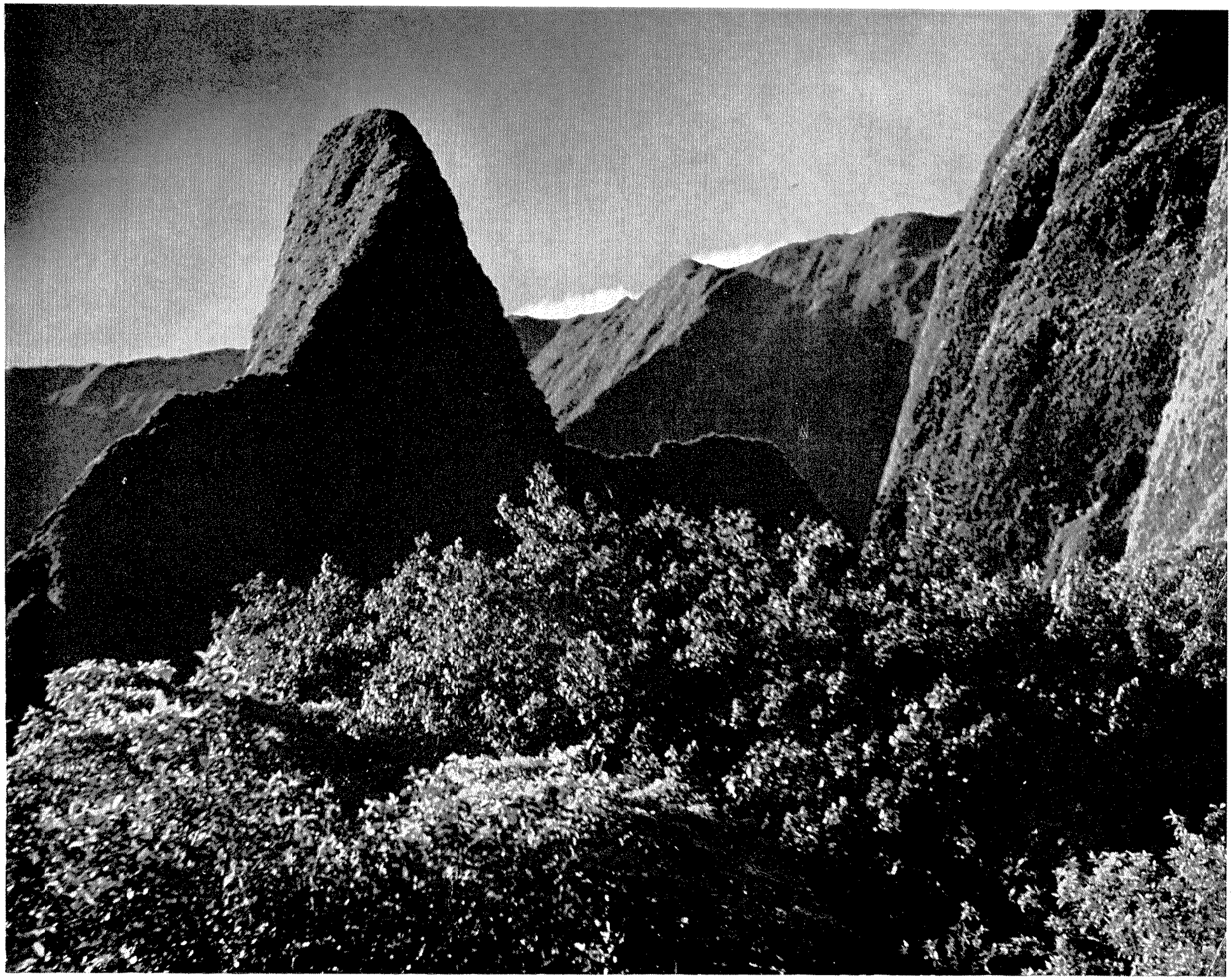


Plate 5. Iao Valley, the ancient eroded caldera of the West Maui volcano, now cool and clothed with forest verdure and famous for its pinnacle, called The Needle. Photo by Pan Pacific Press Bureau.



FOREWORD

MAUI FROM THE AIR

In the distant soft blue velvety haze a huge bulky dark mass that seems to be sailing eastward rises through a limitless sea of white downy clouds. Faint green tinges the eddy in its wake. Projecting through the cloud-foam on the north side of the eddy is a black sharp pinnacle. Thus appear the bulky dome of Haleakala and Puu Kukui, the pinnacled top of the dissected West Maui volcano, from a plane approaching Maui at an altitude of 5,000 feet. The three lower neighboring islands of Molokai, Lanai, and Kahoolawe are not yet visible, but on the far distant horizon like three pale-blue phantom mountains in a mirage rise the tops of the domes of Mauna Kea, Mauna Loa, and Hualalai on the island of Hawaii. As the plane rises higher and higher above the flat roof of the trade-wind clouds, their unbrokenness proves to be an optical illusion, for they are isolated cottony tufts with azure patches of sea between. The red ochre surfaces of Lanai and West Molokai now become visible through the clouds.

Farther away, and extending for miles over the sea from Kahoolawe, is a red dust streamer of earthy filings in the sky, scraped from the surface of the island and borne seaward by the wind.

Still higher and eastward the plane flies and there, far below, the narrow steep concordant ridges of the West Maui Mountains lie like gaunt and weatherbeaten ribs on the projecting prow of a partly sunken old barge. To the east and seeming to be a different island, lies the roughly triangular mass of Mt. Haleakala, which from this height appears very smooth except for great deep dark scars which look as if four huge landslides had sloughed off the eastern side of the summit.

The plane circles downward and a green flat isthmus can be seen connecting Haleakala to the West Maui Mountains. To the north stretches pale-green water separated from the sapphire-blue ocean by a white fringe where the surf breaks at the edge of the coral reef. Elsewhere the white fringe hugs the shore. As the plane descends, more features become visible. A yawning depression bordered by steep rocky cliffs broken by two side notches indents the summit of Haleakala. Across this hole march smooth red and black cinder cones on a black carpet of stiff stark lava. A black strip extends from the depression down the great Keanae Valley, one of the scars seen from higher up. Seaward the blackness changes to grayness, then to gray-green, and finally to dark-green as the lava flows become cloaked with jungle.

Another black strip stretches from the summit depression southward through Kaupo Valley and fans into a black and green polka dot pattern. There, scattered trees and patches of grass struggle valiently to cover the nudity of the lava on the dry leeward slope. The other two great scars, now distinguishable as Kipahulu and Waihoi Valleys, have the same form as the first two, but the late lava that covers their head walls and floors is completely masked with dense dark-green vegetation.

A belt of rocky brownish land spotted with green brush and yellow grass surrounds the high summit depression. This belt lies too high to catch the almost constant drizzle of the trade-wind rains. Below it lies a dark-green band of forest that extends unbroken to the sea on the north and east slopes but pinches out longitudinally to the south and west into light yellow-green areas of pasture and darker fields of the egregious weed, pamakani, Hawaiian for "blown by the wind."[1]

Below the pasture land on the broad west slope of Haleakala is a narrow strip of gray-green pineapple fields in checkerboard patterns. Below them, and extending across the Isthmus to the very base of the precipitous slopes of the West Maui Mountains, is a great expanse of a brighter green—fields of sugar cane. Glittering among them are numerous small circular mirrors—sunlight reflected on nearly-round storage reservoirs. From the mirrors extends a vast network of narrow gleaming ribbons—the main irrigation ditches. Three larger ditches can be seen extending eastward to the jungle. These bring to the thirsty Isthmus the flow of streams from the rainy windward northeast slope.

Dusty unirrigated arid lands, being overgrown slowly by the keawe tree, stretch southward from the cane fields in a belt of spotted red and yellow-green. South of these arid lands and spreading eastward to Kaupo Valley are fields strewn with black flows of fresh and forbidding lava. They are arranged in pennants which stream from a line of cinder cones and shallow craters that march northeastward across the summit depression. These cones lie in the southwest and east rift zones of the volcano. The flows from these rifts take on the green clothing of the jungle at the east end of the island as they march down into the sea. "Here the mouths have been stopped with earth. A silky turf lies snug over the curves of the

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[1] This plant was imported about 1900 and planted at Ulupalakua, Maui, for a garden border. It now covers and renders worthless vast areas of former pasture.

volcanoes, all is suavity in the scene. Each fissure in the crust is sutured up by this tender flax. The earth is smooth, the slopes are gentle; one forgets the travail that gave them birth. The turf effaces from the flanks of the hillocks the sombre sign of their origin."[2]

Scattered hills, the upper ones forested and the lower ones checkered with pineapple fields, crown the bulge of the older rift that extends northward from the summit.

The West Maui Mountains with their deep dark foreboding canyons are tightly belted by a road which skirts the sea, crowded there by the steep slopes behind. Indenting the summit area is a nearly circular green depression through which silvery streams of water find their way to a common outlet on the east side where they run through a deep gorge into the sea. This circular valley head, the ancient caldera of the West Maui volcano, is now cool and clothed with forest verdure and is famous for its pinnacle called Iao Needle (pl. 5).

On the summit and to the northward are swampy flats in which small pools of water gleam. These are peat swamps, so acid that they support only acaulescent plants, stunted trees, and silversword. They look like extensive landing fields awaiting a squadron of planes.

Sugar cane and pineapple fields cover the narrow coastal flats and the fans of gravel dropped hurriedly by great floods on their way to the sea. Some of the fields creep daringly up the interstream divides but are beaten back by the jungle or stopped abruptly by declivities that no animal nor machine can cultivate (pl. 7).

The southeast slope of the greatly dissected dome is semi-arid and the layers of lava rock paralleling the steep slopes resemble layers in a cake that puffed too high in the middle, was baked to a crisp, and then cracked radially. Capping the ridges like a white frosting are the later silica-rich lavas which weather light gray in contrast to the darker, underlying basaltic lavas. Interstratified with the darker layers are yellowish thin ones of weathered firefountain ash resembling cream filling in the cake. Narrow dark dikes cut across all layers.

One realizes at this height that glistening streams pour forth, some small, some large, from nearly all the canyons in the West Maui Mountains, but, on the great expanse of Haleakala, the sparkle of running water is visible in very few places and those are near the coast. In spite of its great stretches of rain forest, the surface of

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[2] Saint Exupery, A., Wind, sand, and stars, Reynal and Hitchcock, Inc., New York, p. 100, 1939.

Haleakala is covered with lava flows still sufficiently young to be very porous. Much of the vast quantities of rain, amounting in some places to 500 inches a year, sinks without difficulty.

Descending still farther, groups of buildings with their clumps of scarlet Bougainvillea and red and green roofs mark the sites of camps on pineapple and sugar plantations. Clustered around the harbor on the north side of the Isthmus are the buildings and wharfs of Kahului, and a short distance to the west at the foot of the West Maui Mountains lies Wailuku. Like a narrow ribbon waving in the air, a solitary road can be seen winding in and out of the ravines along the north and east slopes near the coast and connecting the lonely but charming plantation at Hana on the east tip of the island with the main settlement on the Isthmus. Roads avoid the barren lands, the jungle, the lava fields, and the sands. They all lead to the smooth land where man has made water abundant.

The plane lands amid the sugar cane on the Isthmus. Small sheds housing wells from which pipes discharge great quantities of irrigation water are seen here and there. The cool air of the clouds is gone. The persistent warm humid trade winds of the tropics meet the passenger as he disembarks. A broad stubby rainbow brilliantly colors an oncoming squall. Then the rain falls softly.

GENERAL GEOLOGY AND GROUND-WATER RESOURCES OF THE ISLAND OF MAUI, HAWAII

By HAROLD T. STEARNS

ABSTRACT

Maui, the second largest island in the Hawaiian group, is 48 miles long, 26 miles wide, and covers 728 square miles. The principal town is Wailuku. Sugar cane and pineapples are the principal crops. Water is used chiefly for irrigating cane. The purpose of the investigation was to study the geology and the ground-water resources of the island.

Maui was built by two volcanoes. East Maui or Haleakala Volcano is 10,025 feet high and famous for its so-called crater, which is a section of Hawaii National Park. Evidence is given to show that it is the head of two amphitheater-headed valleys in which numerous secondary eruptions have occurred and that it is not a crater, caldera, or eroded caldera. West Maui is a deeply dissected volcano 5,788 feet high. The flat Isthmus connecting the two volcanoes was made by lavas from East Maui banking against the West Maui Mountains. 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. Volcanic terms used in the report are briefly defined. A synopsis of the climate is included and a record of the annual rainfall at all stations is given also. Puu Kukui, on West Maui, has an average annual rainfall of 389 inches and it lies just six miles from Olowalu where only 2 inches of rain fell in 1928, the lowest ever recorded in the Hawaiian Islands. The second rainiest place in the Territory is Kuhiwa Gulch on East Maui where 523 inches fell during 1937. Rainfall averages 2,360 million gallons daily on East Maui and 580 on West Maui. Ground water at the point of use in months of low rainfall is worth about $120 per million gallons, which makes most undeveloped supplies valuable.

The oldest rocks on East Maui are the very permeable primitive Honomanu basalts, which were extruded probably in Pliocene and early Pleistocene time from three rift zones. These rocks form a dome about 8,000 feet high and extend an unknown distance below sea level. Covering this dome are the Kula volcanics, extruded probably in early and middle Pleistocene time, and characterized by andesites, andesitic basalts, and picritic basalts. They are 2,000 feet thick on the summit and 50 to 200 feet thick at the periphery. They contain a sufficient number of interbedded soils, thin vitric tuff beds, and lava-filled valleys in their upper part to give rise to valuable perched springs in wet areas. The Kula lavas accumulated during a waning volcanic phase which was followed by a quiescence long enough for the erosion of deep amphitheater-headed valleys in the east or wet half of the mountain. Volcanic activity was renewed in middle(?) to late Pleistocene time and continued until Recent time, during which the Hana volcanic series was laid down. The last lava flow was erupted about 1750. The Hana lavas comprise andesitic, picritic, and olivine basalts. They veneered large areas of the east and south slopes, partly filled the deep amphitheater-headed valleys, and deeply buried the smaller valleys in the eastern half of the mountain. The Hana rocks are exceedingly permeable and much rain sinks into them.

The oldest rocks on West Maui are the very permeable primitive Wailuku basalts, which were extruded probably in Pliocene and early Pleistocene time from two rifts and from many radial fissures. The basalts form a dome about 5,600 feet high and extend an unknown distance below sea level. Iao Valley is the eroded caldera of this dome. Forming an incomplete veneer over the dome are the Honolua soda trachytes and oligoclase andesites. They were extruded in late Pliocene(?) or early Pleistocene time, chiefly from bulbous domes. The clinker beds carry some water but the rocks are generally too dense to be good aquifers. During early(?) Pleistocene the West Maui volcano was cut by deep amphitheater-headed valleys and then all of Maui was deeply submerged.

Four scattered eruptions occurred on West Maui in middle(?) and late Pleistocene time. The cones and lavas cover only small areas and are called the Lahaina volcanic series.

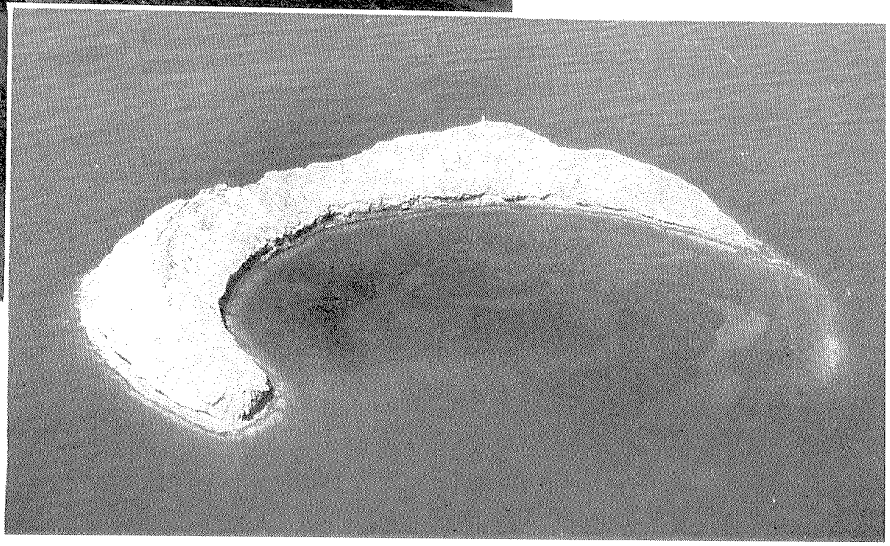
The sedimentary rocks of both East and West Maui are chiefly late Quaternary and comprise fans, landslide debris, delta deposits, and valley fills, mostly of poorly permeable and poorly assorted bouldery alluvium. They are overlain on the Isthmus by extensive calcareous dunes of three ages. A mud flow more than 300 feet thick is exposed in Kaupo Valley. During the fluctuations of the ocean in the Pleistocene, the island was emerged and submerged several times. Calcareous fossiliferous marine conglomerates deposited during this period are found up to an altitude of 250 feet on West Maui.

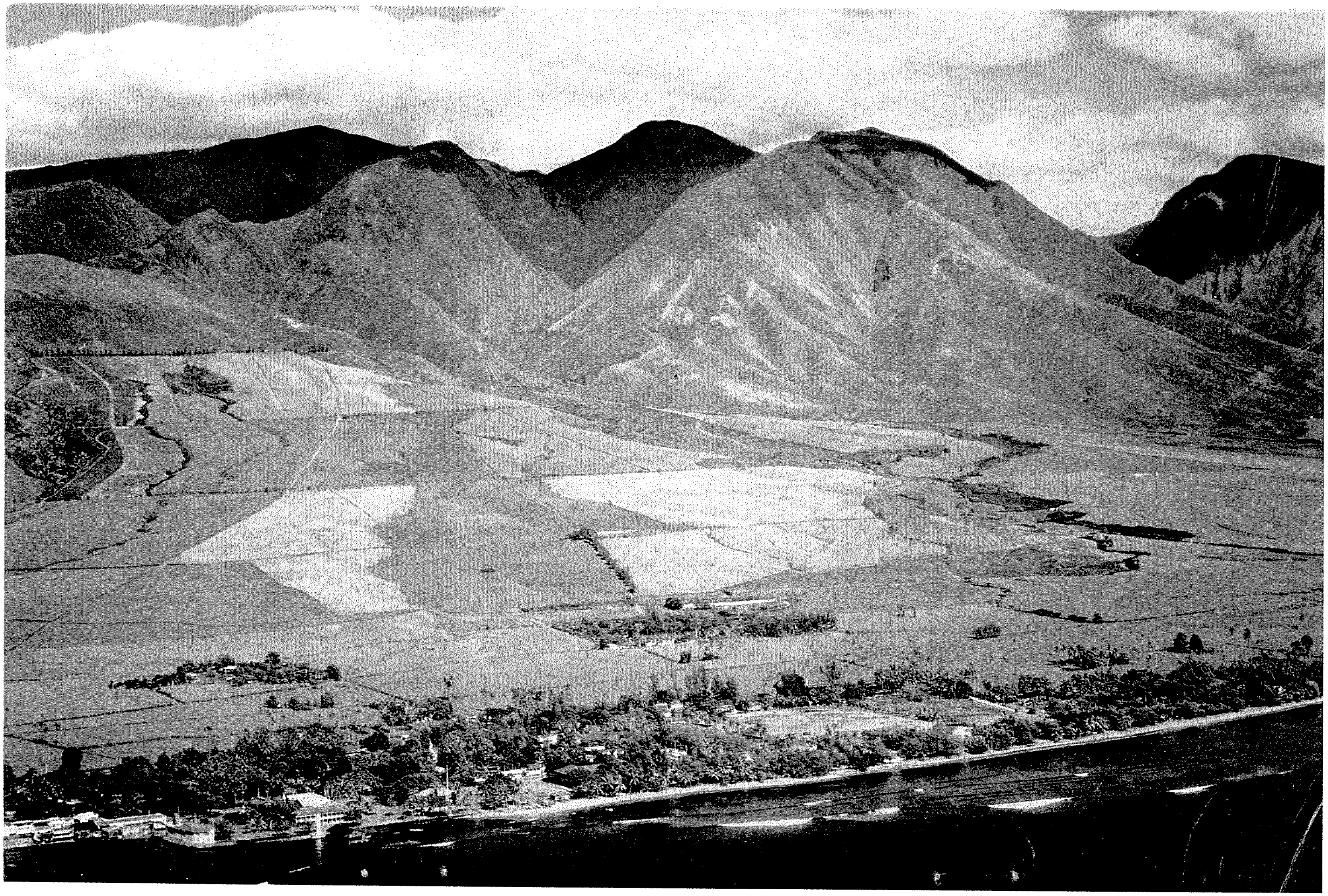
The Honomanu, Wailuku, and Kula lavas are the chief aquifers. They supply 28 irrigation wells which yield an average of 170 million gallons a day of basal water. These wells are mine-like shafts with infiltration tunnels and are called Maui-type wells. Well 16 yields 40,000,000 gallons daily with a 2½-foot drawdown, which is the largest amount yielded by any well in the Hawaiian Islands. The largest spring (no. 26) on the island is artesian. It yields 10,400,000 gallons daily and issues from Kula lavas near Nahiku. West Maui has numerous perennial streams supplied by springs from a dike complex. Twenty-three tunnels in West Maui recover 20.5 million gallons a day of high-level water, mostly from this dike complex. East Maui has few perennial streams in proportion to its size, and they are chiefly small due to the water sheds being underlain with permeable lavas. Forty tunnels recover 6 million gallons a day of high-level water in East Maui and all from structures other than dikes.

It is estimated that about 100 million gallons a day of basal water wastes into the sea from West Maui and about 700 million gallons a day from East Maui. A number of sites are described where wells could be sunk to recover this water. Sites are also described where tunnels could be driven to recover high-level supplies. The hydrology of East and West Maui is conspicuously different in many respects, mainly because of the difference in the stage of dissection, the extensive veneer of very permeable Hana lavas on East Maui, and the comparatively small area of the Lahaina lavas of similar age on West Maui. The only thermal water known in the Hawaiian Islands, except on the active volcano of Kilauea, is in a well in West Maui.

Above: Plate 6A. The upper part of the southwest rift zone of Haleakala Volcano as seen from 13,000 feet altitude. Minor explosions occurred in the pit craters in late Hana time. Weathered remnants of Kula cones project through the heavy ash and cinder mantle. Courtesy of the National Park Service.

Below: Plate 6B. Molokini Islet, a tuff cone built on the southwest rift of Haleakala Volcano by a submarine eruption. Photo by Fleet Air Base, U. S. Navy, Pearl Harbor, T. H.





Opposite page: Plate 7. Fields of sugar cane on the slopes of the West Maui Mountains behind Lahaina. Courtesy of Hawaiian Airlines, Limited.

INTRODUCTION

LOCATION AND AREA.—Maui, the second largest island of the Hawaiian group, lies in mid-Pacific about 2,100 miles southwest of San Francisco and about 4,600 miles northwest of Panama. It lies between 21° 02′ and 20° 35′ north latitude and 155° 59′ and 156° 42′ west longitude. The island covers 728 square miles and is about 58 miles southeast of Oahu (fig. 1). It has a maximum length of 48 miles and a maximum width of 26 miles. Maui had a population of 46,919 in 1940, and Wailuku, the principal town and seat of Maui

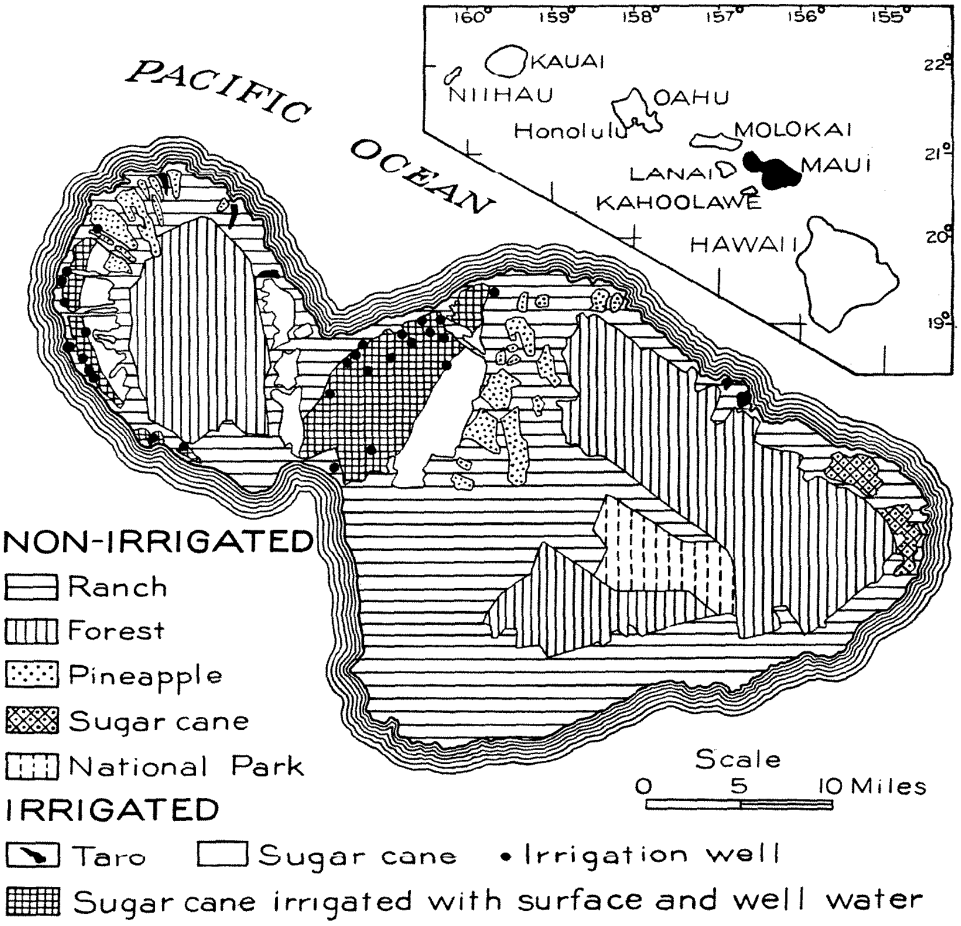


Figure 1. Map of Maui showing land utilization in 1937 and position of Maui in the Hawaiian group. The taro and the white areas of sugar cane are irrigated with surface water only. (After pl. 35, First Progress Rept., Territorial Planning Board, 1939.)

County, had a population of 7,319. Kahului is the principal port on the windward side and Lahaina (population 5,217) is the principal port on the leeward side. The island is reached by inter-island steamers and planes. The main airport is near Puunene.

Maui is composed of two volcanoes. The East Maui volcano is widely known as Haleakala (House of the sun). The West Maui volcano is dissected into several high peaks. They are called the West Maui Mountains. For brevity and easy comparison the two volcanoes will be referred to herein as East Maui and West Maui. These two geographic terms are well established locally and in the literature. An imaginary north-south line connecting Kahului Bay and Maalaea Bay (pl. 1) may be used to separate the lavas and associated pyroclastics and sediments of the East Maui volcano from the sharply eroded slopes forming West Maui. The broad flat land connecting the two volcanoes is called the Isthmus. The two volcanoes have their own physiographic and geologic histories and their ground-water bodies are not connected. For these reasons they are treated separately in this report.

Maui is known as The Valley Isle because of its numerous canyons. Best known among them is the scenic jungle-covered valley of Iao on West Maui (pl. 5). The depression on the summit of East Maui is sufficiently spectacular to have been set aside as part of Hawaii National Park. (See frontispiece.) The highest point on East Maui is Red Hill, 10,025 feet above sea level, and on West Maui, Puu Kukui, altitude 5,788 feet.

HISTORICAL SKETCH.—Maui is named after a Polynesian demigod. According to legends, Maui, after pulling the islands of New Zealand from the ocean, came to the island of Maui to live where he snared the sun in order to lengthen the day. The first white man to see the island of Maui was Captain James Cook, on November 26, 1778, on his second voyage to the Hawaiian Islands.[3] On May 28, 1786, La Perouse, the French explorer, anchored off the southwest side of Haleakala in a bay since named in his honor. In 1790 a massacre occurred at Olowalu when Kamehameha, the King of Hawaii, invaded Maui.

American missionaries settled at Lahaina in May, 1825, and in 1831 established Lahainaluna school. Children were sent to this school from California during the gold-rush years. Wheat, corn, and other produce were raised on the slopes of Haleakala and shipped

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[3] Alexander, W. D., A brief history of the Hawaiian people: p. 107, New York, 1899.

to California. Lahaina Roads, the channel between Maui and Lanai, became a great anchorage for whaling vessels in the middle of the century. The channel is now often used for anchorage by the United States fleet.

ABBREVIATIONS OF COMPANY NAMES.—The names of the sugar and pineapple plantations, ranches, and water companies will be abbreviated herein according to long established use on Maui in order to save cumbersome repetition.

Abbreviations of company names

Name	Abbreviation	Location	Product
Baldwin Packers	B. P.	W. Maui	pineapple
East Maui Irrigation Co.	E. M. I. Co.	E. Maui	water
Grove Ranch Co.	G. R. Co.	do.	cattle
Haleakala Ranch Co.	H. R. Co.	do.	do.
Hawaiian Commercial & Sugar Co.	H. C. & S. Co.	do.	sugar
Kaeleku Sugar Co.	K. S. Co.	do.	do.
Kaupo Ranch Co.	K. R. Co.	do.	cattle
Libby, McNeill & Libby	L. McN. & L.	do.	pineapple
Maui Agricultural Co.	M. A. Co.	do.	sugar
Maui Pineapple Co.	M. P. Co.	do.	pineapple
Pioneer Mill Co.	P. M. Co.	W. Maui	sugar
Ulupalakua Ranch Co.	U. R. Co.	E. Maui	cattle
Wailuku Sugar Co.	W. S. Co.	W. Maui	sugar

INDUSTRIES.—Sugar production is the chief industry. The M. A. Co., H. C. & S. Co., and K. S. Co. are on East Maui, and the W. S. Co. and P. M. Co. are on West Maui. The H. C. & S. Co. is the lowest cost producer in the Hawaiian Islands. The area planted to sugar cane is shown in figure 1. Production of sugar and acreages for 1940 follow:

Sugar production for 1940
(Data obtained from annual reports of the companies.)

Name	Acreage	Tons of Sugar	Value of sugar and molasses at market
Hawaiian Commercial & Sugar Co., Ltd.	7,426	74,794	$3,491,966
Maui Agricultural Co., Ltd.	4,958	[a]41,712	2,183,161
Pioneer Mill Co., Ltd.	5,794	48,331	2,589,805
Wailuku Sugar Co., Ltd.	3,275	21,817	1,176,573
Kaeleku Sugar Co., Ltd.	2,214	6,745	383,656

[a] Commercial grade. Add 3% to obtain weight of 96° sugar.

All plantations are irrigated except that of the K. S. Co., which uses all available high-level water for fluming cane. Flume water is being replaced by trucks to transport cane to the mill, as the supply of water is not dependable. The H. C. & S. Co. and M. A. Co. own jointly the E. M. I. Co., which operates the ditch systems and develops water by high-level tunneling but does not operate the irrigation wells of the two plantations.

Four companies grow pineapples on Maui. The Territory of Hawaii tax office reported 8,098 acres in pineapples in 1940, including leased lands, distributed as follows: Baldwin Packers, Ltd., 2,210 acres; Hawaiian Pineapple Co., Ltd., 73 acres; Maui Pineapple Co., Ltd., 3,648 acres; and Libby, McNeill and Libby, 2,167 acres. Their canneries are at Haiku, Pauwela, Kahului, and Mala. The Hawaiian Pineapple Co.'s cannery at Haiku has been closed. No water is used to irrigate pineapples.

About 175,000 acres are in cattle ranches; the largest are listed below:

Principal ranches on Maui[a]

Ranch	Acres[b]	Cattle	Ranch	Acres[b]	Cattle
Ulupalakua	63,409	4,033	Honolua (B. P. Ltd.)	7,369	974
Haleakala	32,435	4,872	Wailuku Sugar Co...	6,294	594
Kaonoula (H. Rice)..	23,130	2,152	Pioneer Mill Co.	5,027	875
Kaupo	15,305	1,209	R. H. Drummond ...	2,588	401
Grove (M. A. Co.) ...	8,234	2,378			
			Total	163,791	17,488

[a] Data from Territory of Hawaii tax office.
[b] Does not include land unfit for grazing but includes leased lands.

Most of the beef is shipped to Honolulu. Water is scarce on most of the ranches and the smallest seeps are carefully husbanded and piped to troughs. During droughts many cattle die from lack of water. Some ranches have large acreages of cactus (*Opuntia megacantha*), which contain sufficient water in their leaves to save the cattle during dry periods.

Maui has several power systems. Each sugar mill generates power from bagasse, the waste pulp from sugar cane. Irrigation pumps and municipal electric companies use the surplus power. Stand-by plants are necessary when the mills do not run. The largest is the central power plant near Kahului which supplies electric power to the Isthmus. The Kaanapali plant supplies much of the power for the lee side of West Maui. The generators are cooled with ground water. The island is served by an extensive network of power lines. The following table lists all plants and sources of their water for power and cooling:

Power plants on Maui[a]
(Data furnished by owners)

Owner	Location	Installed (year)	Type	Capacity KW (1941)	Source of power	Source of cooling water
B. P.	Honokahua	1914	Hydro	64	Drop in Honokohau ditch	
E. M. I. Co.	Kolea	1935	do.	64	Haipuaena[b] ditch	
H. C. & S. Co.	Puunene Mill	1915	Steam	750	Bagasse and oil	
Do.	do.	1915	do.	750	do.	
Do.	do.	1939	do.	4,000	do.	Well 17
Do.	Central power plant[c]	1918	do.	1,250	Oil	Well 20
Do.	do.	1920	do.	2,000	do.	do.
Do.	do.	1922	Diesel	750	do.	do.
Do.	do.	1925	Steam	3,000	do.	do.
Do.	Kaheka	1925	Hydro	4,002	Drop from Wailoa to Lowrie ditch	
K. S. Co.	Hana	1925	Diesel	75	Oil	Surface water
Do.	do.	1930	do.	80	do.	do.
Do.	do.	1936	Steam	45	Bagasse	do.
M. A. Co.	Paia[d]	1912	Hydro	800	Wailoa ditch	
Do.	Paia mill	1924	Steam	1,200	Bagasse and oil	Well 29
Do.	do.	1927	do.	1,200	do.	do.
Do.	do.	1932	do.	2,000	do.	do.
P. M. Co.	Honokowai	1918	Hydro	250	Honokowai Stream and tunnels 20A & B	
Do.	Kauaula	1914	do.	500	Kauaula Stream and tunnel 16	
Do.	Kauaula-iki	1915	do.	150	do.	
Do.	Wahikuli	1920	do.	180	Kahoma Stream and tunnels 18 and 19	
Do.	Olowalu	1926	do.	75	Olowalu Stream and tunnel 13	
Do.	Lahaina	1915	Steam	800	Bagasse and oil	Well 7
Do.	do.	1936	do.	3,000	do.	do.
Do.	Kaanapali	1924	do.	1,500	Oil	Well 3
Do.	do.	1926	do.	3,000	do.	do.
W. S. Co.	Wailuku	1906	do.	105	Bagasse and oil	Iao Stream
Do.	do.	1923	do.	300	do.	do.

[a] Two public utility companies, Maui Electric Co. and Lahaina Ice Co., purchase all their power from plants listed.

[b] This ditch utilizes the fall from Spreckels ditch to Koolau ditch.

[c] Near Kahului.

[d] In gulch behind Maunaolu Seminary above Upper Paia.

History and purpose of the investigation.—This report represents the completion of 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 of the Territory of Hawaii. The work was done under the general supervision of O. E. Meinzer, geologist in charge of the division of ground water of the Federal Survey. The study was started by the senior author in 1932 and carried on intermittently until January 1942. Traverses were made on foot or horseback of the entire island. The senior author lived on Maui from 1932 to 1938. H. A. Powers spent from October 1932 to December 1934 investigating and preparing a report on the geology and ground-water resources of the so-called "ditch country" of East Maui. J. H. Swartz made a preliminary magnetometer and electric resistivity survey of the Nahiku area of East Maui in 1936 and a final survey between March 1938 and November 1939. He was assisted by G. R. MacCarthy and A. C. Byers. G. R. MacCarthy made a resistivity survey of the Isthmus in 1939.

G. A. Macdonald spent from September 1939 to January 1940 making a geologic map of the Nahiku area. In February he examined tunnels on West Maui, assisted in the geologic mapping of Ukumehame, Olowalu, Launiupoko, Kahoma, and Kahakuloa Valleys, and collected additional rocks for his petrographic report.

All sugar plantations on the island were short of water in 1932, except the W. S. Co. Many of the towns, including Wailuku and Kahului, and the camps and ranches were in need of water also. During the following eight years water was developed to supply most of these needs. Some of it has been developed by plantation engineers, largely under the guidance of W. O. Clark, geologist for the Hawaiian Sugar Planters' Association, and some as a result of data gathered and recommendations made during these studies. By 1940, the H. C. & S. Co. had three new Maui-type wells with a capacity of 55 million gallons a day; the P. M. Co. three with a capacity of 20 million gallons a day; and the M. A. Co. three with a capacity of 33.5 million gallons a day besides increasing the yield of the Lower Paia well. Also, the E. M. I. Co. had driven 17 tunnels to develop perched water in the Nahiku area. Maui County drove tunnel 7 in Iao Valley under the direction of the senior author and developed sufficient water to supply Wailuku and Kahului. The tunnel is now being extended by the W. S. Co. to increase their supply for irrigation.

An intensive study supplemented by one deep test hole was made to remedy the shortage of water in the Kula District, but no additional water was found. Intensive studies were made to determine how water from Big Spring, in Hanawi Gulch, might be recovered at the Koolau ditch level by a tunnel. The results are summarized in Part 2.

Base map.—Plate 1 is a reconnaissance geologic map of Maui. The contours on the base map for the mountain areas and thinly settled slopes are so generalized that it is impossible to plot the geology accurately in such places. The topographic base shows erroneous drainage in the heads of many canyons, especially in Iao, Waihee, Kahakuloa, Kipahulu, and south of Nahiku. The North and South Waiehu Streams are shown flowing from the summit on nearly uniform grades. Actually a short distance from their sources they plunge into deep narrow canyons and flow seaward on fairly flat grades similar to Iao Stream. It was necessary to plot outcrops of trachyte on the west side of Kahakuloa nearly half a mile from their actual positions in order to fit interstream divides on the map. The topography of the mountainous and inaccessible areas should be redrawn from aerial photographs, many of which have already been taken.

Acknowledgments.—The Geological Survey is greatly indebted to the East Maui Irrigation Co. for its splendid cooperation throughout the work. Mr. J. H. Foss, manager of the company, helped in ways too numerous to list. Other members, including Messrs. J. Marsh Heizer, David S. Summers, John H. Hofmann, and John Plunkett, rendered valuable assistance. W. O. Clark, geologist for the Hawaiian Sugar Planters' Association, worked in close cooperation with the Survey. All plantations and ranches contributed generously. Their managers, Messrs. Frank F. Baldwin, Harry A. Baldwin, William D. Baldwin, Dwight H. Baldwin, Edward H. K. Baldwin, Harold Rice, Stafford Austin, Ray M. Allen, Caleb Burns, W. C. Jennings, and David Fleming, cooperated heartily. Messrs. Robert Bruce, engineer, Wailuku Sugar Co.; Clarence A. Brown, engineer, Pioneer Mill Co.; Robert E. Hughes, engineer, Hawaiian Commercial and Sugar Co.; and Al S. Spencer, chairman, County of Maui, gave indispensable aid. Others who assisted in various ways are Messrs. K. W. Kinney, William Starkey, Henry Gibson, Mundo Nunes, and a long list of faithful laborers, guides, packers, rodmen, and trail breakers. Mr. Sam Elbert and Miss Jean Braund edited the report and J. Y. Nitta prepared the illustrations. The

manuscript was criticized by Messrs. M. H. Carson, G. A. Macdonald, O. E. Meinzer, and C. S. Ross. Their criticisms were very helpful.

Previous investigations.—Maui received little study by geologists. J. D. Dana sailed past it during the Wilkes Expedition and wrote a brief description, chiefly physiographic, based on notes of the expedition by Pickering and Drayton.[5] Drayton's sketch of Haleakala Crater was the first map made of it. Dana's observations as a result of a few days on Maui in 1887, nearly half a century later, were published in two papers.[6] He recognized that the isthmus was underlain chiefly by Haleakala lavas and that the limestone there, which previously had been considered marine, was eolian.

Brigham thought that Kahoma and Iao Valleys might have craters at their heads because of their great depth.[7] Dutton made a brief trip through the summit depression and around the east end of Haleakala. Many of his conclusions were unsound because of his short stay and his unfamiliarity with tropical island processes. He noted, however, that the drowned mouths of valleys on East Maui indicated recent submergence[8] and that the streams of West Maui, being incised in their fans, indicated emergence.

E. S. Dana was the first to describe the petrography of Maui lavas. He called attention to the occurrence of soda trachyte on West Maui.[9] A detailed review of the petrographic contributions may be found in Part 3.

Hyatt and Pilsbry concluded from a study of the distribution of land snails that Maui with Lanai and Molokai formed a single island up to late Pliocene or even to Pleistocene time.[10]

Cross observed that the cones on West Maui were secondary and that many of the valleys on East Maui had been partly filled with recent lavas.[11] He was the first to call attention to the possibility of an erosional origin for the summit depression.[12] Other theories of the origin will be found elsewhere.[13]

Sidney Powers recognized the trachytic veneer on the ridges and

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[5] Dana, J. D., U. S. Exploring Expedition 1838-42, vol. 10, Geology, pp. 226-231, 1849.

[6] Idem, Points in the geological history of the islands of Maui and Oahu: Am. Jour. Sci., vol. 37, pp. 81-103, 1889; Characteristics of volcanoes, pp. 269-282, New York, 1890.

[7] Brigham, W. T., Notes on the volcanic phenomena of the Hawaiian Islands: Mem. Boston Soc. Nat. Hist., vol. 1, pt. 3, p. 366, 1868.

[8] Dutton, C. E., Hawaiian volcanoes: U. S. Geol. Survey 4th ann. rept., p. 202, 1884.

[9] Dana, E. S., Contributions to the petrography of the Sandwich Islands: Am. Jour. Sci., vol. 37, pp. 464-466, 1889. Also in Dana, J. D., Characteristics of volcanoes, New York, pp. 351-352, 1890.

[10] Hyatt, A., and Pilsbry, H. A., Manual of Conchology: Proc. Acad. Sci., Phila., vol. 21, p. 19, 1911.

[11] Cross, Whitman, Lavas of Hawaii and their relations: U. S. Geol. Survey Prof. Paper 88, p. 25, 1915.

[12] Idem, p. 92.

[13] Stearns, H. T., Origin of Haleakala Crater, Maui, Hawaii: Geol. Soc. America Bull., vol. 53, pp. 1-14, 1942.

the thick conglomerates extending far up the major valleys,[14] but mistook the conglomerates for explosive breccia. He noted that Molokini was a tuff cone like Diamond Head.

Foster noted that Eke is not a crater, as previously supposed.[15] Hinds reviewed what was known regarding the geomorphology of Maui.[16] The geologic history of West Maui,[17] the high marine deposits,[18] and the origin of Haleakala Crater[13] have been described by the senior author.

W. O. Clark has made intensive studies in the Nahiku area since 1930 as consultant for the E. M. I. Co. He has imparted freely all knowledge gained by his field studies and tunneling. He was the first to recognize and prove the existence of numerous lava-filled valleys in that area. He recognized also that much ground water was moving through the base of the lavas filling these valleys. Tunnels excavated according to his advice tapped some of these underground streams at the Koolau ditch level, thereby reducing the water wasting from these springs farther seaward in the same geologic structures. He recognized most of the lava flows later mapped by Macdonald in the Nahiku area and by Powers in Keanae Valley. His contribution to the geology of Maui and the development of water there is large and important.

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[14] Powers, Sidney, Notes on Hawaiian petrology: Am. Jour. Sci., vol. 50, p. 262, 1920.

[15] Letter quoted by Washington, H. S., and Keyes, M. G., Petrology of the Hawaiian Islands: VI Maui: Am. Jour. Sci., vol. 15, p. 200, 1928.

[16] Hinds, N. E. A., The relative ages of the Hawaiian landscapes: Pub. Univ. Calif., vol. 20, no. 6, pp. 172-175, 1931.

[17] Stearns, H. T., Geologic history of West Maui, Hawaii: Abst., B. P. Bishop Mus. Special Pub. 33, pp. 10-11, 1939.

[18] Idem, Pleistocene shore lines on the islands of Oahu and Maui, Hawaii: Geol. Soc. America Bull., vol. 46, pp. 1932, 1939, 1940, 1944, 1950-1956, 1935.

VOCABULARY OF VOLCANIC TERMS

A description of the geology of Maui requires the use of many volcanic terms vaguely or not uniformly defined in textbooks of geology. Several good classifications have been published, but the terms have not reached common usage, largely because these classifications either restricted the meaning of terms long in general use, or applied them to all types of volcanic action. There follow definitions of the terms used in this report. They should be considered as definitions applicable to the Hawaiian type[19] of volcanic products and processes but not necessarily applicable to all types of volcanoes.

COMPOSITION OF THE VOLCANIC ROCKS

The volcanic rocks of Maui are more diverse than those of Kilauea or Mauna Loa Volcanoes and comprise basalts, gabbros, picritic basalts, nepheline basanites, basaltic andesites, andesites, and soda trachytes. They are defined as follows:

Basalts are rocks with fine-grained or aphanitic groundmass containing plagioclase with an average composition at least as calcic as labradorite. *Gabbros* are coarse-grained intrusive rocks of basaltic composition that have visible mineral grains. *Picritic basalts* are basalts rich in ferromagnesian minerals with less than 35 percent feldspar. *Nepheline basanites* are basaltic rocks containing olivine and nepheline. *Basaltic andesites* are rocks containing andesine feldspar but of basaltic aspect and texture. *Andesites* are rocks with aphanitic groundmass containing plagioclase with an average composition within the range of andesine or oligoclase. *Soda trachytes* are rocks containing sodic amphiboles and pyroxenes with a fine-grained groundmass in which the prevalent feldspar is alkalic.

SHIELD-SHAPED DOMES

The East and West Maui mountains are two broad *shield-shaped*

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[19] For more details see:
Brigham, W. T., The volcanoes of Kilauea and Mauna Loa: B. P. Bishop Mus. Mem. vol. 2, no. 4, 1909.
Dana, J. D., Characteristics of volcanoes: New York, Dodd, Mead & Co., 1890.
Hitchcock, C. H., Hawaii and its volcanoes, 1909; 2d ed., with supplement, Honolulu, Hawaiian Gazette Co., 1911.
Jaggar, T. A., Jr., Volcanic investigations at Kilauea: Am. Jour. Sci., 4th ser., vol. 44, 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, 1930.
Stearns, H. T., and Vaksvik, K. N., Geology and ground-water resources of the island of Oahu, Hawaii: Hawaii Div. Hydrography, Bull. 1, 1935.
Wentworth, C. K., Ash formations of the Island Hawaii: Hawaiian Volcano Research Assoc., 1938.
Wentworth, C. K., and Williams, H., The classification and terminology of the pyroclastic rocks: Nat. Research Council Bull. 89, pp. 19-53, 1932. See references listed in this paper.
Williams, H., 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.

domes consisting chiefly of thin-bedded lava flows dipping away from their respective summit vents and rift zones. Their profiles are given in figure 2 in comparison with the profiles of Mauna Kea and Mauna Loa, Hawaii. West Maui is 5,788 feet high and about 18 miles across its longest dimension. East Maui is 10,025 feet high and 33 miles across.

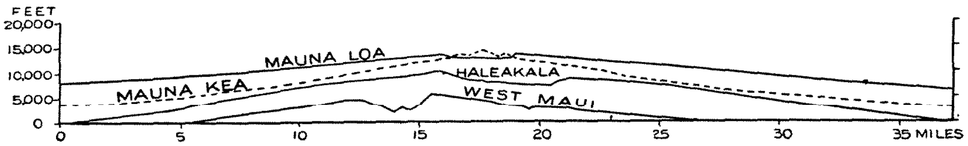

Figure 2. Profiles of East and West Maui in comparison with Mauna Kea and Mauna Loa, Hawaii.

CALDERAS AND CRATERS

A *caldera*[20] is a large, more or less circular or amphitheatral basin formed by engulfment or by explosion and collapse, usually on the summit of a volcano. 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 product laid down in a caldera.

An *eroded caldera* is one enlarged by erosion. Iao Valley is an eroded caldera. The so-called Haleakala Crater is believed to be neither a caldera nor an eroded caldera but the heads of two valleys in which subsequent volcanic activity has occurred. For this reason it is referred to herein as the *summit depression,* although the established geographic name of Haleakala Crater has been retained on plate 1 and in a few other places.

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

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

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[20] The word has loose use 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.

Many craters have been enlarged by loose cinders rolling down into the vents after firefountaining ceased. Some have been enlarged by collapse when the top of the lava 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 the firefountain ceased.

SECONDARY CONES

Five types of cognate secondary cones are superimposed on the two main domes; in order of decreasing number they are cinder cones, spatter cones, bulbous domes, lava cones, and tuff cones. The profile of each type is given in figure 3.

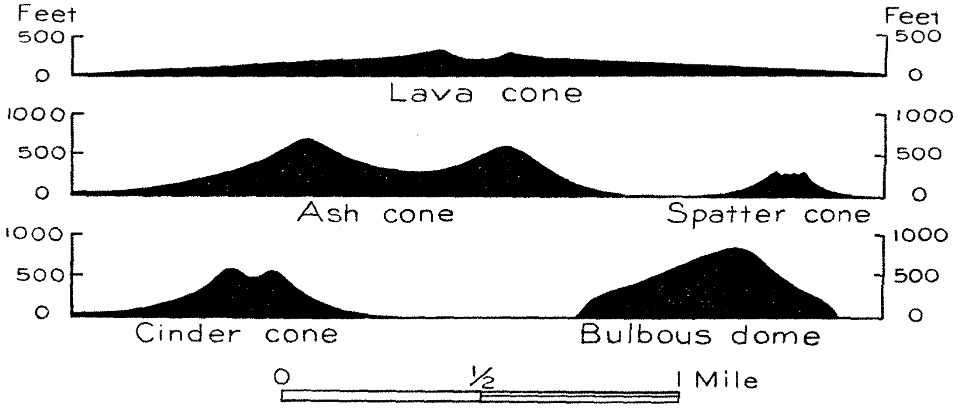

Figure 3. Profiles of cognate secondary cones. Ash cones after consolidation are called tuff cones.

Cinder cones.—The cinder cones range from 50 to 600 feet in height and reach three-quarters of a mile in diameter. (See frontispiece.) The largest cones are not primitive olivine basalt but are the product of eruptions of either less or more silicious types of magma.

Cinder cones are produced by the frothing of the erupting magma, called *firefountaining* in Hawaii. They consist of bedded magmatic ejecta only. The agglutinated clots are *spatter;* the heavier scoriaceous fragments are *cinders;* the smaller fragments, lighter in weight than cinders and extremely cellular in texture, are *pumice;* and those ellipsoidal, discoidal, or spheroidal forms produced by mechanical forces acting upon them during their flight through the air are *bombs*[21] (pl. 44C). Some of the ejecta contain crystals of olivine, augite, or feldspar, but others are composed of glass commonly blackened with magnetite dust.

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[21] Reck, Hans, Physiographische Studie über vulcanische Bomben: Erganzungsband Zeitschr. Vulcanologie, Tafeln 1–15, 1915.

During eruptions, *Pele's hair, Pele's tears,* and thin glassy ribbons are made by the firefountains, but they are fragile and soon disappear by weathering. Strong winds at the time of some eruptions, especially those on high ridges, cause the cones to grow asymmetrically and to spread pumiceous material fanwise for several miles to the 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; elsewhere it oxidizes brilliant red. These layers upon consolidation are called *vitric* or *glassy tuffs,* or *vitric crystal tuffs* if they carry crystals[22] (pl. 8B). The terms ash and tuff, if not qualified by descriptive adjectives, refer herein to such firefountain deposits. Cinder cones are not great ash makers, but deposits as thick as 30 feet accumulated in favorable places on Maui near rift zones where firefountains played repeatedly. 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 always referred to herein as *tuff.*

A very few cinder cones contain fragments of older rock. Such fragments fall down vent cracks when eruptions start and are carried up by the magma. The fragments are commonly coated with vesicular glass or they form the core of a cinder or bomb. Cinder cones are not the product of catastrophic blasts that tear wall rock from the volcanic throat, but are the result of free 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 firefountains typify eruptions of the early primitive olivine basalts but are scarce among the later differentiated lavas. Spatter cones on the tops or slopes of some cinder cones result from the dying gasps of the firefountains. Most bombs are made during this stage. Ash is not made during the building of a spatter cone.

BULBOUS DOMES.—Scattered over the landscape of West Maui are humps or mamelons differing in profile and origin from any of the common Hawaiian cones. These will be called *bulbous domes,* as they are made by viscous trachytes and related rocks, higher in

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[22] Pirsson, L. V., The microscopical characteristics of volcano tuff: Am. Jour. Sci., 4th ser., vol. 40, p. 191, 1915.

silica than basalts, squeezing out of a point on a crack (fig. 3). They are known also as puys, plug domes, domes, etc.[23] The term dome alone has been in use so long to describe the form of the main stratified volcanoes of Hawaii that it does not seem desirable to use it herein for bulbous masses of trachyte. The term plug dome implies that the dome has been formed by the upheaval of a previously cooled intrusive plug. None of the bulbous domes on Maui originated in this way.

The bulbous domes range from 100 to 600 feet in height and from 1,000 to 3,000 feet in diameter. All were formed by viscous lava being squeezed from a small vent, like paint from a tube. These mamelon-shaped bodies are bordered by breccia resulting from the fragmentation of the mass during its protrusion (pl. 38B). The eroded domes show that the lava rose through fissures 8 to 25 feet wide and swelled like a bulb either at or close to the surface. Those that swelled below the surface pushed aside and upward the adjacent older lava beds. Many spread down the slope as lava flows, the more silicious the lava the stubbier and thicker the flow. Many show crescentic growth ridges and concentric indipping shrinkage cracks (pl. 9 and fig. 4). A few were preceded by firefountains that built cinder cones, and the lava was emplaced as a mound separated in most places from the rim of the cinder cone by a moat.

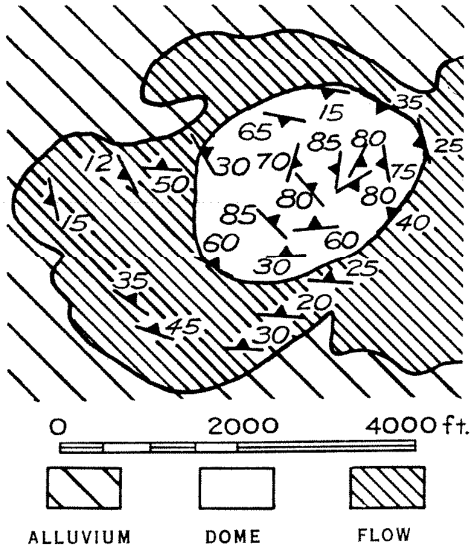

Figure 4. Map showing dip and strike of flow banding in Puu Launiupoko, West Maui, a bulbous dome of trachyte. Survey by G. A. Macdonald.

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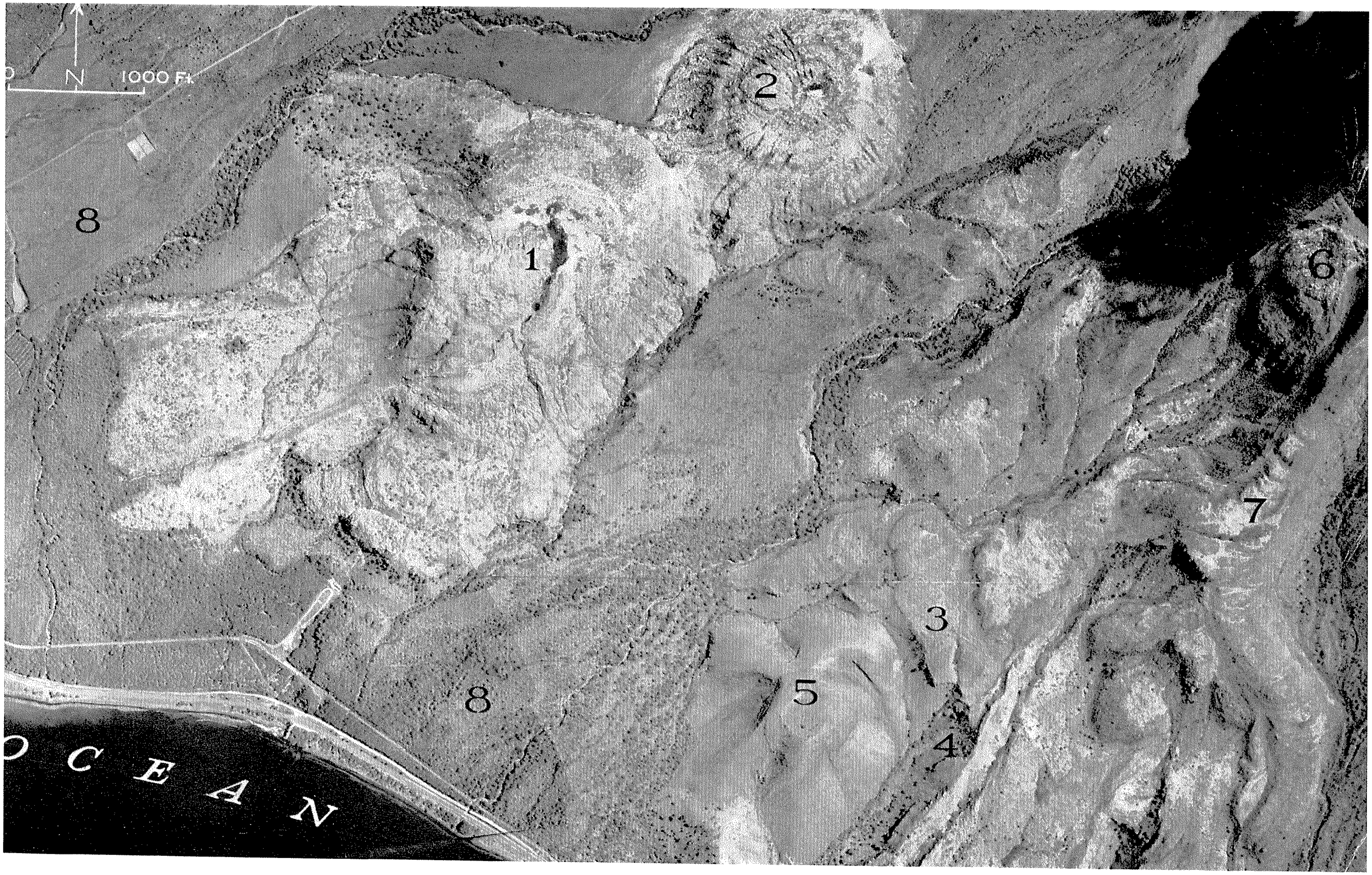
[23] For an excellent review of their origin, form, and terminology, see Williams, H., History and character of volcanic domes: Univ. of Calif. Pub. Bull., Dept. Geol. Sci., vol. 21, no. 5, pp. 51-146, 1932.

Right: Plate 8A. Road cut in south end of West Maui showing pahoehoe with thin flow units (1), interbedded aa (2), and lava tube (3).

Below: Plate 8B. Typical firefountain deposit of coarse pumiceous vitric tuff along the road to Haleakala National Park.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Opposite page: Plate 9. Looking down on Puu Launiupoko (1), West Maui, a typical bulbous dome of trachyte formed simultaneously over a fissure with another unnamed dome (2). The concentric growth ridges in the short flows that spread from them are discernible. Also shown is a trachyte flow (3) partly burying an eroded trachyte cinder cone (5), the Olowalu fossil locality (4), and an unnamed bulbous dome (6) partly buried by a later trachyte flow containing crescentic spreading ridges (7). Alluvial fans (8). Photo by U. S. Army Air Corps.

LAVA CONES.—The secondary *lava cones* are miniature lava domes. The lava was emitted in highly fluid condition with little or no gas effervescence. The cones were built of layers 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 if erupted on nearly level land (fig. 3). The exposed lava cones on Maui were built on fairly steep slopes; hence, they are asymmetrical, most of the lava having flowed downslope. They are composed mostly of primitive olivine basalt.

TUFF CONES.—The term *tuff cone* is restricted herein to the cone built by violent or catastrophic explosions. The only unburied cone of this type is Molokini Islet (pl. 6B). This cone is composed of thin-bedded consolidated ash, cinders, and angular and subangular fragments of rocks.[24] It is apparently phreatomagmatic in origin, having been caused by hot magma exploding in contact with sea water over a vent in the southwest rift of East Maui. Ash beds laid down during such explosions are called *vitric-lithic tuff,* the word *lithic* referring to the stony fragments present. Molokini differs from a normal cinder cone by the preponderance of comminuted material in the matrix, the presence of beds of breccia or agglomerate containing coral and other fragments of the basement, and its form. The part of the cone above sea level was deposited subaerially.

BRECCIAS

EXPLOSION BRECCIA.—Several beds of debris containing blocks of volcanic rock torn from the vent walls and lying in a matrix of comminuted rock were found on West Maui. The absence of magmatic ejecta indicates that the explosions were phreatic. They took place far from the sea and before streams had been established on the mountain; hence, they were probably caused by ground water entering vents and there being converted to steam by contact with bodies

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[24] Palmer, H. S., Geology of Molokini, with notes on the flora of Molokini, by E. L. Caum: B. P. Bishop Mus. Occasional Papers, vol. 9, no. 1, 1930.

of hot rock. The coarse deposits laid down by these explosions are called *explosion breccia* and the fine-grained deposits *lithic tuff.*

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 nearby firefountains or subsequently washed into the vents. Vent breccias formed close to the surface usually have poorly developed bedding, dipping centripetally 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. Other types of breccias are defined on pages 167 to 172.

EXTRUSIVE ROCKS

PAHOEHOE.—Lava laid down with a relatively smooth billowy entrail-like surface, in places ropy, is called *pahoehoe.* It 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. 8A). Pahoehoe flows are commonly composed of several *flow units,*[25] one above the other (pl. 8A). Each unit or layer represents a different period of spreading, a few hours, days, or months apart, during a single eruption. Glass skins a fraction of an inch thick that weather to red or yellow wavy streaks in cross section, characterize the surface of the units. Scoriaceous lava containing closely spaced round vesicles caused by gas bubbles, forms the upper or crustal parts of the units. This rock is known in Hawaii as *pukapuka,* meaning full of holes. 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 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

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

steam, snow, or water.[26] No pillow lava was found on Maui. Small undrained tubes with their concentric structures are sometimes mistaken for fossil logs.

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* (pl. 8A). If the flows are massive they have well developed columnar jointing. Tubes are rarely formed. Aa rivers, 5 to 30 feet wide, advance nearly to the margins of the flows. On steep slopes they are bordered by agglutinated splash and veneers of glassy vesicular rock. These spattery deposits along aa channels are easily confused with spatter cones. Aa flows are indescribably rough on the surface.

Pahoehoe is emitted with much included gas. If the gas is stirred out rapidly by flowing, cooling, or violent firefountaining, 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.[27] It is definitely established, however, that aa cannot revert to pahoehoe. It may appear to do so where pahoehoe emerges from a tube under aa or when a new phase of the eruption sends pahoehoe streaming down over previously erupted aa.

All lava flows on Maui can be classified as pahoehoe or aa. The trachyte flows are all aa, and angular blocks instead of spiny clinker dominate in their fragmental part. They are sometimes called *block lavas*.

KIPUKA.—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*,[28] in Hawaii. Kipukas are caused by topographic irregularities or the viscosity of the lava. The land in a kipuka may be lower or higher than the surface of the lava surrounding it. Commonly, they lie below the level of the lava although prior to its eruption they may have been knolls.

CRATER-FILLS.—Lava in pit craters and cinder-cone depressions generally congeals as a dense pod-shaped mass with pronounced columnar jointing. These masses are called *crater-fills*. 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

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[26] Stearns, H. T., Pillow lavas in Hawaii (abstract): Geol. Soc. America Proc., p. 26, 1938.

[27] Stearns, H. T., op. cit. (Water-Supply Paper 616), pp. 108-112.

[28] Idem, p. 45.

usual crustal features of lava flows, a valuable criterion for recognizing their origin when these features 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 the dikelets or offshoots from the mass can be found intruding the adjacent walls, it may be assumed, with rare exceptions, that the mass is not a crater-fill. Cinders, talus, or weathered rock usually border a crater-fill and where present are the best criteria.

INTRUSIVE ROCKS

Dikes and sills.—In general the flows on Maui were fed by magma that rose through fairly straight, vertical, narrow cracks. The solidified magmas in these cracks are called *dikes*. 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 are bordered by black glass a fraction of an inch wide. 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, herein called *dike complexes* (pl. 10B).

Relatively few intrusions follow the bedding planes. Those which do, form vertical-jointed nearly horizontal *sills* 1 to 50 feet thick. Sills are relatively scarce in comparison to dikes, but they are fairly abundant about the main vents. Sills are rarely 300 feet long and are usually much shorter.

Stocks, bosses, and plugs.—A relatively small subjacent intrusive body is called a *stock*.[29] 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*. Several bosses and plugs are found in or close to the main vents on Maui, 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. They range on Maui from 100 to 3,000 feet across (pl. 10A).

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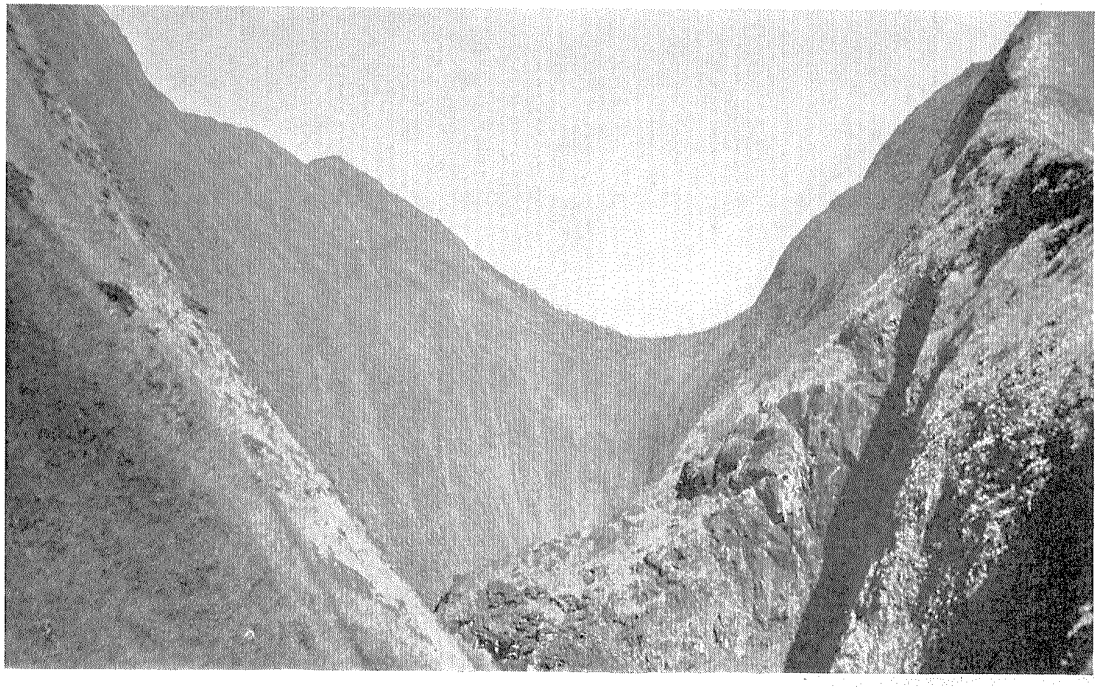
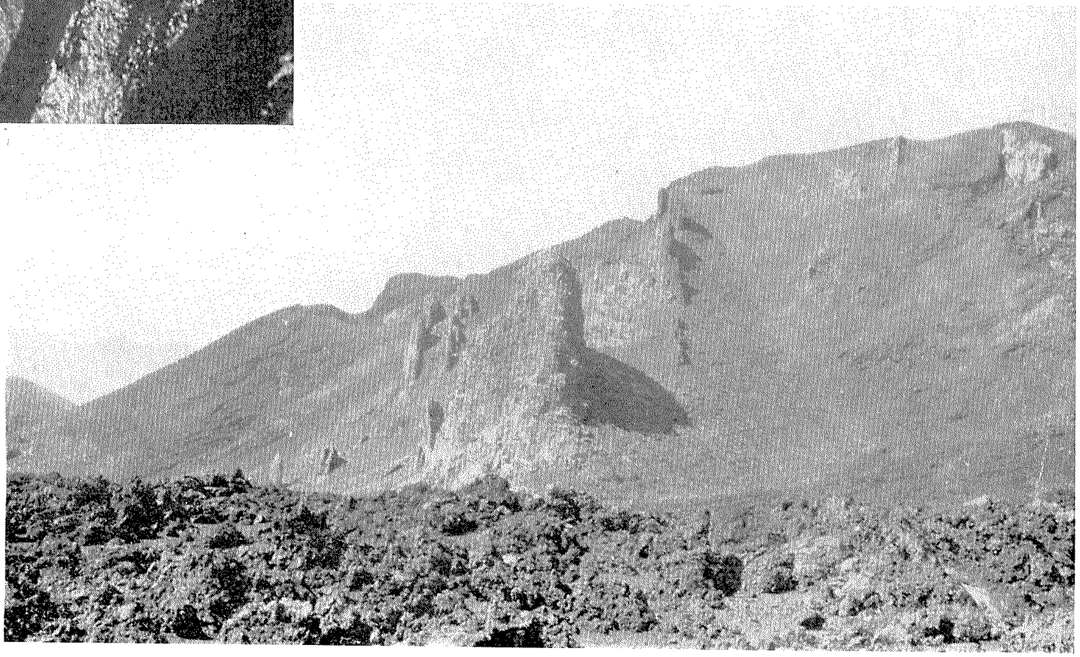
[29] Daly, R. A., Igneous rocks and the depths of the earth (revised), p. 113, 1933.



Below: Plate 10B. Dike swarm in the dike complex of the east rift zone of Haleakala Volcano exposed in the floor of the summit depression. Younger Hana cinders and lava veneer part of the slopes and bury the dike complex in the foreground.

Above: Plate 10A. Black Gorge, West Maui, a typical amphitheatre-headed valley. The massive rock in the foreground is the Black Gorge boss.



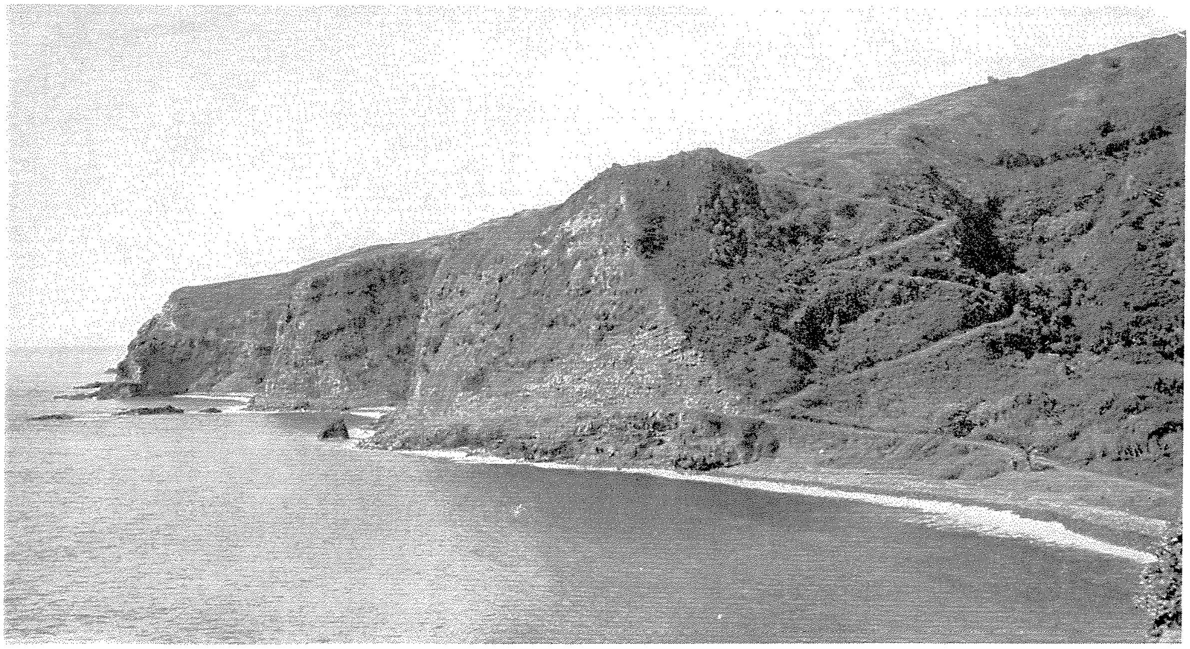
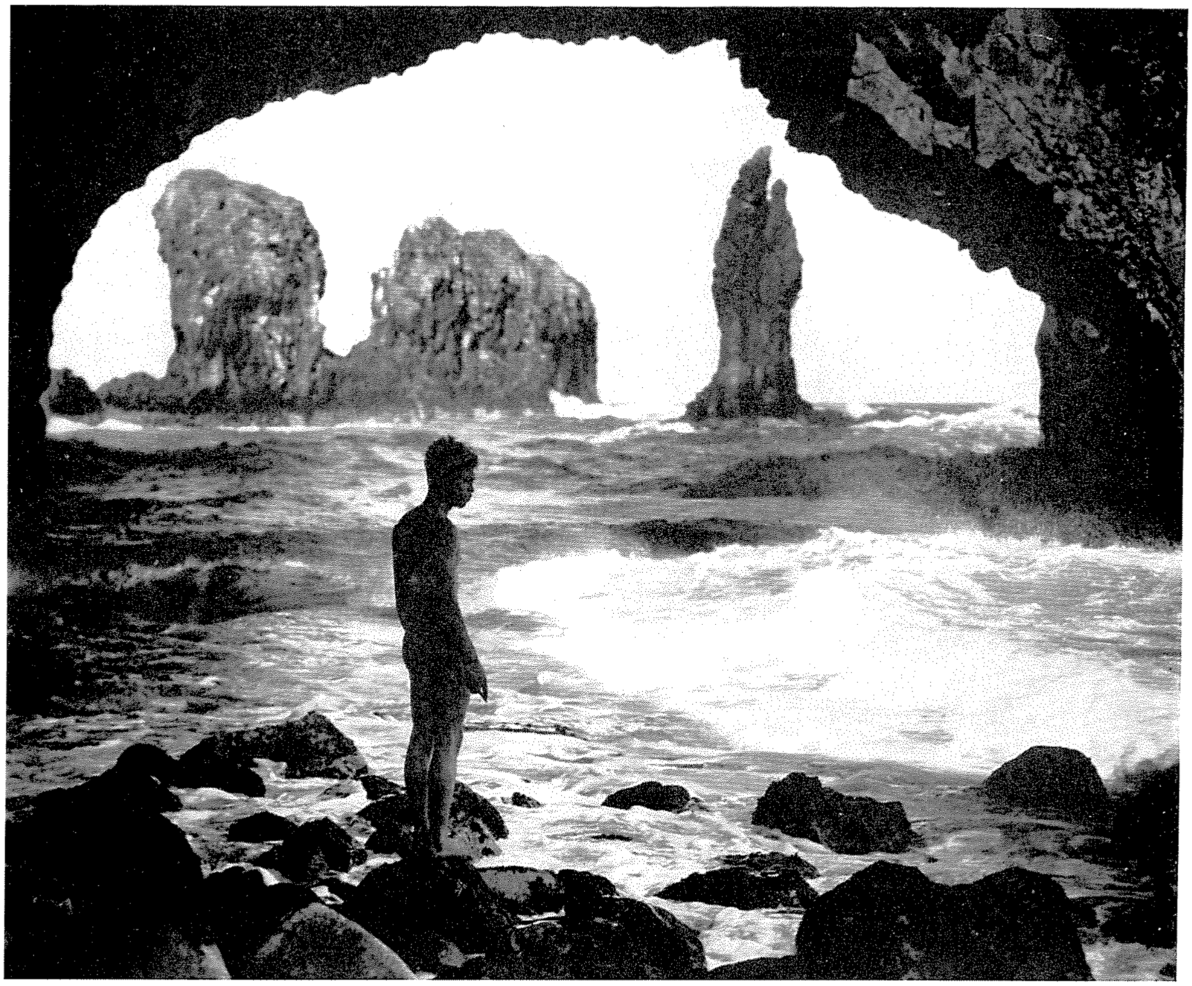


Plate 11A. Looking westward from Kaapahu Bay near Kipahulu, East Maui, showing sea cliffs cut in Kula lavas.

Plate 11B. Sea cave and stacks in the lava at Pauwalu Point, near Keanae, East Maui. Photo by Hawaii Tourist Bureau.



CLIMATE

TEMPERATURE, WIND, AND HUMIDITY.—The climate varies with altitude and to a lesser extent with position to windward or leeward. It is semitropical on the lowlands and temperate on the upper slopes of East Maui. The average mean temperature decreases from 3° to 4° F. for each rise in altitude of 1,000 feet. At Wailuku, altitude 200 feet, the mean temperature is 75°, the absolute maximum 93°, and the absolute minimum 51°. At Haleakala observatory, altitude 9,750 feet, corresponding temperatures are 49°, 68° and 18°, but the record is for 20 months only. August and September are the warmest months and January and February the coolest. The leeward drier and sunnier slopes have the highest temperatures. Temperate records follow:

Mean monthly temperatures at stations on Maui, in Fahrenheit degrees, up to and including 1938
(Data furnished by U. S. Weather Bureau)

Stations[a]	Altitude (feet)	Length of record (years)	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Haiku	530	22	70.4	70.0	69.9	70.9	72.6	74.1	74.8	75.2	75.4	75.4	73.5	71.6	72.8
Hana	200	31	71.7	71.5	71.4	72.1	73.6	75.0	75.9	76.4	76.7	76.3	74.5	73.1	74.0
Kaanapali	12	33	71.5	71.3	72.3	73.6	76.0	77.7	78.4	79.0	78.9	77.6	75.2	73.0	75.4
Kailiili	2440	14	61.8	61.8	62.1	62.4	64.4	66.0	67.0	67.7	67.7	67.1	64.8	62.9	64.6
Kailua	700	33	67.7	67.8	67.9	68.6	70.5	71.9	72.6	73.0	73.4	72.4	70.6	69.0	70.4
Kula Sanatorium	3004	20	60.7	60.5	61.3	62.2	64.1	65.6	66.7	66.9	67.0	66.0	64.1	62.3	64.0
Wailuku	200	34	71.0	70.8	71.4	72.4	74.6	76.4	77.5	78.1	78.0	76.8	74.4	72.4	74.5

[a] Haleakala summit temperatures, Apr. 1940 to June 1941 follow: 48.6, 47.8, 51.8, 52.0, 50.4, 49.5, 49.9, 48.4, 48.5, 46.6, 45.1, 45.0, 49.0, 48.2, 51.1; mean, 48.8.

Maui lies in the belt of the northeasterly trade winds, which persist throughout much of the year. During the fall and winter months they are interrupted by kona or southerly winds which usually last only a few days at a time. Light kona winds commonly cause clear weather, as the low-level trade-wind clouds do not form. Heavy winds sometimes accompany kona storms, but real typhoons do not occur in Hawaii. A tornado accompanied by heavy rain swept inland from Kihei on January 30, 1937, damaging buildings and trees along its path extending N. 10° E. from the Maui Polo Field past the Makawao Union Church in upper Paia. Beyond this point no evidence existed of the tornado. Fallen trees indicated a counter-clockwise rotation of the wind. It is the only tornado recorded in the Territory.

East Maui has sufficient bulk to alter the persistent northeast trade winds and cause prevailing southwesterly winds up the west slope and easterly winds along its southern coast. Wind velocities average 11.5 miles per hour at Haiku, the only station where records are available. The velocities are greatest in the afternoon.

No humidity records are available, but on Oahu, relative humidity is lowest in July and highest in December. High humidity accompanying light kona winds in the fall reaches about 95 percent and causes very uncomfortable weather. The humidity is less on the leeward than on the windward shore.

Lunar rainbows are frequently seen from the slopes of Haleakala during light misty showers on moonlight nights. The spectre of the Brocken is commonly seen from the western rim on late sunny afternoons when the summit depression is full of clouds. It is an enormously magnified misty shadow of the observer, cast upon a cloud bank and surrounded by a pale rainbow.

TIDAL WAVES.—Tidal waves sometimes sweep into the bays. They are caused generally by earthquakes in Japan, the Aleutian Islands, or Alaska. The largest in late years struck Kahului on February 3, 1923. The first receding wave left an inter-island vessel stranded on the harbor floor and when the wave returned it flooded Kahului and overturned cars parked on the main road. The waves reached heights of 6 to 12 feet and did $1,500,000 damage in Kahului.[30]

PRECIPITATION.—The annual precipitation at 114 stations on Maui is given on pages 35 to 42 and the mean monthly precipitation on page 30. The areal distribution of the rainfall and the location of the stations are shown in figure 5. The stations are so few on the eastern part of Haleakala and most of the records are so short that the isohyets in this area are approximate only.

Most of the precipitation is rain except on the top of Haleakala, where snow and sleet sometimes fall. Hail falls occasionally during infrequent thunder storms. More rain occurs from November to April than from May to October.

The average annual precipitation on East Maui varies from about 12 inches on the southwest coast to 386 inches at an altitude of 2,800 feet on the northeast slope. The precipitation reaches its maximum at this altitude and decreases until only 40 inches are recorded at the summit at 10,025 feet. The lowest annual rainfall ever recorded on East Maui is 2.46 inches at Puunene in 1912, but gages do not exist in the Makena area, where the rainfall may at times be even

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[30] Honolulu Advertiser, Feb. 4, 1923.

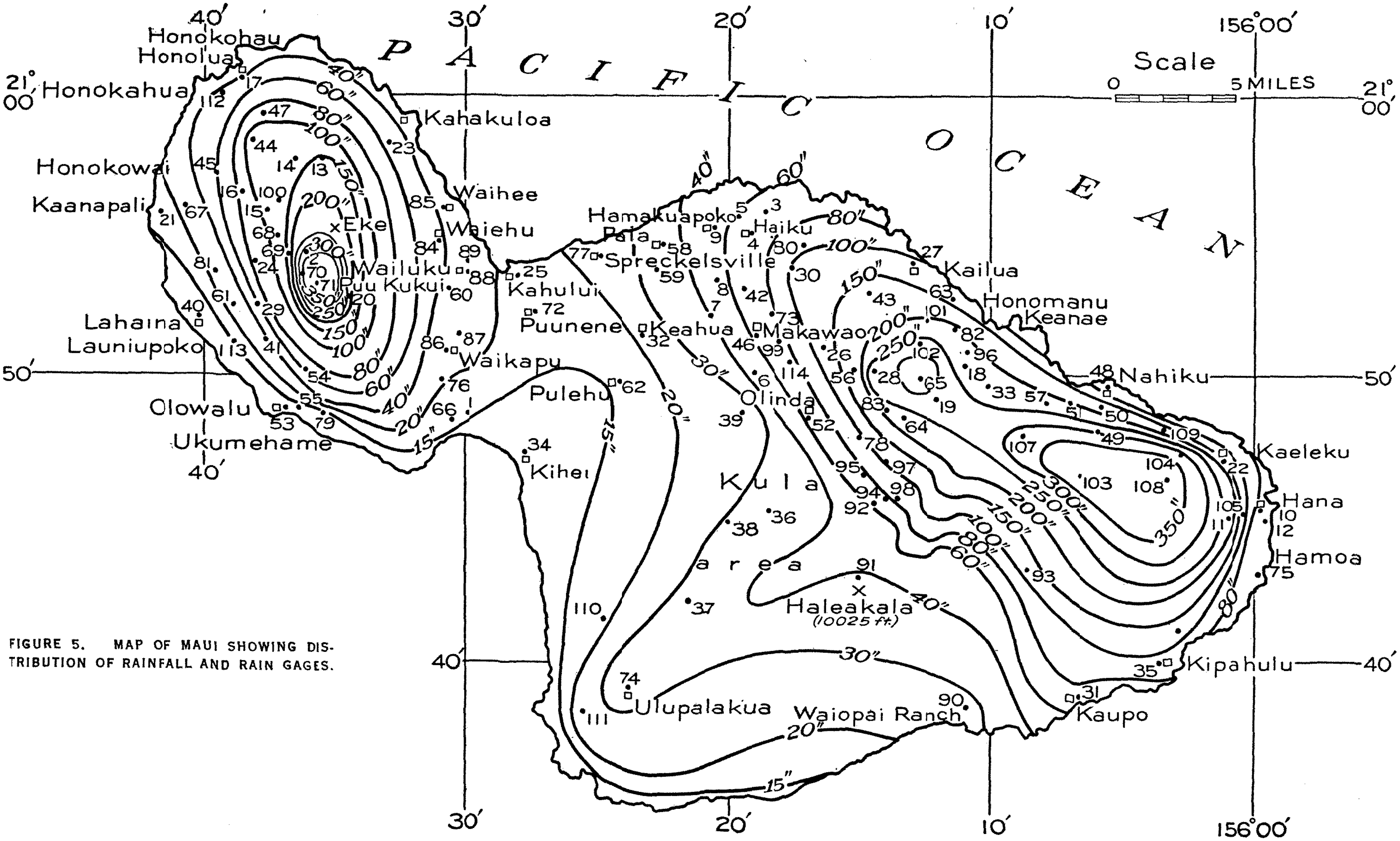

FIGURE 5. MAP OF MAUI SHOWING DISTRIBUTION OF RAINFALL AND RAIN GAGES.

Mean monthly rainfall on Maui through 1938[a]

(Data obtained from Territorial Planning Board Rept., 1939)

Station	Altitude (feet)	No. years record	January	February	March	April	May	June	July	August	September	October	November	December	Annual
1. Camp No. 7	80	13	2.59	3.40	2.11	1.50	1.06	0.06	0.03	0.07	0.29	0.30	1.09	2.84	15.34
2. Eke	4503	22	22.21	18.41	21.14	26.63	19.92	14.64	21.33	20.19	19.33	14.64	24.10	25.29	247.83
3. Haiku	530	20	8.07	6.27	6.35	7.36	5.14	4.03	5.14	4.58	3.77	4.22	6.84	7.02	68.79
4. Haiku (L. B. Atwater)	700	22	6.35	5.87	8.48	7.67	5.27	4.17	5.22	5.73	4.47	5.17	7.29	7.74	73.43
5. Haiku (Is. Pine Co.)	825	13	6.76	7.29	5.03	7.37	3.86	3.67	4.49	3.54	3.95	3.49	7.36	6.98	63.79
6. Haleakala Ranch	2000	44	7.19	6.60	6.63	4.53	2.33	0.89	1.32	2.08	2.13	2.22	5.59	7.69	49.20
7. Haliimaile Camp	1080	8	4.15	5.84	4.18	5.22	2.56	1.64	1.91	1.04	2.58	1.74	4.68	5.46	41.00
8. Hamakuapoko (Goodale)	800	6	3.78	3.59	3.52	3.83	2.87	2.12	3.69	2.04	1.73	1.65	3.17	4.82	36.81
9. Hamakuapoko Camp	310	16	3.73	3.68	3.70	3.35	2.30	1.78	2.37	1.96	1.40	2.18	3.16	4.00	33.61
10. Hana	200	28	7.90	6.58	7.30	9.08	5.02	3.71	4.39	5.39	5.37	4.87	6.56	9.00	75.17
11. Hana-iuka	1800	4	5.30	7.18	9.14	9.06	4.71	7.06	7.70	9.07	6.61	6.97	9.17	9.47	91.44
12. Hana Plantation	200	4	3.82	5.11	4.12	8.36	2.07	2.66	3.72	3.15	3.32	3.76	8.81	5.98	54.88
13. Honokohau Gulch	800	29	13.30	13.73	12.97	18.72	12.55	8.73	10.70	11.88	10.61	9.41	14.25	16.02	152.87
14. Honokohau Ridge	2300	22	12.39	12.24	11.57	18.06	10.39	6.86	8.93	8.29	8.97	9.20	15.47	15.08	137.45
15. Honokowai Intake	1717	15	12.22	11.09	9.95	12.18	7.20	6.33	8.29	7.68	7.04	6.04	12.00	13.54	113.56
16. Honokowai Power House	1200	8	6.35	5.48	4.78	5.97	4.59	2.36	2.11	2.49	2.96	2.98	6.14	6.52	52.73
17. Honolua Ranch	125	42	4.87	4.58	3.95	3.77	2.15	1.74	2.28	2.59	2.46	2.60	3.81	5.24	40.04
18. Honomanu	1600	31	18.42	18.91	20.45	26.51	17.87	14.97	18.66	21.09	16.92	14.51	21.48	22.21	232.00
19. Honomanu (Mauka)	2950	13	16.03	29.40	17.00	37.91	18.74	17.91	20.39	13.97	15.71	10.29	23.14	18.03	238.52
20. Iao Valley (Cave)	1720	4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	161.95
21. Kaanapali	12	38	3.44	2.79	1.99	1.42	0.65	0.24	0.36	0.71	0.45	0.62	1.58	3.51	17.76
22. Kaeleku	350	9	9.48	12.78	8.69	12.57	8.14	5.82	8.19	7.41	7.34	6.27	10.98	10.56	108.23
23. Kahakuloa	1000	10	5.92	5.66	3.50	6.85	2.69	1.45	3.07	1.99	3.20	3.31	5.56	6.84	50.04
24. Kahoma Intake	2000	25	10.30	8.10	8.17	6.89	4.88	4.83	5.23	4.78	5.59	4.64	8.17	10.58	82.16
25. Kahului	8	25	3.36	2.17	2.05	1.92	0.94	0.22	0.38	0.43	0.43	0.95	1.93	3.53	18.31
26. Kailiili	2440	11	12.78	13.38	11.65	17.53	8.84	8.03	9.21	8.12	8.05	5.26	13.10	12.26	128.21
27. Kailua	700	32	11.37	10.08	11.57	13.90	9.48	8.53	9.73	11.51	9.75	8.97	11.52	12.55	128.96
28. Kailua (Mauka)	3075	13	16.89	30.19	18.86	34.11	19.54	18.74	19.83	14.46	17.60	11.17	27.29	19.29	247.97
29. Kauaula Intake	1550	17	5.65	4.27	4.57	2.90	1.35	1.56	1.94	1.47	2.96	2.18	3.84	6.78	39.47
30. Kaupakulua	1050	15	11.76	10.05	8.36	10.96	6.50	5.52	7.18	6.42	5.95	6.18	11.06	9.49	99.43
31. Kaupo (Mokulau)	285	8	6.52	8.94	10.84	5.59	6.94	2.99	5.84	5.70	4.72	6.19	9.48	5.96	79.71
32. Keahua Camp	525	18	3.74	2.94	2.44	1.83	1.35	0.38	0.48	0.40	0.63	0.72	2.31	3.93	21.15
33. Keanae	1000	31	18.85	19.05	20.11	26.01	17.51	15.26	18.64	20.71	16.53	14.36	21.48	22.59	231.10
34. Kihei	45	8	2.44	3.26	1.87	0.32	0.12	0.08	0.16	0.21	0.09	0.63	0.71	1.40	11.29
35. Kipahulu	350	35	8.01	7.66	8.00	6.40	5.54	5.07	5.98	6.26	6.71	6.11	6.73	7.75	80.22
36. Kula (Erehwon)	4000	46	4.75	4.52	3.71	2.53	2.50	1.75	1.86	2.73	2.94	2.18	2.10	3.89	35.46
37. Kula Sanatorium	3004	19	4.14	3.70	2.00	3.81	1.88	1.83	1.63	1.95	2.30	2.22	1.73	4.82	32.01
38. Kula (Waiakoa)	2700	6	4.67	4.77	5.59	0.86	1.38	1.32	1.34	2.16	2.04	1.37	2.18	4.32	32.00
39. Kula Camp	2200	10	3.20	4.82	2.51	1.98	0.51	0.29	1.20	0.93	1.43	1.12	3.20	4.15	25.34
40. Lahaina	50	22	2.62	1.61	1.68	0.99	0.35	0.08	0.07	0.13	0.36	0.44	0.89	2.58	11.80
41. Launiupoko	1300	22	5.00	3.40	3.66	2.38	0.87	0.71	0.97	1.50	1.42	1.79	3.38	5.24	30.32
42. Lilikoi	1225	8	6.38	8.74	5.80	7.84	4.56	3.65	4.49	2.63	4.13	2.48	8.48	7.40	66.58

43. Lupe	1275	39	14.30	12.92	15.41	17.85	13.26	10.32	13.03	14.31	11.21	11.17	15.76	15.61	165.15
44. Mahana	1400	39	9.76	9.60	8.98	10.59	7.81	5.70	7.59	8.51	7.00	6.55	9.65	10.87	102.61
45. Mahinahina	750	22	8.45	5.58	5.85	5.78	3.10	2.24	2.94	2.73	2.91	2.77	6.25	8.44	57.04
46. Makawao	1700	23	8.62	6.10	6.77	6.36	3.65	1.38	2.70	3.31	3.22	3.76	6.25	9.99	62.11
47. Mokupea	1000	37	8.51	8.66	7.37	8.97	6.22	4.64	6.10	6.61	5.67	5.52	8.24	9.17	85.68
48. Nahiku (120)	120	4	5.39	8.70	4.95	11.01	6.92	4.07	11.56	7.15	6.20	9.92	9.62	7.35	92.84
49. Nahiku (Mauka)	1600	5	24.55	15.31	32.71	33.94	18.31	16.24	25.01	32.55	22.90	20.22	29.91	28.24	299.89
50. Nahiku (740)	740	16	14.28	11.80	17.93	17.21	12.34	11.96	13.04	17.55	14.05	13.25	17.64	17.76	178.81
51. Nahiku Camp	1200	31	18.28	16.99	18.28	24.58	16.03	14.04	16.91	19.57	15.63	13.68	21.29	21.18	216.46
52. Olinda	4000	23	6.50	5.35	5.24	4.73	3.02	1.11	1.72	1.66	2.24	2.18	4.82	7.67	46.24
53. Olowalu	10	20	4.81	2.45	2.44	1.67	0.20	0.08	0.06	0.12	0.20	0.36	1.00	2.86	16.25
54. Olowalu (Mauka)	700	24	9.52	7.07	8.07	5.97	4.24	4.23	4.50	3.90	4.35	3.55	7.27	8.04	70.71
55. Olowalu (A. Haneburg)	15	9	1.80	2.10	0.66	0.17	0.22	0.08	0.02	0.34	0.01	0.55	0.87	1.27	8.09
56. Opana	3052	13	12.75	21.87	14.52	28.23	14.63	11.14	12.23	9.29	12.17	7.40	16.49	15.03	175.75
57. Paakea	1250	31	18.28	16.99	18.28	24.58	16.03	14.04	16.91	19.57	15.63	13.68	21.29	21.18	216.46
58. Paia	125	20	4.11	3.41	3.18	3.35	2.28	1.66	1.94	1.53	1.86	1.85	3.93	4.92	34.02
59. Paia	180	12	3.96	5.70	5.74	2.87	1.83	1.37	1.68	1.95	1.77	2.43	4.94	4.09	38.33
60. Penhallow's Residence	390	22	4.27	4.73	4.18	3.52	1.72	0.46	0.44	0.78	0.68	1.68	2.47	4.69	29.62
61. Power Station No. 2	967	15	2.85	2.50	2.22	1.56	0.38	0.51	0.45	0.58	1.29	1.19	1.38	4.11	19.02
62. Pulehu	560	11	1.94	2.73	2.01	0.89	0.20	0.14	0.09	0.07	0.27	0.46	1.66	3.35	13.81
63. Punaluu	700	29	11.46	11.03	12.02	14.15	9.45	8.20	9.80	11.32	10.08	8.90	11.88	12.79	131.08
64. Puohokamoa	4300	18	26.04	18.39	25.88	25.99	13.90	13.40	17.89	19.36	14.17	15.85	28.23	27.14	246.24
65. Puohokamoa No. 2	2900	12	17.91	36.77	21.30	42.11	21.91	21.40	24.46	16.63	19.66	13.03	26.63	20.06	281.87
66. Puuhele	90	6	2.80	2.26	1.07	2.06	0.31	0.09	0.04	0.11	0.32	0.33	1.28	2.92	13.59
67. Puukolii	425	20	4.26	2.81	2.54	1.98	0.79	0.26	0.44	0.44	0.81	0.68	2.02	4.05	21.08
68. Puu Kukui (Lower)	2500	24	11.23	9.41	9.17	10.98	7.19	6.00	6.90	6.78	5.81	5.80	9.34	11.14	99.75
69. Puu Kukui (Upper)	4450	13	21.31	23.43	18.17	24.71	21.08	21.15	23.00	22.85	22.15	13.54	20.77	22.85	255.01
70. Puu Kukui (Upper)	5000	11	43.39	25.67	35.69	38.62	23.09	24.96	33.87	31.87	21.04	22.14	33.32	29.07	362.73
71. Puu Kukui (Crest)	5788	10	24.39	35.75	27.57	37.45	34.25	30.25	42.78	34.00	32.22	17.60	31.80	33.50	381.56
72. Puunene	73	10	3.15	4.01	3.33	1.55	0.64	0.27	0.36	0.70	0.68	0.95	1.67	4.11	21.42
73. Puuomalei	1480	41	8.09	9.62	8.67	8.45	5.12	3.40	4.32	4.62	4.43	4.55	8.40	9.02	78.69
74. Raymond Ranch (Ulupalakua)	2000	5	4.31	2.91	2.29	1.86	2.78	1.83	2.11	2.56	2.59	3.03	2.32	3.62	32.21
75. Reciprocity Mill (Hamoa)	60	7	3.69	6.20	8.38	4.46	4.07	2.76	4.06	3.78	2.88	6.03	7.24	4.91	58.46
76. Reservoir No. 8	300	19	2.62	3.17	1.88	3.06	0.56	0.22	0.21	0.20	0.48	0.87	2.02	3.97	19.26
77. Spreckelsville	50	17	3.39	2.90	2.63	3.14	1.55	0.51	0.83	0.83	0.66	0.94	1.95	4.11	23.44
78. Ukulele	5150	31	8.65	8.74	7.55	8.59	4.51	2.33	4.67	4.98	5.18	3.97	8.03	10.32	77.52
79. Ukumehame	75	6	2.17	1.97	1.49	0.38	0.15	.....	0.06	0.18	0.29	0.42	1.47	1.74	10.32
80. Ulumalu	825	13	9.68	10.00	7.49	11.17	6.92	6.81	8.30	7.08	6.18	6.37	10.57	9.74	100.31
81. Wahikuli	580	11	2.99	2.49	2.09	1.81	0.51	0.40	0.68	0.41	0.97	1.11	1.54	3.71	18.71
82. Waikamoi[b]	1200	29	18.51	17.97	19.14	24.19	16.69	14.17	17.29	19.15	15.91	14.15	20.42	21.59	219.18
83. Waikamoi Gulch[b]	4250	25	24.18	18.53	21.22	24.08	16.33	13.24	16.10	16.38	15.02	13.72	24.77	24.86	228.43
84. Waiehu	250	9	7.18	4.01	4.57	5.62	3.16	0.83	1.04	1.82	1.70	1.64	3.20	6.28	41.05
85. Waihee	100	37	4.50	4.34	3.60	3.56	1.44	0.75	1.08	1.08	1.30	1.76	3.26	4.61	31.28
86. Waikapu	470	35	3.71	4.10	3.21	3.39	1.26	0.54	0.41	0.60	0.75	1.20	2.76	4.34	26.27
87. Waikapu (Everett)	250	8	4.33	5.57	3.89	2.86	1.58	0.53	0.82	1.35	0.62	2.21	2.97	4.28	31.01
88. Wailuku	200	34	4.69	3.89	3.64	3.36	1.34	0.52	0.67	0.82	0.86	1.19	2.81	4.91	28.70
89. Wailuku Mill	175	28	4.14	4.86	3.91	2.15	1.52	0.41	0.62	1.03	0.89	1.42	3.02	3.88	27.85
90. Waiopai Ranch	200	38	4.05	3.93	3.52	2.25	0.76	0.13	0.25	0.60	1.17	1.07	2.12	4.30	24.15

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[a] Comparison was made of mean annual rainfalls at 8 stations, some very wet and others dry, to and including 1940. The additional dry years 1939 and 1940 lowered the annual averages in the 8 stations only about .001 percent.

[b] Also spelled Waiakamoi.

lower. The highest record is at Kuhiwa Gulch, where 523 inches fell in 1937. A total of 28.20 inches fell at Hana on April 27, 1915. This record has probably been exceeded at other stations where only monthly readings are made. Monthly rainfalls of 100 inches are fairly common. At some windward stations rain falls 320 days a year, in contrast to stations in the rain shadow of Haleakala, where rain falls on an average of only 16 days a year.

The average annual rainfall on West Maui ranges from 13 inches at Lahaina on the leeward coast to 389 inches at Puu Kukui, altitude 5,788 feet, the summit of the mountain. The rainfall increases steadily all the way to the top. The summit of West Maui is the third rainiest place in Hawaii, being exceeded by Waialeale on the summit of Kauai and the Kuhiwa Gulch station on East Maui. A total of 496 inches were recorded on Puu Kukui in 1937. The lowest for any year was 2.00 inches recorded at Olowalu in 1928. This is the lowest rainfall ever recorded officially in the Territory. The annual rainfall is generally less at Olowalu than at any other Weather Bureau stations in the Hawaiian Islands, in spite of its location only 6 miles from Puu Kukui, one of the rainiest places on earth.

More rain may fall on the leeward coast during a single kona storm than during the rest of the year. Persistent kona weather, and also winds from the east, may cause droughts on the northeast slope where the great irrigation ditches collect their water. A heavy storm struck Haleakala summit on February 1, 2, and 3, 1936. It was accompanied by an extremely low barometer and 15.5 inches of snow fell. Heavy rain and hail fell between 6,000 and 9,000 feet altitude, and the slope was white with streams and waterfalls. Sheetflood erosion was extremely fast, the loose clinker and pumice moving rapidly down the steep slopes. The gulches became raging torrents, but all the water sank before it reached the Isthmus. The senior author reached the summit at 11 a. m. February 2 and found a high wind blowing and 3 inches of wet snow on the ground. The wet fog blowing against the vegetation coated the shrubs with ice. The snow extended to an altitude of 9,300 feet. Several persons in stalled cars were saved from death by freezing by rescue parties on the night of February 1.

The rainfall varies widely not only with altitude, topography, and season, but also from year to year. Droughts come in the winter as well as in the summer. In very wet areas there are no well-marked

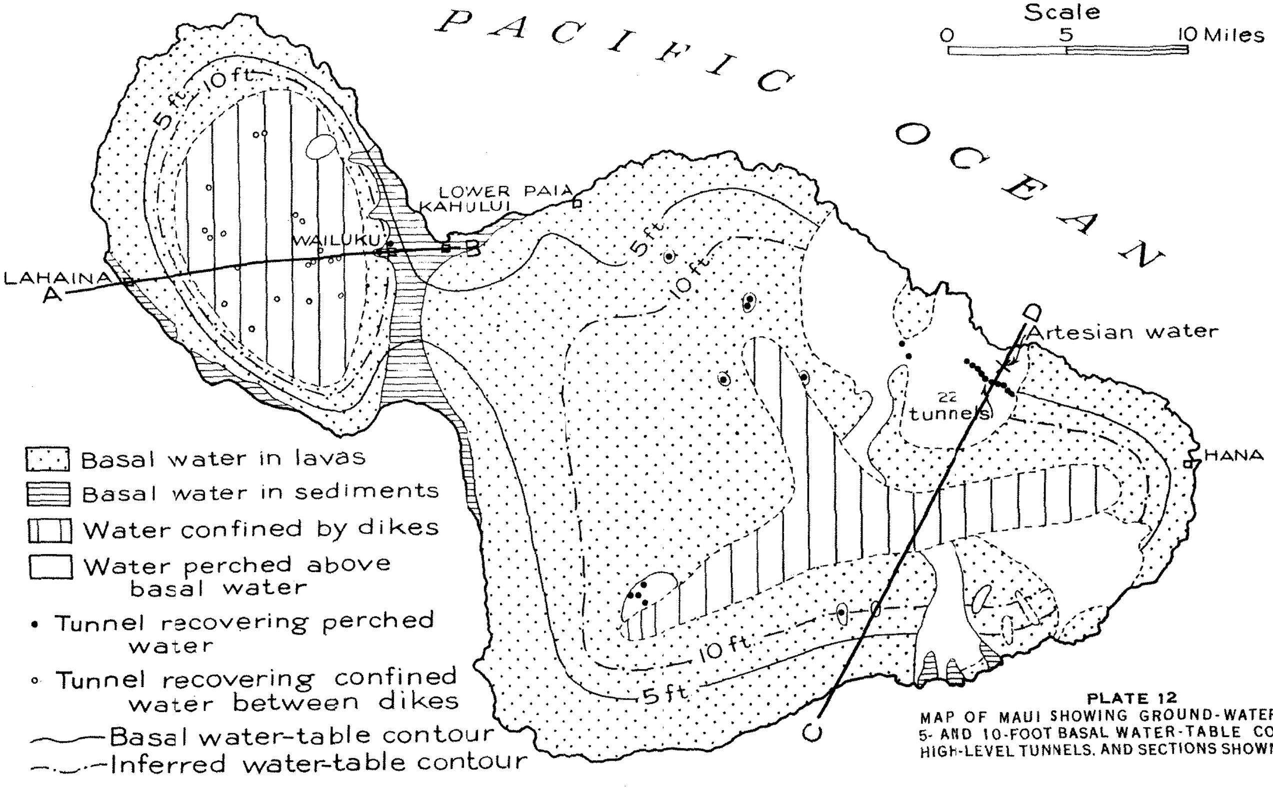
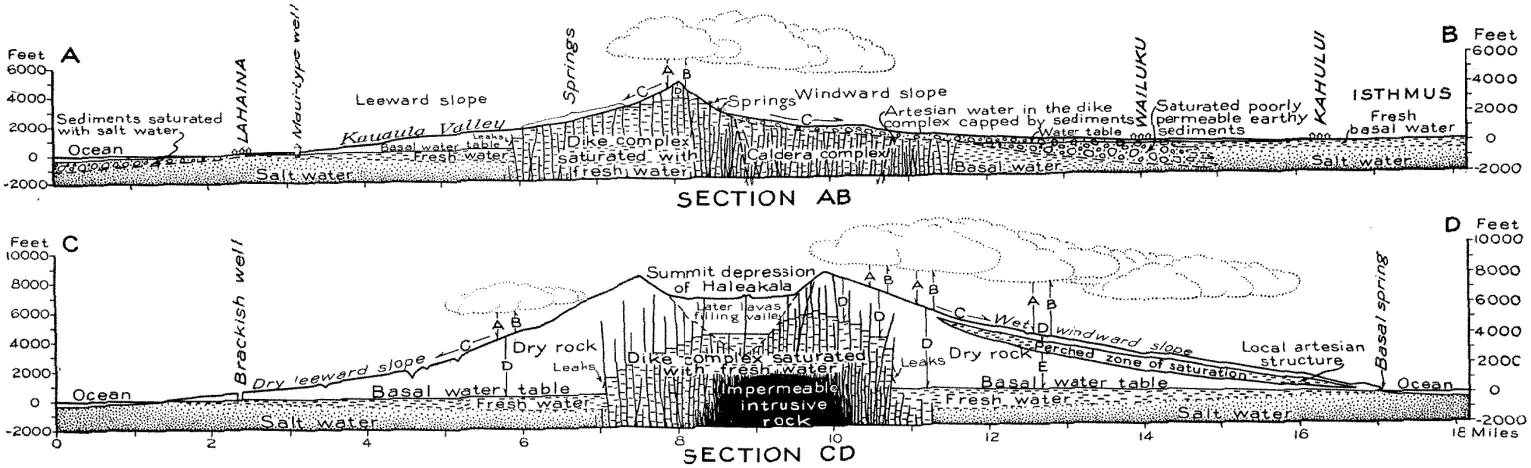


PLATE 12
MAP OF MAUI SHOWING GROUND-WATER AREAS, 5- AND 10-FOOT BASAL WATER-TABLE CONTOURS, HIGH-LEVEL TUNNELS, AND SECTIONS SHOWN BELOW.



SIMPLIFIED SECTIONS OF WEST MAUI (AB) AND EAST MAUI (CD) SHOWING THE SOURCE AND DISPOSAL OF RAINFALL. **A**, Rainfall; **B**, fly-off or evaporation and transpiration; **C**, run-off; **D**, run-in or recharge to zone of saturation; **E**, percolation from perched zone of saturation to basal water table. Shows the various high- and low-level springs and the bodies of rock saturated with ground water.

wet and dry seasons. Naulu[31] showers fall on leeward slopes in hot weather when neither trade nor kona winds blow. The comparative monthly distribution of rainfall in various parts of Maui is shown in figure 6. The stations are arranged to show graphically how the maximum rainfall is affected by the form and height of the mountain.

The average annual rainfall computed for the entire island from the isohyetal map (fig. 5) is 85 inches, equivalent to 1,460 million gallons per square mile per year, or 2,940 million gallons per day. The average annual rainfall is equivalent to a depth of 88 inches or more than 7 feet on East Maui and 74 inches or more than 6 feet on West Maui.

DISPOSAL OF RAIN.—The ultimate source of nearly all ground water is rain. The presence of thermal water in well 12 at Ukumehame may indicate a very small quantity of magmatic water under West Maui. Even there, most of the thermal water is rain water that has penetrated to bodies of hot rock. The source and disposal of rain is shown diagrammatically in plate 12. A large quantity of all rain evaporates directly from the ground and vegetation on which it falls. If the shower is heavy, part may run off and part sink into the ground. The more permeable the ground the more rain it can absorb. Not all that is absorbed reaches the zone of saturation. A part is returned to the atmosphere by capillary action in the soil, and another part is drawn up through roots of plants and transpired through the leaves. In dry areas most light showers are so dissipated. But in regions of heavy rainfall, especially where underlain by permeable lavas without well-developed stream channels, most of it may percolate to the zone of saturation.

Ground-water recharge is insufficient to supply wells with potable water in the dry leeward areas, but under wet areas the recharge is rapid and ground water is abundant.

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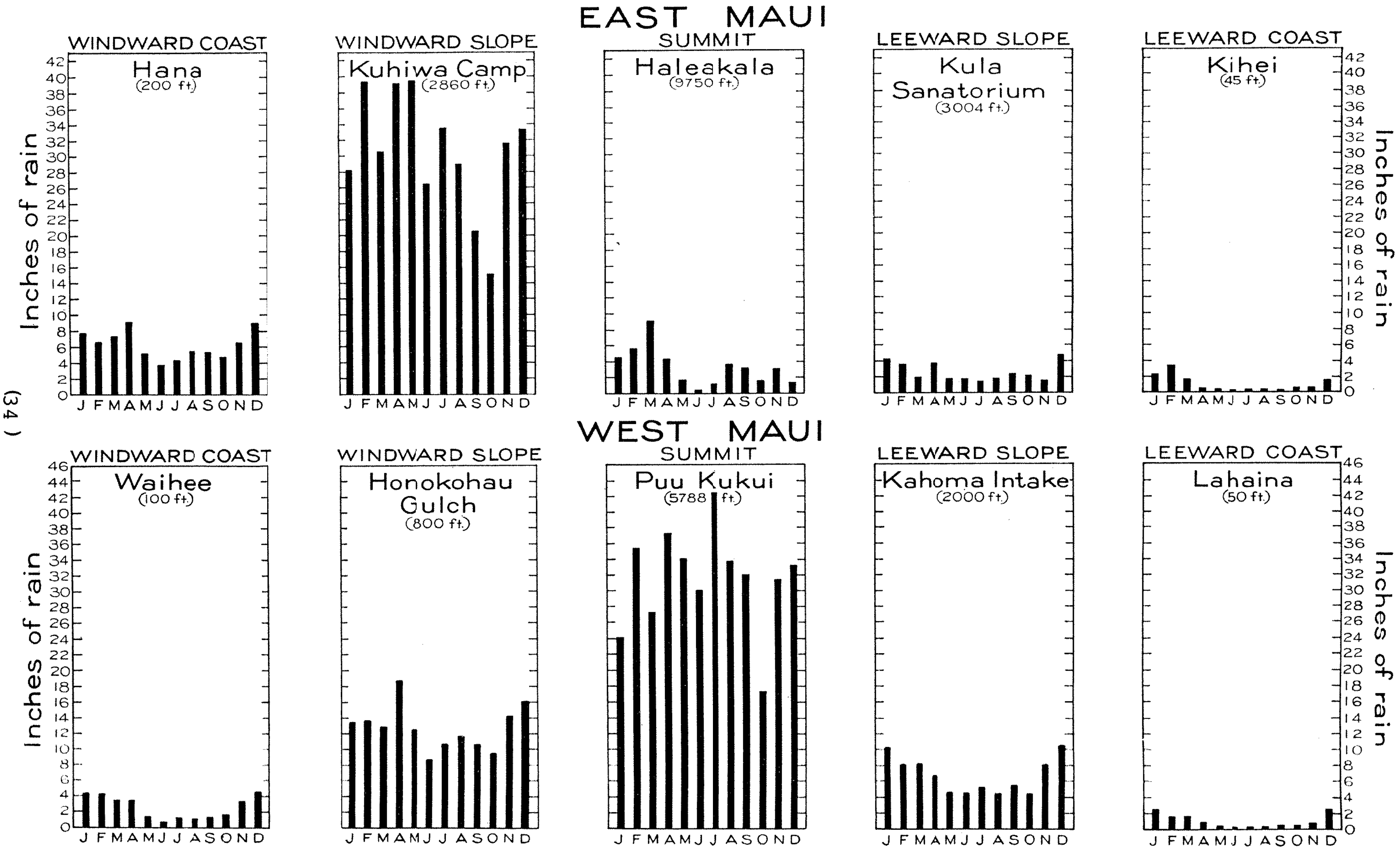
[31] Stearns, H. T., Geology and ground-water resources of the islands of Lanai and Kahoolawe. Hawaii: Hawaii Div. of Hydrography, Bull. 6, p. 66, 1940.

FIGURE 6. COMPARATIVE MONTHLY DISTRIBUTION OF RAINFALL ON MAUI.



Rainfall at stations on Maui, in inches, 1879–1940*

(Data furnished by U. S. Weather Bureau and plantations)

Sta. no. (fig. 5)	1	2	3	4 & 5	6	7	8 & 9	10 & 12[a]	13	14	15	16
Name	Camp 7	Eke[b]	Haiku	Haiku	Haleakala Ranch	Haliimaile Camp	Hamakuapoko Camp[c]	Hana	Honokohau Gulch	Honokohau Ridge	Honokowai Intake[d]	Honokowai Power House
Alt. (ft.)	90	4503	530	825	2000	1080	310	200	800	2300	1717	1200
Year												
1884	......	......	......	......	......	......	33.33	......	......	......	......	......
1885	......	......	......	......	......	......	52.10	......	......	......	......	......
1886	......	......	......	......	......	......	24.70	......	......	......	......	......
1887	......	......	......	......	......	......	35.45	......	......	......	......	......
1888	......	......	......	......	......	......	29.47	......	......	......	......	......
1889	......	......	......	......	......	......	21.87	......	......	......	......	......
1890	......	......	......	......	......	......	57.30	......	......	......	......	......
1891	......	......	......	......	......	......	29.35	......	......	......	......	......
1892	......	......	......	......	[e]44.26	......	29.53	......	......	......	......	......
1893	......	......	......	......	[e]21.50	......	28.55	......	......	......	......	......
1894	......	......	......	......	43.70	......	31.80	61.93	......	......	......	......
1895	......	......	......	......	36.52	......	36.79	67.79	......	......	......	......
1896	......	......	......	......	28.70	......	31.70	47.62	......	......	......	......
1897	......	......	......	......	24.71	......	20.46	42.20	......	......	......	......
1898	......	......	......	65.15	31.28	......	39.18	......	......	......	......	......
1899	......	......	......	49.37	33.40	......	35.97	......	......	......	......	......
1900	......	......	......	63.34	54.57	......	50.21	......	......	......	......	......
1901	......	......	......	59.81	67.12	......	49.50	......	......	......	......	......
1902	......	......	......	97.79	111.83	......	67.44	......	......	......	......	......
1903	......	......	......	85.40	60.46	......	57.00	......	......	......	......	......
1904	......	......	......	74.73	77.80	......	56.84	......	......	......	......	......
1905	......	......	......	80.49	40.88	......	49.11	......	......	......	......	......
1906	......	......	......	75.40	82.77	......	46.78	......	......	......	......	......
1907	......	......	......	76.98	53.65	......	52.59	......	[e]131.42	......	......	......
1908	......	......	......	59.20	25.88	......	42.49	60.08	105.07	......	......	......
1909	......	......	......	75.37	27.73	......	59.10	75.74	137.22	......	......	......
1910	11.28	......	......	91.23	46.55	......	66.77	96.94	164.45	......	......	......
1911	13.01	......	......	77.73	33.58	......	55.11	71.02	171.57	......	......	46.43
1912	2.46	......	......	56.45	22.10	......	39.71	40.92	123.60	......	......	30.76
1913	10.31	......	......	62.83	34.22	......	45.14	59.30	122.61	......	......	41.42
1914	13.71	354.72	......	102.87	59.85	......	68.32	125.87	254.55	222.00	......	65.12
1915	9.67	229.80	......	70.26	49.27	......	49.52	103.26	162.11	144.00	......	47.54
1916	33.14	317.20	94.82	89.31	98.19	......	68.91	......	[e]234.59	186.00	......	87.97
1917	18.26	155.20	48.69	43.99	38.59	......	34.67	53.84	97.09	117.80	......	31.87
1918	29.14	370.50	102.51	105.94	94.19	......	81.66	101.92	252.68	195.40	......	......
1919	8.11	186.50	49.51	......	20.24	......	39.01	43.20	98.04	87.83	......	......
1920	11.92	199.80	45.62	......	31.85	......	35.16	65.47	107.54	91.00	......	......
1921	10.43	308.50	76.48	......	59.37	......	54.60	71.35	158.55	140.40	118.54	......
1922	7.13	226.00	74.55	......	52.51	......	55.46	72.89	123.05	101.40	......	......
1923	21.16	296.50	81.04	73.31	79.99	......	62.58	91.95	184.68	157.20	136.19	......
1924	23.67	275.20	73.44	67.20	70.63	......	51.90	64.86	157.05	150.30	118.44	......
1925	8.14	254.50	67.75	51.64	46.89	......	46.24	58.90	122.86	137.40	109.18	......
1926	8.40	150.50	47.59	35.84	32.60	......	25.32	44.46	95.43	97.31	60.02	......
1927	25.66	311.00	82.75	73.76	49.30	......	65.58	87.17	202.33	161.00	138.35	......
1928	10.30	242.00	56.15	59.18	31.64	......	36.62	59.66	150.47	100.20	111.33	......
1929	33.28	260.66	78.98	85.00	71.71	......	64.83	81.88	171.68	151.89	120.99	......
1930	25.21	299.04	79.72	85.48	65.41	60.21	62.72	90.29	192.48	184.99	151.00	......
1931	11.51	229.92	65.97	76.65	46.49	43.11	44.02	69.08	153.99	139.75	120.31	......
1932	24.93	226.56	79.69	79.11	45.09	45.99	60.17	90.74	175.01	148.16	133.20	......
1933	15.17	152.00	47.98	41.62	40.19	26.53	29.72	60.14	96.58	97.25	83.52	......
1934	10.49	199.00	62.59	52.65	39.36	35.38	37.12	73.10	161.90	123.00	106.50	......
1935	8.07	156.00	59.66	47.87	42.66	31.33	39.10	71.27	125.15	99.00	81.21	......
1936	18.50	239.00	74.49	69.07	49.95	50.55	49.74	65.26	171.81	147.00	125.98	......
1937	22.24	269.00	82.21	82.54	62.00	50.34	55.50	99.01	218.71	192.50	154.71	......
1938	17.32	270.75	66.48	[e]67.02	48.68	39.70	47.97	65.19	211.24	180.00	144.47	......
1939	17.16	[e]255.60	69.23	......	44.67	31.89	51.70	61.14	179.21	183.00	147.58	......
1940	23.52	208.50	60.51	......	46.58	35.80	46.10	61.93	162.64	145.00	111.79	......
Mean	16.24	246.07	69.14	70.85	49.41	40.98	46.31	71.04	158.16	143.73	119.65	[f]52.73

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* No records prior to 1884 for stations 1 to 16.

[a] Record in inches for Hana-iuka station 11, altitude 1,800 feet: 1895=104.20; 1896=78.94; 1897=75.91; W.B. mean=91.44.

[b] 1935–1940 for Nakalalua station on the Kukui trail at about the same altitude as the former Eke station.

[c] 1883–1890 for Hamakuapoko station no. 8 (Goodale), location not known exactly but probably about 800 feet altitude.

[d] An incomplete record exists for a station at an altitude of 1,500 feet in Honokowai Gulch from Dec. 1911 to Mar. 1917 with an annual mean of 124.75 inches.

[e] Missing monthly records estimated by the Weather Bureau.

[f] Weather Bureau mean of all monthly readings including those for incomplete years not listed in this table.

Rainfall at stations on Maui, in inches, 1879–1940—*Continued*

Sta. (fig. 5)	17	18	19	20	21	22	23	24	25	26	27	28
Name	Honolua Ranch	Honomanu	Honomanu (mauka)	Ino Valley Cave	Kaanapali	Kaeleku	Kahakuloa	Kahoma intake	Kahului	Kailiili	Kailua	Kailua (mauka)
Alt. (ft.)	125	1600	2950	1720	12	350	1000	2000	8	2440	700	3075
Year												
1879 ..	......	......	......	......	......	......	......	......	......	......	......	......
1880 ..	......	......	......	......	......	......	......	......	......	......	......	......
1881 ..	......	......	......	......	......	......	......	......	......	......	......	......
1882 ..	......	......	......	......	......	......	......	......	......	......	......	......
1883 ..	......	......	......	......	......	......	......	......	......	......	......	......
1884 ..	......	......	......	......	......	......	......	......	......	......	......	......
1885 ..	......	......	......	......	......	......	......	......	......	......	......	......
1886 ..	......	......	......	......	......	......	......	......	......	......	......	......
1887 ..	......	......	......	......	......	......	......	......	......	......	......	......
1888 ..	......	......	......	......	......	......	......	......	......	......	......	......
1889 ..	......	......	......	......	......	......	......	......	......	......	......	......
1890 ..	......	......	......	......	......	......	......	......	......	......	......	......
1891 ..	......	......	......	......	......	......	......	......	......	......	......	......
1892 ..	......	......	......	......	22.71	......	......	......	......	......	......	......
1893 ..	......	......	......	......	24.85	......	......	......	11.27	......	......	......
1894 ..	30.11	......	......	......	26.46	......	......	......	......	......	......	......
1895 ..	35.18	......	......	......	28.54	......	......	......	......	......	......	......
1896 ..	31.43	......	......	......	24.59	......	......	......	15.50	......	......	......
1897 ..	22.82	......	......	......	17.46	......	......	......	9.77	......	......	......
1898 ..	31.98	......	......	......	......	......	......	......	......	......	......	......
1899 ..	24.19	......	......	......	......	......	......	......	......	......	......	......
1900 ..	47.28	......	......	......	......	......	......	......	......	......	......	......
1901 ..	35.56	......	......	......	......	......	......	......	......	......	......	......
1902 ..	50.12	......	......	......	......	......	......	......	......	......	......	......
1903 ..	49.08	......	......	......	......	......	......	......	......	......	......	......
1904 ..	51.22	......	......	......	......	......	......	......	......	......	119.75	......
1905 ..	32.72	276.38	......	......	8.45	......	......	......	8.90	......	139.59	......
1906 ..	41.86	222.80	......	......	e18.50	......	......	......	14.04	......	115.47	......
1907 ..	63.09	262.52	......	......	33.54	......	......	......	......	......	127.76	......
1908 ..	28.25	229.50	......	......	5.51	......	......	......	6.76	......	115.92	......
1909 ..	46.88	261.90	......	......	17.65	......	......	......	18.87	......	131.30	......
1910 ..	45.12	300.91	......	......	e16.95	......	......	......	21.49	......	149.99	......
1911 ..	46.66	285.11	......	g188.00	18.11	......	......	48.61	16.92	......	156.69	......
1912 ..	27.81	194.34	......	105.71	8.07	......	......	27.06	10.06	......	100.83	......
1913 ..	30.02	173.97	......	131.90	12.76	......	......	45.80	......	......	125.75	......
1914 ..	51.09	361.48	......	222.20	20.91	......	......	45.65	31.50	......	216.65	......
1915 ..	34.15	235.78	......	......	e12.70	......	......	46.23	18.41	......	154.67	......
1916 ..	62.60	290.53	......	......	33.37	......	......	90.72	40.93	......	188.05	......
1917 ..	27.54	121.75	......	......	16.95	......	......	42.91	15.79	......	98.58	......
1918 ..	49.23	357.59	......	......	26.28	......	......	89.84	38.16	......	215.04	......
1919 ..	19.76	171.31	......	......	6.22	......	......	69.05	13.75	......	94.28	......
1920 ..	23.66	178.74	......	......	12.58	......	......	89.11	18.24	......	111.95	......
1921 ..	32.09	248.42	......	......	17.31	......	......	135.18	15.93	......	131.81	......
1922 ..	26.26	240.21	......	......	8.12	......	......	108.34	15.99	......	138.04	......
1923 ..	45.06	275.09	275.58	......	25.47	......	66.38	131.59	33.78	......	142.97	......
1924 ..	35.81	227.54	227.49	......	21.27	......	47.78	85.51	......	......	110.99	......
1925 ..	25.99	222.50	228.65	......	e14.46	......	32.26	114.82	......	e127.89	106.08	......
1926 ..	15.84	142.45	113.04	......	6.40	......	26.35	48.31	......	77.02	77.71	......
1927 ..	54.43	283.61	207.46	......	27.13	e132.21	90.27	125.06	......	132.59	139.76	......
1928 ..	25.72	262.81	275.70	......	7.34	91.31	42.06	95.86	......	131.65	111.44	......
1929 ..	45.26	255.63	214.80	......	24.93	110.17	60.04	103.63	......	161.03	122.56	e263.81
1930 ..	44.77	248.74	300.80	......	19.84	115.73	48.45	106.30	......	170.71	142.99	316.60
1931 ..	30.89	194.09	252.80	......	14.72	102.55	42.40	89.57	......	146.81	120.15	261.80
1932 ..	45.06	217.84	257.00	......	15.93	122.59	......	93.32	......	130.48	135.99	228.60
1933 ..	38.45	112.55	143.80	......	15.31	73.84	......	69.03	......	86.99	75.27	159.40
1934 ..	35.85	191.65	271.20	......	6.13	112.42	......	89.21	......	133.90	108.25	262.00
1935 ..	35.79	156.31	227.80	......	9.54	113.15	......	77.78	......	111.27	100.63	215.60
1936 ..	30.48	256.66	281.01	......	16.08	108.64	......	123.71	......	163.36	130.52	286.45
1937 ..	63.49	306.07	364.60	......	29.23	140.26	......	150.77	......	180.59	153.15	338.40
1938 ..	37.24	225.71	309.52	......	16.30	93.78	......	e141.57	......	165.79	133.07	325.37
1939 ..	42.69	195.09	311.20	......	21.47	98.43	......	137.54	......	154.09	132.07	278.20
1940 ..	43.74	162.66	225.85	......	23.46	102.66	......	100.95	......	114.50	105.63	224.90
Mean ..	38.37	237.32	249.35	161.95	17.94	108.40	f50.04	90.77	f18.31	136.79	129.23	263.43

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e Missing monthly records estimated by the Weather Bureau.

f Weather Bureau mean of all monthly readings including those for incomplete years not listed in this table.

g Nov. 5, 1910 to Dec. 2, 1911 inclusive.

Rainfall at stations on Maui, in inches, 1879–1940—*Continued*

Sta. no. (fig. 5)	29	30	31	32	33	34	35	36	37 & 38	39	40	41
Name	Kauaula intake	Kaupakulua	Kaupo (Mokulau)	Keahua Camp	Keanae	Kihei	Kipahulu[h]	Kula (Erehwon)	Kula Sanatorium[i]	Kula Camp	Lahaina	Launiupoko
Alt. (ft.)	1550	1050	285	525	1000	45	350	4000	3004	2200	50	1300
Year												
1879	......	......	......	......	......	......	......	......	......	......	......	......
1880	......	......	......	......	......	......	......	......	......	......	......	......
1881	......	......	......	......	......	......	......	......	......	......	......	......
1882	......	......	......	......	......	......	......	......	......	......	......	......
1883	......	......	......	......	......	......	......	......	......	......	......	......
1884	......	......	......	......	......	......	......	......	......	......	......	......
1885	......	......	......	......	......	......	......	......	......	......	......	......
1886	......	......	......	......	......	......	......	......	......	......	......	......
1887	......	......	......	......	......	......	......	......	......	......	......	......
1888	......	......	......	......	......	......	......	......	......	......	......	......
1889	......	......	......	......	......	......	......	......	......	......	......	......
1890	......	......	......	......	......	......	......	56.46	......	......	......	......
1891	......	......	......	......	......	......	......	29.01	......	......	......	......
1892	......	......	......	......	......	......	......	44.53	......	......	......	......
1893	......	......	......	......	......	......	......	32.19	......	......	......	......
1894	......	......	......	......	......	......	......	......	......	......	......	......
1895	......	......	......	......	......	......	......	38.35	......	......	......	......
1896	......	......	......	......	......	......	......	23.18	......	......	......	......
1897	......	......	......	......	......	......	......	......	......	......	......	......
1898	......	......	82.60	......	......	......	83.02	34.83	......	......	......	......
1899	......	......	68.57	......	......	......	44.92	......	......	......	......	......
1900	......	......	68.34	......	......	......	......	......	......	......	......	......
1901	......	......	100.55	......	......	......	108.57	58.12	......	......	......	......
1902	......	......	97.02	......	......	......	122.51	70.96	42.00	......	......	......
1903	......	......	72.23	......	......	9.81	80.34	35.06	18.70	......	......	......
1904	......	......	88.77	......	......	26.48	88.29	67.64	48.19	......	......	......
1905	......	......	......	......	248.70	2.78	66.08	28.96	15.05	......	......	......
1906	......	......	......	......	214.92	15.00	......	[e]47.57	34.78	......	......	......
1907	......	......	......	......	252.40	15.00	......	35.85	......	......	......	......
1908	......	......	......	......	208.97	4.31	......	14.32	......	......	......	......
1909	......	......	......	......	251.80	12.49	85.43	26.90	......	......	......	......
1910	......	......	......	24.58	297.13	14.35	75.73	30.30	......	......	......	......
1911	......	......	......	20.81	274.74	4.97	92.53	35.02	......	......	......	......
1912	......	......	......	9.88	209.40	......	62.69	16.30	......	......	......	......
1913	......	......	......	19.19	203.72	......	72.38	29.50	......	......	......	......
1914	......	......	......	34.94	397.26	......	101.38	44.68	......	......	[e]15.28	[e]16.82
1915	......	......	......	19.19	240.53	......	89.58	24.80	......	......	7.83	[e]12.15
1916	......	......	......	38.59	308.80	......	111.63	50.42	......	......	27.92	41.65
1917	......	......	......	......	129.01	......	78.03	41.40	42.33	......	14.59	17.70
1918	......	......	......	......	332.31	......	116.00	35.02	43.90	......	18.84	42.41
1919	......	......	......	......	151.69	......	54.24	15.97	16.92	......	5.14	21.93
1920	37.02	......	......	......	174.56	......	78.17	38.23	42.48	......	10.29	28.64
1921	44.00	112.87	......	......	244.67	......	75.47	23.90	20.72	......	8.48	40.33
1922	......	105.46	......	......	228.48	......	......	27.07	25.20	......	3.54	17.66
1923	60.52	122.86	......	......	268.70	......	86.55	46.49	44.45	......	19.24	48.67
1924	45.60	109.28	......	......	206.99	......	77.85	40.95	41.99	......	15.35	40.18
1925	42.99	94.67	......	16.92	191.94	7.41	65.82	27.22	[e]22.04	......	8.87	45.93
1926	21.49	65.92	......	13.33	126.98	3.15	35.68	30.40	26.50	......	4.88	16.59
1927	59.38	118.77	......	27.57	256.96	18.20	24.76	[e]45.40	52.56	25.53	20.32	42.60
1928	31.81	103.01	......	15.60	208.76	7.62	52.49	25.19	[e]17.15	20.95	3.65	29.97
1929	48.04	110.70	......	34.30	236.15	23.29	85.74	44.20	[e]26.00	42.91	20.74	45.26
1930	45.74	127.60	......	23.11	282.63	4.77	102.36	43.20	36.75	40.60	17.54	38.68
1931	29.23	93.88	......	14.54	214.89	7.52	87.90	25.83	24.03	15.13	4.16	16.57
1932	40.79	107.12	......	23.58	259.68	15.66	118.43	29.91	[e]32.75	19.91	9.57	28.77
1933	37.47	58.28	......	17.37	141.23	16.44	86.14	25.21	[e]24.61	19.96	10.77	24.40
1934	34.48	86.70	......	14.36	226.08	4.81	87.24	29.56	[e]35.55	16.97	6.79	25.46
1935	34.98	74.50	......	15.96	189.39	9.64	69.55	29.42	37.56	22.55	8.76	24.68
1936	60.57	112.24	......	17.63	243.80	12.44	82.08	42.02	39.25	25.88	16.25	35.90
1937	65.36	114.53	......	25.70	309.34	17.99	153.88	36.64	41.90	28.75	21.76	51.78
1938	57.22	......	......	22.01	265.48	13.08	148.60	33.51	44.47	29.76	16.92	52.81
1939	61.54	......	......	19.54	280.02	14.13	106.96	32.33	31.57	14.68	17.49	55.08
1940	53.47	......	......	24.46	202.91	21.19	92.25	39.35	36.38	21.43	19.65	48.09
Mean	45.09	[f]102.18	79.71	21.44	235.58	12.10	85.56	35.82	33.30	24.64	13.13	33.73

[e] Missing monthly records estimated by the Weather Bureau.

[f] Weather Bureau mean of all monthly readings including those for incomplete years not listed in this table.

[h] 1898–1906 for gage, altitude 308 feet.

[i] 1902–1906 is for station 38 at Waiakoa, altitude 2,700 feet (W.B. mean is 32.00 inches).

Rainfall at stations on Maui, in inches, 1879–1940—*Continued*

Sta. (fig. 5)	42	43	44	45	46	47	49[j]	50	51	52	53 & 55	54
Name	Lilikoi	Lupe	Mahana	Mahina-hina	Makawao[k]	Mokupea	Nahiku (mauka)	Nahiku	Nahiku Camp	Olinda	Olowalu[l]	Olowalu (mauka)
Alt. (ft.)	1225	1275	1400	750	1700	1000	1600	740	1200	4000	10	700
Year												
1879...	......	......	......	......	109.42	......	......	......	......	......	......	......
1880...	......	......	......	......	73.88	......	......	......	......	......	......	......
1881...	......	......	......	......	138.38	......	......	......	......	......	......	......
1882...	......	......	......	......	75.88	......	......	......	......	......	......	......
1883...	......	......	......	......	......	......	......	......	......	......	......	......
1884...	......	......	......	......	74.70	......	......	......	......	......	......	......
1885...	......	......	......	......	120.98	......	......	......	......	......	......	......
1886...	......	......	......	......	......	......	......	......	......	......	......	......
1887...	......	......	......	......	......	......	......	......	......	......	......	......
1888...	......	......	......	......	......	......	......	......	......	......	......	......
1889...	......	......	......	......	......	......	......	......	......	......	......	......
1890...	......	......	......	......	......	......	......	......	......	......	......	......
1891...	......	......	......	......	......	......	......	......	......	......	......	......
1892...	......	......	......	......	......	......	......	......	......	......	15.60	......
1893...	......	......	......	......	......	......	......	......	......	......	7.26	......
1894...	......	......	......	......	......	......	......	......	......	......	*10.11*	......
1895...	......	......	......	......	......	......	......	......	......	......	10.64	......
1896...	......	......	......	......	......	......	......	......	......	......	10.70	......
1897...	......	94.47	65.42	......	......	......	......	......	......	......	3.81	......
1898...	......	140.69	100.95	......	......	......	......	......	......	......	5.77	......
1899...	......	......	101.95	......	......	......	......	......	......	......	3.53	......
1900...	......	128.72	105.14	......	......	87.88	......	......	......	......	......	......
1901...	......	106.94	78.59	......	......	69.99	......	151.10	......	......	......	......
1902...	......	202.25	159.81	......	......	130.97	......	275.35	......	......	......	......
1903...	......	169.48	136.10	......	......	114.15	319.76	......	......	......	......	......
1904...	......	138.83	146.40	......	......	130.77	237.87	165.51	......	......	......	......
1905...	......	167.90	138.63	......	79.66	119.70	308.12	176.30	240.58	......	......	......
1906...	......	148.11	91.57	......	*119.07*	*79.91*	*233.17*	*170.05*	*196.91*	......	......	......
1907...	......	155.86	105.69	......	86.79	88.73	......	182.06	230.89	......	......	......
1908...	......	137.00	93.85	......	45.10	82.48	......	122.75	192.03	......	......	......
1909...	......	161.42	99.70	......	......	84.66	......	153.41	237.10	......	......	......
1910...	......	180.19	115.92	......	91.24	91.74	......	175.05	263.40	......	......	......
1911...	......	188.94	119.90	......	49.79	85.48	......	174.55	245.61	[e]77.18	......	......
1912...	......	*149.76*	84.75	......	33.54	*60.85*	......	*130.29*	*177.01*	[e]43.87	......	66.20
1913...	......	139.93	89.00	......	46.04	63.87	......	161.99	186.20	[e]36.41	......	114.75
1914...	......	279.05	181.54	62.39	67.26	131.66	......	242.13	355.45	......	......	[e]113.24
1915...	......	223.94	97.49	50.08	54.64	77.86	......	......	269.63	......	......	69.00
1916...	......	202.01	152.32	91.26	89.74	125.69	......	192.18	261.89	[e]110.92	73.07	[e]121.84
1917...	......	101.88	54.53	36.47	41.87	43.09	......	......	130.58	52.99	38.20	42.00
1918...	......	*254.61*	*122.15*	*79.98*	*76.79*	*118.97*	......	......	318.29	101.27	55.49	88.00
1919...	......	112.70	61.07	29.50	34.73	57.24	......	......	146.88	26.79	5.21	25.75
1920...	......	117.57	71.52	37.63	......	59.62	......	......	152.88	41.44	11.21	41.14
1921...	......	183.53	122.63	67.35	64.57	94.18	......	......	234.78	61.82	7.54	79.75
1922...	......	175.90	83.22	52.67	53.52	64.61	......	......	215.72	56.96	3.18	46.50
1923...	85.99	203.08	105.95	87.42	69.11	98.59	......	......	267.04	36.61	17.47	75.25
1924...	*79.10*	*168.69*	*100.14*	*79.57*	*65.49*	*89.29*	......	......	187.64	30.25	14.80	62.75
1925...	60.32	152.43	87.82	54.67	45.49	73.73	......	......	176.07	18.25	6.10	68.75
1926...	42.71	107.34	58.77	34.94	32.62	50.64	......	......	130.96	14.40	4.52	24.75
1927...	81.35	219.03	136.36	82.64	55.70	108.92	......	......	262.03	[e]42.77	19.99	83.25
1928...	62.82	179.54	90.18	51.41	......	77.17	......	......	206.67	66.00	2.00	48.25
1929...	87.98	190.62	100.13	82.82	......	104.49	......	......	226.75	56.50	18.56	72.25
1930...	90.22	223.58	123.31	68.22	......	96.02	......	......	263.66	[e]66.27	14.51	79.53
1931...	71.92	184.00	96.72	42.57	......	72.17	......	......	205.36	[e]26.09	3.51	75.75
1932...	75.86	189.67	106.25	53.03	......	97.47	......	......	236.62	[e]16.29	10.87	132.50
1933...	39.98	115.07	66.70	41.00	......	54.28	......	......	142.63	21.90	10.22	56.50
1934...	56.91	176.74	82.36	38.47	......	63.32	......	......	192.99	33.15	2.84	61.00
1935...	47.00	146.22	71.71	30.74	......	49.12	......	......	178.48	19.57	5.66	48.75
1936...	......	213.94	105.36	50.60	......	62.35	......	......	235.13	43.82	11.44	74.75
1937...	......	244.24	134.10	70.68	......	103.20	......	......	286.54	45.88	*21.56*	*103.40*
1938...	......	211.32	118.65	59.56	......	108.70	......	......	238.43	......	9.86	83.40
1939...	......	201.32	104.70	60.53	......	101.70	......	......	220.28	......	11.74	71.90
1940...	......	162.85	103.95	52.15	......	91.65	......	......	168.66	......	19.12	42.08
Mean...	66.58	170.96	103.93	57.35	70.22	87.00	[f]299.89	[f]178.81	218.94	[f]46.13	14.12	71.48

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[e] Missing monthly records estimated by the Weather Bureau.

[f] Weather Bureau mean of all monthly readings including those for incomplete years not listed in this table.

[j] An incomplete record exists at Nahiku station 48, 120 feet altitude. The only complete year is 1900 with 105.13 in. (W.B. mean using all available months is 92.84 in.)

[k] 1879–1885 for a different station than the later records.

[l] 1892–1899 is for Olowalu station 55 (Haneburg), 15 feet alt. (W.B. mean is 8.09 in.)

Rainfall at stations on Maui, in inches, 1879–1940—*Continued*

Sta. (fig.5)	56	57	58 & 59	60	61	62	63	64	65	66	67	68
Name	Opana	Paakea[m]	Paia[n]	Penhallow Wailuku	Power Station 2 (Kauaula)	Pulehu	Punaluu	Puoho-kamoa	Puohoka-moa 2	Puuhele	Puukolii	Puu Kukui (lower)
Alt. (ft.)	3052	1250	125	390	967	560	700	4300	2900	90	425	2500
Year												
1879..	......	......	......	......	......	......	......	......	......	......	......	......
1880..	......	......	......	......	......	......	......	......	......	......	......	......
1881..	......	......	......	......	......	......	......	......	......	......	......	......
1882..	......	......	......	......	......	......	......	......	......	......	......	......
1883..	......	......	......	......	......	......	......	......	......	......	......	......
1884..	......	......	......	......	......	......	......	......	......	......	......	......
1885..	......	......	......	......	......	......	......	......	......	......	......	......
1886..	......	......	......	......	......	......	......	......	......	......	......	......
1887..	......	......	......	......	......	......	......	......	......	......	......	......
1888..	......	......	......	......	......	......	......	......	......	......	......	......
1889..	......	......	......	......	......	......	......	......	......	......	......	......
1890..	......	......	......	......	......	......	......	......	......	......	......	......
1891..	......	......	......	......	......	......	......	......	......	......	......	......
1892..	......	......	......	......	......	......	......	......	......	......	......	......
1893..	......	......	......	......	......	......	......	......	......	......	......	......
1894..	......	......	......	......	......	......	......	......	......	......	......	......
1895..	......	......	33.48	......	......	......	......	......	......	......	......	......
1896..	......	......	27.81	......	......	......	......	......	......	......	......	......
1897..	......	......	17.52	11.29	......	......	......	......	......	......	......	......
1898..	......	......	25.50	14.71	......	......	......	......	......	......	......	......
1899..	......	......	21.59	15.59	......	......	......	......	......	......	......	......
1900..	......	......	43.97	28.43	......	......	......	......	......	......	......	......
1901..	......	......	38.95	33.10	......	......	......	......	......	......	......	......
1902..	......	......	63.94	41.68	......	......	......	......	......	......	......	......
1903..	......	......	53.76	31.02	......	......	......	......	......	......	......	......
1904..	......	......	61.10	42.36	......	......	......	......	......	......	......	......
1905..	......	240.58	39.92	18.70	......	......	......	......	......	......	......	......
1906..	......	196.91	......	29.49	......	......	......	......	......	......	......	......
1907..	......	230.89	......	31.19	......	......	107.74	......	......	......	......	......
1908..	......	192.03	......	8.89	......	......	120.87	......	......	......	......	......
1909..	......	237.10	......	22.70	......	......	141.89	......	......	......	......	......
1910..	......	263.40	......	29.54	......	......	138.73	......	......	......	......	......
1911..	......	245.61	40.45	26.78	......	......	[e]154.39	......	......	......	......	......
1912..	......	177.01	31.73	12.94	......	......	[e]120.68	281.34	......	......	......	[e]114.46
1913..	......	186.20	23.04	29.76	......	......	130.18	212.51	......	......	......	118.23
1914..	......	355.45	28.75	51.40	......	......	220.58	......	......	......	......	153.10
1915..	......	269.63	44.25	29.01	......	......	150.54	......	......	......	......	98.20
1916..	......	261.89	29.17	56.58	......	......	162.52	......	......	......	40.88	182.50
1917..	......	130.58	50.04	24.79	......	......	87.47	133.14	......	14.65	20.43	56.00
1918..	......	318.29	......	60.41	......	......	208.78	370.32	......	29.28	36.26	[e]134.13
1919..	......	145.78	......	......	......	......	88.69	168.25	......	7.16	11.09	57.40
1920..	......	152.91	......	......	......	......	113.81	168.00	......	12.71	12.94	55.14
1921..	......	231.18	......	......	14.09	......	133.95	285.11	......	12.14	20.06	103.40
1922..	......	215.72	......	......	10.03	......	142.57	259.50	......	......	14.62	84.28
1923..	......	267.04	......	......	30.73	......	147.06	251.43	......	......	30.38	117.00
1924..	......	187.64	34.94	......	23.87	......	120.57	218.87	......	......	26.53	98.20
1925..	......	176.07	27.67	......	19.52	11.46	114.10	254.75	......	......	17.44	113.40
1926..	......	130.96	17.61	......	8.38	8.14	80.94	150.90	......	......	6.73	63.60
1927..	......	262.03	41.85	......	32.40	21.90	155.98	224.41	......	......	31.47	118.20
1928..	......	206.67	25.81	......	11.85	9.85	119.36	253.02	......	......	13.59	92.20
1929..	[e]195.01	226.75	48.78	......	30.74	24.68	130.23	228.77	[e]293.78	......	31.67	113.20
1930..	230.00	263.66	46.10	......	22.03	14.82	143.23	......	353.20	......	27.28	114.80
1931..	187.80	205.36	39.12	......	8.85	9.55	129.86	......	289.20	......	10.87	82.80
1932..	172.00	225.04	39.11	......	16.48	17.00	147.87	......	290.60	......	22.35	111.20
1933..	112.00	143.48	22.18	......	18.80	16.57	77.17	......	182.80	......	18.46	73.40
1934..	182.20	192.99	30.54	......	12.89	6.14	115.07	......	306.60	......	12.18	80.20
1935..	151.20	178.48	28.69	......	16.35	11.76	103.80	......	253.80	......	11.94	62.00
1936..	201.85	235.09	35.13	......	27.34	21.31	127.10	......	324.78	......	23.04	84.40
1937..	241.60	285.54	45.97	......	30.97	21.11	142.97	......	407.00	......	36.44	109.20
1938..	238.21	238.63	36.86	......	23.32	12.76	123.34	......	368.58	......	25.06	93.00
1939..	213.60	220.32	33.28	......	24.95	15.22	118.61	......	341.40	......	30.96	109.40
1940..	155.00	168.73	37.33	......	30.10	21.14	95.67	......	253.10	......	26.77	94.00
Mean	190.04	218.52	36.17	[f]29.62	20.68	15.21	129.89	[f]246.24	305.40	13.59	22.38	99.55

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[e] Missing monthly records estimated by the Weather Bureau.

[f] Weather Bureau mean of all monthly readings including those for incomplete years not listed in this table.

[m] Formerly listed as Kopiliula.

[n] 1895–1905 is for Paia station 59, altitude 180 feet (W.B. mean is 38.33 inches).

Rainfall at stations on Maui, in inches, 1879–1940—*Continued*

Sta. no. (fig. 5)	69	70	71	72	73	74	75	76	77	78	79	80
Name	Puu Kukui (upper)	Puu Kukui (upper)	Puu Kukui (summit)	Puunene	Puuomalei	Ulupalakua Ranch[o]	Hamoa[p]	Reservoir 8 (Waikapu)	Spreckelsville	Ukulele	Ukumehame	Ulumalu
Alt. (ft.)	4450	5000	5788	73	1480	1900	105	300	50	5150	75	825
Year												
1879 ...	......	......	......	......	......	......	......	......	......	......	......	......
1880 ...	......	......	......	......	......	......	......	......	......	......	......	......
1881 ...	......	......	......	......	......	......	......	......	......	......	......	......
1882 ...	......	......	......	......	......	......	......	......	......	......	......	......
1883 ...	......	......	......	......	......	......	......	......	24.27	......	......	......
1884 ...	......	......	......	......	......	......	......	......	27.29	......	......	......
1885 ...	......	......	......	......	......	......	......	......	30.53	......	......	......
1886 ...	......	......	......	......	......	......	......	......	......	......	......	......
1887 ...	......	......	......	......	......	......	......	......	......	......	......	......
1888 ...	......	......	......	......	......	......	......	......	18.80	......	......	......
1889 ...	......	......	......	......	......	......	......	......	12.98	......	......	......
1890 ...	......	......	......	......	......	......	......	......	36.40	......	......	......
1891 ...	......	......	......	......	......	......	......	......	14.87	......	......	......
1892 ...	......	......	......	......	......	......	......	......	......	......	......	......
1893 ...	......	......	......	......	......	......	......	......	......	......	......	......
1894 ...	......	......	......	......	......	......	......	......	......	......	......	......
1895 ...	......	......	......	......	68.72	......	......	......	......	......	......	......
1896 ...	......	......	......	......	58.29	......	47.16	......	......	......	......	......
1897 ...	......	......	......	......	39.50	......	42.18	......	......	......	......	......
1898 ...	......	......	......	......	64.47	......	62.93	......	......	......	......	......
1899 ...	......	......	......	......	[e]43.45	......	......	......	......	......	......	......
1900 ...	......	......	......	......	71.99	......	51.23	......	18.01	......	......	......
1901 ...	......	......	......	......	68.58	......	64.48	......	21.09	......	......	......
1902 ...	......	......	......	23.10	124.17	......	......	......	24.24	......	......	......
1903 ...	......	......	......	22.29	87.40	......	......	......	19.15	......	......	......
1904 ...	......	......	......	43.39	85.44	......	......	......	27.01	......	......	......
1905 ...	......	......	......	11.46	78.66	......	......	......	13.60	69.85	......	......
1906 ...	......	......	......	21.07	77.80	51.74	......	......	20.44	83.35	......	......
1907 ...	......	......	......	23.38	73.54	35.77	......	......	23.40	81.00	......	......
1908 ...	......	......	......	6.39	53.44	13.88	......	......	8.78	71.68	......	......
1909 ...	......	......	......	20.01	76.11	31.89	......	......	22.49	64.27	......	......
1910 ...	......	......	......	21.58	92.12	......	......	......	21.46	104.70	......	......
1911 ...	......	......	......	19.56	79.60	......	......	......	15.03	106.21	......	......
1912 ...	......	396.47	......	6.77	58.66	......	......	......	11.40	44.52	......	......
1913 ...	......	334.00	......	16.49	73.73	......	......	......	20.91	85.64	......	......
1914 ...	......	421.20	......	28.47	131.01	......	......	......	32.64	123.05	......	......
1915 ...	......	286.90	......	15.81	78.98	......	......	......	18.89	72.90	......	......
1916 ...	......	367.40	......	40.55	119.37	......	......	......	40.70	153.65	......	......
1917 ...	......	232.50	......	15.31	52.31	......	......	15.70	14.04	56.74	......	......
1918 ...	......	562.00	......	33.01	135.51	......	......	33.80	41.93	142.59	......	......
1919 ...	......	399.50	......	10.41	50.53	......	......	11.23	13.77	34.70	......	......
1920 ...	......	256.50	......	19.24	49.88	......	......	14.44	19.05	47.72	......	......
1921 ...	......	402.00	......	15.38	84.69	......	......	18.78	22.99	72.82	......	......
1922 ...	......	346.00	......	12.66	72.90	......	......	9.37	21.46	88.26	......	......
1923 ...	[e]288.14	......	......	29.12	98.80	34.28	......	35.30	35.96	100.03	......	95.30
1924 ...	257.00	......	......	24.70	94.79	46.46	......	[e]30.80	36.00	81.45	......	100.87
1925 ...	261.00	......	......	14.44	71.68	31.67	......	[e]15.11	20.85	77.35	......	105.97
1926 ...	124.00	......	......	6.30	46.58	31.63	......	12.55	10.23	35.32	......	67.54
1927 ...	301.00	......	......	21.98	93.56	49.52	......	35.30	32.75	75.67	......	148.05
1928 ...	270.00	......	[e]371.96	8.22	76.90	17.53	......	13.49	14.99	59.38	......	120.58
1929 ...	232.00	......	317.00	25.89	108.35	46.36	......	32.13	35.78	80.89	......	131.42
1930 ...	333.00	......	474.00	26.23	90.55	46.76	......	18.83	27.07	86.85	16.45	122.97
1931 ...	265.00	......	356.00	14.48	71.77	23.77	......	10.54	22.54	65.85	5.44	98.39
1932 ...	357.00	......	419.00	18.83	72.15	42.52	......	[e]21.66	27.87	60.95	15.27	111.15
1933 ...	189.00	......	250.00	13.61	43.38	36.17	......	[e]17.05	15.68	50.75	12.41	55.90
1934 ...	240.00	......	344.75	8.58	65.98	39.35	......	11.71	15.18	65.52	4.61	80.91
1935 ...	198.00	......	306.00	9.62	59.15	24.30	......	7.90	20.89	70.10	7.44	64.97
1936 ...	254.00	......	444.00	16.97	83.89	34.11	......	17.98	27.75	74.91	13.32	97.74
1937 ...	282.00	......	496.00	21.69	101.65	50.60	105.67	21.50	29.88	83.73	21.39	100.77
1938 ...	281.00	......	456.00	14.64	......	36.87	70.76	21.20	23.34	73.21	15.04	......
1939 ...	......	......	472.00	16.08	......	36.01	65.56	15.03	24.64	62.96	14.46	......
1940 ...	......	......	351.00	22.54	......	39.67	62.28	20.99	26.02	71.78	23.27	......
Mean ...	258.26	[f]362.73	389.05	18.98	[f]77.44	[f]36.40	[f]63.58	19.27	23.02	77.23	13.55	[f]99.82

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[e] Missing monthly records estimated by the Weather Bureau.

[f] Weather Bureau mean of all monthly readings including those for incomplete years not listed in this table.

[o] 1906–1909 for station called Raymond's Ranch, now Ulupalakua Ranch. Record since 1923 furnished by the Ulupalakua Ranch Co.

[p] 1896–1901 for Hamoa station 75 (Reciprocity Mill), altitude 60 feet (W.B. mean is 58.46 inches).

Rainfall at stations on Maui, in inches, 1879–1940—*Continued*

Sta. no. (fig. 5)	81	82	83	84	85	86	87	88	89	90
Name	Wahikuli	Waikamoi	Waikamoi Gulch	Waiehu	Waihee[q]	Waikapu[r]	Waikapu (Everett)	Wailuku[s]	Wailuku Mill	Waiopai Ranch
Alt. (ft.)	580	1200	4250	250	100	470	250	200	175	200
Year										
1879	......	......	......	......	......	......	......	29.83	......	......
1880	......	......	......	......	......	......	......	18.82	......	......
1881	......	......	......	......	......	......	......	38.25	......	......
1882	......	......	......	......	......	......	......	28.07	......	......
1883	......	......	......	......	......	......	......	27.84	......	......
1884	......	......	......	......	......	......	......	......	......	......
1885	......	......	......	......	......	......	......	......	......	......
1886	......	......	......	......	......	......	......	......	......	......
1887	......	......	......	......	......	......	......	......	......	......
1888	......	......	......	......	......	......	34.53	......	25.61	......
1889	......	......	......	......	......	......	20.45	......	15.71	......
1890	......	......	......	......	......	......	64.66	......	52.57	......
1891	......	......	......	......	......	......	15.25	......	11.01	......
1892	......	......	......	......	......	......	33.19	......	29.83	......
1893	......	......	......	......	......	......	26.92	......	......	......
1894	......	......	......	......	......	......	......	......	......	......
1895	......	......	......	......	......	......	......	......	......	......
1896	......	......	......	......	......	15.58	......	......	22.38	......
1897	......	......	......	......	......	8.00	......	......	......	......
1898	......	......	......	......	......	9.94	......	......	......	28.72
1899	......	......	......	......	17.50	16.28	......	......	......	......
1900	......	......	......	......	36.22	15.10	......	......	......	18.48
1901	......	......	......	......	34.50	25.40	......	......	......	41.56
1902	......	......	......	......	39.93	24.78	......	39.66	......	35.34
1903	......	......	......	......	26.45	25.22	......	28.97	......	12.95
1904	......	......	......	......	44.22	39.15	......	55.02	54.52	39.03
1905	......	......	......	......	19.67	16.14	......	19.79	19.13	12.23
1906	......	......	......	......	29.75	......	......	30.02	30.98	15.29
1907	......	202.16	......	......	36.23	......	......	34.20	32.48	33.18
1908	......	180.98	......	......	8.42	......	......	10.20	8.71	4.97
1909	......	211.54	......	......	14.01	......	......	25.26	23.21	20.60
1910	......	239.97	......	41.27	31.65	......	......	34.95	34.50	15.26
1911	......	245.64	349.26	35.62	33.81	......	......	23.92	24.43	20.16
1912	......	179.63	239.46	15.18	[e]14.05	10.95	......	13.19	11.90	9.64
1913	......	200.19	225.73	29.36	24.16	27.81	......	24.46	25.67	18.32
1914	......	392.07	[e]346.08	62.88	53.89	52.51	......	42.70	44.97	43.57
1915	......	256.77	[e]301.64	29.47	29.15	27.96	......	22.91	23.51	32.57
1916	......	287.50	[e]427.55	73.12	64.38	57.00	......	53.25	......	44.38
1917	......	135.29	138.99	20.41	24.70	24.73	......	20.18	......	31.52
1918	......	351.03	378.82	62.12	61.68	55.79	......	45.26	......	32.66
1919	......	161.27	166.94	......	19.70	16.24	......	18.32	......	10.73
1920	......	183.64	196.39	......	30.18	23.25	......	22.80	......	21.91
1921	16.52	251.78	328.16	......	24.91	27.17	......	27.39	......	19.16
1922	8.80	251.95	324.64	......	28.00	16.21	......	21.65	......	26.14
1923	27.88	252.03	309.32	......	55.90	44.60	......	44.58	......	41.76
1924	20.51	217.64	265.96	......	34.00	35.82	......	31.97	......	23.86
1925	12.99	192.72	291.15	......	22.04	19.52	......	21.78	......	17.75
1926	4.95	132.14	150.86	......	17.97	16.42	......	12.71	......	10.01
1927	25.89	238.24	178.68	......	44.88	44.61	......	38.63	......	36.38
1928	10.60	199.24	197.74	......	23.43	16.24	......	18.79	......	15.62
1929	26.14	210.38	188.60	......	46.56	41.03	......	43.84	......	25.19
1930	24.95	252.53	[e]199.88	......	39.27	35.75	......	36.44	......	21.47
1931	7.45	197.04	[e]81.33	......	32.01	18.95	......	23.33	......	7.50
1932	13.99	223.60	[e]48.68	......	[e]29.74	35.32	......	29.27	......	39.25
1933	16.09	127.23	59.49	......	20.94	23.85	......	24.02	......	31.33
1934	9.58	207.70	128.72	......	19.10	19.59	......	20.43	......	16.83
1935	13.05	174.16	[e]135.72	......	20.04	15.77	......	17.43	......	20.15
1936	22.61	225.33	161.22	......	31.58	30.84	......	30.00	......	24.57
1937	34.73	262.25	314.65	......	37.81	32.23	......	33.24	......	26.25
1938	28.42	213.70	302.06	......	25.69	28.65	......	24.27	......	24.99
1939	29.85	196.44	271.08	......	25.58	22.20	......	22.48	......	24.88
1940	29.27	148.20	183.32	......	35.25	32.11	......	34.57	......	33.11
Mean	19.21	217.76	229.74	41.05	31.27	26.89	[f]31.01	28.74	27.85	24.51

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[e] Missing monthly records estimated by the Weather Bureau.

[f] Weather Bureau mean of all monthly readings including those for incomplete years not listed in this table.

[q] A record exists for a station at an altitude of 275 feet in Waihee Valley from July 1915 to Dec. 1918 with an annual mean of 53.88 inches.

[r] 1896–1918 for gage first at 470 and later at 690 feet alt. Date of change not known.

[s] 1879–1883 for Alexander Station, Wailuku, altitude 250 feet.

Rainfall at stations on Maui, in inches, 1879–1940[x]—*Continued*

(No records prior to 1921 for these stations.)

Sta. no. (fig. 5)	91	92	93	94	95	96	97	98	99	*100*	*101*	*102*
Name	Haleakala (summit)	Haleakala (Ranger station)	Palikū Cabin	Waikamoi (Park tanks)	Waikamoi (Nianiau)	Honomanu	Honomanu Gulch	Honomanu Gulch (upper)	Piiholo Camp	Fleming's Mt. House	Oopuolo Gulch	Oopuolo Gulch (upper)
Alt. (ft.)	9750	7030	6360	7300	6800	1350	6250	7550	1800	2987	1375	2075
Year												
1928 ..	......	......	......	......	......	......	......	......	64.73	......	......	......
1929 ..	......	......	......	......	......	......	......	......	67.68	......	......	......
1930 ..	......	......	......	......	......	......	......	......	77.46	......	......	......
1931 ..	......	......	......	......	......	......	......	......	65.18	......	101.70	116.09
1932 ..	......	......	......	......	......	......	......	......	67.67	......	106.89	[e]138.46
1933 ..	......	......	......	......	......	......	......	......	45.11	97.25	[e]46.28	[e]59.24
1934 ..	......	......	......	......	......	......	131.25	......	65.35	123.00	[e]88.77	113.81
1935 ..	......	......	......	......	......	......	103.74	......	54.11	99.00	[e]79.84	93.84
1936 ..	27.50	......	......	......	......	......	[e]126.62	......	82.46	147.00	......	......
1937 ..	76.44	......	......	......	......	......	[e]163.68	......	......	192.50	......	......
1938 ..	35.73	......	......	......	......	......	[e]123.25	......	......	180.00	......	......
1939 ..	36.00	[t]49.61	......	......	......	195.09	[e]132.10	[e]105.80	......	*183.00*	......	......
1940 ..	23.59	40.19	......	......	70.70	162.66	101.20	78.24	......	145.00	......	......
1941 ..	[e]29.31	[e]44.84	[u]180.60	66.00	97.00	217.60	133.19	91.60	......	......	......	......
Mean ..	38.10	44.88	......	......	83.85	191.78	126.88	91.88	65.53	145.84	84.70	104.29

[e] Missing monthly records estimated by the Weather Bureau.
[t] June to Dec. 1941 only. 11 inches fell in 2 hours on Nov. 19, 1941.
[u] Gage read irregularly. Annuals are totals of readings to last reading before end of year.
[x] Record for 1941 given for stations 91 to 114 where available.

Sta. no. (fig. 5)	103	104	105	106	107	108	109	110	111	112	113	114
Name	Kuhiwa Gulch	Honomaele	Hana (mauka)	Hahalawe[u]	Wailua-iki	Puu Paki	Mokulehua	Puuloa	Kanahena	Honokahua[v]	Launiupoko (Hirai Camp)	Haleakala Branch
Alt. (ft.)	2860	980	925	1100	2540	2100	600	*1200*	650	*150*	*250*	*2163*
Year												
1921..	......	......	......	......	......	......	......	......	......	52.20	......	......
1922..	......	......	......	......	......	......	......	......	......	42.93	......	70.03
1923..	......	......	......	......	......	......	......	......	......	71.47	......	92.15
1924..	......	......	......	......	......	......	......	......	......	53.82	......	*81.07*
1925..	......	......	......	......	......	......	......	......	14.98	44.24	......	78.16
1926..	......	......	......	......	......	......	......	......	17.01	22.18	......	41.17
1927..	......	......	......	......	......	......	......	......	34.18	73.09	18.75	75.58
1928..	......	......	......	......	......	......	......	2.15	8.93	26.45	2.08	76.04
1929..	......	......	......	......	......	......	......	9.15	41.82	47.87	18.48	99.56
1930..	......	......	......	......	......	......	......	*21.62*	35.70	*49.88*	*16.69*	98.88
1931..	......	......	......	110.20	......	......	......	9.44	13.68	29.31	1.28	71.37
1932..	......	......	......	153.75	......	......	......	24.23	39.87	41.33	9.95	66.11
1933..	......	......	......	131.10	......	......	......	15.34	19.09	29.12	13.70	48.19
1934..	393.00	......	......	134.10	......	......	......	24.22	27.40	31.75	6.55	71.46
1935..	314.25	......	......	136.28	......	......	......	14.19	18.97	28.21	8.54	61.50
1936..	414.00	......	......	119.60	......	......	......	20.07	27.73	37.05	14.00	87.81
1937..	523.00	(w)	......	......	......	......	......	37.79	41.67	54.84	19.60	95.71
1938..	437.00	410.65	198.23	121.50	351.00	......	155.00	28.34	28.01	39.04	11.37	90.57
1939..	366.00	364.05	235.62	105.70	306.00	341.00	158.00	21.47	31.90	43.71	14.54	80.51
1940..	259.00	276.30	198.18	103.40	235.50	266.50	120.50	32.91	36.71	42.41	19.35	65.59
1941..	364.50	(w)	......	105.60	345.00	325.50	148.00	14.47	14.40	28.34	4.28	92.31
Mean ..	383.84	350.33	210.68	122.12	309.00	311.00	145.00	19.67	26.59	43.24	11.94	77.19

[u] Gage read irregularly. Annuals are totals of readings to last reading before end of year.
[v] 47.42 inches in 1912 and 57.45 inches in 1913.
[w] 392.54 inches in 10 months in 1937 and 317.64 inches in 11 months in 1941.

SURFACE WATER

All streams are flashy because of the steep permeable terrane and the intensity of the rainfall. The differences in the character of the runoff from the porous and permeable lava-veneered East Maui surface and the deeply eroded West Maui surface is shown graphically by typical streams in figure 7. The frequency of floods is shown in figure 8. A summary of the records of stream flow to 1938 has been compiled by the Territorial Planning Board.[32] Daily discharges are published in the annual Water-Supply Papers of the Geological Survey.

The type and age of the rocks greatly influence the depth and shape of stream channels. Channels cut in the weak East Maui Honomanu or West Maui Wailuku basalts[33] have relatively flat grades and are floored with continuous gravel deposits for long distances from the coast. Such streams lose heavily. This characteristic differentiates them from the streams in the strong Kula, Hana, and Honolua lavas, which are series of cascades and have only short stretches of gravel.

The average daily rainfall on East Maui is 2,360 million gallons, of which only 3.4 percent reappears in the low-water stream flow. The average rainfall on West Maui is 580 million gallons, of which 13.1 percent reappears in the low-water stream flow. The increased percentage is due entirely to differences in geologic structure and stages of erosion of the two volcanoes. The high permeability of the youthful Hana lavas and the lack of deep canyons cutting the dike complexes of East Maui are the chief causes of the great difference in low flow. It is estimated that the volume of high-level ground water in East Maui lost because of these unfavorable geologic conditions averages at least 200 million gallons per day.

Few perennial streams are found on East Maui in spite of the heavy rainfall on the northeast slope. They originate from springs at relatively low altitudes between Haiku and Nahiku. A few are found on the southeast slope also, between Muolea and Kaupo. In contrast, most of the streams on West Maui are perennial (fig. 9).

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[32] Surface-water resources of the Territory of Hawaii: Territorial Planning Board Rept., Honolulu, 1939.

[33] See Geology for description of rock formations.

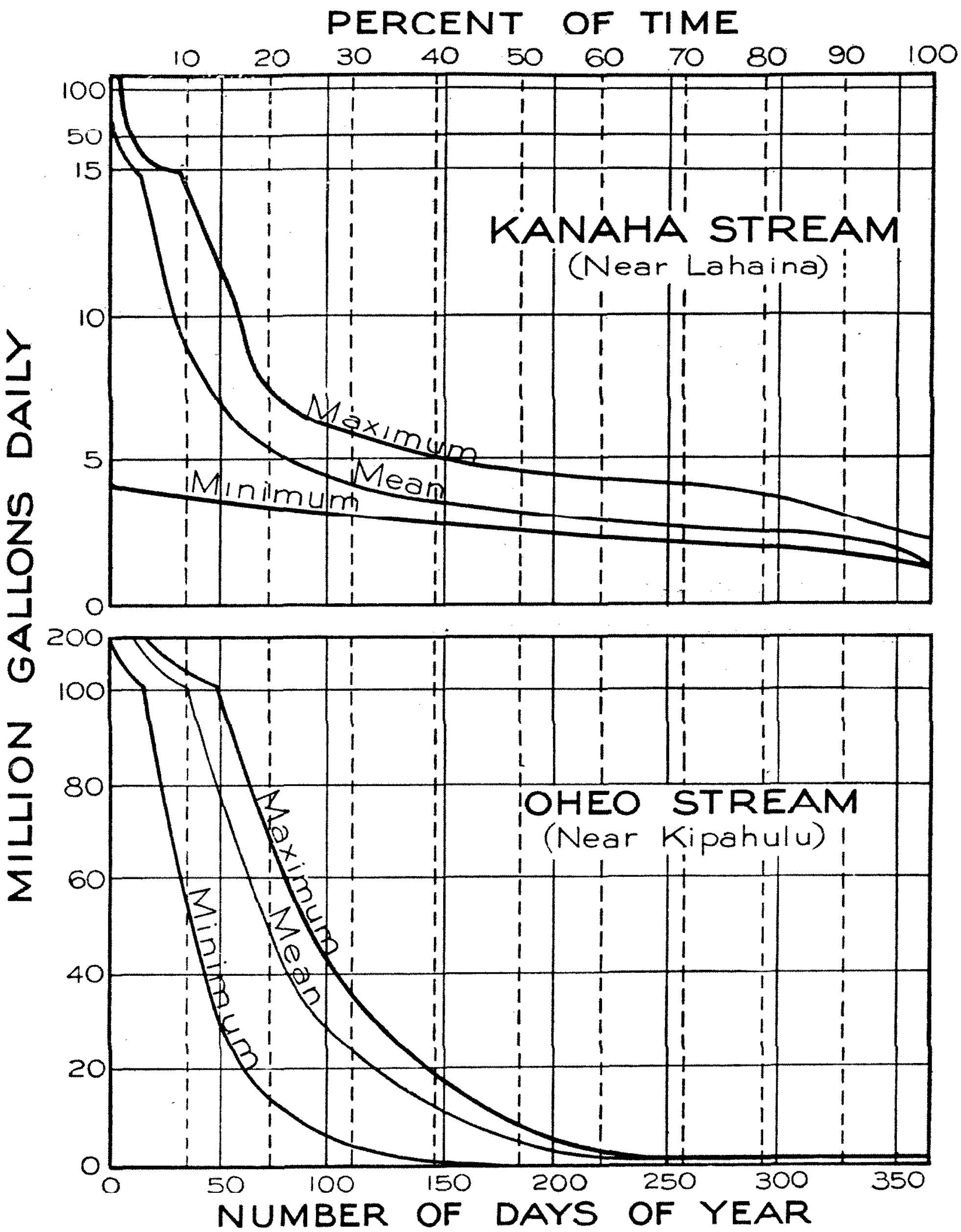

Figure 7. Duration-discharge curves for Oheo Stream, East Maui, and Kanaha Stream, West Maui. (After pl. 64, First Progress Rept., Terr. Plan. Bd., 1939.)

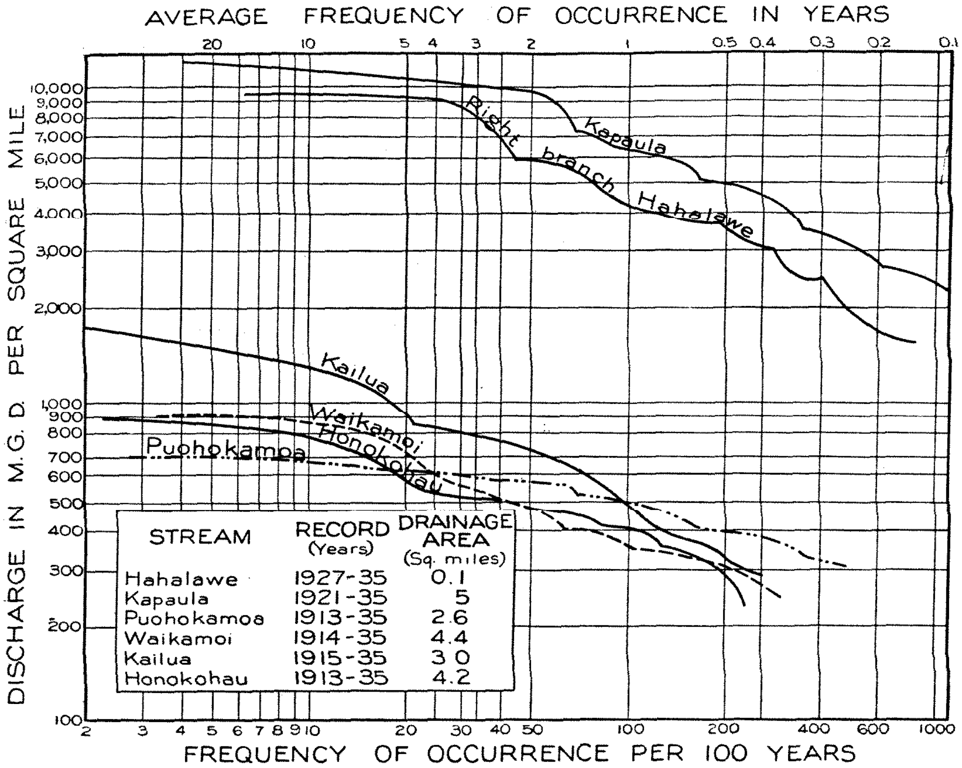

Figure 8. Frequency-intensity curves for six streams on Maui. (After pl. 68, First Progress Rept., Territorial Planning Board, 1939.)

The following table records the low flow of the streams, or that available 95 percent of the time. Where continuous records are not available, published miscellaneous measurements and scattered observations are used. Much more ground water is discharged into all streams in wet than in dry weather, but records are too incomplete to determine the quantity derived from the ground.

Discharge of spring-fed or perennial streams

East Maui

Stream or spring	Mean low flow (gallons daily)[a]
All streams from Maliko to Makapipi on north coast:	
Wailoa ditch, 1200 ft.[b]	40,000,000
Kauhikoa ditch, 900 ft. (old Hamakua)	100,000
Lowrie ditch, 500 ft.	1,500,000
Haiku ditch, 250 ft.	1,500,000
Below all ditches:	
Haiku to Honomanu[c]	1,500,000
Honomanu	5,000,000
Palaukulu (Store Spring)	2,200,000
Waiokamilo (Banana Spring)	2,880,000
Waianu (Ohia Spring)	3,040,000
Balance in Keanae area[d]	500,000
Springs between Keanae and Nahiku except Big Spring	6,000,000
Big Spring	10,400,000
Waihoi Spring	75,000
Alaalaula	100,000
W. Wailua (Manamana)	500,000
E. Wailua (Honolewa)	50,000
Malohianaiwi	200,000
Kaili	500,000
Waieli	500,000
Hahalawe	1,100,000
Puaaluu	175,000
Waimoku	1,000,000
Koukouai	200,000
Kukuiula	150,000
Alelele	300,000
Manawainui	350,000
Miscellaneous springs	200,000
Total	80,020,000

West Maui

Stream or spring	Mean low flow (gallons daily)[a]
Honokohau	11,500,000
Kahakuloa	2,400,000
Makamakaole	750,000
Waihee	25,000,000
N. Waiehu	3,000,000
S. Waiehu	2,000,000
Iao	11,000,000
Waikapu	3,000,000
Ukumehame	3,000,000
Olowalu	2,750,000
Launiupoko	600,000
Kauaula	4,000,000
Kanaha	2,000,000
Kahoma	2,000,000
Honokowai	2,500,000
Honolua	500,000
Total	76,000,000

[a] The mean low flow as used herein is the average of the stream flow records during long periods without rain when the entire flow is derived from high-level ground-water bodies drained by the streams. The discharge of Honomanu Stream below the Koolau Ditch comes from springs near its mouth less than 25 feet above sea level and may be basal rather than high-level ground water. The mean low flow of all streams which have not been regularly gaged at any time is estimated from miscellaneous measurements and includes the flow of any tunnels discharging into these streams.

[b] Includes flow of tunnels in the Nahiku area.

[c] Based largely on miscellaneous measurements by David Summers.

[d] Does not include the flow from Kano reentrant (largely Plunkett Spring), which amounts to 1,750,000 gallons per day 90 percent of the time, as all of this water sinks in the bed of Palaukulu Stream and part of the flow may reappear at Store Spring (no. 19).

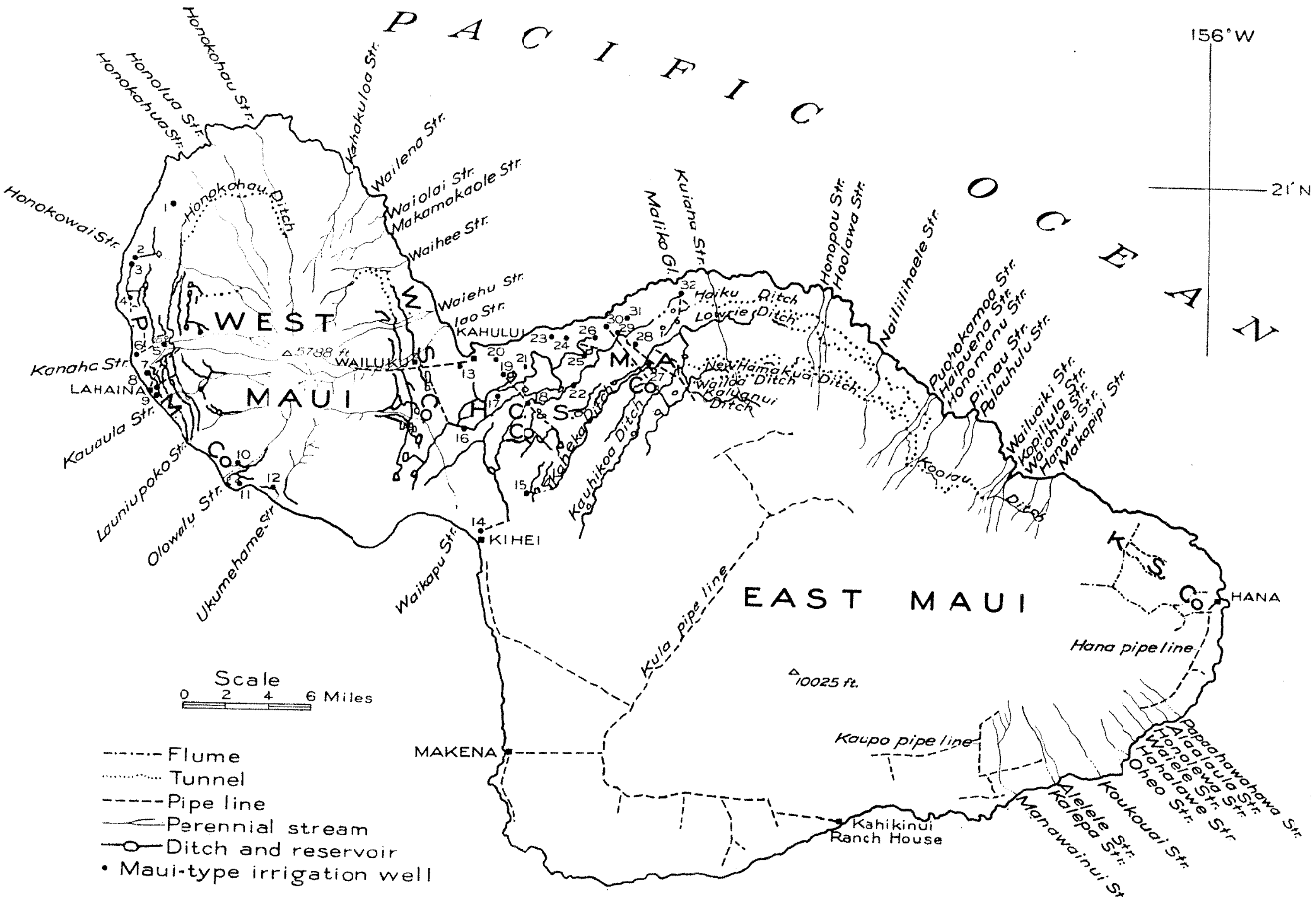

Figure 9. Map of Maui showing perennial streams, pipe lines, and irrigation ditches and wells.

The streams[34] in the table above are supplied by high-level springs issuing from geologic formations as follows:

Geologic formations supplying perennial streams

East Maui

	Gallons per day
Honomanu volcanic series:	
Streams supplied by springs perched on tuffs	350,000
Streams supplied by leakage from a perched artesian structure (Big Spring)	10,400,000
Unknown structures[35]	7,880,000
Kula volcanic series:	
Streams supplied by springs perched on soils, decomposed clinker, ash, or issuing from valley fills of lava	43,550,000
Hana volcanic series:	
Streams supplied by springs issuing from valley fills of lava	15,640,000
Older alluvium (Store Spring)	2,200,000
Total	74,320,000

West Maui

Wailuku volcanic series:	
Streams supplied by springs issuing from dike structures	75,000,000
Honolua volcanic series:	
Streams supplied by springs issuing from clinker beds or perched on interbedded soils	1,000,000
Total	76,000,000

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[34] Includes the flow of any tunnels discharging into the streams.

[35] Does not include 1.75 m.g.d. from Plunkett Spring which sinks in Palaukulu Gulch.

VALUE AND SOURCE OF WATER SUPPLIES

All streams on Maui in droughts are spring fed; hence springs, tunnels, and wells supply all water used during dry weather. The chief use of ground water is to irrigate sugar cane, but it is also used for municipal, domestic, and livestock supplies, and for cooling power-plant generators. The gross water requirement excluding rainfall to raise a ton of sugar on the P. M. Co.'s plantation is 737,000 gallons, or 1,000,000 gallons for each 1.35 tons of sugar. Data regarding the value of water for growing sugar on the P. M. Co.'s plantation follow:

Average water needs, 1935–1940[a]
(Rainfall excluded)

On 10,000 acres of cane	Water	
Annual amount used	34,107,874,000	gallons
Monthly amount used	2,842,322,500	gallons
Amount per acre per crop (21.57 months)	6,130,884	gallons
Amount per acre per annum	3,410,787	gallons
Amount per acre per month	284,232	gallons
Amount per acre per annum	10.4	feet
Amount per acre per month	10.4	inches
Amount per acre per crop	18.7	feet
1.35 tons of sugar (96° H.S.)	1,000,000	gallons
1 ton of sugar (96° H.S.)	737,000	gallons
1 ton of sugar (96° H.S.)	3,070	tons

[a] Annual rept. of Pioneer Mill Co., Ltd., for the year ending Dec. 31, 1940, p. 3, Wailuku, Maui, 1941.

Shaw computed the value of irrigation water as a growth factor during months of low rainfall to be about $120 per million gallons, even at the low price of sugar in 1936. Soils require a minimum application of 3 to 4 acre-inches per acre for a 30-inch penetration.[36] Only 38.7 percent of the gross water supply is utilized by the cane, the rest is consumed by transpiration, evaporation, deep percolation, and conveyance seepage.[37]

Sugar cane is raised on lateritic soils, alluvial soils, ash soils, and boulder deposits on Maui. Some of the rockiest fields farmed anywhere in the world grow large crops of cane near Olowalu. Shaw has aptly expressed the part played by water and nutrients in the following:

> Agricultural text books for the past century have glorified the fertile, mellow loam, and have implied that the farmer who cannot sink his plow into a deep friable soil is indeed destitute. The present school of agricultural workers look upon the soil as a mass of inert rock fragments of various shapes, sizes, and chemical composition, but with no other function than as a physical support for the plants, and as a reservoir for water and nutrients from which

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[36] Shaw, H. R., Water supply, in Moir, W. W. G., and others, Handbook of Hawaiian soils, p. 214, Honolulu, 1936.

[37] Idem, p. 219.

> the plant may draw. The capacity of this subterranean reservoir may vary with the physical nature of the soil particles, but essentially there should not be a great difference in the inherent productivity of soils so long as the soil reservoir is filled with the proper amounts and combinations of raw materials from which the plant is manufactured.
>
> We need not look far for examples of such heretical theory, for no place in the world better illustrates this conception than the Hawaiian Islands. Many of the fields in which Hawaii consistently establishes high-production records are tight black adobes, thin sheets of top soil over a base of coral rock, or boulder-strewn flats in which cultivation is performed with pick and shovel. In all these cases, the factors that cause record yields are not the beautiful farming loams, but a fortunate combination of ideal climatic conditions, and a skillful forced feeding of water and artificial fertilizers.[38]

Mr. J. H. Foss, manager of the East Maui Irrigation Co., estimates[39] that the value of a continuous low flow of 1 million gallons a day from water-development tunnels at the ditch level in the Nahiku area of East Maui is $16,000. Thus, about $175,000 could be spent if necessary to tap Big Spring (no. 26) in the Nahiku area if its entire flow could be diverted at ditch level.

Three great ditch systems, the Wailoa, Kauhikoa, and Haiku, built at a cost of $1,500,000, bring water to the Isthmus from the streams and tunnels on the northeast slopes of East Maui. Open ditch sections have been replaced largely with tunnels because of the high cost of maintenance. The main ditches are lined with concrete to prevent seepage. Various stretches of the ditches have different names, as shown in the table below and in figure 9. They are operated by the E. M. I. Co., owned jointly by the M. A. Co. and H. C. & S. Co.

Principal ditches on East Maui

Name	Altitude (feet)	Length (miles)	Capacity[a] (m.g.d.)	Function
Wailoa system	1150	18	163	
Wailoa	1150	10	163	Diverts streams between Alo and Halehaku streams.
Koolau	1300	8	140	Diverts surface and tunnel water between Makapipi and Alo streams. Includes Nahiku ditch with 45 m.g.d. capacity and Makapipi ditch with 20 m.g.d. capacity.
Kauhikoa system	900	25	112	
Kauhikoa	900	6	112	Diverts streams between Halehaku and Maliko streams. Replaced old Hamakua ditch west of Halehaku Stream.
Kaluanui	2500	5	1.5	Heads in Opana Stream and joins new Hamakua ditch west of Maliko Gulch.
New Hamakua	1100	14	75	Goes to Paia from Halehaku Stream. Abandoned west of Halehaku Stream. Replaced by Wailoa and now used for storm water only.

[a] Capacity at point of delivery from E. M. I. Co. chart dated Aug. 1934. Most ditches decrease in capacity toward intake.

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[38] Idem, p. 215.

[39] Oral communication, December 9, 1941.

Principal ditches on East Maui—*Continued*

Name	Altitude (feet)	Length (miles)	Capacity[a] (m.g.d.)	Function
Haiku system	250	41.5	93	
Haiku	250	16	93	Diverts all streams between Kailua and Maliko streams. Replaces Spreckels ditch west of Kailua Stream.
Lowrie	500	15	84	Supplied by Spreckels, Manuel Luis, and Center ditches; collects mainly storm water since completion of Wailoa ditch.
Center	500	3	90	Diverts streams below all main ditches between Waikamoi and Kailua streams. Picks up M. Luis ditch water and at Kailua Stream drops into Lowrie.
Manuel Luis	500	1.5	30	Diverts flow of Kolea, Haipuaena, and Puohokamoa streams below Koolau and Spreckels ditches and discharges into Waikamoi Gulch, where water is picked up by Center ditch.
Spreckels	several	6	77	Diverts all streams between Nuaailua and Kailua streams. It diverts above Koolau ditch as far as Puohokamoa Stream and from there to Kailua Stream it diverts below the Wailoa and New Hamakua ditches but above Center ditch. At Kailua Stream its water is diverted into Lowrie ditch.

The P. M. Co. has two main ditches. Honokohau ditch diverts water from 806 feet altitude in Honokohau Stream and extends chiefly as a tunnel to Lahaina, a total length of 7 miles. It cost $563,800. Honokowai ditch diverts water to Lahaina from 1,570 feet altitude in Honokowai Stream. It is 5½ miles long. Shorter ditch systems divert water from Honolua, Kahoma, Kanaha, Launiupoko, Olowalu, and Ukumehame Streams (fig. 9).

The H. C. & S. Co. diverts seven-twelfths of the flow of Waihee Stream and all South Waiehu Stream through the plantation of the W. S. Co. to the south end of its plantation. W. S. Co. diverts water from Waihee, Iao, North Waiehu, and Waikapu Streams through a ditch and reservoir system which cost $512,549 (fig. 9). Water development tunnels cost an additional $113,710.

A County pipe line extends from Iao Valley to Wailuku and Kahului. Another County pipe line diverts water at 4,300 feet altitude from Waikamoi Stream through a pipe line to the Olinda reservoir and thence through Kula to Ulupalakua, where lines branch off to Kihei and Kahikinui (fig. 9). Another branch leads from Olinda reservoir to Makawao and adjacent villages.

Ground water is very valuable on Maui because satisfactory sites for reservoirs do not exist. The rocks are so permeable that all unlined reservoirs leak heavily and are used chiefly for overnight and storm-water storage. Also, the steep gradients of the canyon floors and the great amount of debris carried by the streams are added difficulties in building and maintaining satisfactory large reservoirs.

An average of about 130 million gallons of water from wells and tunnels is used daily on East Maui and 65 million gallons daily on West Maui. Kaeleku Sugar Co. is the only plantation that does not irrigate, and it needs water for fluming sugar cane.

Maui must base its future development largely upon its water supply. Any new water that can be economically developed has great potential value.

GEOMORPHOLOGY OF EAST MAUI

Original form.—Haleakala, prior to the erosion of the summit depression, was a mountain between 10,500 and 11,000 feet above present sea level with its summit studded with cones, as shown in plate 24A and in section AA′, plate 1. It then closely resembled the present form of Mauna Kea Volcano, Hawaii (fig. 2). The summit lay about 1 mile east of the present top, as shown by large masses of intrusive rock in the depression walls (pl. 1). An east rift, southwest rift, and north rift, ranging in length from 15 to 17 miles and studded with cinder cones, radiate from the former summit. As the rifts are of nearly equal length, flows from them have produced a rounded pyramidal cone.

Origin of Haleakala Crater.—It is believed that the so-called crater on Haleakala is due chiefly, and probably entirely, to stream erosion, as a result of the top of the mountain having been removed by the headward erosion of Keanae and Kaupo Valleys prior to the eruption of the Hana volcanics (pls. 24 and 25). This erosional hypothesis was first stated by Cross.[40] Erosion of the loosely knit cinder cones and lavas of the summit was probably accelerated by more precipitation there during the warm interglacial epochs than at present. However, the annual average is 40 inches on the summit and between June and December 1941, a total of 180 inches fell in the east end of the depression, more than enough to form vigorous streams prior to the eruption of the late lavas. Keanae and Kaupo Valleys, like the adjacent lava-filled valleys of Kipahulu and Waihoi, eroded a little beyond the crest as a result of being supplied by springs in the dike complexes at their heads. In this respect they parallel the erosional history of the great windward canyons on Oahu.[41]

Following the erosion of deep amphitheaters at the heads of Keanae and Kaupo Valleys, renewed volcanic activity produced a line of cinder cones along the dike complex or ancient rift zones crossing these valleys. The cones and their flows masked the divide between the two valleys and partly filled them to the sea. Stream erosion between eruptions undercut and widened the valley heads, a process still in operation. Additional details and the several hypotheses regarding the origin of the great depression have already been published.[42]

Origin of the Isthmus.—The Isthmus connecting East and West

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[40] Cross, Whitman, Lavas of Hawaii and their relations: U. S. Geol. Survey Prof. Paper 88, p. 92, 1915.
[41] Stearns, H. T., op. cit. (Bull. 1), p. 28.
[42] Stearns, H. T., Origin of Haleakala Crater, island of Maui, Hawaii: Geol. Soc. America Bull., vol. 53, pp. 1-14, 1942.

Maui is composed chiefly of lava flows from Haleakala Volcano and earthy sediments (pl. 1). It has a similar origin to that of the Schofield Plateau on Oahu and the Hoolehua Plain on Molokai. It was built by the lava flows from Haleakala ponding against the older West Maui volcano. The lava beds dip about 12° on the summit of Haleakala but are practically horizontal on the Isthmus. Elsewhere on Haleakala they retain steep dips to the sea except toward the island of Kahoolawe, against which they are also ponded, but the connecting isthmus is now entirely under sea.

Much of the Isthmus is covered with alluvium, chiefly deposited by streams from West Maui. The streams of East and West Maui are torrential and flow on steep gradients. When they reach the flat Isthmus their velocity abruptly decreases and they drop most of their sediments. Much of their water is lost in the permeable rocks there. The strip of very permeable calcareous dunes shown on plate 1 extending from Kahului to Kihei has added to the height of the Isthmus and increased the loss from streams crossing them. Marine fossils in test hole 107 indicate that the sea also has contributed sediments during higher stands.

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] West Maui has been inactive long enough for traces of most of them to be present, but shore lines on East Maui, older than the Olowalu, have been buried by subsequent lava flows, and the evidence of those prior to the Kaena is meager.

Pleistocene shore lines in the Hawaiian Islands

Approximate altitude (feet)	Name	Evidence on Maui	Type locality (island)
0	—	Present shore line	
+5	Kapapa	Wave-cut bench at this level	Oahu
+25	Waimanalo	Wave-cut platforms and terraces	do.
—60±	Waipio	Partly drowned dunes, and lava-filled valleys cut to this depth below present sea level	do.
+70	Laie	Wave-cut platform with marine fossils	do.
+100	Kaena	Wave-cut platforms and terraces	do.
—300	Kahipa	Submarine shelves	do.
+250±	Olowalu	Benches of fossiliferous marine conglomerate and stripping of soil	Maui
+325±	—	Not identified	Lanai
+375±	—	do.	do.
+560	Manele	Stripping of soil from West Maui only	do.
+625±	—	Not identified	do.
+1,200±	Mahana	Traces of soil stripping to this level	do.
—1,200 to —1,800	Lualualei	Submarine shelf at 1,800 feet and deeply submerged valley mouths	Oahu

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[43] Stearns, H. T., op. cit. (Bull. 6), p. 21.

The mouths of Keanae, Kaupo, Kipahulu, and Waihoi Valleys are deeply drowned. Their walls projected downward indicate a submergence of about 1,200 feet. This estimate may not be reliable because of undercutting by streams crowded laterally by lava flows. Evidence is given on page 107 to show that the Kaupo mud flow was emplaced during Kahipa time. So little change in the form of Kaupo Valley has occurred since the mud flow and so much erosion occurred before it, that probably Kaupo Valley was cut prior to the Lualualei submergence, as were all the other major valleys of East Maui. The great depth of weathering on unveneered slopes of pre-valley age supports this hypothesis. The 1,800-foot submarine shelf is present on West Maui and lacking on East Maui, from which it is implied that the pre-valley dome of Haleakala was built later than the West Maui volcano and at the close of the shelf-building epoch.

Evidence of high shore lines above the Kaena is poor on East Maui. Much soil has been stripped from interstream flats to at least 250 feet above sea level on the dry slopes of Kula lavas inland from Kihei, and traces of shingle are found. Also the color of the soil changes from brown to red at 500 feet altitude along the Pukalani Road to Haleakala summit. This may possibly be the result of submergence to the Manele shore line.

Abundant evidence exists of the shore lines younger than the Kahipa, such as gravel terraces along the coast graded to the Kaena and Waimanalo shore lines, valleys cut to the Waipio shore line and filled with lava in Hana time (sections BB′ and CC′, inserts A and B, pl. 1), benches along the coast west of Maliko Gulch cut in lava rock and alluvium during the Waimanalo and Kapapa stands of the sea, and marine fossiliferous conglomerate at Kihei 50 feet above sea level, as determined with a barometer. The older dunes on the north coast of the Isthmus extend below the ocean and were blown inland during the Waipio low stand of the sea. Small remnants of lithified calcareous dunes, probably of the same age, were found in crevices 50 feet above sea level at Hana Bay, where the shore is now composed of black lava sand only.

MARINE FEATURES.—East Maui has three stretches of coast that are cliffed by the sea. The longest and highest begins at Paia and slowly increases in height to 500 feet in the Keanae area. It abruptly terminates at Nahiku due to burial by younger lavas, but its presence under these lavas is indicated by a declivity about 1 mile inland all the way to Hana. It faces the dominant northeast trades; hence is exposed to the roughest seas, which accounts for its height.

The second stretch is about 2½ miles long between Muolea and Oheo Gulch, and the third is between Kaapahu Bay and Kaupo. As shown on plate 1, high cliffs exist in the older Kula and Honomanu lavas only. Soundings indicate that they are partly drowned. Cliffs 10 to 100 feet high form much of the south coast from Kaupo to La Perouse Bay.

A powerful longshore current sweeps around the north tip of East Maui carrying great quantities of debris into Kahului Bay. Deposition and erosion of the west coast of East Maui is nearly in equilibrium as a result of lying to the lee of Haleakala and being protected from kona storms by Kahoolawe and a narrow reef.

Kanaha Pond near Kahului and Kealia Pond near Kihei are lagoons blocked by barrier beaches during the present stand of the sea. La Perouse and Nuu Bays are reentrants between peninsulas built by Recent lava flows. Hana Bay lies between a Recent lava flow and an eroded cinder cone. Most smaller bays where lava flows of Hana age form the coast (pl. 1) are reentrants between lava flows. Where the coast is composed of older rocks, the bays are valley mouths drowned by submergence.

The clinkery beds, tubes, and other internal structures in the late lava flows, where subjected to wave attack, give rise to spectacular spouting horns, caves, natural bridges, and stacks. One of the largest sea caves and bridges is at Pauwalu Point near Keanae (pl. 11B); another is west of Nuu.

A fringing coral reef starts at Paia and widens toward Kahului. This coast, long a place of marine deposition and extension, has been rapidly washing away during the last 40 years. Some believe that the breakwater built in 1908 at Kahului is the cause, but it does not seem likely from its location to have upset the regimen of ocean currents as far away as Spreckelsville. The eastern breakwater wall was built in 1908 and extended in 1931.[44] The western was started in 1918 and finished in 1919.[45] The only artificial change in the coast line is the growth of large trees and the anchoring of the beach dunes by vegetation. The trees deflect the wind upward and stop the drifting of sand inland from the beaches. Calcareous beach sand or sandstone, as it is known locally, lithified by ground water carrying organic acids,[46] is exposed as arcuate rocky ledges at low tide near Spreckelsville. Old residents state that these ledges were under beaches of 25 years ago where numerous slightly brackish springs issued at low tide.

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[44] Maui News, Dec. 12, 1931.

[45] Oral communication, J. H. Foss, Dec. 9, 1941.

[46] Stearns, H. T., op. cit. (Bull. 1); for detailed discussion of origin see pp. 41-43.

A narrow coral reef fringes Maalaea Bay and some of the coast to the south. Swimming beaches are scarce on East Maui because of the shallow reef in front of the sandy shores or lava cobbles on the bottom. Most of the coast line is rocky or composed of smooth water-worn boulders which pound against each other in the surf like gigantic ball mills in action. The beach near Nanualele Point is composed of boulders averaging 8 inches or more in diameter. The boulders have been used extensively in Hana for decorative walls and sidewalks. The extensive cobble beach flat starting half a mile west of Nuu is said to have been built during a single storm.

From 1932 to 1938 several great storms struck Maui. The quantity of debris carried into the ocean from Maliko Gulch on January 4, 1937, was exceptionally large. Longshore currents carried the finer silt as far as Kahului, and the water over the reef was muddy for weeks afterwards. Such floods probably inhibit or kill many reef-building organisms and partly account for the small amount of fringing reef on Maui. Also great quantities of calcareous sand are constantly driven across the north shore reef by the same currents. After another storm the shore of Maalaea Bay was littered with dead slugs, shell fish, and other marine organisms killed by the mud and possibly by fresh water. Doubtless, soil erosion has been accelerated in historic time by ploughing, overgrazing, and deforestation; hence, floods now carry more silt than they would have carried in prehistoric time. The great damage wrought by floods in areas not altered by man on East Maui prove conclusively, however, that severe storms cause much of the erosion. Weathering in the interim prepares the debris for rapid removal.

DEPTH OF WEATHERING.—The depth of weathering varies from place to place with the climate, steepness of terrane, rate of soil erosion, and age of the lava flows. The Kula rocks are weathered to soil for depths of 15 feet or more in the road cuts near Haiku and are sufficiently soft to be cut with a pick and shovel to depths of 50 feet or more. The same lavas followed to the top of the mountain, where the rainfall is less and the temperature lower, become firm and nearly free of soil. The thickness of soil on Kula rocks of similar age decreases rapidly toward the south or dry leeward slope. In the very wet steep areas to the east where erosion is rapid, rocks of Kula age may have only 1 to 10 feet of soil.

The youthful Hana lavas (pl. 1) carry insufficient soil for farming except near the rift zones where ash covers them.

The depth of weathering is generally less on East Maui than on the extinct volcanoes of West Maui, Lanai, and Kahoolawe. Consideration of all factors governing soil accumulation indicates that the oldest surfaces of East Maui are probably younger than those on these neighboring volcanoes.

GEOMORPHIC EFFECTS OF LAVA FLOWS FILLING LARGE CANYONS.—Erosion continued in all the great valleys on East Maui during their filling with Hana lavas. A decrease in erosive power resulted from the burial of springs in the canyon heads and the high permeability of the new lavas into which all but great floods sink. The number of interruptions to valley cutting was determined by the number of lava flows, and the depth of erosion by the time interval between them.

The geomorphic and hydrologic effects of basalt filling extensive valleys in the United States have already been described.[47] The effects of basalt filling steep, short, box-headed canyons on an island volcano are sufficiently different from those filling continental valleys to warrant description. The following theoretical history fits that of a valley such as Kipahulu, except that more lava flows and more minor erosional epochs occurred than are shown in the simplified diagrams in plates 13 and 14.

The history starts with a basaltic island dome with heavy rainfall on the upper slopes. Normal stream erosion by a master stream develops an amphitheater-headed canyon while the sea cliffs the coast[48] (pl. 13A). Lava flows partly fill the canyon and build a fan of basalt at its mouth (pl. 13B). Continued eruptions finally fill the lower part of the valley and the lava overflows the sidewalls and sea cliffs (pl. 13C). Such buried sea cliffs are expressed by a declivity fronted with a flat. The streams on the slopes outside the buried canyon sink at first into the margins of the porous basalt, but cut channels alongside during floods and finally reach the sea. If a repose period occurs, the side drainage soon cuts deep canyons into the weathered older rock at the margins (pls. 13D and 14A).

Valley-filling lavas are left on the inner banks generally far above the canyon floors as on the west bank of Koukouai Canyon at an altitude of 1,250 feet. The stage shown in plate 14A is recognized by the canyon walls farthest from the lava fill being higher than

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[47] Stearns, H. T., Geology and water resources of the Upper McKenzie Valley, Oregon: U. S. Geol. Survey Water-Supply Paper 597-D, pp. 174-178, 1929; Geology and water resources of the Middle Deschutes River basin, Oregon: U. S. Geol. Survey Water-Supply Paper 637, pp. 145-146, 1931; Origin of the large springs and their alcoves along the Snake River in Southern Idaho: Jour. Geology, vol. 44, p. 440, 1936; (with Lynn Crandall and W. G. Steward) Geology and ground-water resources of the Snake River Plain in Southeastern Idaho: U. S. Geol. Survey Water-Supply Paper 774, pp. 65-69, 1938.

[48] Stearns, H. T., op. cit. (Bull. 1), pp. 24-26.

those composed of lava fill, especially a mile or so inland; for example, Manawainui Stream, 1 mile from its mouth. Also in this stage the outer walls make an obtuse angle at the points where the lava fill formerly overtopped the ancient canyon walls as shown in plate 13D. An example may be seen in Kaupo Valley just below the National Park boundary (pl. 1).

If eruptions are renewed, the lava will be confined at first to the two marginal canyons. But if very voluminous, it will overflow the inner or lower walls and start covering the earlier lava fill near the coast (pl. 14B). Drainage deflected along the inner margins of the two new lava fans will, if sufficient time is available, leave the earlier fill as a terrace pointing downstream (pl. 14C). Palikea, the peak 3 miles up Kipahulu Valley, is the seaward end of such a terrace. Erosion cuts valleys again along the outer edge of the new lava fill. By this time deep amphitheater-headed tributary canyons, as for example Waimoku in Kipahulu Valley, notch the higher outer valley walls, and a great difference is found in the height of the sea cliffs on the old rocks, compared with those on the new lava fill (pl. 14C). With progressively longer quiescence the lava fill will become two triangular shaped blocks with a peak between their upstream apexes (pl. 14D). Eventually even these remnants will be cut away. The flaring mouth of a deep canyon may be the only evidence, then, of the long cycle of lava filling.

EARTHQUAKE OF 1938 AND ITS GEOMORPHIC EFFECTS.—At 10:03 p. m., January 22, 1938, the Hawaiian Islands were shaken by a destructive earthquake with its epicenter at sea 25 miles north of Pauwalu Point, Maui, and 65 miles below the surface, as reported by the U. S. Coast and Geodetic Survey. Damage was limited chiefly to Maui and totaled about $200,000. The senior author was living in an old wooden frame house on the loose sand beach at Spreckelsville. The intensity there was between VII and VIII on the Rossi-Forel scale. Damage consisted of broken water pipes, breaking of the electric circuit, overthrown furniture, and displacement of the porch several inches. No tidal wave accompanied the shock which was even felt by vessels at sea. Many observers noticed lights flashing in the heavens. Possibly they were due to high tension lines hitting each other. A loud rumbling noise accompanied the earthquake. Objects were toppled at Spreckelsville N. 50° W.; at Paia N. 45° W.; at Hamakuapoko N. 25° W.; at Makawao N. 45° E.; at Keahua N.-S.; and at Kula Sanatorium S. 35° E. The nearest seismograph was in Honolulu; it was dismantled by the shock. After-shocks continued for several days.

A great difference was noted in the damage and intensity of the shock in several parts of Spreckelsville. Damage in the center of the village, which was built on bedrock consisting of old Kula lavas, was negligible. Less than half a mile away, residences built on loose beach sand were damaged considerably.

No destructive earthquake had been recorded previously on Maui. The geomorphic significance was the great change wrought in the terrane. Vast quantities of debris had crumbled, weathered, or crept into position where, saturated from winter rains, it was ready to slide. More soil and rocks moved in the short span of a few seconds during the earthquake than would move in several centuries by normal erosion. Ridges in the ditch country of East Maui were decapitated, and great slides choked valleys and buried roads and ditches. Much of the road from Kailua to Nahiku was buried and it took several months to clear away the landslides. The green-forested steep-walled canyons of West Maui were marred with hundreds of landslide scars, the largest of which were still bare 3 years later. The streams with steep canyon walls were muddy for months afterwards, and much of the heavy debris was still being washed downstream during floods in 1940.

Rocks loosened and cliffs cracked by the 1938 earthquake still fall during intense winds and storms. Manawainui Canyon near Kaupo was hazardous to climb in 1941 because of the falling rocks and trees. The floor is cluttered with debris. Talus slopes in Haleakala were still sliding and readjusting in 1941. Appreciation of the important role of minor catastrophies in erosion is growing among geologists.[49]

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[49] Bryan, Kirk, Gully gravure—a method of slope retreat: Jour. Geomorphology, vol. 3, no. 2, p. 91, 1940.

Plates 13 and 14.

Eight stages illustrating the geomorphic effect of lava flows filling a deep valley on a volcanic island.

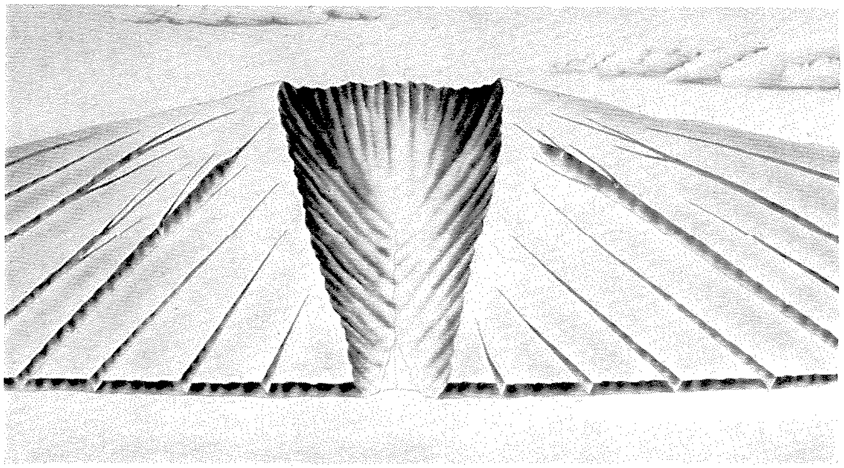


Plate 13A.

Stage 1. Amphitheater-headed valley on a volcanic island.

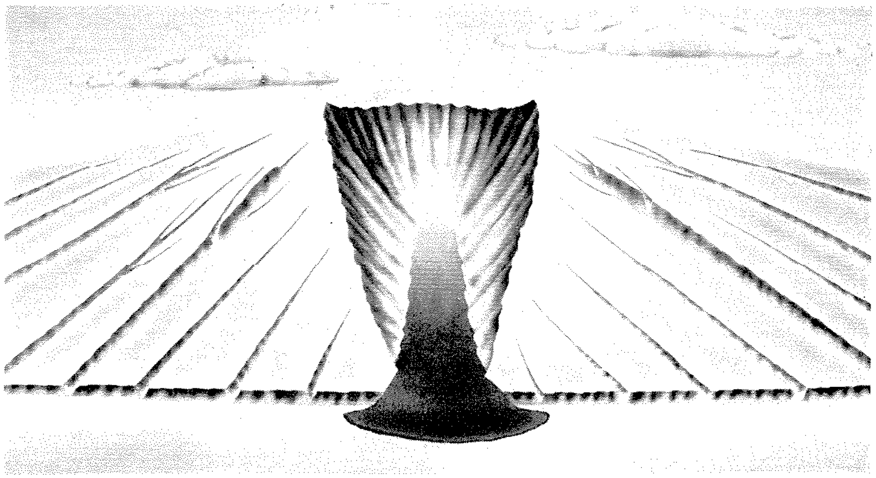


Plate 13B.

Stage 2. Filling of the valley with lava begins.

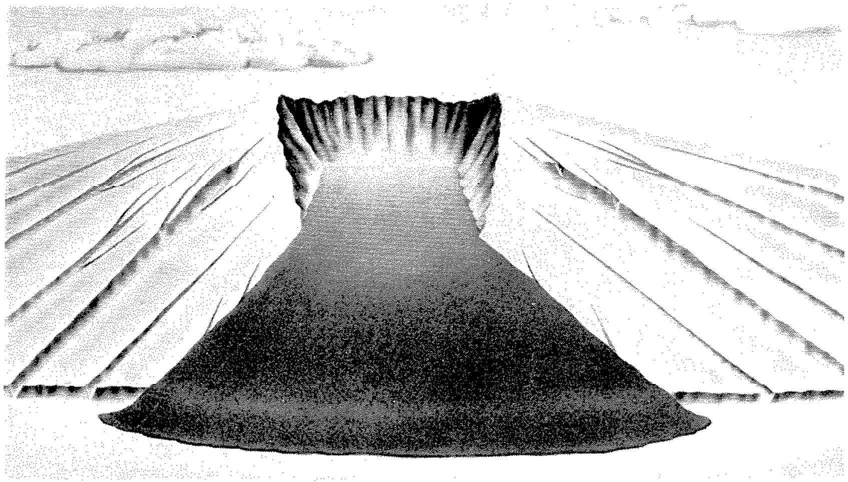


Plate 13C.

Stage 3. Lava overflows the valley walls near the coast.

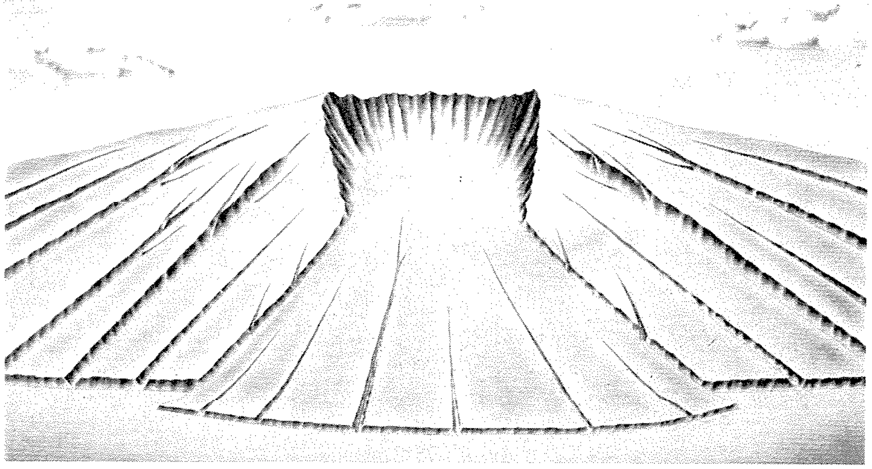
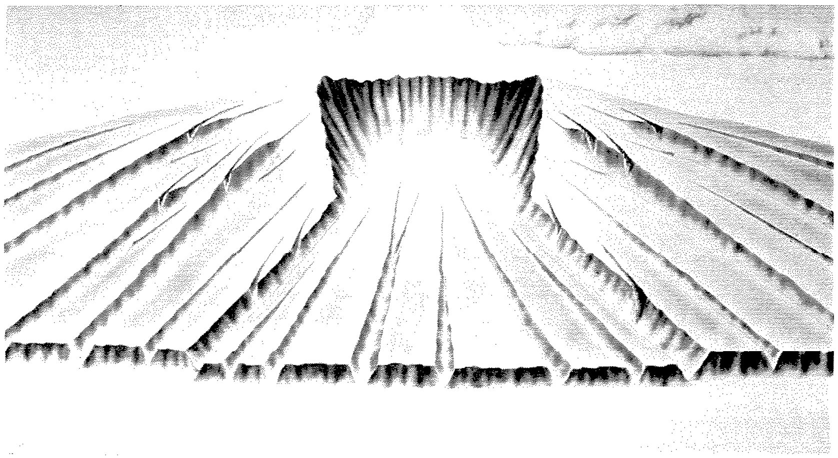


Plate 13D.

Stage 4. The lava fill is eroded by streams and cliffed by the sea.

Plate 14A.

Stage 5. Erosion continues, developing deep valleys at the margin of the lava fill. The sea cliff is lower on the fill than on the adjacent older rocks.



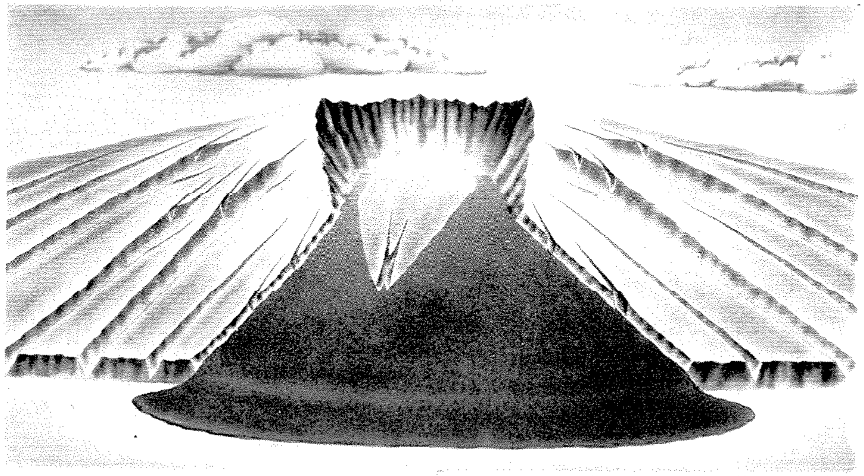
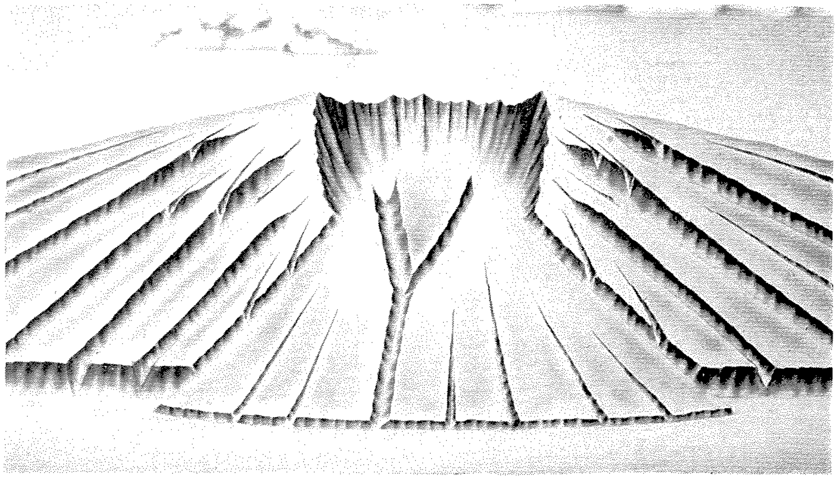


Plate 14B.

Stage 6. Renewed eruptions bury with lava the valleys and sea cliff formed in stage 5.

Plate 14C.

Stage 7. Renewed stream and marine erosion leaves remnants of the early lava fill above the late lava fill.



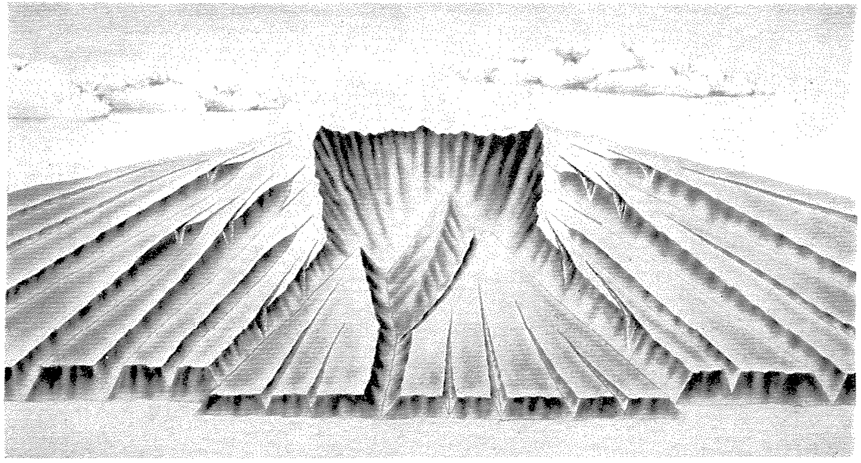


Plate 14D.

Stage 8. Continued erosion forms a peak near the center of the valley and leaves sector - shaped remnants of the lava fill, which are lower than the adjacent island slopes.

GEOLOGY OF EAST MAUI

GENERAL CHARACTER, AGE, AND WATER-BEARING PROPERTIES OF THE ROCKS

East Maui or Haleakala Volcano built first a shield-shaped dome of primitive olivine basalts from three rift zones and presumably from a summit vent (pl. 23A). The basalts were laid down in a highly fluid condition as very vesicular pahoehoe and aa flows averaging about 15 feet in thickness. Vitric tuff deposits are scarce in all exposures but probably more are buried near the rift zones. The dome reached an approximate height of 8,500 feet in relation to present sea level (pl. 23C). Its rocks are the oldest in East Maui and are called the Honomanu volcanic series.

The composition of the magma began to change at the end of the dome-building period. Olivine basalts became scarcer and more silicious, and slightly viscous andesites and related rocks were erupted from the same rifts. Picritic basalts were erupted also and pyroxene phenocrysts appeared for the first time. Many of the outbreaks were accompanied by firefountains, the frozen foam of which formed bulky cinder cones. Bits of pumice and vitric ash, the lighter products of the fountains, were deposited in depths ranging from a thin film to 30 feet adjacent to the cones and especially to their leeward. The gamut of products of this epoch is called the Kula volcanic series. They completely veneered the old Honomanu dome, being about 2,500 feet thick near the summit and only 50 to 200 feet thick near the periphery (pl. 24A). Individual flows reach thicknesses of 100 feet or more.

The time between the Kula eruptions lengthened and streams carved valleys. Deep canyons were eroded on the wet slopes, especially those infrequently overrun by flows and where valleys had cut through the veneer of stronger silicious lavas into the underlying weaker basalts. Some canyons were filled with lava flows which displaced the streams laterally. Others were only partly filled and were soon re-excavated by their streams and cut deeper. The record of some of these accidents to the drainage is clearly exposed. It is believed that many others are deeply buried. The period culminated with the excavation of the great canyons of Keanae, Waihoi, Kipahulu, and Kaupo. Their streams ate away most of the eastern part of the summit ridge, leaving it deeply scalloped (pl. 24C). Spring-fed streams flowed seaward in them, supplied by water in the dike systems that underlay the rift zones and that had been exposed by the deep erosion. Lesser canyons, now unnamed and obliterated by later flows, also corrugated the slopes.

A period of great submergence during which valley mouths were drowned to a depth of hundreds of feet followed the erosional period. The submergence caused streams to cease downcutting and to alluviate their valleys with coarse poorly assorted thick conglomerates (pl. 25A). Lesser emergences and submergences occurred near the close of this period, which left their record in gravel terraces above sea level and valley notches that go below sea level along the coast. During one of these periods of emergence, heavy rains, perhaps followed by an earthquake, set in motion the voluminous talus deposits at the foot of the walls in Kaupo Valley. They moved seaward as a gigantic mud flow sweeping everything in its path (pl. 25C). Fragments of talus breccia in the alluvium at the mouth of Keanae Valley indicate that a similar mud flow probably moved down it and is now buried by later lavas or is eroded away.

During the later emergences and submergences volcanic activity was renewed and lava flows came in too rapid succession for the streams to remove them (pl. 25C). The flows followed valleys and swales, chiefly, leaving many of the interstream divides bare. The north rift failed to reopen, and all the lava came from the southwest and east rifts (pl. 26A). Thus, most of the west and north slope was not inundated by lava. The southwest slope being little eroded was completely veneered. Many of the intercanyon areas on the eastern side of the mountain were not covered, as the lava erupted on them cascaded into the adjacent canyons. Other areas were shut off from flows by cone chains. The amphitheater heads of the major canyons were filled with thousands of feet of lava and some with great fans of cinders that slid from cones on their rims.

These later eruptives were from fissures and produced chains of cones bordered by vitric ash deposits. They have been named the Hana volcanic series and differ from the Kula volcanic series only in the greater proportion of olivine basalts. (See Part 3.) The eruptions continued until about 1750 and there is a good chance that more are yet to come (pl. 26C).

The age of the rocks is uncertain. The great dome probably began erupting above sea level in Pliocene time. It is thought that the Kula volcanic series, which has 20 feet of soil in places, is probably early and middle(?) Pleistocene in age. The Hana volcanic series is obviously young and was erupted chiefly in late Pleistocene and Recent time, correlative with the series of emergences and submergences induced by glaciation and concurrent changes in the level of the oceans.

The Honomanu basalts are very permeable and yield large supplies of water to wells. The andesites of the Kula series are less permeable and in wet places commonly contain water perched on interstratified soils, conglomerate, or ash. Many tunnels have been driven into them for water in the Nahiku area. The thick coarse ash deposits carry small quantities of water on some of the weathered and compacted intercalated finer layers. The Hana lavas carry little water except where they bury perennial streams. The conglomerates supply a few springs but in many localities they are too poorly sorted to yield water freely and are more valuable as perching formations than as aquifers. The various types of sediments that overlie the basalts from Haleakala on the Isthmus supply water to wells, but most of it is too brackish for domestic use. It is satisfactory for irrigation, refrigeration, and certain industrial uses. The loose gravels are the best and the silts are the poorest of the sedimentary aquifers.

The stratigraphic rock units on East Maui in comparison with those on West Maui are given in the table on page 65. The general character and water-bearing properties of the East Maui rocks are summarized in the succeeding table.

EAST MAUI VOLCANIC ROCKS AND THEIR WATER-BEARING PROPERTIES

The East Maui volcanic rocks comprise all the lava flows, intrusive rocks, pyroclastic rocks, breccias, and intercalated soils in East Maui. Haleakala Volcano was their source. The rocks have been subdivided into three series. The lavas of the lower or Honomanu series are separated from the lavas of the middle or Kula series by a petrologic difference. The contact is marked in some places with a thin red soil, but in many places a transitional petrologic phase exists, and the correct assignment of rocks in this transition zone, which is 50 to 200 feet thick, cannot always be made with certainty.

Below the transition zone the lavas are all olivine basalts of the primitive type without pyroxene phenocrysts. (See Part 3.) Above the transition zone, except on the Isthmus and northwest coast, is a thick section of dense gray, commonly massive and platy, aphanitic lavas of andesitic type containing some porphyritic augite olivine basalts. These are the Kula lavas.

Pahoehoe is abundant among the Kula lavas near their sources but is scarce elsewhere, whereas it is abundant everywhere in the Honomanu series, even at the periphery of the volcano. The clinker beds in the Kula lavas, instead of being 2 to 4 feet thick as in the lower Honomanu lavas, range from 5 to 25 feet in thickness. Thickness alone makes the outcrops of the Kula lavas very different from the lower. The Kula lavas are separated from the Honomanu lavas by a profound angular unconformity in the south wall of the summit depression (fig. 10).

The upper or Hana series is always separated from the Honomanu basalts by a profound erosional unconformity and is much fresher. Thus, the two members are easily differentiated in the field. The Hana lavas are separated generally from the Kula lavas in the eastern part of the mountain by a great erosional unconformity. In a few places, where the Hana lavas buried a smooth interstream area underlain by Kula rocks, a residual soil and rotted zone several feet thick lie between them. The younger Hana flows are readily differentiated in the eastern half of the mountain by their freshness and by the soil at their base. But the older Hana flows, especially near the summit where weathering has been slow because of aridity and a temperate climate, are separated with difficulty in some places from the slightly weathered youngest Kula flows. Fortunately, the Hana cinder cones are much less consolidated and weathered than the Kula cones, factors that enable most of them to be separated with certainty. Also many of the flows from the Hana vents can be traced to the coast, where they fill valleys eroded in the Kula lavas or overlie a residual soil. At low altitudes where an ashy loess veneers most cones, some cannot be differentiated. Some of the yellow soil-covered cones that rise above the black lava fields in the Ulupalakua-Makena area may be Kula in age, although they are mapped as Hana cones on plate 1. The difficulty of separating them correctly is increased by dense brush on some cones and by late eruptions which broke out of the sides of Kula cones and thinly veneered them with fresh cinders. In this respect these cones resemble some of the old cones, like Puu Keokeo on the southwest rift of Mauna Loa Volcano, where the record of numerous eruptions is much clearer.[50]

The Hana member is composed of flows of ultrabasic olivine pyroxene porphyries, olivine basalts, feldspar porphyritic basalts, basaltic andesites, and fine-grained andesites. Basalts are more abundant than in the Kula series. (See Part 3.) Aa predominates as in the Kula member, and both low spatter mounds and large bulky cinder cones were formed by the firefountains. No Hana lavas

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[50] 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. 124, 1930.

Stratigraphic rock units on the island of Maui

Major geologic unit	East Maui			West Maui	
	Major rock units (plate 1)	Subdivisions in the Nahiku area (Insert B, pl. 1)	Subdivisions in the Keanae area (Insert A, pl. 1)	Major rock units (Plate 1)	Subdivisions[a] (Plate 1)
Historic volcanic rocks	Volcanics erupted in 1750(?) near Makena				
Recent sediments	Unconsolidated deposits	Unconsolidated deposits	Unconsolidated deposits	Unconsolidated deposits	
Pleistocene sediments	Calcareous dunes Consolidated earthy deposits Kaupo mudflow		Consolidated earthy deposits	Calcareous dunes Consolidated earthy deposits	
Pleistocene and Recent volcanic rocks	Hana volcanic series (Includes Kipahulu member in Kipahulu Valley)	Hanawi basaltic andesite Paakea basalt Kuhiwa basaltic andesite Mossman picritic basalt Makaino basaltic andesite Kapaula basaltic andesite Waiaaka basaltic andesite Makapipi basalts Big Falls picritic basalts	Keanae basalt Waiokamilo basalt Piinaau basalt Ohia basalt Wailuanui basalt[b] Pauwalu basalt	Lahaina volcanic series	Kekaa cinder cone Laina volcanics Kilea volcanics Hele cinder cone
Great erosional unconformity					
Pliocene(?) and Pleistocene volcanic rocks	Kula volcanic series			Honolua volcanic series	
	Honomanu volcanic series			Wailuku volcanic series	

[a] Mapped separately on Plate 1 but shown with the same pattern as they do not join.

[b] Shown on Plate 1 as undifferentiated Hana lava along Wailuanui Stream but not shown in insert A, Plate 1.

Stratigraphic section of East Maui

(Similar data for the rocks of Keanae Valley and the Nahiku area are given on pages 95 and 230.)

Major geologic unit	Rock assemblage	Thickness (feet)	Symbol on map (pl. 1)	General character	Water-bearing properties
Historic volcanics	Lava flows and cones of 1750(?)	20±	Rl	Two olivine augite porphyritic basalt flows near Makena.	Contain brackish water along the coast and no water inland.
		100±	Rlc	Two cones of cinder and spatter at the source of the flows.	Carry no water.
Recent sedimentary rocks	Unconsolidated deposits	50±	Ra	Chiefly younger alluvium consisting of loose poorly sorted, poorly rounded, stream-laid brown silt, sand, and gravel. Large talus fans in the summit depression and small amounts of calcareous sand and wave-rounded cobbles along beaches are included.	The alluvium along the coast yields brackish water, especially below lands irrigated with brackish well water. The talus fans are highly permeable but do not carry water.
Local erosional unconformity					
Middle (?) and late Pleistocene and Recent lavas and pyroclastics	Hana volcanic series	10 to 1,000+	Qh	Lava flows consist of dense and vesicular jointed aa and pahoehoe olivine basalt, picritic basalt, basaltic andesite, and andesite poured out in rapid succession. Where the flows fill valleys they aggregate 1,000 feet or more in thickness, but elsewhere they form a veneer 10–200 feet thick over the older lavas. The younger flows are bare and black.	Most of the flows are highly permeable except in the dense massive parts that fill narrow canyons. They serve chiefly as an intake formation, but perched water is found in the basal part of most of those filling valleys in wet areas. They yield water to wells at sea level, but it is brackish on the leeward shore.
		20–600	Qhc	Cones consist of friable red to black bedded cinders, spatter, and layers of very thin scoriaceous lava built along fissures at the source of the flows.	Very permeable and serve chiefly as an intake member, although a few in wet areas carry very small perched bodies of water on intercalated soil layers. Two small ponds are perched in the craters of cinder cones at the head of Kipahulu Valley.
		1–20	Qhf	Firefountain deposits consist of red, yellow, and black friable vitric ash and pumice deposits blown from cones by the wind.	Very permeable but contains no water.
		150+	Qhp	Lithic-vitric tuff in Molokini Islet only.	Contains only sea water.
		1–10	Red lines	Dikes composed chiefly of dense cross-jointed rock similar to the lava flows they fed. A few are vesicular and platy.	Confine water under the three rift zones and probably several thousand feet above sea level under the east rift.
	Erosional unconformity				
		750+	Qk	Kipahulu member composed of basalt, picritic basalt, and basaltic andesite in Kipahulu Valley only.	Permeable and probably carries large quantities of water at its base.

Erosional unconformity					
Middle(?) and late Pleistocene sedimentary rocks in part contemporaneous with the Hana volcanic series	Consolidated calcareous dunes	1–200	Qd	Chiefly consolidated and partly consolidated calcareous dunes consisting of thin-bedded and cross-bedded eolian limestone composed of pale-yellow uniform grains of sand blown inland from beaches during and since the minus 60-foot stand of the sea. Includes some Recent unconsolidated beach and dune sand along the west and north shores.	Permeable but only those along the coast carry water, and it is brackish in most places.
	Consolidated earthy deposits	150±	Pa	Consolidated and partly consolidated earthy deposits consisting of older alluvium, ancient talus, landslide deposits, and marine noncalcareous sediments. In the valleys the alluvium is characterized by friable ochre to red-brown poorly sorted lenticular conglomerates which along the coast contain brown interstratified siltstones. They form valley fills and fans and are usually terraced. The ancient talus forms compact breccias along canyon walls.	They lie mostly above the water table on the Isthmus, but near the coast they yield brackish water to wells. Perched water is found in a few gravel lenses in Keanae and Kaupo valleys, but the earthy deposits are chiefly valuable for perching water in the overlying Hana lava flows. The deposits west of Nuu do not carry water.
Erosional unconformity					
Middle(?) Pleistocene sedimentary rocks	Kaupo mud flow	300+	Qkm	Mudflow member consists of coarse breccia with blocks reaching 50 feet across at mouth of Kaupo Valley only.	Perches water in overlying gravel and lava.
Great erosional unconformity					
Probably early and middle Pleistocene volcanic rocks	Kula volcanic series	50 to 2,000	Tk	Lava flows composed of dense and vesicular, jointed basaltic andesite, andesite, basalt, and picritic basalt; all chiefly gray aa. The older flows are generally aphanitic, and most of the Kula lavas are more massive than the underlying Honomanu lavas. The lavas in the upper part commonly fill valleys cut between eruptions.	The flows are fairly permeable and carry perched water in the wet eastern part of the mountain, especially at the base of valley fills of lava. The largest spring on Maui issues from a Kula clinker bed.
		20–600	Tkc	Cones consist of friable to firmly compacted red to black bedded cinders, spatter, and thin layers of scoriaceous lava built along fissures at the source of the lava flows.	Fairly permeable and perch a few small springs and seeps.
		1–40	Tkf	Tuffs consist of red and yellow friable weathered vitric tuff commonly interbedded with the lava flows.	Perch many springs, especially in the eastern part of the mountain.
		½–10	Red lines	Dikes composed chiefly of dense cross-jointed rock similar to the lava flows they fed. A few are vesicular and platy.	Confine water under the three rift zones and probably several thousand feet above sea level under the east rift.
Transitional in most places					
Probably Pliocene and early Pleistocene volcanic rocks	Honomanu volcanic series	8,500+	Tho	Lava flows composed of thin-bedded highly vesicular primitive olivine pahoehoe and aa basalt 10 to 75 feet thick.	Highly permeable and freely yield basal water to wells. They supply many springs at tide level.
		5–150	none	Cone and firefountain deposits are scarce except in Manawainui Valley. They consist of basalt, cinder, spatter, and vitric tuff.	Tuff member perches several springs in Manawainui Canyon.
		1–5	Red lines	Dikes are exposed only in Manawainui and Kipahulu valleys.	Confine water in the rift zones.

were erupted from the north rift. Some of the Hana eruptions occurred on the walls at the heads of canyons, which were cut deeply into the east and southwest rift zones (pls. 1 and 26A).

HONOMANU VOLCANIC SERIES

Distribution.—The type locality for the Honomanu basalts is on the northeast slope in Honomanu Valley, a gorge 1,300 feet deep. The basalts form the lower 950 feet of the cliff, and are exposed northwestward in the sea cliffs and in the mouths of the deeper gulches as far as Waipio Bay (pl. 1). They reappear at Maliko Gulch, the next deep gulch to the west. Wells on the Isthmus penetrate them under a cover of Kula lavas 100 to 300 feet thick. They are exposed eastward from the type locality nearly to Nahiku and for 5½ miles up Keanae Valley. They have been encountered in the deep borings in the Nahiku area. Progressing clockwise around Haleakala, they are not exposed again until the deepest alcoves in Kipahulu Valley on the south slope are reached. There they are found in the transitional phase under 2,000 feet of Kula lavas. Farther west, Honomanu lavas of the transitional top phase appear in the bottom of the deep Manawainui Canyon on the east side of Kaupo under a thick mantle of Kula lavas (section AA′, pl. 1). Cobbles of typical Honomanu basalt were collected in Pukai Canyon nearly 4 miles from its mouth at the foot of an impassable dry waterfall, but their source was not reached. Transitional Honomanu basalt crops out nearly 3 miles inland from this point at the base of the south wall of the summit depression. Similar transitional vesicular olivine basalts, assigned to the Honomanu series, crop out between dikes in two small areas of dike complex 2 miles northeastward from the south wall locality near the edge of the depression floor (pl. 1).

Character and structure.—The Honomanu basalt is exposed over less than 1 percent of Haleakala, but is believed to form the basement of the entire mountain to an unknown depth below sea level (section AA′, pl. 1). Prior to the eruption of the Kula lavas it formed a dome about 8,500 feet above present sea level and considerably steeper than the Mauna Loa dome, Hawaii—probably more closely resembling the slopes on the steeper eastern side of Lanai or of the eastern slopes of West Maui. If it paralleled in history the other Hawaiian volcanoes, a caldera may have once indented its summit, but no traces of it have been found. Lack of evidence would not disprove the existence of the caldera as deep exposures in the summit depression are scarce.

The following section occurs at the type locality; additional details will be found in Part 3.

Stratigraphic section along the highway on the west side of Honomanu Gulch, East Maui

(Base of section at an altitude of about 25 feet.)

Kula volcanic series	Thickness (feet)
Dense nonporphyritic aa	20
Upper 10 feet clinker, with red streak at top. Lower 15 feet moderately dense platy gray aa with a few feldspar phenocrysts up to 1 mm long	25
Honomanu volcanic series	
Red ashy soil at contact of Honomanu and Kula volcanic series	0.5
Vesicular aa with scattered feldspar phenocrysts up to 1.5 mm long; pinching out in road cut	7
Vesicular aa with moderately abundant phenocrysts of olivine up to 6 mm long and feldspar up to 4 mm. Red streak at top	14
Vesicular aa with moderately abundant phenocrysts of olivine up to 5 mm long and scarce phenocrysts of feldspar up to 4 mm. Contains a 4-foot streak of dense rock. Thin red streak at top	8
Vesicular pahoehoe with moderately abundant feldspar phenocrysts up to 1 mm long, and rare phenocrysts of olivine. Thin red streak at top	20
Vesicular pahoehoe with moderately abundant feldspar and olivine phenocrysts up to 2 mm long	7
Vesicular pahoehoe with abundant olivine phenocrysts up to 7 mm long and moderately abundant feldspar phenocrysts up to 3 mm	6
Vesicular pahoehoe with abundant feldspar phenocrysts up to 2 mm long and moderately abundant olivine phenocrysts up to 1.5 mm	4
Vesicular pahoehoe in thin flow units with thin red streak at base. Contains moderately abundant phenocrysts of olivine up to 2 mm across, but none of feldspar	8
Vesicular to dense aa with moderately abundant phenocrysts of olivine up to 6 mm long, but none of feldspar	7
Aa like that above	9
Vesicular pahoehoe with moderately abundant olivine phenocrysts up to 1.5 mm long and scattered feldspar phenocrysts up to 2 mm	8
Vesicular aa in thin alternating units of clinker and flow lava with moderately abundant phenocrysts of olivine up to 2 mm long, and feldspar up to 7 mm but mostly less than 4 mm	8
Vesicular pahoehoe with scattered feldspar phenocrysts up to 1 mm long and rare olivine phenocrysts less than 1 mm	8
Vesicular pahoehoe with abundant olivine phenocrysts up to 7 mm long and scattered feldspars up to 1 cm. Contains streaks 1 inch to 2 feet thick of dense nearly nonporphyritic rock	4
Vesicular pahoehoe with scattered feldspar and olivine phenocrysts up to 1 mm long. A trace of soil is present at the top	6
Vesicular aa with moderately abundant feldspar and olivine phenocrysts up to 1.5 mm long	8
Vesicular aa in thin beds, with moderately abundant feldspar and scattered olivine phenocrysts up to 2 mm long	5
Upper half is aa clinker; lower half is dense aa with moderately abundant olivine phenocrysts up to 7 mm long and scattered feldspar phenocrysts up to 2 mm	12
Vesicular pahoehoe with abundant feldspar phenocrysts averaging 2 mm long and moderately abundant olivine phenocrysts averaging 3 mm. The top is decomposed	26
Vesicular pahoehoe with abundant feldspar phenocrysts averaging 2 mm long, and scarce olivine phenocrysts	20
Vesicular pahoehoe with abundant feldspar phenocrysts averaging 5 mm long. Bottom unexposed	30
	270.5

Pahoehoe, as in the above section, dominates elsewhere in the Honomanu lavas. The individual flows range from 10 to 75 feet thick and are usually very vesicular. They range from light-gray to dark blue-gray. All are made of thin flow units[51] and dip from 2° to 22° away from the summit. The flatter dips are in the Isthmus lavas. They resemble the Wailuku basalts in West Maui but as a whole have gentler dips, less aa, and thicker beds. Very few of the Honomanu flows are platy and those few are aa. Most flows carry olivine and/or feldspar phenocrysts. The absence of extensive interbedded soils shows that the lavas accumulated rapidly. Most flows are separated by a wavy red line, the oxidized and slightly weathered glassy crust. In some, similar lines of red oxidized crust weave in and out through the flow, indicating altered glassy skins of billowy flow units.

At an altitude of 1,100 feet in Manawainui Canyon east of Kaupo, a 60-foot bed of porphyritic pahoehoe contains concentrates of olivine and pyroxene crystals ¼ to ½ inch across filling contemporaneous tubes a foot or two in diameter. The walls of the tubes contain scattered crystals less than ¼ inch across. These crystals indicate that the last surges contained heavier and larger crystals. Parallel horizontal aphanitic bands 1 inch wide were noted in a porphyritic pahoehoe with large feldspar crystals in the south wall of Haleakala depression.

The Honomanu lavas are generally transitional into the overlying Kula lavas, as would be expected in a slowly waning and slowly differentiating volcanic hearth. The following section at well 31 at Paia indicates the character of the transition.

Log of well 31, Paia, East Maui

	Thickness (feet)	Altitude of top of bed (feet)
Red lateritic residual soil	20	155
Massive blue lava with 2 feet of clinker at bottom	28	135
Base of Kula lavas	..	107
Compact fine-grained red ashy soil, upper 2 feet baked by overlying lava, and carrying a little perched water	10	107
Vesicular nonporphyritic pahoehoe	17	97
Red soil	1	80
Vesicular pahoehoe with scattered olivine phenocrysts	43	79
Streak of red nonresidual soil	..	36
Massive nonporphyritic blue aa	10	36
Basal clinker of aa flow above, variable in thickness	15	26
Streak of red nonresidual soil	..	11
Top porphyritic clinker	6	11
Dense porphyritic aa with feldspar phenocrysts	5	5
Basal water level that fluctuates with tide	..	4
Basal porphyritic clinker of flow	2	0

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

Log of well 31, Paia, East Maui—*Continued*

	Thickness (feet)	Altitude of top of bed (feet)
Base of transition lavas and top of typical Honomanu....	..	−2
Red top of pahoehoe flow containing a few small feldspar and olivine phenocrysts but strikingly different from flow above and only slightly decomposed at top.............	2	−2
Blue pahoehoe like above. Bottom not reached. (Lower 12 feet determined by boring.).........................	4	−4
	163	

TUFF AND BRECCIA DEPOSITS.—Thin streaks of vitric ash and several cinder cones are interbedded with the Honomanu basalts in the head of Manawainui Canyon. A 5-foot bed of cinders and one layer of spatter are interstratified with the Honomanu lavas in the dike complex in the summit depression. Several beds of vitric tuff 2 to 10 feet thick and a few small spatter cones are interbedded with the basalts in Kipahulu Valley. One thin lithic-vitric tuff bed is intercalated with them in the sea cliff near Hanawi Valley. By analogy with similar primitive-type basalts elsewhere in Hawaii, the eruptions built low spatter cones along fissures but rarely built cinder cones. Thus, vitric tuff deposits should be thin and more numerous next to the rift zones but scarce elsewhere.

An unusual deposit in the Honomanu volcanic series was found along the road in the east wall of Nuaailua Valley near Keanae. It is a breccia 100 feet thick with its base unexposed. A flow of mixed aa and pahoehoe overlies it. The upper 30 feet appears to be a typical red coarse sand-sized aa clinker with small balls and scarce angular fragments of unrelated rock. All the balls have skins of dense rock. One that was broken had a ½-inch rind of glassy lava containing tiny feldspar crystals. It coated a fragment of basalt filled with olivine phenocrysts ¼- to ⅜-inch across. They resemble the ball lava in the flow of 1823 on Kilauea Volcano.[52]

The debris is more angular below and looks like a talus with a coarse sand-sized clinker in the interstices. The matrix is weathered to a soft red dirt. The blocks become larger downward and reach 14 inches across. The breccia has no bedding and its origin is unknown. A pit crater or other depression may have been partly filled with talus from its own walls and subsequently filled with clinker from a flow that cascaded into it. A somewhat similar pyroclastic deposit crops out at Honomanu Spring (p. 128).

The outcrops of tuff and breccia are too small to show on plate 1.

WATER-BEARING PROPERTIES.—The Honomanu basalts are extremely permeable and yield water freely, as shown by the large yields

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[52] Stearns, H. T., The Keaiwa or 1823 lava flow from Kilauea Volcano, Hawaii: Jour. Geology, vol. 34, no. 4, pp. 336-351, 1926.

from wells that penetrate them on the Isthmus. They yield 40 million gallons a day in well 16, which is the largest amount from any well in Hawaii. The pahoehoe is filled with open tubes and the aa carries much loose clinker. Only basal water has so far been recovered from them. The interstratified tuff beds perch small seeps and springs 39 and 40 in Manawainui Valley (fig. 24).

DIKES.—The Honomanu basalts in the summit depression are cut by dikes of Honomanu, Kula, and Hana age. Dikes definitely of Honomanu age are not readily distinguished in the field from those of later age. It is safe to state, however, that not more than ten of the dikes shown on plate 1 are Honomanu as most outcrops of Honomanu basalts are far from the rifts. The dikes are from 1 to 4 feet wide and generally carry olivine; some contain feldspar phenocrysts only or both. The distribution of the lavas indicates that they were poured out of the three main rifts or dike systems. The fact that Honomanu lavas are exposed along the north coast may mean that more of them were extruded from the north rift than from the east and southwest rifts. Honomanu dikes together with dikes of later age probably confine water at high levels in the east rift zone (pl. 12).

ANGULAR UNCONFORMITY IN THE SUMMIT DEPRESSION.—The Honomanu basalts are overlain conformably in most places by Kula lavas. An exception found in a small valley near Nahiku is described on page 233. Another place is at the fault, shown on plate 1, at the base of the south wall of the summit depression.

A great angular unconformity is exposed just north of the peak of Kumuiliahi in a narrow gulch at an altitude of 7,550 feet (fig. 10). The unconformity strikes east and west and dips 83° S. The Honomanu basalt is about 100 feet thick. It is thin-bedded vesicular pahoehoe with phenocrysts of feldspar. It strikes N. 75° W. and dips 8° S. The overlying nonporphyritic dense Kula aa strikes east-west and dips 35° S. The pahoehoe is intruded with an 8-inch sill and filled with dikelets at the unconformity. The dikelets are probably offshoots from a 4-foot vertical dense platy dike 50 feet to the north. The unconformity has along its surface 2 feet of talus composed of vesicular pahoehoe mixed with red ashy soil. The rock beneath the soil is slightly weathered.

No evidence of faulting, such as friction breccia or slickensides, was found. The exposure indicates that soil and talus were accumulating on a cliff which was finally overflowed with lava.

About 200 feet to the west on the adjacent spur the platy dike follows the unconformity, which has an altitude of 7,650 feet. On the west side of the spur 3 feet of talus and soil lies along the unconformity.

The steep dips in the Kula lavas overlying the unconformity extend to the rim or through a thickness of 1,000 feet of lava. At the first spur west of spring 43 and on the south side of a platy dike 10 feet wide, a talus breccia more than 20 feet thick is exposed about 150 feet above the floor. It strikes N. 75° E. and dips 25° S. It is overlain by 25 feet of cinders and bombs of a cone which, like the breccia, is truncated by the wall of the depression. The blocks in the breccia reach 3 feet in diameter. Some are subangular, but most are angular. Lenses of pea- and walnut-sized gravel are interstratified with the talus, indicating hill-wash type of deposition. The breccia is cut by a 1-foot irregular dike that fed the cone, and a 2-foot dike striking N. 55° E. and dipping 70° SE.

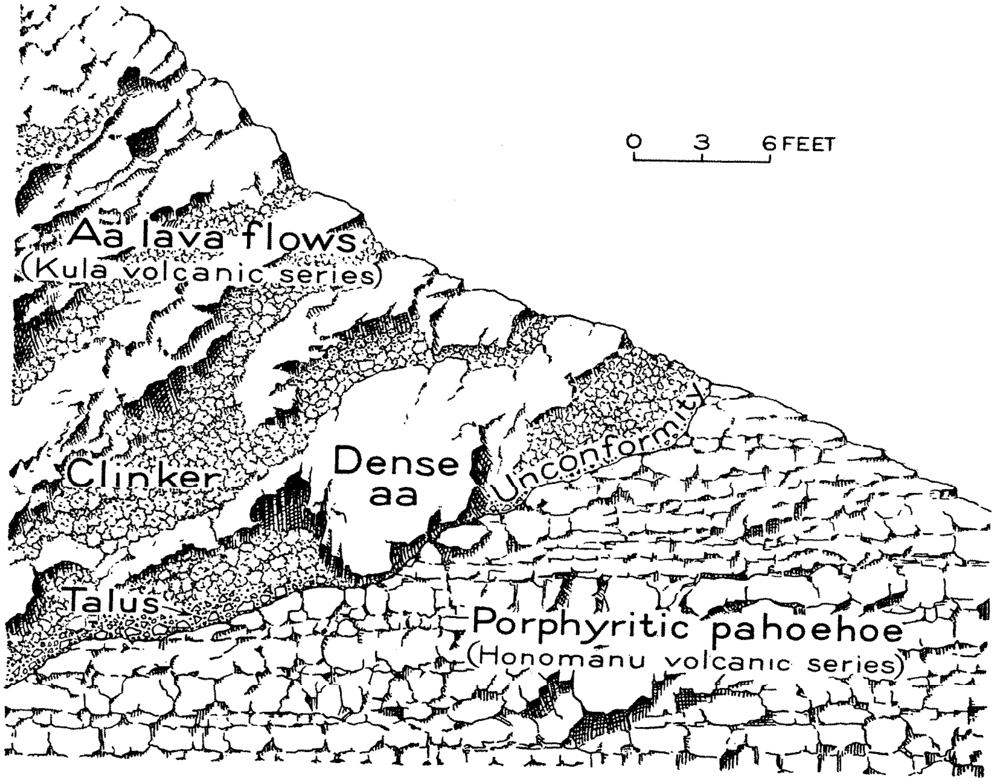

Figure 10. Angular unconformity in the south wall of the summit depression of Haleakala.

The following description as reconstructed from these meager details is conjectural and later work may result in a better interpretation. A cliff at least 500 feet and possibly several thousand feet high as a result of a fault or several parallel faults was formed by the collapse of the south side of the mountain. Perhaps it bounded the south side of a horst block that stood above an ancient caldera of Honomanu age on the north, as shown in plate 23C. When Honomanu basalts ceased overflowing the cliff, soil and talus accumulated on its face. It was overtopped finally by dense heavy Kula aa flows that cascaded down its face. Evidence of its great height is that the 1,000 feet of Kula lavas that subsequently spilled over it failed to smooth the slope created by it. (See section AA′, pl. 1.) Also the south side of the mountain is very short, compared with the other slopes, which points to a great subsidence of that side. The breccia interstratified with the Kula lavas near spring 43 is interpreted as talus that accumulated on the earliest of the lavas that spilled over the cliff.

High cliffs formed by faults near the close of the eruption of primitive basalts and facing seaward between rift zones are common on Hawaiian volcanoes. They are known on the south side of Kilauea and Mauna Loa Volcanoes, Hawaii, where they have likewise been overflowed by later lavas which acquire steep dips and have interbedded talus lenses.[52a]

KULA VOLCANIC SERIES

DISTRIBUTION.—The Kula series are named from Kula, the well established name for the settlement along the upper and lower roads leading to the Kula Sanatorium on the west slope of Haleakala. Waiakoa post office is approximately in the center of this district. Kula is particularly apropos as a name for these volcanics because the word "kula" is Hawaiian for a broad flat upland slope. Thus, the sector-shaped remnants of Kula lavas between Waihoi, Kipahulu, and Kaupo Valleys would be called kula land by the Hawaiians to contrast them with the adjacent valley lands.

Five large areas are covered with Kula volcanics.[52b] The largest is the triangular segment between Keanae Valley on the east, Kula Sanatorium on the south, and Kahului on the west. It includes the entire northwestern flank of the mountain (pl. 1). The lavas have weathered into deep soils because of the long time that has lapsed since the last lava flow in this area. The great agricultural developments on Haleakala lie in this segment. Progressing clockwise around the mountain, the next Kula area is roughly 2 miles wide and 8 miles long and stretches from the north rim of the summit depression to the sea along the east side of Keanae Valley. Next

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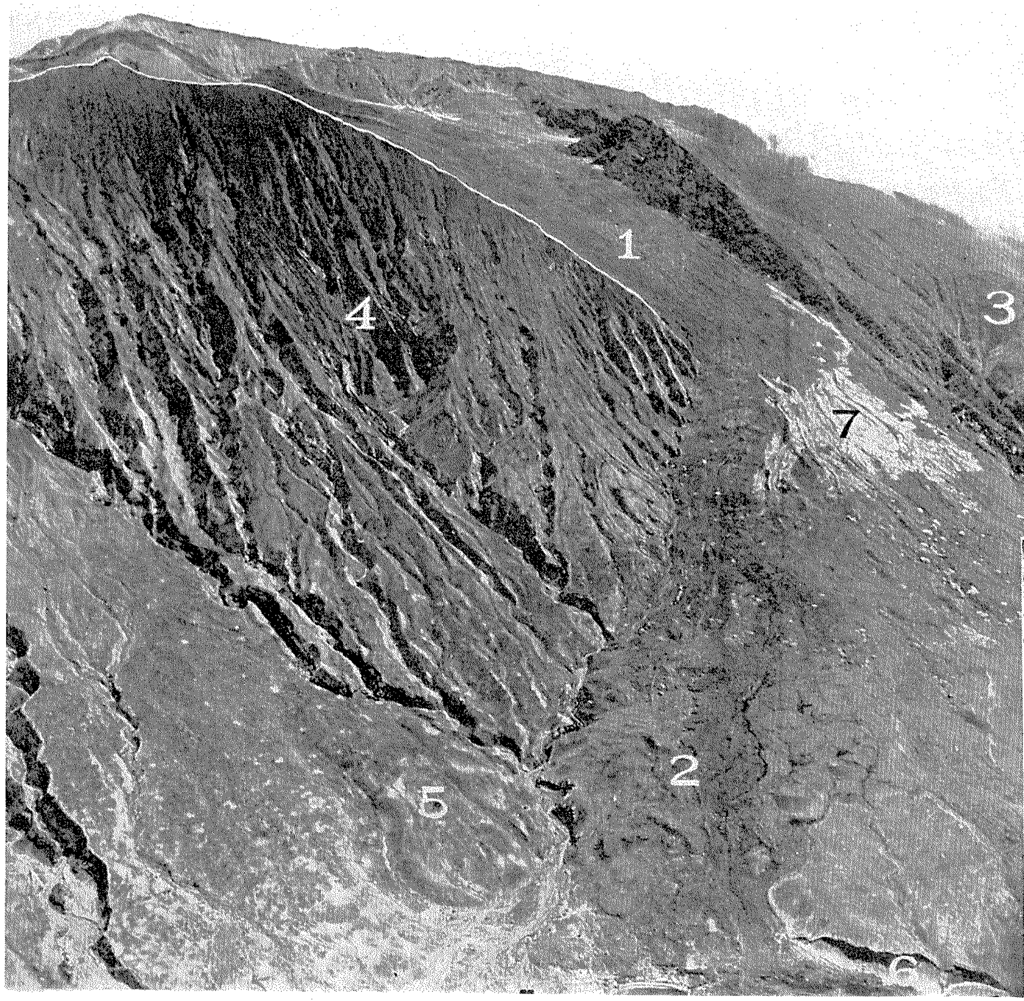
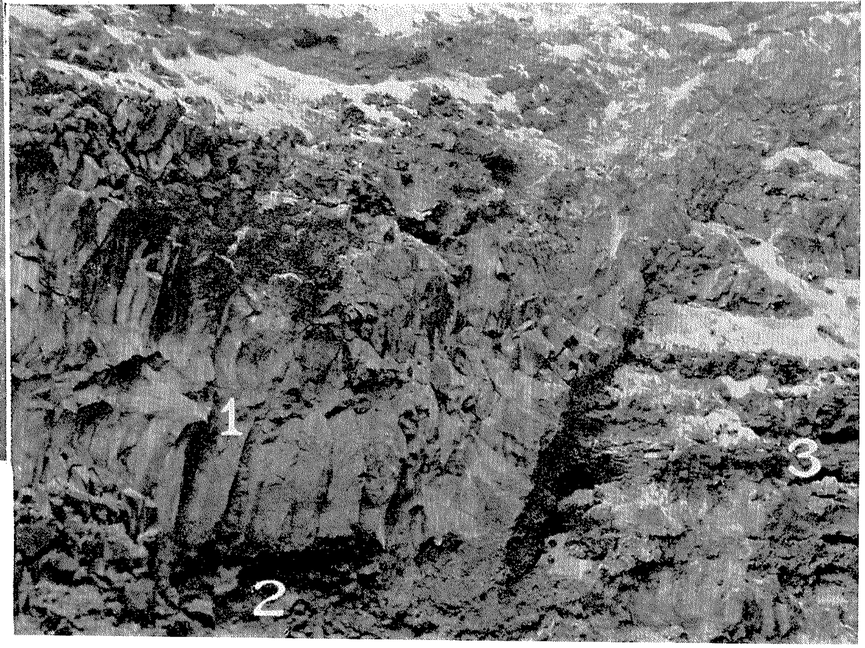
[52a] Stearns, H. T., op. cit. (Water-Supply Paper 616), p. 51.
[52b] Volcanics is used herein as a general term for all the products of a volcano.



Left: Plate 15A. Air view of Kaupo Valley (1) and the summit depression of Haleakala; late Hana lavas partly filling the valley (2); Manawainui Canyon, a deep unfilled tributary (3); numerous deep narrow canyons cut in Kula lavas (4) with the two main canyons diverging because of a fan of late Kula lava (5) burying an ancient valley. All valleys left of Kaupo Valley have been buried at their lower ends and their drainage diverted into the main gulch that follows the margin of the Hana lavas poured from the summit depression. Sea cliff (6) is cut into the Kaupo mud flow. Grasslands (7) on Hana lavas. The white line is drawn along the divide separating the south slope from Kaupo Valley and the summit depression. Photo by Fleet Air Base, U. S. Navy, Pearl Harbor, T. H.



Right: Plate 15B. Late Kula lava (1) underlain by conglomerate (2) and unconformable on earlier Kula lavas (3) at the mouth of Manawainui Gulch west of Kaupo.

Plate 16. Thin-bedded volcanics of the Kula series form the wall of the summit depression of Haleakala along the old Halemauu trail. Photo by U. S. Army Air Corps.

come the sector-shaped remnants between Waihoi and Kipahulu and between Kipahulu and Kaupo Valleys. Finally, there is the area 5 miles wide and 8 miles long lying west of Kaupo Valley and south of the summit depression.

These areas were not flooded by the younger Hana lavas for various reasons. The north rift zone did not reopen in Hana time, and the southwest rift zone opened only on its south side for 3 miles from the summit. In addition, the west wall of Keanae Valley was sufficiently high to prevent the Hana lavas erupted in the summit depression from reaching the area.

The strip of Kula lavas on the east side of Keanae was sheltered from Hana flows by the north rim of the summit depression, although one small stream of Hana lava flowed over the east wall of Keanae Valley (pl. 1).

The interstream remnant was so high between Waihoi and Kipahulu Canyons that it was not overflowed by Hana lavas except near the coast. The remnant was connected to the east rift zone by a ridge too narrow for the later lavas to follow. The larger sector-shaped remnant between Kipahulu and Kaupo Valleys was saved from burial by Hana lavas by similar topography.

The broad flank of Kula lavas west of Kaupo was protected by the west wall of Kaupo Valley and by the south wall of the summit depression.

Sufficient exposures in valley walls and in kipukas in the Hana lavas show that Kula lavas underlie Hana lavas at shallow depths everywhere else in the mountain except on the floors of Keanae, Waihoi, Kipahulu, and Kaupo Valleys, where the Hana lavas are very deep. The Kula lavas probably were entirely removed by erosion in these valleys before Hana time so that the Hana lavas lie either on alluvium or on Honomanu basalts.

CHARACTER AND STRUCTURE.—The Kula lavas are chiefly aphanitic dense gray to steel-blue andesitic-type aa flows with thick clinker beds. They are generally thicker and narrower than the Honomanu basalts. These characteristics produced rough terranes and caused lenticular bedding, which is less pronounced in the Honomanu basalts. Lenticular bedding resulted also from the Kula lavas filling numerous valleys and swales. Thin-bedded aa and pahoehoe are found near the summit, but pahoehoe is scarce farther seaward, except in the transition zone at the bottom of the series. The flows average about 20 feet in thickness near the summit and 50 feet near the periphery, but flows 200 feet thick are not rare.

The dip of the beds ranges from 3° on the Isthmus to 35° on the south rim of the summit depression. Their usual dip is about 10°. Typical block-type andesitic aa was not found, as all the clinker is spiny. Feldspar porphyries are common, but olivine porphyries are scarce except near the top of the section, where augite porphyries and olivine-augite porphyries are found in abundance. (See Part 3.)

The great number of erosional unconformities and interstratified soil beds shows that the upper Kula lavas accumulated in the waning phase of a volcano when the time interval between flows became progressively longer. As these lavas gradually changed to more silicious composition, they became progressively more viscous and their flows shorter. Thus, they accumulated chiefly about the summit, where they attained a thickness of 2,000 feet or more. The summit was steepened also by the addition of the bulky cinder cones that were built simultaneously with the flows. Thus the mountain profile changed from the flatter slopes of a cone of primitive basalts to the steeper slopes of an andesitic cone like Mauna Kea (fig. 2).

The most accessible thick exposures of Kula lavas are along the Kaupo-Kipahulu road. There the massive jointed mostly nonporphyritic lenses of dense aa lying between partly rotted clinker beds and separated by thin red soils, form cliffs 400 feet high.

A thick section of Kula volcanics can be seen along both the old and new Halemauu trails leading into the northwest side of the summit depression near the head of Keanae Valley (pl. 16).

Section along the new Halemauu trail
(Altitudes by barometer)

	Thickness (feet)	Altitude of top of bed (feet)
Eroded platy dense aphanitic aa	4	7,575
Ash soil and hillwash debris	1	7,571
Platy aphanitic aa	120	7,570
Lens of gravel and water-worn boulders up to 18 inches across	3	7,450
Feldspar aa with rotted surface	3	7,447
Thin-bedded aphanitic aa	144	7,444
Vitric tuff	2	7,300
Aa flows	48	7,298
Olivine porphyry filling a swale	25	7,250
Hillwash	5	7,225
Aa flows	100	7,220
Weathered ash	1	7,120
Gravelly hillwash	1	7,119
Weathered ash and clinker	3	7,118
Lava flows, platy at bottom and nonporphyritic	65	7,115
Talus breccia striking N. 40° E. and dipping 28° NW.	25	7,050
Porphyritic aa with tiny feldspars striking N. 20° W. and dipping 28° NE.	75	7,025
Ashy soil and hillwash (thickens to 6 feet nearby)	2	6,950

Section along the new Halemauu trail—*Continued*

	Thickness (feet)	Altitude of top of bed (feet)
Stream-laid deposit of angular, subangular, and well-rounded boulders with layers of silt and brown vitric ash. Bed strikes N. 35° W. and dips 22° NE. and fills a valley, as shown by the conglomerate in vertical contact with a 10-foot joint face of dense aa. It is 100 feet thick where it grades into a talus breccia in the buried east wall of the ancient gulch	23	6,973
Aa flows, upper one containing small scattered feldspar phenocrysts	70	6,950
Coarse vitric tuff and cinders	2	6,880
Lava flow	3	6,878
Coarse vitric tuff	10	6,875
Breccia with silt matrix	10	6,865
Vitric tuff cut by 6-foot vesicular dike striking N. 10° W. and dipping 75° W.	2	6,855
Breccia like above	2	6,853
Lava flows mostly nonporphyritic	176	6,851
Vitric tuff	2	6,675
Lava flow	13	6,673
Vitric tuff	2	6,660
Vesicular and irregular dike full of aa clinker, 1 foot wide at an altitude of 6,650 feet		
Lava flows	108	6,658
Bottom of cliff	...	6,550
	1,050	

The altitudes and thicknesses were determined by barometer only, and the readings were made on a zigzag trail. Resulting errors are not important as the section was made to show the number and thickness of the beds of tuff, hillwash breccia, and conglomerate, rather than the details of the lava flows. The section gives a general picture of the stratigraphy of the Kula volcanic series in the northeast edge of the north rift zone.

The character of the Kula lavas at an altitude of 4,300 feet at the intake of the Kula pipe line and at an altitude of 193 feet 2 miles south of Spreckelsville is shown by the following logs:

Log of test hole 101

(Altitude 4,300 feet, as determined from topographic map. At intake of Kula pipe line on south bank of Waikamoi Stream. Log determined by G. A. Macdonald from core. Drilled by J. M. Heizer, Aug. 1940.)

	Depth (feet)	Altitude of top of bed (feet)
Soil and partly rotted clinker	0–11	4300
Aa containing small phenocrysts of olivine	11–30	4289
Aa containing a few small phenocrysts of feldspar, probably several flows	30–281	4270
Pahoehoe containing scattered small phenocrysts of feldspar	281–312	4019
Aa containing scattered small phenocrysts of feldspar	312–407	3988
Aa containing a few small phenocrysts of augite and olivine	407–436	3893
Pahoehoe containing very few small phenocrysts of feldspar	436–453	3864
Aa containing very few small phenocrysts of feldspar	453–522	3847
Aa containing no phenocrysts	522–554	3778
Aa containing a few small phenocrysts of feldspar	554–565	3746
Pahoehoe containing no phenocrysts	565–575	3735
Aa containing a few small phenocrysts of feldspar	575–650	3725

Log of test hole 111

(Altitude of ground 193 ft. Owner H. C. & S. Co. Log determined by H. T. Stearns from rock cuttings in glass tube furnished by Robert E. Hughes, Sept. 1, 1936. Vesicularity determined largely by the size of the cuttings.)

	Depth (feet)	Altitude of top of bed (feet)
Soil	0–10	193
Rock, almost completely decomposed	10–16	183
Extremely hard aphanitic gray rock	16–41	177
Base of lava flow, distinct break	41	152
Red soil and rotted rock	41–46	152
Partly rotted rock	46–48	147
Very vesicular rock, containing olivine and feldspar phenocrysts	48–72	145
Moderately vesicular rock, many olivine phenocrysts	72–82	121
Base of lava flow	82	111
Brown dense rock containing olivine and feldspar phenocrysts	82–87	111
Similar rock but vesicular and lighter brown	87–91	106
Dense rock with same phenocrysts and with 3 vesicular streaks	91–104	102
Base of lava flow	104	89
Reddish-brown, fairly dense rock with vesicular streaks and olivine and feldspar phenocrysts	104–134	89
Very dense rock	134–143	59
Slightly vesicular rock with 3 layers each 1 foot thick of very vesicular rock at 147, 156, and 158 feet	143–159	50
Dense rock with slightly vesicular layer between 162 and 163 feet and with more olivine phenocrysts between 163 and 167 feet	159–167	33
Base of lava flow	167	25
Dense gray rock with numerous feldspar and scarce olivine phenocrysts	167–172	25
Vesicular dark-gray rock similar to above	172–179	20
Slightly vesicular gray rock similar to above	179–183	13
Possibly base of lava flow	183	9
Fairly dense brownish rock	183–189	9
Extremely dense gray rock. Drilled 16 inches a day only, sharpened bit 4 times a day	189–195	4
Fairly dense gray rock. Specimen recovered in bailer contained small feldspar but no olivine phenocrysts	195–204	–2
Base of flow	204	–11
Very vesicular reddish rock containing olivines 2 to 4 mm across; struck considerable water	204	–11

The number of erosional unconformities within the upper part of the Kula lavas is legion. Some are small and play no part in the movement of water or in deciphering the history of the mountain. Others are large and represent time intervals of thousands of years. Large canyons cut in Kula time and subsequently filled with late Kula flows lie in the area west of Kaupo Valley. Most of the coast of this area is made up of great fans of lava, commonly composed of several flows with thin intercalated soils. The flows were spewed from deep canyons that formerly existed above an altitude of 2,000 feet (pl. 15A). Some of the canyons headed to a peak that stood 3,000 feet or more above the adjacent rim of the present summit depression. The low saddle in the south rim just east of Kumuiliahi

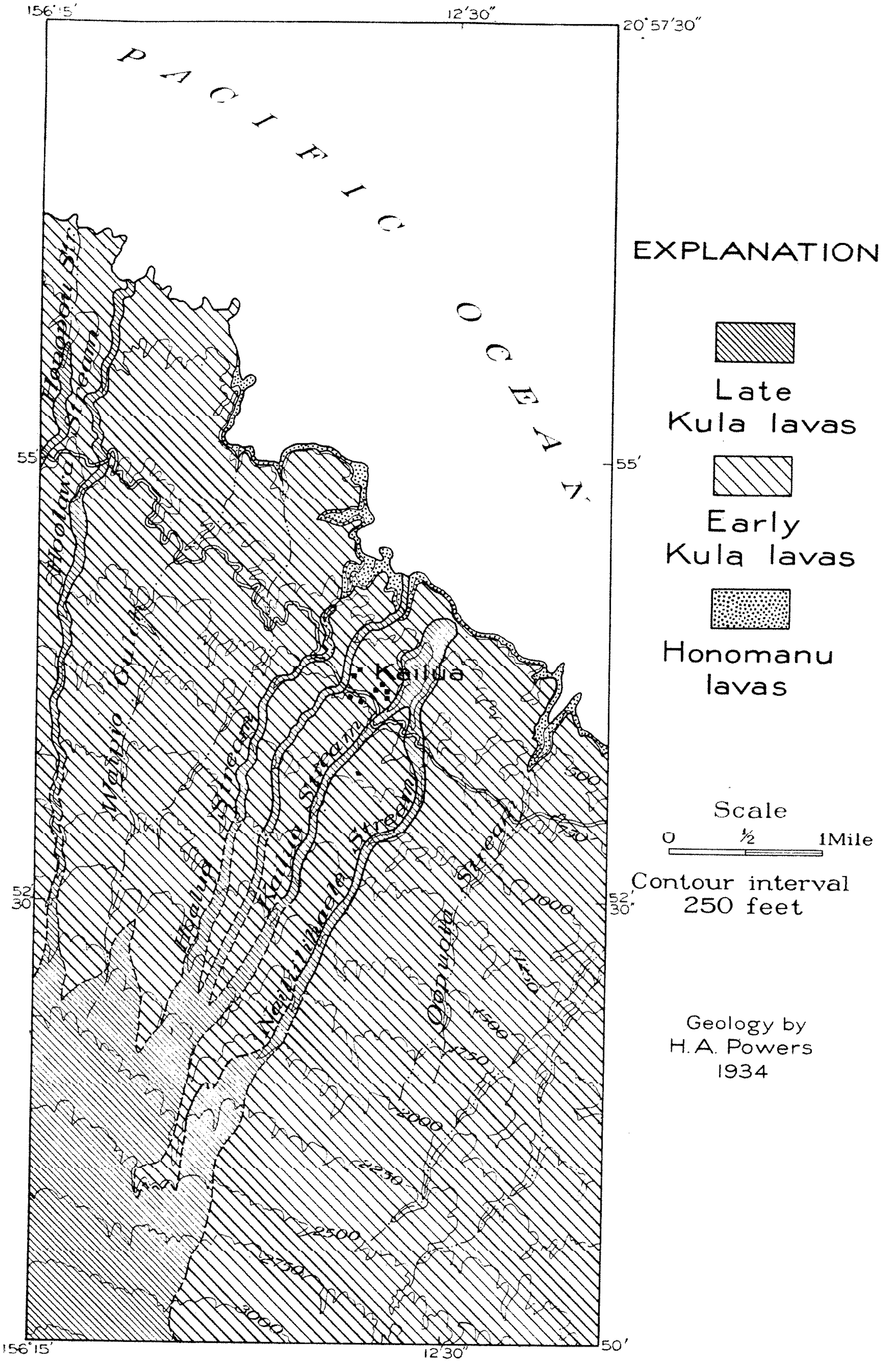


FIGURE 11. GEOLOGIC SKETCH MAP OF LATE KULA LAVAS FILLING VALLEYS EAST OF HAIKU, EAST MAUI.

Peak is the upper part of a canyon cut in Kula lavas and subsequently partly filled with late Kula lavas. The topography on plate 1 is so generalized in this area that the contours do not show the lava-plastered walls of the canyon, although the walls have considerable relief. Steep angular erosional unconformities are exposed in all canyons in this area. The latest of these Kula lavas plasters Waiopai Gulch (pl. 19B). It came from Puu Aniani, a cone at the head of Wailaulau Fork shown on plate 1 at bench mark 8175.

Ahulili Cone at the head of Manawainui Canyon is the source of a late Kula flow that fills a former gulch. It also overflowed the adjacent flat slopes and covered much land on which a deep soil existed. Likewise, the cone north of Ahulili gave vent to a late Kula flow. The Kula remnant between Kipahulu and Waihoi Valleys is likewise an area where late Kula flows filled gullies. These gullies collect ground water and springs emerge where the lava fills are truncated by subsequent erosion.

The greatest number of erosional unconformities is found in the eastern part of the mountain where the rainfall is heaviest and where stream erosion is consequently rapid. The gulches are shallow in the extensive area of Kula lavas on the northwest slope, but even there a few lenses of gravel are found in road cuts and gulch banks. The latest Kula lavas there fill gulches east of Haiku, as shown in figure 11. The ancestral Waikamoi Gulch was filled with lavas that apparently came from above the rim of the summit depression. Kula lavas lying in gullies filled with hillwash and gravel are well exposed in cuts along the road to the summit.

A steep lava-veneered cliff runs from Puu Olii at the entrance to Haleakala National Park for 3 miles southwestward between altitudes of 6,000 and 7,000 feet. It is not straight like a fault cliff, but is scalloped as though originally formed by the coalescence of several amphitheater-headed canyons. (See section AA′, pl. 1.) Perhaps it was formed in some other way, but in view of the great amount of erosion elsewhere on the mountain, it would not be surprising to find evidence of erosion on this slope. Although it lies in a region of comparatively low rainfall, the stream gradients are very steep, and even now occasional floods, as the one on February 2, 1936, remove great quantities of rock. Thus, great canyons surely would have been cut if the surface had not been repeatedly inundated with flows.

Cones and tuff deposits.—Most of the Kula cones are shown on plate 1. Some are exposed in the face of steep cliffs where they have insufficient horizontal dimensions to be plotted on plate 1. This is

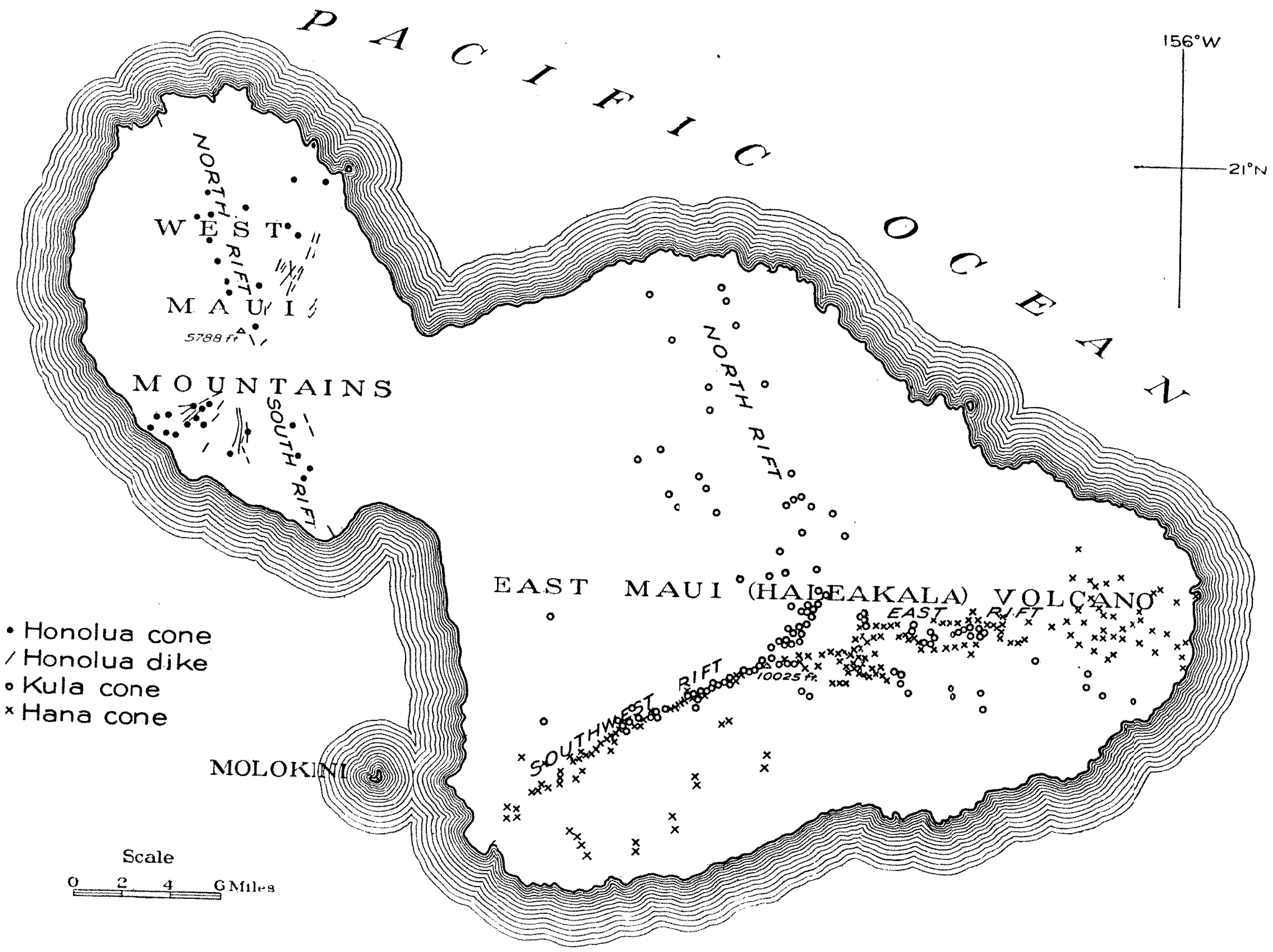


FIGURE 12. MAP OF MAUI SHOWING VENTS OF THE HANA, KULA, AND HONOLUA VOLCANIC SERIES.

particularly so in the walls of the summit depression, especially in the cliff between the old rest house and Halemauu trail, where more than a dozen are omitted. Kula cones range from a ridge of spatter about 10 feet high to cones several hundred feet high. All are composed of the usual gamut of firefountain deposits and with few exceptions, such as Puu o Kali below Kula and Puu Ahulili above Manawainui Stream, lie on three rift zones that fan out from a width of 2 miles near the summit to 5 or 6 miles near the shore (fig. 12). Most of the cones are consolidated in comparison to the Hana cones, and in wet areas their surfaces are weathered to bright red lateritic soils a few inches to 10 feet or more in depth.

Vitric tuff beds are common between Kula flows on almost any part of the mountain, but they are thicker and more numerous near the rift zones. During the building of each cone, pumice and ash fell about it. Next to the rift zones, especially on their leeward sides, such deposits accumulated to depths of 1 to 40 feet, depending on how long a time elapsed before a particular area was overflowed with lava. Some cones, apparently because strong winds were blowing at the time, or because of intense gas effervescence, spread vitric tuffs far and wide (pl. 8B). Puu Pahu on the road to the summit is an example. Tuffs cover a wide sector to the leeward of it (pl. 1). Some layers in these deposits were finer grained than others and were weathered to a brown soil by percolating water, while the coarser permeable layers retained their form but were palagonitized to a dark-yellow band in which the original particles of pumice are recognizable. Deposits of this type are well exposed in the road cuts near Puu Pahu. Small patches and thin mantles of tuff and ash, weathered beyond recognition to soil, were not mapped on plate 1.

Many of the broad interstream flats underlain with early Kula lavas between altitudes of 3,000 and 6,000 feet on the south slope between Kaupo Valley and the Hana lavas are covered with lateritic soils derived partly from ash. It is probable that almost all lateritic soils on Kula lavas contain some decomposed vitric ash, except possibly those on the Isthmus.

Only the more conspicuous or thicker interstratified vitric tuff beds in canyon walls are shown on plate 1 either because of the difficulty of tracing them through the jungle growth covering the walls, or because the scale of the map is too small to show them. A streak of soil generally derived in part from weathered vitric ash lies between nearly all Kula flows. Combined with extensive layers of fairly impermeable lava in the Kula flows in areas of high rainfall these ashy soil beds cause many perched bodies of water, some of which are broad and thick (section CD, pl. 12).

Vitric tuff beds, although very numerous in the Kula volcanic series, do not appear to make up more than 1 or 2 percent of the bulk of the formation. No beds of lithic tuff are known in the Kula volcanic series, indicating either that catastrophic explosions did not occur or that their deposits were deeply buried.

A few of the Kula lavas squeezed up through fissures unaccompanied by firefountains and built bulbous domes 100 feet or more high. Several are exposed in cross section in the walls of the summit depression, especially near the Rest House. Some of these may be cross sections of massive flows just downhill from their cinder cones, the cinders having been cut away. However, some show the feeding dike and the usual fan jointing in the mass above. They are not crater fills, as no remnants of cinder cones are present. This type of eruption is common elsewhere among rocks of similar composition. They are not common on East Maui, however, or more would have been found. Puu Nene, a low hill near Spreckelsville, is probably such a vent.

DIKES AND PLUGS.—About 70 dikes of Kula age are exposed in the west wall of Keanae Valley where it cuts across the north rift zone. About 60 dikes of Kula age are exposed in the east wall of Kaupo Valley where it cuts the east rift zone. A number of dikes project through the mask of later cinders where the southwest rift is cut, but they are mostly hidden. Several dikes were found in the head of Manawainui Canyon and many in the head walls of Waihoi and Kipahulu Valleys wherever Hana volcanics do not conceal them.

Except at vents the dikes range from a few inches to 10 feet in width and average 3 feet. They indicate that the Kula lavas erupted through fissures like the earlier Honomanu basalts. A few dikes reach 20 feet in width within a cone or just under it. They have the same range in petrologic types as the flows. An exceptional dike, however, was found near the cave at the rear of Holua cabin, Haleakala National Park. It is an oligoclase andesite containing feldspar, diopsidic augite, and hornblende in a trachytic groundmass. (See Part 3.)

The Kula dike system determines the three main rift zones or cone chains (fig. 12). An excellent exposure of the dike complex under the east rift zone is in the floor of the summit depression (pl. 10B). Here 20 dikes ranging from 1 to 20 feet in width are exposed.

Great masses of dense intrusive rock, herein called plugs, form the spurs near the west end of the summit depression (pl. 1). Some are huge dike-like swellings, others sill-like bodies cutting vertical intrusive masses, the whole obviously produced by repeated intrusion. Some are porphyritic, some coarse grained, but most of them are aphanitic and closely jointed. Their great concentration in this area indicates proximity to the former summit of Haleakala, which was apparently about 1¼ miles east of the present summit. The great preponderance of intrusive rock is not surprising, as the three rift zones intersected there. It is surmised that similar bodies of intrusive rocks underlie the Hana cones on the floor of the depression at the point of intersection, as shown in section AA′, plate 1.

Water at high levels must be confined under the east and north rift zones by Kula dikes, but the zones have not yet been explored by tunnels or test holes to determine the form and altitude of the saturated bodies (section CD, pl. 12). Test hole 101, which is 650 feet deep at an altitude of 4,300 feet in Waikamoi Gulch, failed to reach confined water in the north rift, in spite of more than 225 inches of rainfall a year; hence, the confined water must be at an altitude lower than 3,650 feet at this point.

INTERSTRATIFIED CONGLOMERATES.—Conglomerates make up a minute part of the Kula formation, but are important because they indicate buried stream channels, many of which carry water. Conglomerates always lie in the bottoms of lava-filled valleys and are exhumed only by fortuitous circumstances. They may be cut by streams, road excavations, or tunnels, or truncated by the sea. Few are known in the western part of the mountain where deep incisions are scarce.

Conglomerates have been found at altitudes of 80 feet in the west bank of Maliko Gulch; at 350 feet on the east side of Kuiaha Gulch at Pauwela; at 200 feet in Honopou Gulch; in a few places in the Nahiku area (Part 2); in the sea cliff on the east side of Wailua Gulch; at 2,180 feet in Hahalawe Valley; at 2,140 feet in the main branch of Waimoku Stream where several inches of gray pottery clay overlain by 6 inches of coarse ash lies at the contact; at 4,250 feet, 1 mile west of Puu Ahulili and about 500 feet east of Helani Stream; at 2,000 feet in the west bank of Kahalulu Gulch and at two different horizons near spring 45; at 350 feet and at tunnel 57 in Pahihi Gulch; and at the mouth of Manawainui Gulch west of Kaupo (pl. 15B). About a foot of carbonaceous clay, apparently peat baked by the overlying flow, crops out 30 feet below the top of the trail on the east side of Pukai Gulch, at an altitude of 1,310 feet.

The following section of Kula lavas including a layer of alluvium is exposed in the sea cliff ¼ mile east of Maliko Gulch:

Section of Kula lavas near Maliko Gulch

	Thickness (feet)	Altitude at top of bed (feet)
Light-brown soil	15	145
Platy gray weathered aa	55	130
Dark-red soil bed	2	75
Platy gray weathered aa	30	73
Unconformity and spring horizon	..	...
Red soil and alluvium, baked brilliant red at top	7	43
Platy gray basalt	36	36
	145	

Interstratified conglomerates and hillwash breccia were found on the west side of the Koolau Gap along the Halemauu trail (p. 77) and in the east wall, ⅞ mile northwest of Hanakauhi Peak at an altitude of 7,000 feet in a spur projecting into Keanae Valley. There, several layers of breccia containing water-worn boulders and reaching 25 feet in thickness are exposed. Glacial erratics were not found. Striae on a weathered block of pahoehoe proved to be grooves formed by the block sliding on another block while still viscous.[53] The sediments are typical of those laid down in gullies and on flats at the foot of swales on the western slope below the present summit, or on the upper slopes of Mauna Kea, Hawaii.

The buried stream-laid deposits in the walls of the summit depression are significant. They indicate that a ridge or peak rather than a large deep caldera lay to the south at the time the Kula lavas were accumulating. The degree of rounding of the gravels indicates that they were not transported far, which is consistent with the fact that some of the deposits lie only one mile from the former crest.

WATER-BEARING PROPERTIES.—The Kula lavas as a whole are far less permeable than the underlying Honomanu basalts or the overlying Hana lavas, but they are very permeable compared with most other rocks in the earth. The younger flows and those in the drier areas where decomposition is slow, are so permeable that no permanent streams exist on them. This applies to the broad area of Kula lavas on the west slope and to those west of Kaupo Valley. Perennial streams and small streams that flow except in severe droughts are found in all the remaining areas of the Kula rocks shown on plate 1. They lie in regions of heavy rainfall and soils cover even the youngest of the Kula lavas. Four conditions make the Kula lavas less permeable than either the Honomanu or the Hana lavas:

(1) Chemical composition. The slightly more silicious composition of Kula lavas makes them more massive, and even where thin-

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[53] Stearns, H. T., Bryan, L. L., and Crandall, Lynn, Geology and water resources of the Mud Lake Region, Idaho: U. S. Geol. Survey Water-Supply Paper 818, pl. 6, 1939.

bedded, they contain more dense continuous sheets with smaller fractures than primitive basalts.

(2) Weathering. The fact that the volcano was in a waning phase during Kula time with the interval between eruptions growing progressively longer, gave time for soils of various thicknesses to form. The clinker beds are commonly almost decomposed in wet areas, so that only lumps of hard gray lava resembling pebbles and cobbles lie scattered through a matrix of red dirt. The matrix is so soft that it may be cut like cheese. The interstices of some clinker beds are filled with a pale-yellow soapy clay mineral, obviously deposited by ground water. Some beds before burial by subsequent flows were already weathered, but others have been decomposed by percolating water. The permeability of the dense rock is also greatly reduced due to decomposition along its joints and crevices.

(3) Ash. The violent firefountaining accompanying the more siliceous lavas caused widespread ash deposits which perch water. The fact that the Kula lavas overflowed less land than the Honomanu lavas during each eruption allowed more time for ash deposits to accumulate on the interflow areas. Thus, thin beds of tuff are found even at great distances from the rifts.

(4) Structure. The Kula lavas have dips of 15° to 25° seaward in most areas of heavy rainfall. Water moves faster down dip on the impervious beds in such steep structures than in flatter flows and consequently has less time to percolate vertically.

The Kula volcanic series must be visualized as an assemblage of interstratified soils, vitric tuff beds, weathered clinker zones, and wide bands of dense rock, to understand its influence on the movement of ground water. Most of the individual lava beds are permeable and unable to perch water. But when the whole formation is considered as a unit, it contains enough more or less impermeable layers, even though discontinuous, to retard greatly the downward percolation of water in areas where 100 to 400 inches of rain falls annually.

Thus, perennial streams, unusual features outside the dike complexes of the Hawaiian Islands, are found in the Kula rocks. The route water travels through them may be traced as follows: Rain percolates to a dense sheet of lava, moves along it for a few feet or a few hundred feet to a place where the rock is jointed; here the water drops to the basal clinker bed and through it, if the bed is not too decomposed to perch water (fig. 13). Then it may meet a soil bed a few inches thick commonly baked to a fairly impervious brick by the overlying lava. The water moves laterally along the top of the

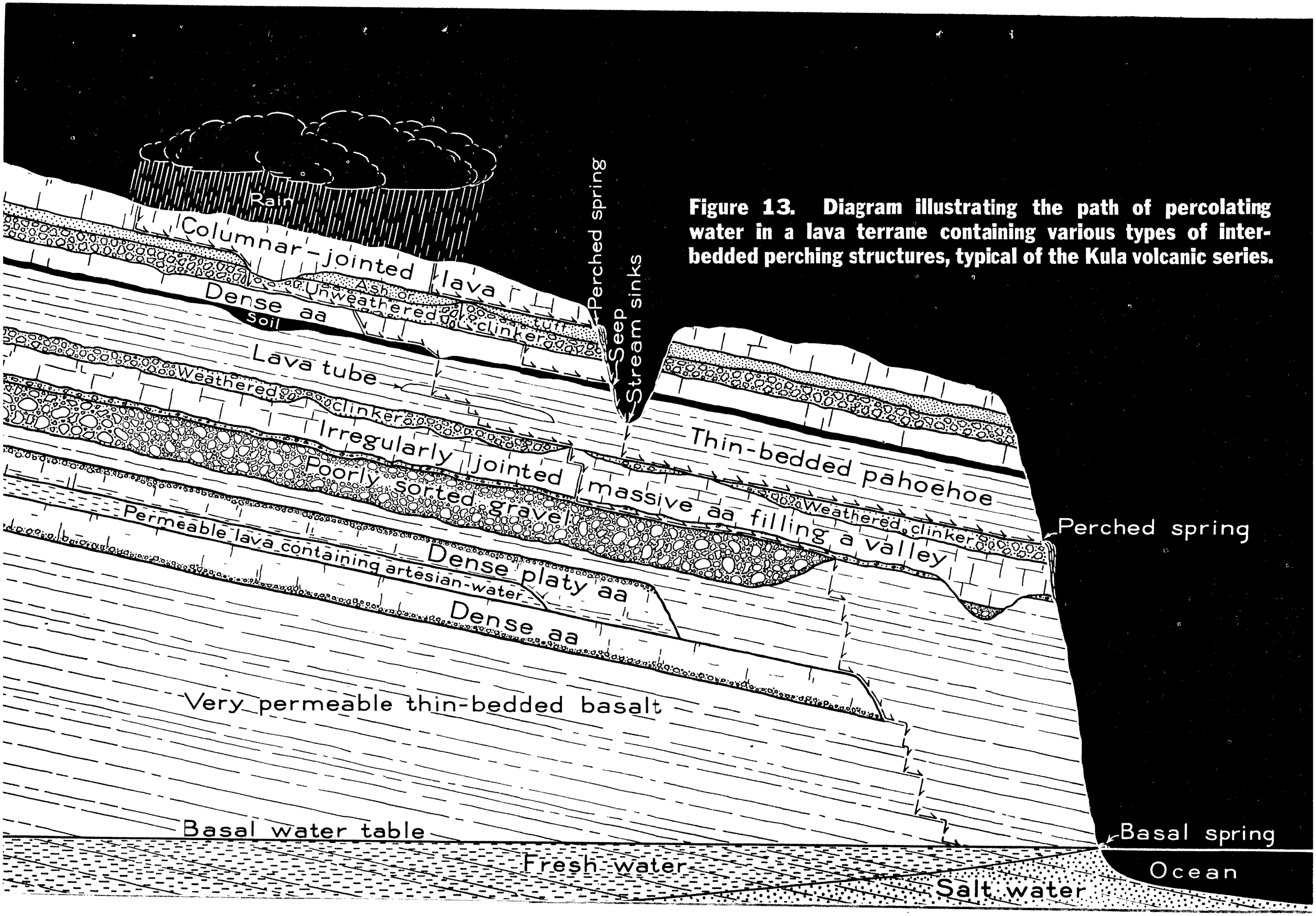

Figure 13. Diagram illustrating the path of percolating water in a lava terrane containing various types of interbedded perching structures, typical of the Kula volcanic series.

soil toward the lowest part of the buried surface, perhaps finding an ancient lava-filled swale where it joins other streamlets. The water continues seaward down the steeply dipping trough until it encounters a hole in the soil underlain with permeable rock. It drops nearly vertically through crevices to an underlying intercalated bed of ash that is intermingled with the underlying clinker and seals its interstices. Vertical progress is impeded, and the water moves down the dip of the ash bed, collecting small tributaries en route. Such interruptions to the downward course of the water may recur many times as the Kula series is hundreds of feet thick. Finally the water may emerge as a spring at the foot of a waterfall, where a surface stream has cut into one of the perching soil, ash, or decomposed clinker beds.

While ascending a canyon cut in the Kula formation one breasts a swift stream flowing for long stretches in smooth gracefully curved grooves that swing first to one bank and then to the other. The stream has cut them along wavy structure lines in hard rock. Such stretches end in gravel-bordered deep shadowed plunge pools at the foot of vertical waterfalls, usually ranging from 10 to 60 feet in height. Weathered or partly weathered ochre-colored clinker beds underlain by a red soil streak are exposed either in the clear water of the pool or a little above its edge. Usually a little more water is flowing from the pool than comes over the fall, or water may be found trickling from the rock just above the soil bed, half hidden by long greenish-brown slimy strings of algae. The visible trickles may total as much as 10 gallons a minute. At the side of some plunge pools, hidden amid the lush tropical water-loving vines and plants in a small reentrant, one may hear the gurgle of water. A search may uncover springs yielding 50 gallons a minute or more, which gush from loose clinker or wide joint cracks in dense rock. By uprooting the plants clinging to the wall, the ubiquitous red ash or soil bed is found. Or if one is lucky, a thin interstratified gravel deposit is found, trending obliquely to the stream. Saturated but commonly yielding little water, the gravel is evidence of an older lava-filled gully that the present canyon has crosscut. Finally after fatiguing hours of clambering over slippery stones through a vast mountain gorge, the silence of which is broken only by the gurgle and splash of water, the drip of rain from overhanging trees, the occasional song of native birds and unseen crickets, one reaches the head of the stream, which by now has dwindled to a streamlet, but still occupies a mighty gorge in which great torrents rush headlong to the sea after frequent heavy rains.

GREAT EROSIONAL UNCONFORMITY

The time between eruptions lengthened and the volume of the flows probably diminished throughout Kula time, as shown by the increasing number of lava-filled valleys in the upper part of the formation. With the decadence large segments of the mountain were sheltered from flows most of the time. Kipuka areas resulted when certain parts of a rift zone opened repeatedly, while others remained sealed, or when the rift zones cracked open on only one side of their crests. Other kipukas were formed where flows were blocked or diverted by rows of cones, long cracks bordered by ledges, fault escarpments, and unknown topographic barriers.

Several valleys with large drainage areas and steep gradients were cut deeply into the rainy eastern half of the mountain. They are Keanae, Waihoi, Kipahulu, Kaupo, and Manawainui Valleys. Apparently two other large ones were cut also, Kuhiwa Valley above Nahiku, and Hana Valley above Hana, but they were subsequently nearly obliterated by lavas (pls. 24 to 26). The first five valleys named were cut through the thick cover of strong Kula lavas and into the weaker Honomanu basalts which yielded rapidly to their powerful streams. Keanae, Waihoi, Kipahulu, and Kaupo Valleys headed into the rainy and loosely knit east rift zone, which was underlain with dike swarms confining water at high levels. When the valley tapped the confined water, perennial springs supplied the streams. Under such favorable conditions it was inevitable that the master streams should develop deep amphitheater-headed canyons. The fact that they all eroded beyond their topographic divides almost to the far side of the dike complexes at their heads, indicates that their streams were unarrested by lava flows of any great volume or frequency during the erosional period (pl. 24C). It is possible, however, that Kuhiwa and Hana Valleys had their history interrupted by flows in late Kula time. Thus, they may never have reached the great size of their neighbors, although the volume of Hana lavas that entered them has been large and probably adequate to have filled huge canyons (pl. 17).

The Hana lavas successively displaced laterally the streams on the floors of the great canyons, causing the side walls to recede by undercutting (pls. 13 and 14), thus widening the Kula valleys in Hana time. If the thickness of Hana lavas in the canyons is subtracted, the ancient valley floors must have been 2,000 to 4,000 feet below the rims at their heads, or comparable in depth to the great valleys on the windward slopes of Kohala Mountain, Hawaii.

Opposite page: Plate 17. Vertical air view of amphitheater-headed Kuhiwa Valley, East Maui, eroded in Kula lavas and now plastered with Hana lavas. Trees make all-over rough texture. The grooves in the forest indicate aa channels, a few of which are enlarged by streams. Photo by U. S. Army Air Corps.

Manawainui Canyon, a former tributary of Kaupo Stream, is the only one of the ancient valleys that escaped filling, although its mouth has been obstructed by Hana flows (pl. 15A). This canyon is 2,650 feet deep at its head although it reached less than half way to the crest. It was obviously small in comparison to its huge neighbors, Kipahulu and Kaupo, because its drainage was limited to the sector-shaped segment between them.

The gutting of the mountain by the master streams determined the distribution of the lavas that came during the rekindling of Haleakala's volcanic hearth in Hana time. The new flows naturally followed the low ground of the valley floors even though erupted on the peaks nearby. Thus, we find Hana lavas in the eastern half of the mountain confined largely to the former great canyons (pl. 1). How the amphitheater heads of Kaupo and Keanae Valleys formed a depression on the summit long mistaken for a caldera is described on page 53.

Haleakala would now have at least 5 and perhaps 7 large permanent rivers had not the ancient valleys been deeply buried by thick mud flows, alluvial deposits, and hundreds of feet of highly permeable Hana lavas. Only long expensive tunnels can tap these buried rivers. Submergence of the island following the erosional epoch and the consequent sinking of the valley floors far below sea level has further complicated the problem of water recovery.

HANA VOLCANIC SERIES

Distribution.—The Hana volcanic series covers three distinct areas—the east end, the southwest end, and the summit depression (pl. 1). It is named after the village of Hana where typical lavas and cones of this series are exposed. It comprises all the volcanics laid down since the great valleys reached their maximum size. A few flows in uneroded areas, where their relation to the underlying lavas is not clear, are mapped as late Kula but may be early Hana in age.

As shown on plate 1, an extensive area of Hana lavas fans seaward from the summit over the southwest flank of the mountain. In the first 6¼ miles from the summit, two or three flows only spread westward from the southwest rift zone but many flowed down the south


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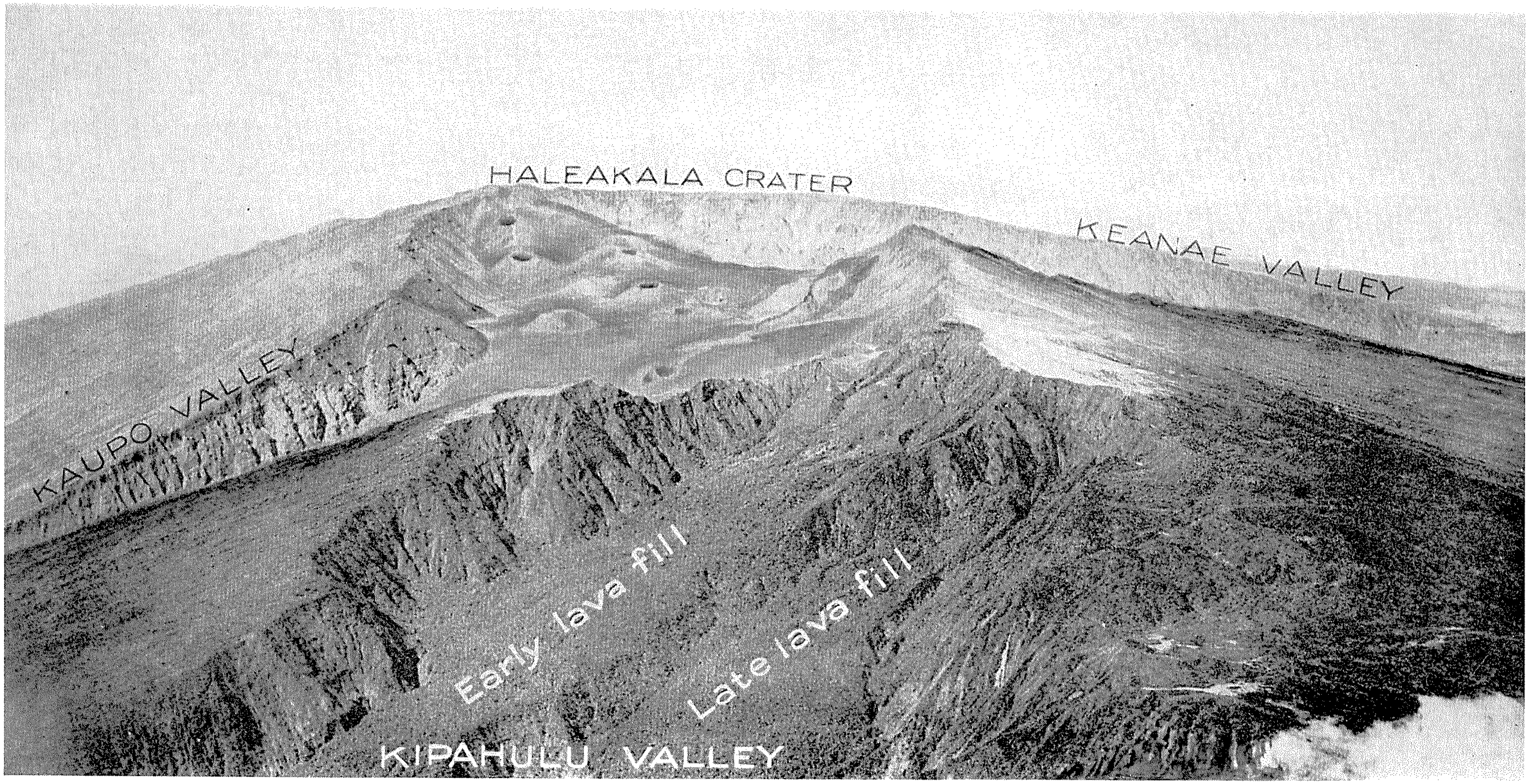

Plate 18. Air view looking westward across Kipahulu Valley showing the terrace of early Hana lavas bordered by valley fill of later Hana lavas. The summit depression of Haleakala is in the background. Photo by U. S. Army Air Corps.

slope from a point 1 mile from the summit. The absence of flows down the west slope in the first 3½ miles is significant. It offers one explanation of deeply eroded segments adjoining uneroded areas. Close examination of the upper part of the rift zone revealed that the fissuring during Hana time was entirely confined to a narrow zone about 100 feet wide, paralleling the chain of cones erupted during Kula time, but slightly south. Part of the cinders of the Hana cones near the summit spreads over the divide, but lavas from these cones were directed by the southward slope of the underlying terrane. This fortuitous circumstance saved many square miles of land covered with deep ash soils from inundation by black barren flows. The location of the center of population and agriculture in the Kula district is largely a result of these soils not being buried.

The rift zone crossing the heads of Keanae and Kaupo Valleys was the scene of many eruptions, as shown by the chain of Recent cones crossing the floor of the summit depression. Flows from these cones were confined between high valley walls and spread seaward as narrow bands, as shown in plate 1. They overtopped the east wall of Keanae Valley and one flow went seaward through Waiokamilo Valley. The lavas overtopped both walls of Kaupo Valley about 3 miles from the summit and spread out toward the sea in a fan less than 1 mile wide at the apex and 4½ miles wide at the coast.

The volume of Hana lavas from the east rift zone probably exceeds that from the southwest rift zone. The lavas flooring Kaupo, Kipahulu, and Waihoi Valleys issued from the east rift zone which extends from the head of Kaupo Valley eastward across the heads of the other two valleys. Some cones north of the east rift poured lavas to the north and east, covering many square miles of thick red Kula soils. Not even a kipuka of Kula lavas was found in the 14-mile stretch between Nahiku and Waihoi Valley, so complete is the veneer of Hana lavas. Most of the cones in the upper part of the east rift zone lie along three parallel fissures about ¼ mile apart.

KIPAHULU MEMBER OF THE HANA LAVAS.—A series of lava flows form a terrace 750 feet high on the west side of Kipahulu Valley (pl. 18). The lavas are chiefly fine-grained aa in dense beds, some of which are columnar jointed. They are exposed over an area 6 miles long by ½ to 1 mile wide and are named the Kipahulu member of the Hana volcanic series (pl. 1). They were poured from a line of cones not differentiated from other Hana cones at the head of the valley under Pohaku Palaha Peak. Vitric ash, 1 to 6 feet thick, covers the lavas for a distance of 1 mile from the cones. The total thickness of the lavas in the Kipahulu member may exceed 1,500 feet as they fill the deep ancestral Kipahulu Valley cut at the end of Kula time.

Subsequently, the main drainage of Kipahulu Valley followed the eastern edge of the lava fill and cut a canyon about half a mile wide and probably more than 1,500 feet deep. A smaller stream cut a narrow gorge 1,250 feet deep on the southwestern side. Renewed eruptions in late Hana time along the east rift of Haleakala Volcano poured flow after flow down the eastern canyon. One flow found its way to the sea through the western gorge. Oheo Stream, on the eastern side of Kipahulu Valley, has removed little of the late fill of Hana lavas (pl. 19A), but low rock terraces along its banks above Palikea indicate that the downcutting has been interrupted several times by lava flows. These later lavas have not been differentiated from each other on plate 1.

A late Hana lava flow found its way down Koukouai Stream. It is mapped on plate 1 for 1¾ miles from the coast, but is eroded away from that point to the head of the deep canyon 3 miles inland. The lava was found again in the north fork of Koukouai Stream at an altitude of 3,900 feet; hence it probably came from a vent in the western reentrant at the head of Kipahulu Valley. A traverse was made part way down Koukouai Stream from where it rises near the summit depression and although late Hana lavas were not found in the stream bed, a narrow late Hana flow may be concealed on the terrace of Kipahulu lavas under the ash cover.

A small patch of rock of uncertain age mapped with the Kipahulu lava is shown on the divide between Kipahulu and Kaupo Valleys on plate 1. The rock consists of two flows of porphyritic augite olivine basalt separated on the west side of the divide by 4 inches of hillwash. The lower flow is only 2 feet thick. The flows strike N. 25° W. and dip 33° NE. They overlie a lens 1 foot thick of partly weathered subangular talus that rests on the eroded dikes and Kula lavas of the divide. The porphyries fill two small valleys tributary to Kipahulu Canyon and disappear eastward under the thick fill of Kipahulu lava. On the surface of the porphyritic flows is a remnant of weathered breccia that is talus from a former valley wall. The porphyries must have been erupted from cones not far to the west, but considerably above the summit depression, probably on the Kaupo-Kipahulu divide when it was wider. Presumably the divide has been undercut and narrowed by streams flowing along the foot of the eastern wall of Kaupo Valley during its filling with Hana lavas. The porphyries are obviously early Hana in age, as shown by their position. They are tentatively assigned to the Kipahulu mem-

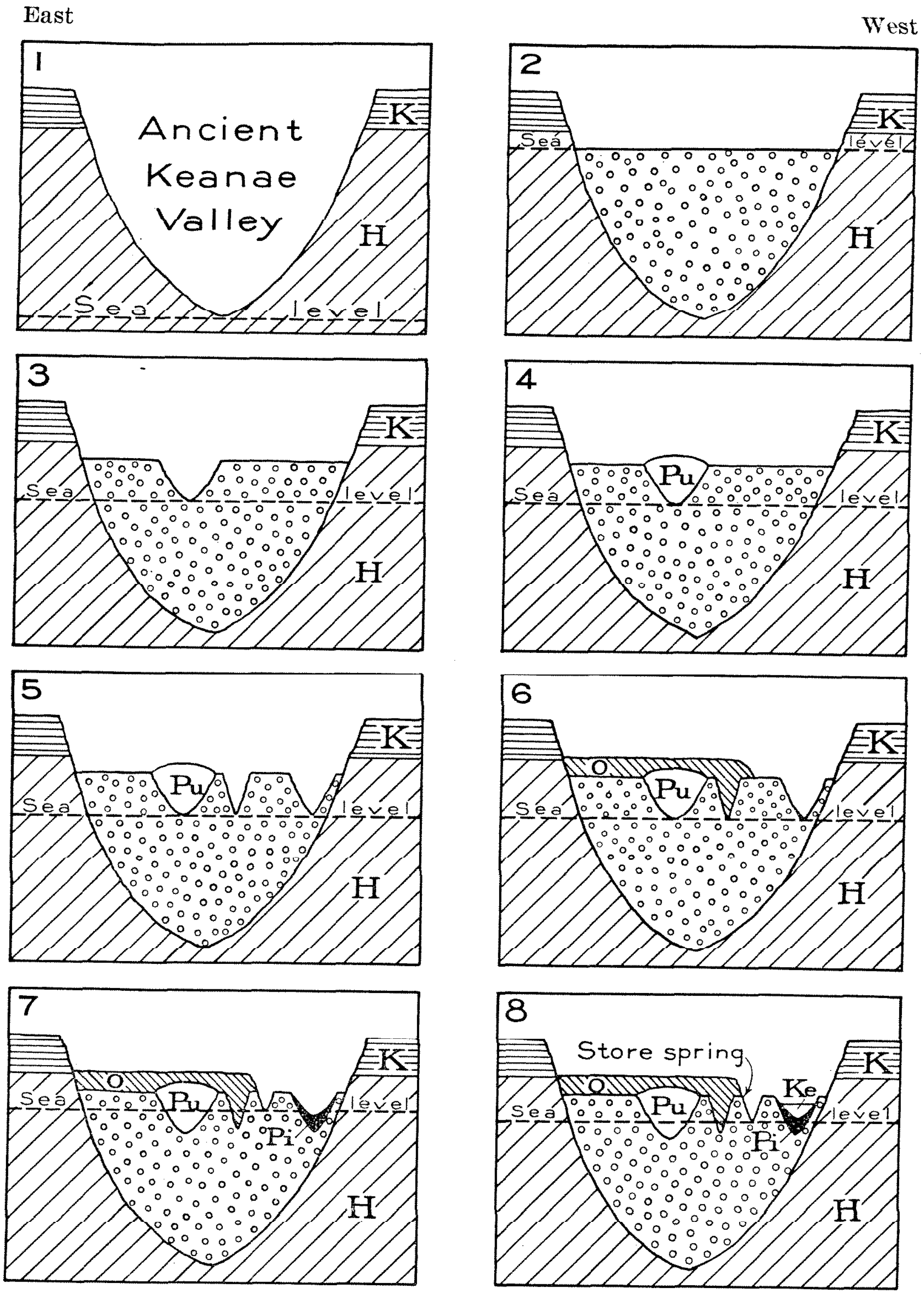

Figure 14. Stages in the development of lower Keanae Valley, East Maui. (1) Cutting of Keanae Valley through the Kula lavas (K) and into the Honomanu lavas (H), probably near the end of Kula time. (2) Alluviation of the lower part of Keanae Valley owing to deep submergence of the valley mouth. (3) Relative fall of sea level, and cutting of a small gulch into the older alluvium. (4) Filling of this gulch by the Pauwalu lava (Pu), the oldest Hana lava in the area. (5) Cutting of small gulches into the older alluvium west of the Pauwalu lava. (6) Burial by the Ohia lava (O) of the eastern part of Keanae Valley, and the more easterly of the post-Pauwalu gulches. (7) Further erosion, and partial filling by the Piinaau lava (Pi) of the more westerly gulch. (8) Eruption of Keanae lava (Ke), partly burying the Piinaau lava.

ber, even though no porphyries were found in the terrace composed of this member. They probably lie in the lower unexposed part.

MEMBERS OF THE HANA LAVAS IN KEANAE VALLEY.[54]—The distribution of the Hana lavas in Keanae Valley is shown on insert A, plate 1. The history of the lower part of Keanae Valley is summarized in figure 14. The Hana lavas were subdivided, for the purpose of detailed mapping, into several members, as shown in the accompanying stratigraphic table.

The Pauwalu basalt is the oldest Hana lava in the valley. It is a dense, fine-grained olivine aa basalt, jointed in columns 6 inches to 2 feet in diameter, with a layer of clinker at the top. It is named after Pauwalu Point, where it is well exposed in the sea cliff, filling a valley cut into older alluvium. The lava-filled valley is about 2,000 feet wide at the coast and extends to an unknown depth below sea level. It may have been cut during the Waipio minus 60±-foot stand of the sea.[54a] In the sea cliff the exposed thickness of the Pauwalu lava is 130 feet, and at Piinaau Falls about 175 feet of Pauwalu lava is exposed, separated into two distinct layers by a bed of clinker.

The Wailuanui basalt is a narrow lava flow which descended the west fork of Wailuanui Valley. It is shown as undifferentiated Hana lava on plate 1, but is not shown on insert A. The rock is a dark gray olivine pahoehoe basalt containing a few olivine phenocrysts reaching 1 mm. across. The platy feldspars in the groundmass are arranged in parallel position by flowage. At the level of the Koolau Ditch the lava rests on gravel. From a short distance below the ditch to the sea it has been largely removed by erosion, but a small remnant of it forms a terrace about 1,000 feet south-southeast of Wailua Bay. It is older than the Ohia lava, but its time relationship to the Pauwalu lava is not known.

The Ohia basalt is named from Ohia Spring, which issues from it (pl. 20B). The lava is a medium- to dark-gray olivine basalt containing rare phenocrysts of feldspar, some of them as much as 8 mm. long, and a few phenocrysts of olivine mostly less than 1 mm. long. Below an altitude of 600 feet the Ohia lava was confined to the eastern side of Keanae Valley, and filled a small gulch previously cut into the older alluvium along the west edge of the Pauwalu lava (stage 6, fig. 14). Near the highway it flowed through a gap in the spur between Keanae and Wailuanui Valleys and spread across a fan of older alluvium to the mouth of Wailuanui Stream. It is exposed overlying alluvium in the sea cliff along the west side of

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[54] This section is prepared partly from work by H. A. Powers.

[54a] Stearns, H. T., Ancient shore lines on the island of Lanai, Hawaii: Geol. Soc. America Bull., vol. 49, p. 625, 1938.

Stratigraphic section of the Keanae area, Maui[a]

Geologic age	Formation		Symbol on insert A, plate 1	Description	Water-bearing properties
Middle (?) and late Pleistocene and Recent	Recent alluvium		Ra	Fans and terraces, many still forming.	Permeable but covers such small areas that it is unimportant.
	Hana volcanic series	Keanae basalt	Ke	Basalt with phenocrysts of olivine, augite, and rarely feldspar.	Highly permeable but most of recharge on this basalt apparently descends to the underlying lavas. Yields water in tunnel 33.
		Local			
		Waiokamilo basalt	Wo	Nonporphyritic basalt. Time relations to other lavas not definitely known.	Highly permeable but has a very small intake area.
		Local			
		Piinaau basalt	Pi	Nonporphyritic basalt.	Permeable but apparently too narrow and dissected to carry appreciable water.
		Local			
		Ohia basalt	O	Basalt with scattered small olivine phenocrysts and rare feldspar phenocrysts.	Highly permeable. Ohia Spring issues from this lava.
		Local			
		Wailuanui basalt	Qh (pl. 1)	Basalt with scattered small phenocrysts of olivine. Not shown on insert A.	Dense lava possibly carrying water above the Koolau ditch.
		Local			
		Pauwalu basalt	Pu	Basalt with scattered small phenocrysts of olivine.	Dense lava not known to carry water but its base is not exposed and may be permeable.
	Local				
	Older alluvium		Pa	Deeply weathered poorly sorted bouldery alluvium.	Poorly permeable as a whole but contains ribbons of permeable gravel. Store Spring issues from such a gravel ribbon, but it may be supplied from the adjacent valley filled with Ohia lava.
Great erosional unconformity					
Probably Pliocene and early and middle Pleistocene	Kula volcanic series		Tk	Dense thick-bedded basalts and basaltic andesites.	Poorly permeable and much of the recharge sinks to interstratified soil and rotted clinker zones and seeps into streams traversing these rocks.
	Honomanu volcanic series		Tho	Thin bedded olivine basalts.	The lavas are very permeable, and carry large volumes of basal water. Plunkett and Banana Springs issue from them on the east side of the valley.

[a] Each formation in the Hana volcanic series in the Keanae area is underlain by a local erosional unconformity but superposition in the table does not necessarily mean superposition in the field.

Wailuanui Bay. Another narrow branch flowed northward through a small gulch which reaches the sea between Pauwalu Point and Keanae Village.

The Piinaau basalt is named after Piinaau Stream, along the banks of which it is exposed. It is a dense, dark gray basalt, with no phenocrysts visible to the unaided eye. The lava flow followed a gulch cut into the older alluvium along the foot of the west wall of Keanae Valley, and at the sea spread out to form a terrace on each side of the gulch. The lava was very fluid, and although it filled the gulch to a considerable depth, the central part of the flow drained away leaving only a thin veneer plastered to the walls (pl. 20A).

The Waiokamilo lava is a dark-gray olivine basalt, with a few phenocrysts of plagioclase up to 5 mm. across in a dense fine-grained groundmass. It followed the valley of Waiokamilo Stream, and cascaded down the cliff at the eastern edge of Keanae Valley, building a small lava fan.

The last lava flow to reach the lower part of Keanae Valley is known as the Keanae basalt from its exposures at Keanae Village. It is a dark gray olivine basalt containing phenocrysts of olivine and augite, some of the latter reaching a length of 1 cm. In places the phenocrysts become so abundant that the rock might be classed as a picritic basalt. At an altitude of 1,300 feet the lava covers the entire floor of Keanae Valley, but farther north it divided into two branches. One branch followed the eastern wall of the valley to an altitude of 500 feet, and the other followed the gulch of the present Piinaau Stream at the foot of the western wall. At the coast the western branch spread out to form a lava delta on which is the village of Keanae.

Character and structure.—The Hana lavas are preponderantly aa, but a few pahoehoe flows are found here and there, especially near the vents where thin, very vesicular lava is common. A few large patches of pahoehoe lie on the floor of the summit depression. Many of the flows extend 9 miles from the top of the mountain to the coast and then for an unknown distance under the sea. Features common to all fresh aa flows are found, such as long winding channels through which the rivers of molten lava flowed and balls of wrapped clinker called "bombes de roulement."[55] In the east side of Koolau Gap, thick flows have parallel ridges of clinker typical of many highly silicious block lava flows found elsewhere in the world. Near the head of one of these flows are heaps of aa 100 feet across

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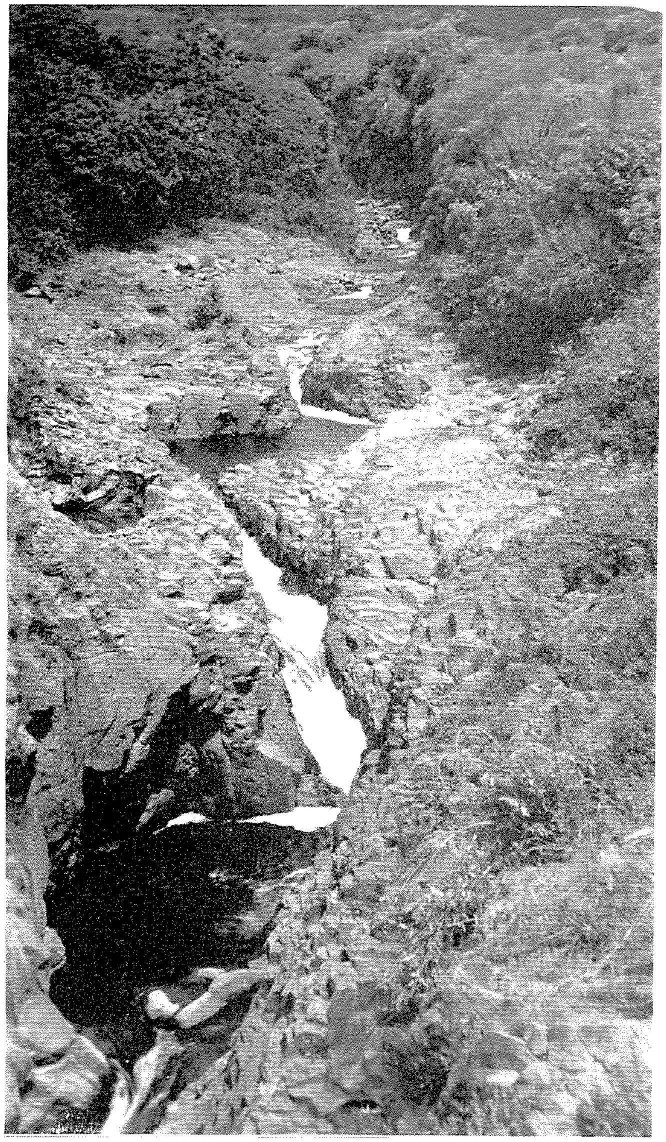
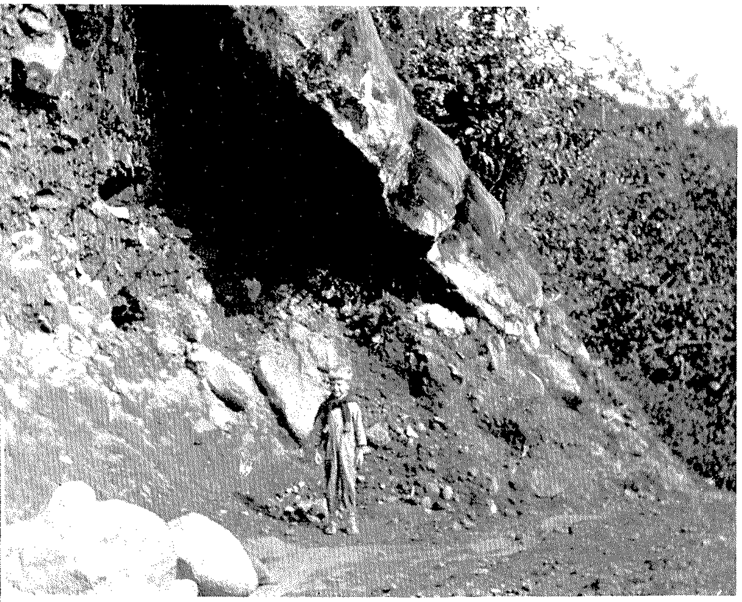
[55] Dana, J. D., Manual of geology: 4th edit., p. 287, 1894.

Right: Plate 19A. Oheo Stream near Kipahulu, East Maui, flowing in jointed aa of the Hana volcanic series, typical of the dense late valley-filling lavas.

Below: Plate 19B. Dense columnar-jointed late Kula basalt (1) unconformable on early Kula lavas (2) at the mouth of Waiopai Gulch, south side of East Maui.





Above: Plate 20A. Plastering lava (1) overlying conglomerate (2) in Palaukulu Valley near Keanae, East Maui.

Below: Plate 20B. Ohia Spring (no. 18) in Keanae Valley issues from a thin plaster of Ohia lava.

and 50 feet high, that may be bulbous domes. One appears to have been pushed up as a solid mass.

The lavas range in composition from ultrabasic olivine augite porphyries to aphanitic andesites, but olivine basalts are most common. Feldspar phenocrysts are fairly common, and are notably large in a flow in the summit depression[56] and in another flow on the east side of La Perouse Bay, where they reach a size ½ by 1 inch. They are mostly of clear gem quality but fractured. Augite phenocrysts reaching ¾ inch across are common in many flows and usually are more numerous in the upper vesicular part of the flow than at the bottom. Some stretches in the Pauwalu lava, where it is cut by the ditch tunnel in Keanae Valley, are free from phenocrysts; others have olivines reaching 4 mm. across, and still others have both olivine and augite phenocrysts. Details of the mineralogy and petrology of the Hana lavas are given in Part 3.

Individual flows range from a few to several hundred feet in thickness. Those more than about 50 feet thick generally owe their massiveness to having been confined between valley walls or in depressions (pl. 19A). The average thickness is about 10 feet on the steep upper slopes where the lavas were very fluid, to 25 feet in the flatter areas near the coast. Those in valleys are variable in thickness, depending on whether they were confined in narrow gorges, filled plunge pools, or spread fanwise at the mouth. They vary tremendously in texture, depending on similar factors. The lavas confined between valley walls may be dense columnar-jointed masses as much as 500 feet thick resembling plugs or they may be thin sheets only 6 inches to 4 feet thick, depending on the pre-valley gradient (pls. 19B and 20A).

An unusual type of thin intercanyon lava flow exists in some of the steep narrow valleys. Such flows have been appropriately named "plastering lavas" by W. O. Clark, who first recognized them in the Nahiku area, but no description of them is found in the literature. They are easily missed because of their thinness. All that remains of these lavas in many gulches is a veneer a few inches to several feet in thickness extending unbroken along the valley walls for miles, and varying in height from a few feet to 50 feet or more above the present stream. All canyons in which the plasters are found are narrow and have steep gradients, indicating that the canyons served as a channel for the aa, instead of the flow building its own channel, as is usual.

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[56] Dana, J. D., Characteristics of volcanoes: p. 277, 1890.

Two plastering lavas of different age, one above the other, have been mapped along Piinaau Stream in Keanae Valley (insert A, pl. 1). The older one called the Piinaau basalt as exposed in Palaukulu Valley at the road crossing near Keanae is shown in plate 20A. It is 1½ to 2 feet thick and veneers the valley wall in the form of a . The aa was about 9 miles from its source when it made these plasters. The plastering lava apparently flowed in the usual manner from the summit depression down Keanae Valley until the main feeding river of molten lava tumbled into a narrow gorge. No longer able to spread laterally, and with a steep gradient, it rushed at velocities of probably 10 to 20 miles an hour toward the sea, filling the gorge from bank to bank 10 to 50 feet deep, tumbling wildly over any waterfall in its path, and behaving somewhat like a flood of water. The younger one, the Keanae basalt, upon reaching the sea built a wide delta and fan of clinkery aa, the peninsula shown on plate 1 as Keanae Homesteads. (See also insert A, pl. 1.) Evidently the lava was so liquid in the gorge that it drained into the sea, leaving stringers of clinker on the valley floor, pods of lava in the former plunge pools, and a veneer or plaster on the walls. The thin plaster now preserved is the bottom crust of the flow where it chilled against the cold canyon wall. In some places stringers of very loose clinker, the advance tongues of the lava flood, underlie the dense plaster. The draining of the molten river at the close of such an eruption is similar to the draining of lava from tubes in pahoehoe, except that a v-shaped trough of hard rock is formed instead of a tube.

Some of the waterfalls over which the lava flowed were so steep and high that the plaster did not cover them entirely, but formed thin horizontal sheets at their lips and parallel vertical sheets, resembling gigantic pieces of upturned plyboard, at their feet. The plunge-pool fills are generally dense columnar-jointed nearly circular masses resembling geology text book illustrations of intrusive plugs. Talus debris that slid from the canyon wall into the lava and bands of sand-textured clinker are found in a few places. The plaster is missing entirely from the walls here and there and the only remnant is a slick hard veneer of blue rock on the canyon floor. Presumably the loose clinker formerly on the surface of the plaster was removed by the stream after it reoccupied its channel.

When one flow followed another with an interval of only a few years, the plasters are separated with difficulty, unless they differ greatly in petrologic type. If alike, a tell-tale lens of gravel or a small tree mold may mark the division.

Plastering lavas affect the movement of water in various ways. A stream may flow for a long distance on the tightly jointed veneer without appreciable loss, then plunge into a hole in the veneer and either disappear permanently or reappear in a plunge pool farther downstream (fig. 26). Thus, the plasters act in some places like flumes. A stream of ground water was flumed in this manner over tunnel 46 in the Nahiku area. Workmen noticed water dripping from a crack in the roof. They drilled upward and to their surprise were deluged with water that is still flowing. Ohia Spring (no. 18) in Keanae Valley issues from crevices in a thin plaster underlain with conglomerate, the latter serving as the perching formation (pl. 20B). On the opposite bank, the Ohia plaster lies against a thin soil and against the earlier valley-filling Pauwalu lava.

Strikes and dips in these plasters obviously have little value. The lava may be horizontal in one place and have a 60° dip 10 feet away. The lava may be 50 feet thick in one exposure and 1 foot thick 25 feet away. The variation is not due to erosion but to the amount of lava that congealed in each place. It is a difficult task to decipher the geologic history of a multiple plastered gulch from its erosional remnants.

No attempt has been made in the small scale of plate 1 to show outcrops of such plasters, nor have all been mapped. However, the maps of the Nahiku and Keanae areas, inserts A and B in plate 1, show detailed surveys of lava-plastered drainages. These are typical of most of the mountain, especially of the more eroded eastern half.

CONES AND ASH DEPOSITS.—The Hana cones and vitric ash deposits are shown on plate 1. Thinly sprinkled areas of ash and small patches a foot or two thick are not shown. They are common about the summit and adjacent to the rift zones. Pumice washed from the upper slopes forms an appreciable part of some of the alluvium on the Isthmus. A bed of ash 6 feet thick lies directly under the soil near Puunene, and flats are covered with it near Kihei. These water-laid deposits are not distinguished on plate 1 from the alluvium. Nine beds of vitric tuff, partly palagonitized, are interstratified with the talus along the former Halemauu trail which led into the summit depression. Such beds are too small to show on plate 1, but they comprise an appreciable part of all the talus in the depression.

The cones range from spatter ramparts a few feet high along cracks to cones 600 feet high. They contain all the usual deposits of firefountains. Except for a few cones on the south slope, they lie in the well defined southwest and east rift zones (pl. 1). Molokini, composed of lithic vitric tuff, similar to Diamond Head on Oahu, was formed by a submarine explosion on the southwest rift during

Hana time (pl. 6B). It has been fully described by Palmer.[57] A submarine cone a quarter of a mile across lies offshore from the Kipahulu Church on the east rift zone at a depth of 900 feet, according to W. C. Jennings, who does deep sea fishing there. Probably detailed soundings would discover many others on the seaward extension of the rift zones.

A diagnostic feature of the Hana cones is their loose fresh black glassy cinders, in contrast to the red and yellow weathered cinders in the Kula cones. Some Hana cones near Makena are coated with a yellow ashy loess that conceals black cinders. The older Hana cones on the wet eastern slope are weathered generally to a depth of 1 foot or more.

Some of the vents in the summit depression are unusual. Fissure vents opened on the face of cliffs so that spatter and thin flows are found plastering former gullies in the talus fans (pl. 22). Other eruptions from similar vents produced enough cinders to form thick fans, as under Haleakala Peak. Some of the spatter cones have been named from their bizarre forms, as Pele's Pig Pen (Ka Puaa o Pele) and the Bottomless Pit on the trail across the floor. The latter has a crater about 75 feet deep shaped like a well. It was explored in 1940 by Frank Hjort, ranger in charge, Haleakala National Park. He found sealed jars containing umbilical cords of infants, evidently dropped into the crater by superstitious Hawaiians. The cone of Ka Moa o Pele is strewn with well formed volcanic bombs. Dense porphyritic bombs are abundant on the northwest slope of the cone Halalii (pl. 44C). Some have smooth glazed surfaces and others are rough and vesicular. Some have ears but many are ball- or egg-shaped. They appear to have been lumps of solid and nearly solid rock, from which most of the gases had escaped, that were hurled into the air, thereby being detached from the surrounding vesicular frothy magma in which they floated.

Numerous blocks of gray dense rock, coated with black vesicular crusts and clusters of small fragments forming a breccia in breadcrust bombs, lie scattered among the cinders on the rim of the summit depression, ¼ mile east of Magnetic Peaks and on the east slope of Puu Keokeo. Apparently the magma picked up considerable wall rock near the surface, possibly as a result of a landslide from the talus slope through which it erupted.

The Hana ash deposits shown on plate 1 range in thickness from 1 to 20 feet. Bedding is present in the thicker mantles. The de-

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[57] Palmer, H. S., Geology of Molokini: B. P. Bishop Mus. Occasional Papers, vol. 9, no. 1, 18 pp., 1930.

posits form sufficient soil on the rough lava flows near Hana to grow sugar cane. They also form much excellent grazing land at Ulupalakua. A few areas of ash in the summit depression where it was not possible to determine the underlying rock are shown by a solid pattern on plate 1.

Very few interstratified ash beds of Hana age are exposed, and they are too small to show on plate 1. Many such beds must occur in the Ulupalakua and Hana areas, but streams have not yet cut deeply enough to expose them.

EXPLOSION DEPOSITS ON THE SOUTHWEST RIFT.—Five craters have thrown out wall rock on the southwest rift between altitudes of 7,500 and 9,250 feet (pl. 6A). The rocks lie mostly within a radius of 200 feet of the vents and form deposits next to their rims from 2 to 10 feet deep, indicating that the explosions were not violent. The debris covers areas too small to be shown on plate 1. The gray weathered blocks, chiefly derived from Kula crater fills, flows, and dikes in the throats of the craters, are conspicuous against the red and black cinders underlying them. Some cinders lie among the blocks. The cinders appear to have been derived from the crater walls and from later Hana eruptions. A few of the dense blocks exhibit breadcrusting, as though some of the rocks were hot when ejected, as witnessed at Kilauea Volcano in 1924.[58] Some of the debris is covered with late lava and spatter. The explosions appear to have been phreatic and of shallow origin.

DIKES.—Dikes of Hana age are not differentiated on plate 1 from older dikes. Due to the youthfulness of the Hana volcanics, only a few are exposed. A few dikes show in the cones cut by the sea at Hana and Hamoa. There can be no doubt, however, that many dikes were intruded into the east and southwest rift zones in Hana time, as shown by the numerous fissures bordered by spatter near the summit.

INTERSTRATIFIED GRAVELS.—Few interstratified gravels are exposed in the poorly dissected Hana lavas. Lenses of water-worn boulders are interbedded with the lava flows from Kaupo Gap that repeatedly blocked the mouth of Manawainui Canyon (pl. 21A). From 3 to 10 feet above stream level in the exposure illustrated in plate 21A are molds in the aa that show well defined checker patterns caused by the lava filling cracks in charred logs. Other interstratified gravels crop out at an altitude of 500 feet in Koukouai Gulch, and in a few

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[58] Stearns, H. T., The explosive phase of Kilauea Volcano, Hawaii, in 1924: Bull. Volcanologique, nos. 5 and 6, p. 200, 1925.

places between this gulch and Keanae where Hana lavas filling valleys have been truncated by sea cliffs.

WATER-BEARING PROPERTIES.—The Hana lavas are so permeable that they act like a great sponge absorbing immense quantities of rain. Streams are unable to flow to the sea down slopes veneered with these volcanics except during cloudbursts, and then only where channels exist. Thus, the slope between Hana and Nahiku, which receives about 200 inches of rain annually, has no perennial streams. River beds are the sites of mighty torrents a few days each month, and are dry the rest of the time. A few streams that rise at large springs near the coast manage to reach the sea by flowing on dense plastering lava, namely Oheo Stream below Waimoku Fork near Kipahulu (pl. 19A), Kapaula and Paakea Streams near Nahiku, and those at the mouth of Keanae Valley.

General lack of interstratified perching beds allows most of the rain to percolate to the base of the Hana volcanics. There it may be perched in lava by nearly impermeable conglomerates, breccias, or by soil on top of the Kula formation. If such water-bearing lavas terminate or are cut by erosion, springs appear from their base, such as Ohia Spring (no. 18) in Keanae Valley (pl. 20B), or Waiu Spring (no. 41) in Kaupo Valley.

Vast quantities of ground water must be moving seaward at the base of the Hana lavas in the eastern half of the mountain, especially in the bottom of the lava-filled canyons. By comparison with the run-off from adjacent areas, J. H. Foss[59] estimates that 35 million gallons daily is the unaccountable underflow from Keanae Valley into the sea. The total for the eastern half of the mountain must be 5 to 10 times larger.

The ash beds in the Hana member are mostly too coarse and permeable to perch water. They give rise to small springs above Kaeleku that flow for about three weeks after rains. Some of the springs are perched in lava overlying ash, and others are seeps issuing from coarse beds overlying slightly weathered fine-grained ash or ash soils.

HISTORIC LAVA FLOW

Many of the lava flows in the summit depression and in the Ulupalakua-Nuu area are black and bare, obviously erupted in Recent time. Two of the freshest are near La Perouse Bay. They are differentiated from the other Hana lavas on plate 1 simply because Hawaiian legend has recorded them.

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[59] Oral communication, December, 1941.

The upper one broke out of a fissure 1¼ miles south of Ulupalakua (Makena P. O.) on the south slope of the old cone, Puu Mahoe, at an altitude of 1,550 feet. The spatter bordering the fissure is covered with brush and the upper stretches of pahoehoe support a little vegetation. Farther seaward, where there is little rain and the aa clinker is very rough and open, the lava looks as fresh as some of the flows on Mauna Loa that have been poured out in the last 50 years (fig. 15). The flow is 3 miles long, 5 to 20 feet thick, and is an olivine augite porphyry. It extended the coast line about three-quarters of a mile.

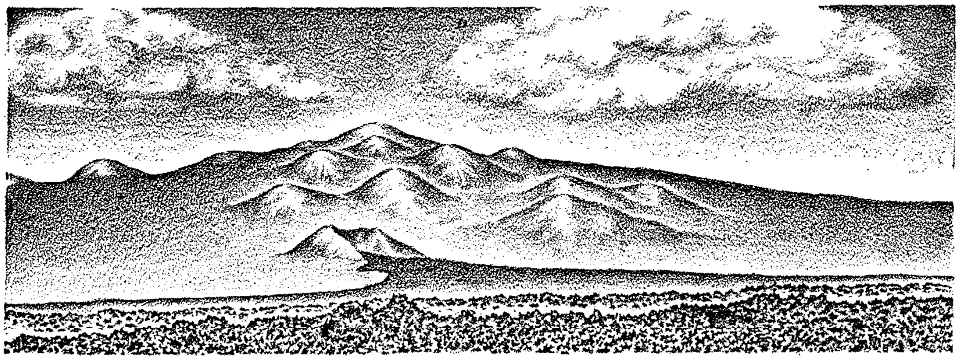

Figure 15. Looking northeastward to the cones of the southwest rift zone of Haleakala Volcano from the 1750(?) lava flow near Makena.

The lower flow broke out at Kalua o Lapa cone, which is on a fissure parallel to the upper vent, but a little to the eastward at an altitude of 575 feet. The flow is similar to the upper one and is covered with rough aa clinker and a little pahoehoe that congealed while changing to aa. It overlies the Mahoe flow but may have been laid down only a few hours or a few days later. Both flows contain large balls, or wrapped masses of aa typical of many Hawaiian lava flows.

The earliest published record seems to indicate that the Lapa flow might be the historic flow and the Mahoe flow earlier, but the similarity of petrology and degree of weathering suggest simultaneous eruption. The opening of two distinct vents during one eruption on the same rift is common in Hawaii.

The record appears in Dana, who states "The period of the last summit eruption is unknown. Mr. Bailey, of Wailuku, Maui, has stated that, according to an island tradition, a lateral eruption of the mountain occurred about 150 years since in the district of Honuaaula of the southern part of East Maui, at an estimated elevation above the sea of about 400 feet."[60] This definitely describes the lower flow.

The late Lorrin A. Thurston, a serious student of Hawaiian volcanoes and lore, published the following account, which confirms the recency of the eruption. It is quoted in full because many geologic writers have given categorically the date 1750 to the lava flow:

> Popular impression and report is to the effect that there is no record, or even tradition, of volcanic activity on the island of Maui, although the mute evidence thereof, both in the crater of Haleakala and on its outer slopes, in the shape of comparatively recent lava flows, are many and plain.
>
> Among more recent flows, one, especially, is quite as fresh in appearance as the 1801 flow from the western slope of Hualalai, in Kona, Hawaii, which was seen and the date recorded by a white resident.
>
> The writer shared the popular opinion, and, about 1879, remarked upon the supposed fact to Father Bailey, the venerable American missionary who came to Hawaii in 1837. He was stationed on Maui in 1841 and lived there for many years.
>
> In his usual deliberate drawl, Father Bailey replied: "That is not so!"
>
> "What do you know to the contrary?" I asked.
>
> He thereupon made in substance the following statement, which for 26 years was all that I heard concerning knowledge or tradition of volcanic activity on the island of Maui.
>
> "I was first stationed on Maui in 1841," said Father Bailey. "In my trips about the island I noticed a lava flow at Honuaula, at the south end of East Maui, which appeared much fresher than the other flows—much more so than it appears now (1879).
>
> "I asked the natives if they knew when that flow occurred, and they told me that their grandparents saw it. They also told me that a woman and child were surrounded by the flow, but escaped after it cooled."
>
> I have since visited the locality indicated by Father Bailey and examined several other recent appearing flows nearby. The government map of Maui shows three such flows, all in Honuaula and originating below the upper road around the island. The flow in question, manifestly the latest, begins about half-way down, between the upper road and the sea. It spreads to a width of a mile or so at the coast, having built quite a promontory out into the ocean. Its source is at a small hillock or crater, two rocky projections with perpendicular interior sides, a few feet apart, marking the spot from which the torrent of lava poured forth. The flow rapidly widening, ran to the sea, a distance of a couple of miles or so. The lava is rough aa, entirely devoid of vegetation, and looks as though it might have first seen daylight in the twentieth instead of the eighteenth century.
>
> The flow forms the western side of Keoneolo, or La Perouse Bay, named after the French explorer who landed there in 1780. The government lighthouse, known as the Kianu Light, is at the eastern point of the bay. The flow partially surrounds and forms an almost completely protected section, some 10 feet deep, at the head of the bay, which had been converted into a fish pond by the old natives. A storm opened a passage through the wall, and the interior forms a perfectly landlocked little harbor, safe in all weather, for

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[60] Dana, J. D., Characteristics of volcanoes: pp. 278-279, N. Y., 1890.

sampans and boats of that size. Dr. Raymond built a wharf there, which is still in good condition. There is a small settlement on the beach amid a splendid growth of algaroba trees.

The flow is manifestly of later formation than the adjacent flow to the north and the other more recent flows to the eastward. The flow immediately eastward has considerable growth of the old dry-country type, among others there being wiliwili trees with trunks up to four feet in diameter. This is the tree the wood of which is so light that it is used by the Hawaiians as the ama, or float, of outrigger canoes.

About 1906 I happened to be camping on the outer Hana slope of Haleakala, near the summit, with Louis von Tempsky. We pitched tent and went into camp late in the afternoon, just as it began to rain. It did not stop raining for two days and nights, so that four of us, with three Hawaiian cowboys, were storm-bound for that length of time.

In passing away the time, I mentioned the above conversation with Father Bailey, when one of the cowboys, a half-Chinese named Charlie Ako, said: "I know about that."

"What do you know?" I inquired.

"I married a woman from Honuaula," said Ako, "and my father-in-law, of Honuaula, who died last year, at the age of 92 years, told me that when the flow at Keoneoio ran out, his grandfather saw it, and that, at that time, he (the grandfather) said he was old enough to carry two coconuts from the sea to the upper road."

This is a distance of 4 or 5 miles. The trail is rough and the upper road is at an elevation of approximately 2,000 feet.

I obtained no further information from Ako.

I told several others of what I had heard about the flow; but did not myself visit Keoneoio until 1922, when I made a close inspection of the flow and sought information concerning it from the kamaainas living along the beach between Makena and Keoneoio.

There I met three old Hawaiian men, all of whom had known Ako's father-in-law during his lifetime. Each of the three men, separate from the others, told me the following tradition, or legend concerning the flow in question, differing only in minor details.

"A man and a woman with two children, a boy and a girl, lived at the point in Honuaula, where the lava flow which forms the west side of Keoneoio originated.

"They owned a flock of chickens and had made a vow that no one should have one of these chickens until some of them had been sacrified to Pele, the goddess of the volcano.

"One day an old woman appeared and said she was hungry and asked for a chicken to eat.

"The couple replied that they could not give her a chicken because of their vow to Pele.

"The old woman thereupon became enraged, disclosed herself as Pele, and, with the typical cruel and vengeful spirit of the Hawaiian gods, instead of being grateful to the couple for their faithfulness in their vow to herself, cast a spell upon the earth and produced a lava flow on the spot, with which to destroy the offenders.

"The mother seized her little girl and started to run up the mountain to escape the lava.

"Pele seized the woman and split her in two; turned her and her child into stone and fixed the halves, one on each side of the spot where the lava was pouring from the ground, where they can be seen to this day, conclusive evidence of the truth of this legend.

"Meanwhile the father grabbed his little son and started to run with him for the coast, intending to swim across the channel for safety to the island of Kahoolawe, some eight miles away.

"While Pele was destroying the woman, the man made some distance down hill before Pele could attend to him. Having disposed of the woman, Pele at the head of her lava flow, then chased after the husband. He, arriving first at the beach, plunged into the sea, and, with his son, had reached several hundred feet from shore when Pele arrived. She threw rocks at him, finally hitting and killing both father and son. She turned both to stone. They can be seen to this day, a big rock and a little, rising from the sea, several hundred feet out from shore, undisputed proof of the truth of this story, as anyone can see who chooses to go and look."

None of the above mentioned three kamaainas could give me any information bearing on the date of the lava flow in question.

The foregoing is all the information I have been able to gather bearing on this lava flow, except that I checked the story by seeing the "remains of the woman," frozen into rock at the source of the lava flow, and saw the father and son in the sea, where they had been turned into rocks, off the ocean end of the lava flow, exactly as the kamaainas said they were.[61]

Checking the statements made by Father Bailey, a rough estimate of the date of the flow is arrived at in the following manner:

Father Bailey stated that about 1841 people then living told him that their grandfathers had seen this volcanic eruption.

Allowing the usual number of years to a generation, say 33, the ages of the fathers and grandfathers of people living in 1841, would, combined, amount to 66 years. To this add the age of Father Bailey's informants, say another 33 years. This would carry back the date of the flow approximately 99 years prior to 1841, or, say, to 1742.

Checking the date of the flow by Charlie Ako's story, we get the following:

Ako's father-in-law was 92 in 1905. That would carry us back to, say, 1813. His father's age, say 33 years off, would carry the date back to, say, 1780.

A boy who could "carry two coconuts from the sea to the upper road" must have been at least 10 years of age. Deducting this 10 years from the years of a generation, 33, leaves 23. Deduct this figure from 1780, and it leaves 1757.

These two methods of calculation are rough, but they come within 15 years of each other.

Take the average between the two dates and we have 1750, as the approximate date of the last lava flow on Maui. If anyone has a different method of calculation, a different theory or other information, the field is open for speculation, conclusion and publicity.

I have searched the histories and early accounts of Hawaii for any record or tradition of the last volcanic activity on Maui but have found only two references thereto—one in a comparatively recent issue of the Hawaiian Annual, and one in James A. Dana's *Characteristics of Volcanoes*, published in 1891.

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[61] Mr. Thurston, of course, meant that these are natural forms in the aa resembling human forms (H. T. S.).

> Both refer to Father Bailey as authority for saying that there had been a lava flow, but the editor of the annual, Thomas G. Thrum, tells me that he got the story concerning Bailey's statement from me, so that is no corroborating evidence. It is probable, also, that Mr. Dana's statement emanated from the same source, as he was in the islands shortly before his book was published, and he simply credits Father Bailey with the statement that the flow was "about 150 years ago," which would make it 1740.
>
> If anyone can direct me to any other record or evidence or tradition of recent volcanic activity on Maui, I will accept and publish it gratefully. It will add an interesting item to Hawaiian volcanic lore.[62]

J. F. G. Stokes,[63] Hawaiian ethnologist, thinks Thurston's use of 33 years as the length of a Hawaiian generation is too long and that 25 years is better. He favors the year 1770. As a definite date cannot be assigned, 1750 is used herein because it has come into general use.

The numerous black lava flows are indicative of late volcanic activity, and judging from the time interval between these late flows as shown by the amount of weathering and vegetation, it may be that Haleakala will erupt again. Possibly the large number of earthquakes since 1937 having epicenters near Maui have volcanic significance.

QUATERNARY SEDIMENTARY ROCKS

Kaupo mud flow.—The Kaupo mud flow crops out over about 1½ square miles at the mouth of Kaupo Valley, from which it is named (pl. 1). It forms hills that project through the later Hana lavas and Pleistocene gravels, and cliffs 300 feet high along the coast (pl. 15A). It has an exposed thickness of 355 feet in the sea cliff at Puu Maneoneo, but it must be thicker, as it extends below sea level. The mud flow, after consolidation, was cut by streams, the beds of which go below present sea level. The valleys of these streams are filled with gravel which forms a terrace with its top at an altitude of 150 feet at the coast. The gravel apparently was graded to the Kaena shore line, about 100 feet above the present sea, and notched by valleys that go below sea level, probably of Waipio age. The valleys are filled with Hana lava. This sequence would place the mud flow during the Kahipa minus 300-foot stand of the sea, or some time before the ocean had reached present sea level on its rise to the Kaena 100-foot strand.

The fragments in the mud flow are similar in appearance to those now accumulating in talus fans in the summit depression. The mud flow consists of fairly fresh angular and subangular dense and

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[62] Thurston, L. A., The last lava flow on Maui: Honolulu Advertiser, Feb. 24, 1924.

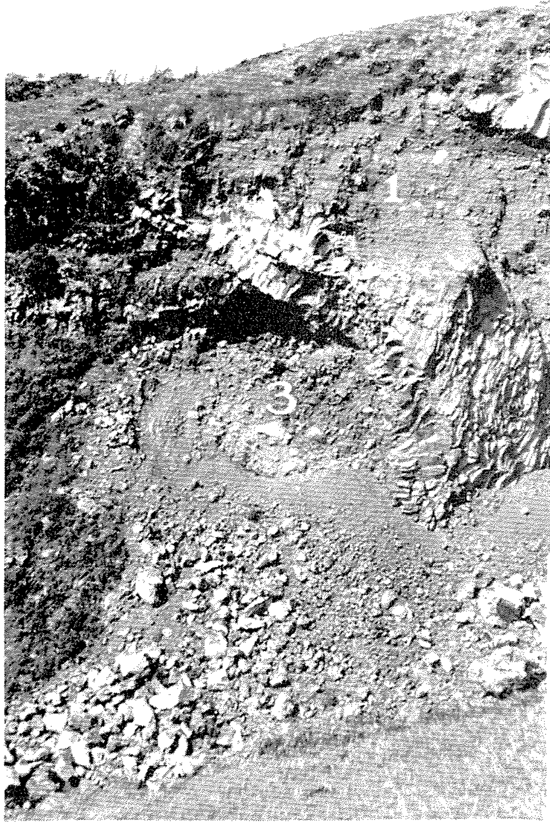
[63] Letter to H. S. Palmer dated Aug. 26, 1936, a copy of which Prof. Palmer kindly sent the senior author.

vesicular blocks of basalt and andesite arranged in helter-skelter fashion in a sparce matrix of sandy material derived from the same rocks (pl. 21B). The blocks are chiefly red and gray, but other colors are present, depending upon the degree of staining by weathering. Some were stained before incorporation in the mud flow and others after it came to rest. In the breccia one quarter of a mile northeast of Kamanawa Point is a block of vitric tuff 50 feet in diameter carrying bombs and cut by a platy feldspar porphyritic dike. Squeezed into cracks in the block are pseudo dikelets 18 inches long and 3 to 5 inches wide composed of mudflow. Nearby are a 5-foot block of tuff and many small fragments that broke away from the large block as it moved along. The complete lack of sorting and stratification in the deposit stands in strong contrast to the overlying stream-laid conglomerates which contain many well-rounded cobbles and definite crossbedding.

The loose talus fans at the foot of the wall under the rest house on the rim of the summit depression are in such delicate equilibrium that they frequently form slides. Many large slides occurred there during and after the 1938 earthquake. The talus fans are prevented from moving down Keanae and Kaupo Valleys now by rough lava. It is probable that prior to the eruption of the lava, a cloudburst, perhaps followed by earthquake, set similar debris in motion. Once started and lubricated by its interstitial mud, the debris formed a mud flow that moved many miles down the valleys. An explosion of great magnitude would have been required to produce such a great volume of debris. The absence of lithic tuff deposits on the flat surfaces bordering Kaupo Valley indicates that an explosion did not form the mud flow. A mud flow seen in 1926 on Mt. Shasta Volcano, California, resulting from a saturated body of debris flowing down a steep slope following rapid thawing of deep snow, shows that volcanic explosions are not necessarily the cause of mud flows on volcanoes.

The Kaupo mud flow is virtually impermeable and perches water in the overlying lava and gravels. Spring 41 is perched by it in the overlying very pervious aa.

CALCAREOUS MARINE DEPOSITS.—Fossiliferous marine conglomerate a few inches to 2 feet thick crops out in the gulch ¼ mile from the coast and 4¼ miles south of Kihei (pl. 1). It was found up to an altitude of 50 feet, as determined by an aneroid barometer. It consists of subangular and rounded basalt pebbles and cobbles firmly cemented in a matrix of calcareous limestone composed of detrital reef debris, fossil shells, and coral. Small patches of lime-



Left: Plate 21A. Conglomerates of different ages (1 and 3) interstratified with Hana basalt flows (2 and 4) that blocked the mouth of Manawainui Canyon, East Maui.

Right: Plate 21B. Kaupo mud flow near Waiu Spring (no. 41), East Maui, showing helter-skelter arrangement of the blocks.

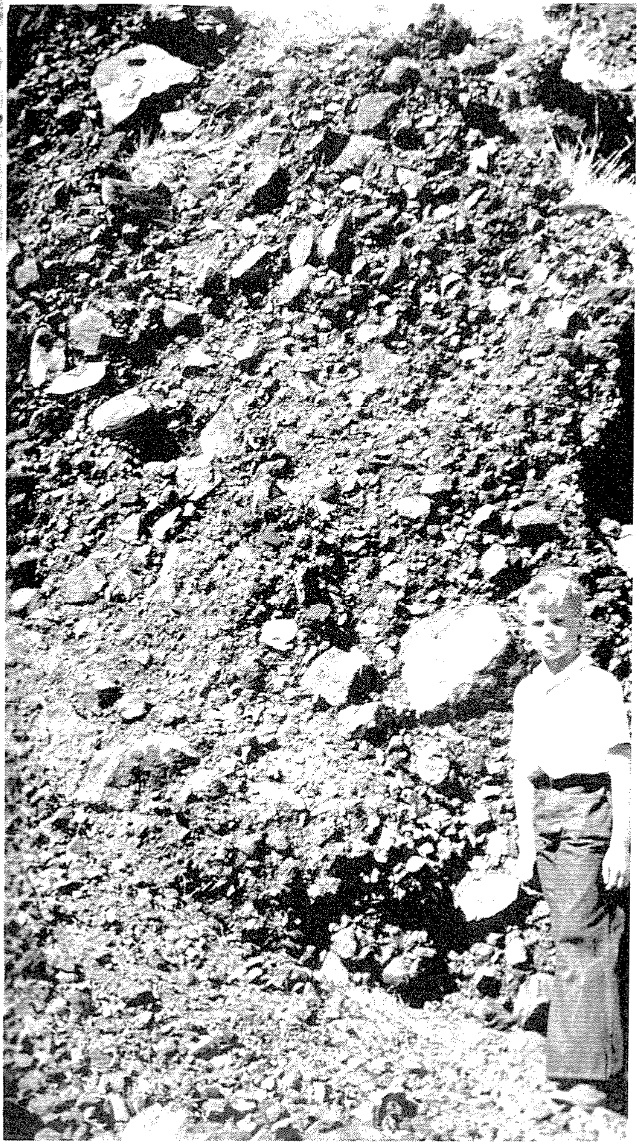


Plate 22. Vertical air view of the north rim of the summit depression of Haleakala showing a chain of spatter cones along a fissure cutting obliquely up a 1,300-foot cliff (1), fresh black aa flow from the fissure (2), talus older than the fissure eruption (3), Kula lava (4), tongues of late Hana aa lava from vents to the west (5). Photo by Fleet Air Base, U. S. Navy, Pearl Harbor, T. H.

cemented conglomerate were seen much higher, but marine fossils were not found in them; hence they may not be marine. Some of the earthy conglomerates up to 100 feet in altitude along this coast may be marine.

Marine fossils were found 40 feet above sea level in test hole 107 near the center of the Isthmus. Clam-type shells and corals were bailed out, according to Mr. R. E. Hughes, indicating marine sediments interstratified with fanglomerates.

Several inches to a foot of limestone caps Ka Lae o ka Ilio, 73 feet above sea level at the mouth of Kaupo Valley. It contains numerous shells of *Littorina scabra* Linnaeus,[64] a common periwinkle. These marine snails were found alive and climbing the cliff. The limestone is the type deposited by evaporating spray. It appears, therefore, that this deposit containing fossils is being made now, and hence is not evidence of emergence, in spite of its great height above the sea.

CONSOLIDATED AND UNCONSOLIDATED DUNES.—Consolidated dunes stretch from Kahului for 8½ miles southward toward Kihei across the Isthmus (pl. 1). They attain heights of 200 feet near the north coast but diminish rapidly in height and size toward the leeward coast. The sand is chiefly comminuted coral, shells, and foraminifera, with small amounts of basaltic sand. The dunes show three different degrees of consolidation. The lowest sand is the hardest and is cemented to a firm rock or eolianite.[65] Along the coast between the mouths of Iao and Waiehu Streams eolianite extends below sea level and is also benched above sea level by the 5-foot and probably by the 25-foot stands of the sea. Above the eolianite is a brownish-red chiefly residual soil, from 2 to 6 feet thick. Above it lie dunes that are weakly cemented. In places these partly cemented dunes are overlain by recent unconsolidated dunes. The soil contains fossil shells of land snails indicative of open forest conditions less arid than at present.[66]

The eolianite is believed to have been formed when the sea stood about 60 feet lower than at present, as test hole 104 ended in this rock 7½ feet below sea level. The overlying partly consolidated dunes apparently formed during the 25-foot sea. The dunes of different ages have not been separated on plate 1, but most of those shown are partly cemented.

Small unconsolidated and weakly consolidated dunes extend inland short distances from each sandy beach southward from Kihei.

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[64] Identified by J. M. Ostergaard, Univ. of Hawaii.

[65] Sayles, R. W., Bermuda during the ice age: Am. Acad. Arts Sci. Proc., vol. 66, no. 11, p. 390, 1931.

[66] Oral communication by C. M. Cooke, III, who examined the outcrops with the senior author.

Some of those in the Kamaole homesteads (pl. 1) are probably correlative with ancient stands of the sea. Areas of beach sand are distinguished from dune sand on plate 1 by a brown stipple.

All the dunes are highly permeable, but all lie above the zone of saturation, except those along the coast north of Wailuku, where a few small springs are found.

CONSOLIDATED EARTHY DEPOSITS.—The consolidated earthy deposits are chiefly older alluvium with lesser amounts of talus breccia. The alluvium consists of mottled-brown to red-brown, deeply weathered, poorly sorted, friable conglomerates. Near steep valley walls they grade into coarse angular talus and landslide deposits. The most extensive deposits are near the mouths of streams on the Isthmus, but they are mantled there with a nearly continuous thin layer of younger alluvium. For this reason the older alluvium laid down on the Isthmus by East Maui streams is not shown on plate 1. It reaches thicknesses of 50 feet or more, is lenticular and poorly sorted, and contains considerable silt and pumice. No water has been found in it.

Two other large deposits are in Keanae and Kaupo Valleys, both of which are alluvial fans, apparently graded to the 100-foot stand of the sea. They form a cliff 120 feet high at Keanae and 150 feet at Kaupo. Both extend an unknown distance below sea level and are sufficiently cemented with limonite to form nearly vertical cliffs. Some of the lenses contain fairly well sorted rounded gravel, and at Keanae long lenses of silt several feet thick crop out. At both places small springs issue from conglomerate beds overlying silt. Spring 19 discharges 2,200,000 gallons a day from conglomerate in Keanae Valley, but its source appears to be the adjacent Ohia lava. As a whole these deposits are fairly impermeable and perch water in the overlying Hana lavas.

Smaller deposits of older alluvium lie west of Nuu; they are remnants of fans graded to higher seas (pl. 1). Thick deposits of older alluvium must be interbedded with and underlie the lavas filling all the great canyons. (See Kaupo Valley in section AA′, pl. 1.)

UNCONSOLIDATED DEPOSITS.—The unconsolidated earthy deposits are chiefly poorly sorted, poorly rounded stream-laid brown silt, sand, and gravel lying in recent stream channels. Many narrow bands along streams were too small to show on plate 1. Those shown on the Isthmus are a few inches to 50 feet thick and form a discontinuous mantle over older alluvium. Narrow strips of calcareous sand along the beaches and large talus fans in the summit depression are mapped with the younger alluvium on plate 1. Some of the fans contain considerable ash, but they have been mapped with the unconsolidated deposits unless they are completely mantled.

GEOLOGIC STRUCTURE

Haleakala is made up of three broad fairly flat constructional arches with their axes underlying the three rift zones. The arches are due to the lavas pouring from three systems of cracks that converge at the summit (pl. 23C and section AA′, pl. 1). Thus, the arches plunge seaward from the crest. The axis of each arch has been intruded repeatedly with hundreds of narrow dikes, one or more coincident with each eruption (section AA′, pl. 1). The dikes increase in number downward until, at a depth of a mile or so, the axis of the arch probably becomes a solid mass of intrusive rock. The lava flows that originally existed in the rift zone are completely replaced, largely by thin slices of them sinking into the underlying magma chamber. Some fragments of the flows floated upward in the erupting lava, and a few others were blown out by explosions. The amount removed by explosion was small. To a certain but probably very small extent the lava flows were pushed laterally by the intrusions. If Haleakala followed the history of most other Hawaiian volcanoes, trough-shaped fault depressions probably indented the axes of the rift zones and a collapse caldera lay on the summit prior to the eruption of the Kula lavas. A hypothetical caldera has been shown in plate 23C following this theory. It may be that cracks or low fault cliffs persisted on the summit to the close of Kula time to direct much of the drainage into two streams, Kaupo and Keanae. just as cracks have directed most of the drainage of the summit of Kohala Mountain, Hawaii, into Waipio and Pololu Canyons, giving them mastery over the other streams on that mountain. No fault cliffs are now known on Haleakala, although what is probably a buried fault that dropped the south side of the mountain a few thousand feet at the close of Honomanu time is described on page 73. Many other faults are probably buried by lavas and concealed by vegetation.

GEOLOGIC HISTORY

All altitudes in this chapter are based on the assumption that Maui is now submerged 1,200 feet. The projection of the large canyon walls below sea level indicates that the submergence was probably not materially less than this amount. The amount may be more if the 1,800-foot submarine shelf off West Maui is a submerged shore line. It has been estimated also that 500 to 1,000 feet have been removed from the summit by stream erosion. The geologic history of Haleakala is summarized as follows:

PROBABLY PLIOCENE AND EARLY PLEISTOCENE TIME

1. Building of a shield- or dome-shaped island of highly fluid primitive Honomanu olivine basalts about east, southwest, and north rifts with a crater at their intersection (pl. 23A).
2. Culmination of the Honomanu dome about 8,500 feet above present sea level. The flows of the East Maui volcano, banking against the older West Maui volcano and Kahoolawe, built up isthmuses, and Haleakala ceased to be a separate island. A large fault apparently existed on its south side, and possibly a caldera was formed by collapse on its summit. Plate 23C shows this stage just before the joining of the dome with West Maui and Kahoolawe.
3. Eruption of the Kula lavas and their bulky cinder cones. Volcanic activity gradually waned, allowing soils to form and streams to cut valleys. These lavas steepened the dome, added 2,000 to 3,000 feet to the summit, and deeply buried the fault cliff on the south slope. Haleakala reached a height about 12,000 feet above the shore of that time (pl. 24A).

EARLY(?) PLEISTOCENE TIME

4. Long period of erosion during which canyons more than 5,000 feet deep ate headward beyond their summit divides, and high sea cliffs were cut (pl. 24C). A few lava flows may have been erupted during this period.
5. Gradual submergence, probably of more than 1,450 feet, deeply drowning the valley mouths and separating East and West Maui again (pl. 25A). Meager evidence of a shore line at this level exists on Haleakala, but on West Maui it is the well established Olowalu shore line. The submergence may have been as much as 2,500 feet. Sedimentation occurred at the valley mouths.

MIDDLE(?) PLEISTOCENE TIME

6. Fairly rapid emergence of 550 feet or more with several short halts on the way and the development of a shore line about 300 feet below present sea level, correlative with the Kahipa minus 300±-foot stand of the sea. East and West Maui were again joined, and they also connected with Lanai, Kahoolawe, and Molokai to form a large island (pl. 25C). Renewed stream erosion removed most of the sediments deposited previously.

7. Kaupo mud flow moved into the sea and became consolidated and eroded (pl. 25C).
8. Resubmergence of about 400 feet and the deposition of thick conglomerates at the mouths of the large canyons and over the Isthmus. East and West Maui became separated for the second time by a narrow strip of water. Marine fossiliferous sediments were deposited on the Isthmus, and gravels in the valleys previously cut in the Kaupo mud flow. This shore line corresponds to the 100-foot Kaena stand of the sea.

LATE PLEISTOCENE TIME

9. Re-emergence of about 160 feet, corresponding to the Waipio shore line. Formation of calcareous dunes on the Isthmus and terraces in the alluvium, especially at the mouths of Keanae and Kaupo Valleys. Valleys were cut about 60 feet below present sea level into the gravels that overlie unconformably the Kaupo mud flow. Renewed volcanism on the southwest and east rifts and the extrusion of the Hana volcanics (pl. 26A). Probably the early Kipahulu lavas were poured out in the preceding epoch and there was activity elsewhere on Haleakala, but the earliest geologically dated Hana lavas are those filling valleys of Waipio age at the mouths of Keanae and Kaupo Valleys.
10. Resubmergence of about 85 feet forming a shore line correlative with the Waimanalo stand of the sea. The earlier formed dunes were partly submerged and cliffed. Benches were cut into the partly weathered lavas near Maliko Gulch. Again the streams alluviated their valley mouths and Hana lavas continued to be erupted, deeply filling the great valleys eroded at the end of Kula time.
11. Re-emergence of 20 feet and a halt corresponding to the Kahipa shore line. Streams cut into the alluvium deposited in the preceding stage, leaving terraces at their mouths. The sea remained long enough to cut only a narrow bench along the lava coasts. Continued eruption of Hana lavas.

RECENT

12. Re-emergence of 5 feet and partial destruction of fringing marine bench (pl. 26C). Continued eruption of Hana lavas with a lava flow about 1750 near La Perouse Bay from the southwest rift.

PLATES 23 TO 26 SHOWING EIGHT STAGES IN THE DEVELOPMENT OF MAUI

23A. Stage 1 in the development of Maui showing the East Maui and West Maui volcanoes as separate islands erupting primitive basalts.

23B. Silhouette of stage 1.

23C. Stage 2 in the development of Maui showing East Maui volcano with a caldera on its summit and faults on its south side, and West Maui volcano erupting Honolua lavas and joined to Lanai and Molokai volcanoes.

24A. Stage 3 in the development of Maui showing East and West Maui joined with Kahoolawe, Lanai, and Molokai. East Maui volcano is erupting Kula lavas. Present outline of Maui indicated by a dotted line.

24B. Silhouette of stage 3.

24C. Stage 4 in the development of Maui showing the canyon-cutting period of early Pleistocene time with all volcanoes dormant. Present outline of Maui indicated by a dotted line.

25A. Stage 5 in the development of Maui after the great submergence during the Olowalu 250-foot stand of the sea. East and West Maui are separate islands. The valleys have been deeply filled with alluvium.

25B. Silhouette of stage 5.

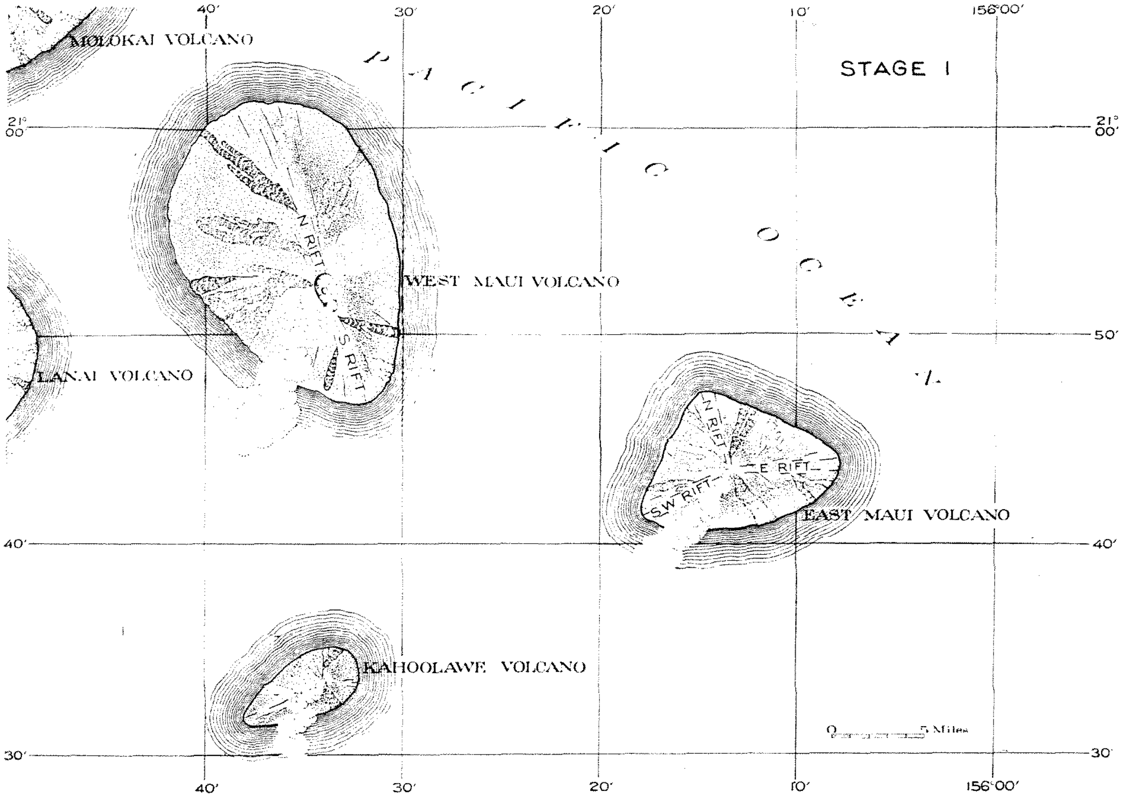
25C. Stage 6 in the development of Maui showing East and West Maui united during the Kahipa minus 300-foot stand of the sea. Hana lavas have started to fill the canyons on East Maui, and the Kaupo mud flow has just been emplaced.

26A. Stage 7 in the development of Maui showing the island during the Waipio minus 60-foot stand of the sea with the Hana and Lahaina lavas being erupted and dunes forming on the Isthmus.

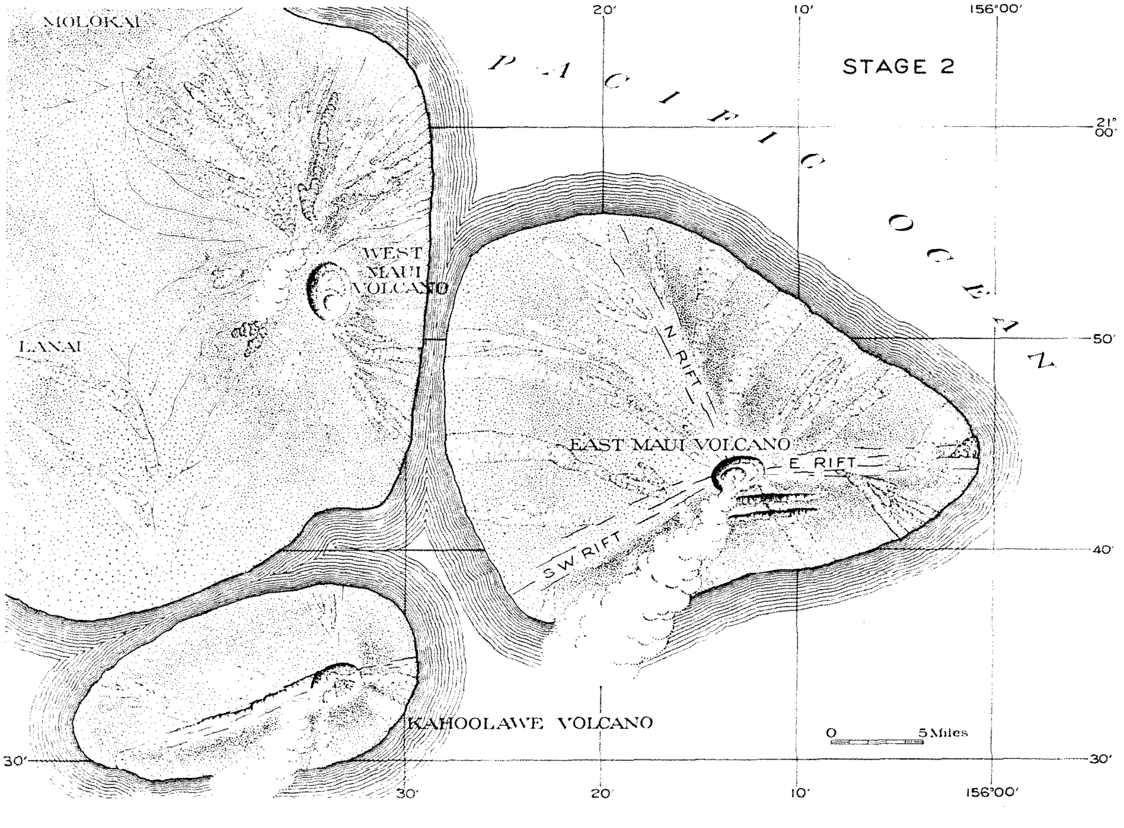
26B. Silhouette of stage 7.

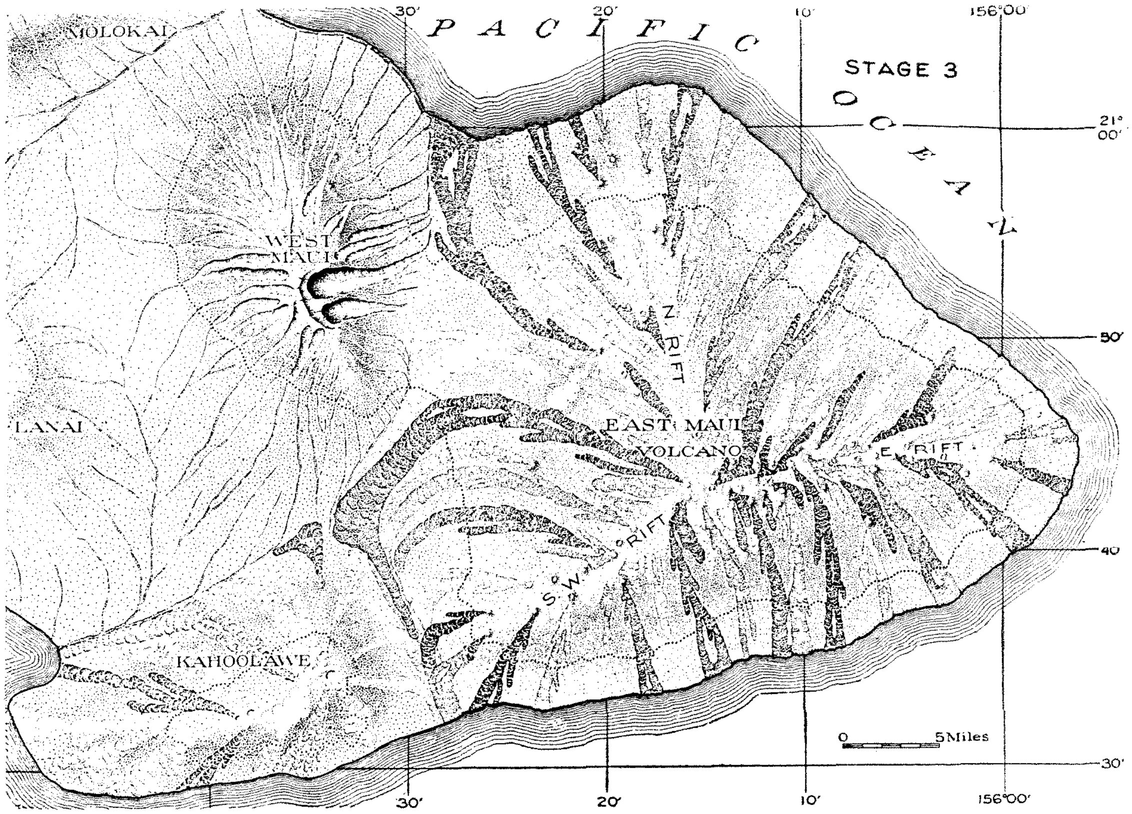
26C. Stage 8, Maui at the present time.

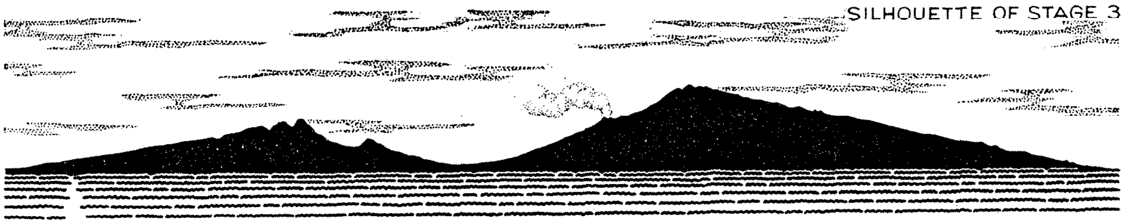
(Silhouettes are sections of Maui where important changes have occurred.)

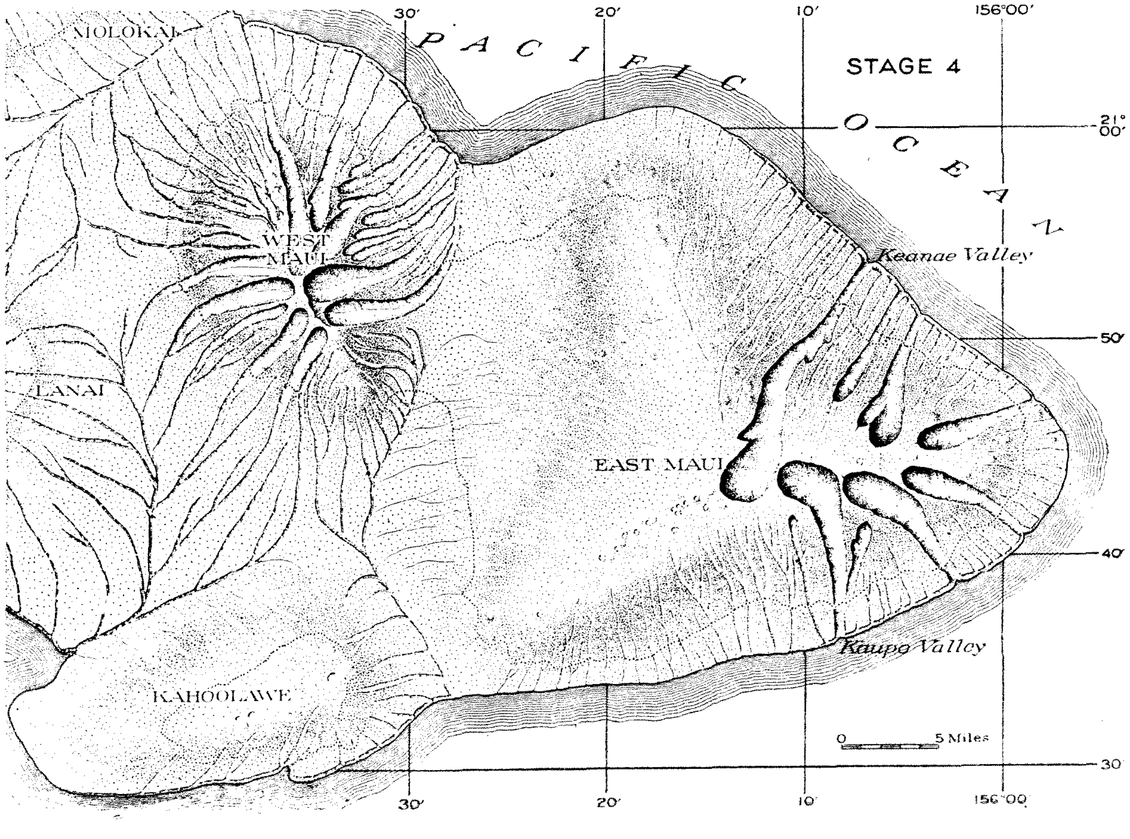

STAGE 1
PACIFIC OCEAN
MOLOKAI VOLCANO
WEST MAUI VOLCANO
N RIFT
S RIFT
LANAI VOLCANO
EAST MAUI VOLCANO
N RIFT
E RIFT
S.W. RIFT
KAHOOLAWE VOLCANO
0 5 Miles
40'
30'
20'
10'
156°00'
21° 00'
50'
40'
30'

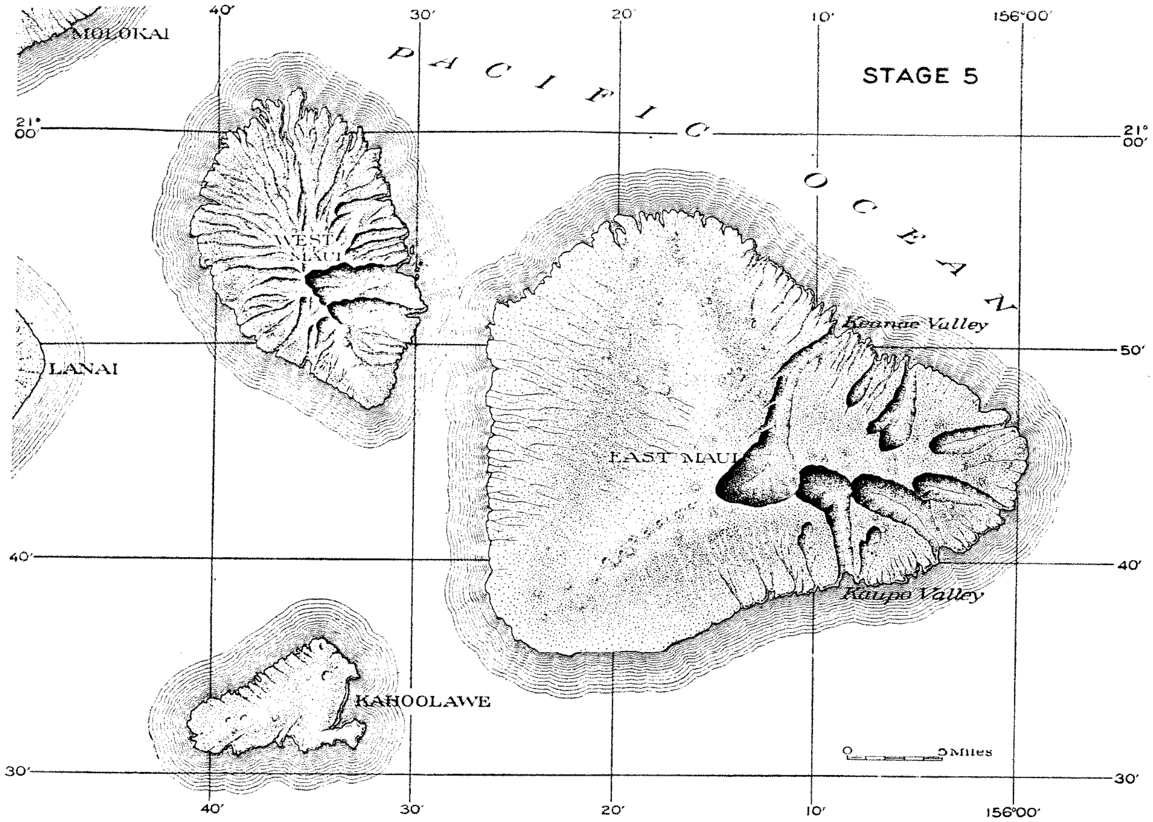

SILHOUETTE OF STAGE 1

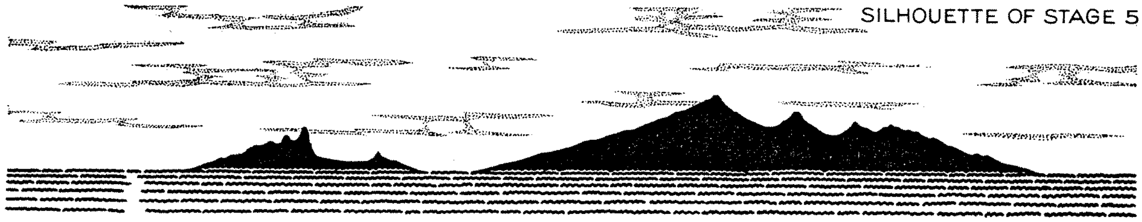

STAGE 2
PACIFIC OCEAN
MOLOKAI
LANAI
WEST MAUI VOLCANO
EAST MAUI VOLCANO
N RIFT
E RIFT
S.W. RIFT
KAHOOLAWE VOLCANO
0 5 Miles
20'
10'
156°00'
21° 00'
50'
40'
30'
30'

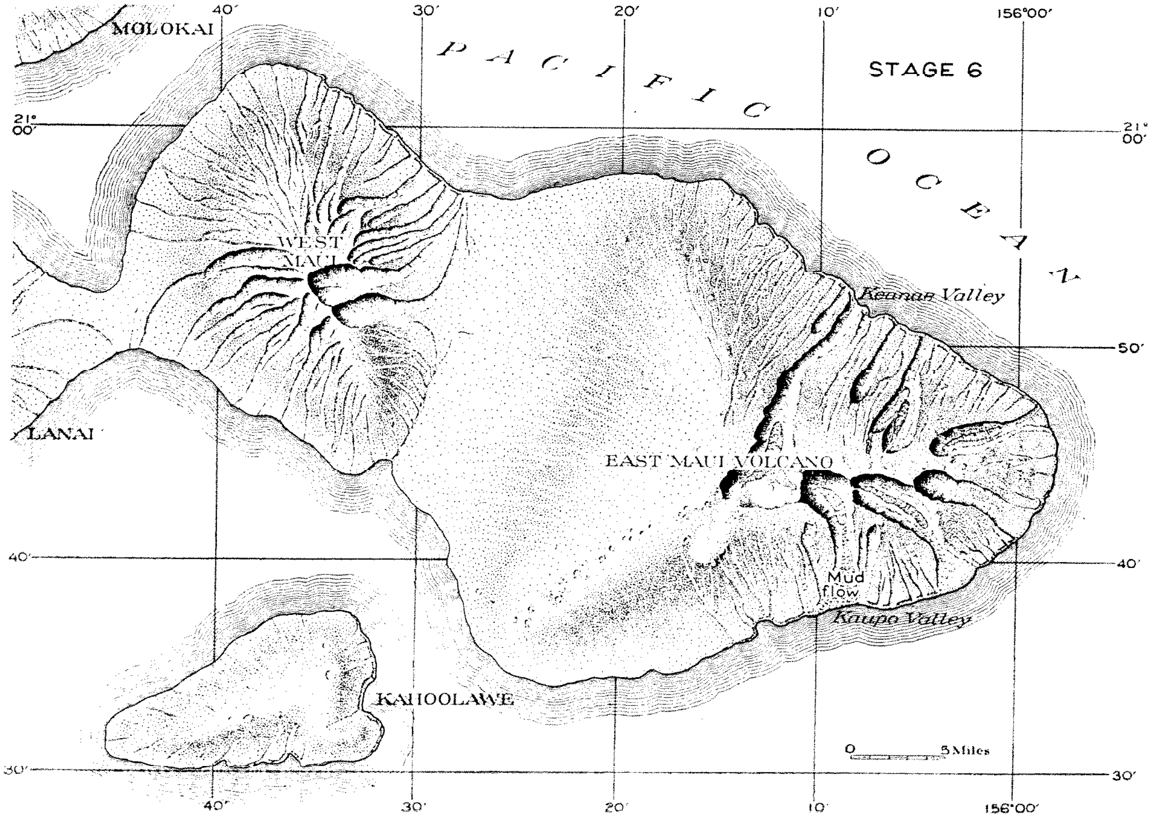

STAGE 3
PACIFIC
OCEAN
MOLOKAI
WEST MAUI
LANAI
KAHOOLAWE
N. RIFT
EAST MAUI VOLCANO
E. RIFT
S.W. RIFT
30′
20′
10′
156°00′
21° 00′
50′
40
30′
0
5 Miles

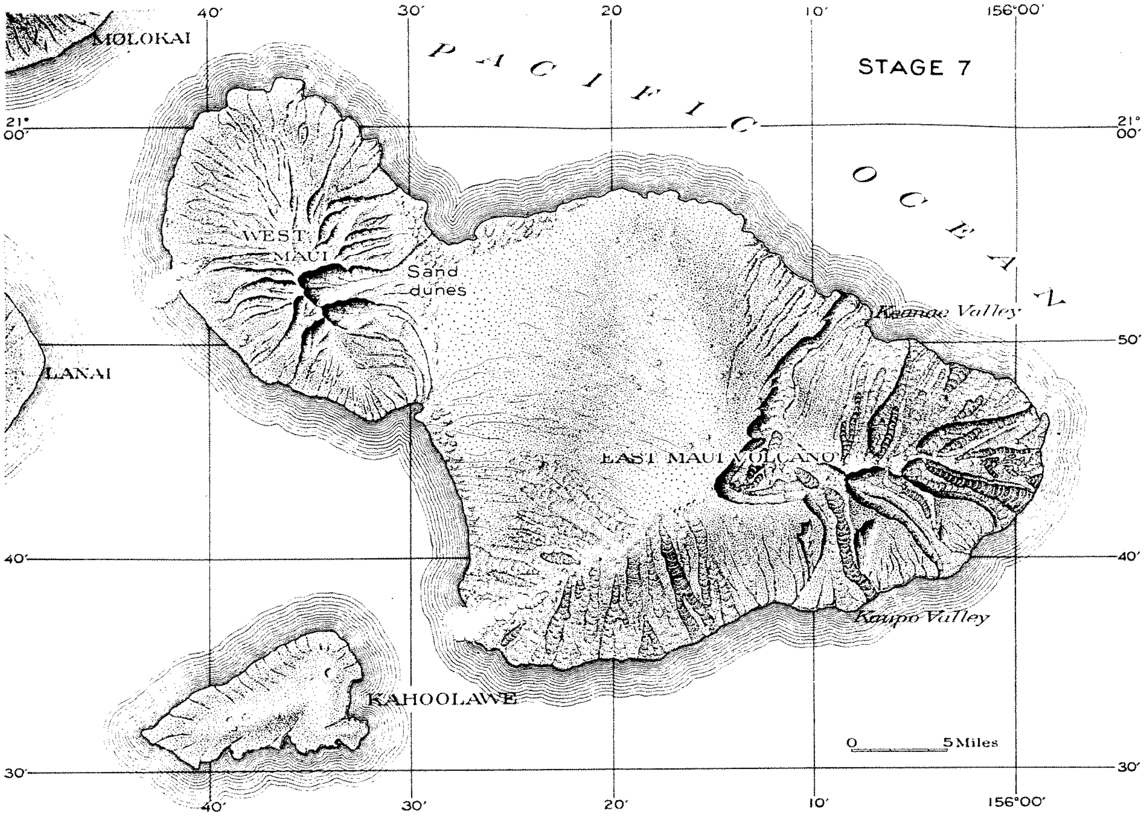

SILHOUETTE OF STAGE 3

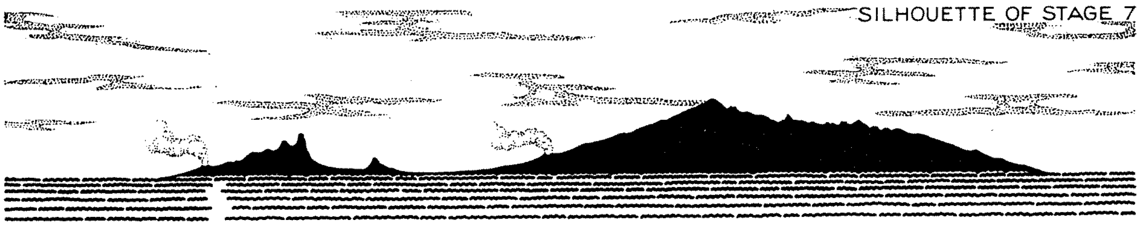

STAGE 4
PACIFIC
OCEAN
MOLOKAI
WEST MAUI
LANAI
KAHOOLAWE
EAST MAUI
Keanae Valley
Kaupo Valley
30′
20′
10′
156°00′
21° 00′
50′
40′
30′
0
5 Miles

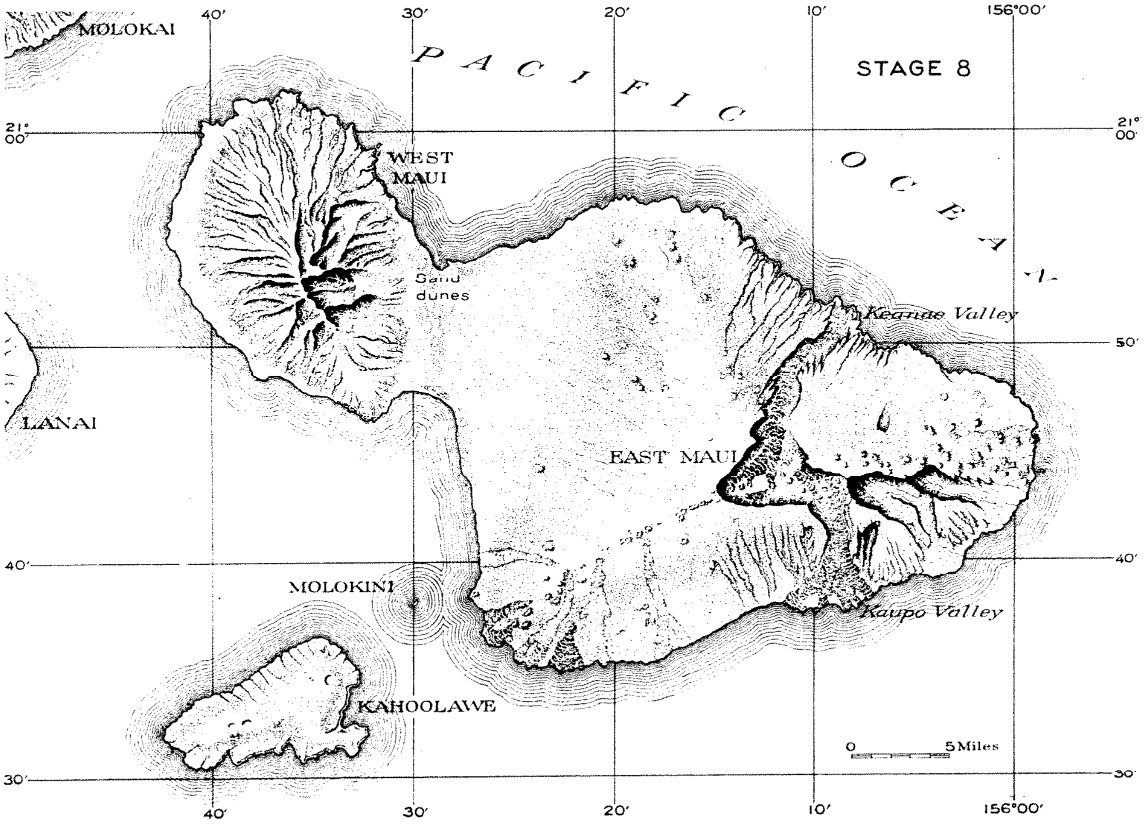

STAGE 5


SILHOUETTE OF STAGE 5


STAGE 6


STAGE 7
PACIFIC OCEAN
MOLOKAI
LANAI
WEST MAUI
Sand dunes
Keanae Valley
EAST MAUI VOLCANO
Kaupo Valley
KAHOOLAWE
0 5 Miles
40′
30′
20
10′
156°00′
21° 00′
50′
40′
30′
20′


SILHOUETTE OF STAGE 7


STAGE 8
PACIFIC OCEAN
MOLOKAI
LANAI
WEST MAUI
Sand dunes
Keanae Valley
EAST MAUI
Kaupo Valley
MOLOKINI
KAHOOLAWE
0 5 Miles
40′
30′
20′
10′
156°00′
21° 00′
50′
40′
30′

ROAD METAL

The massive flows and valley fills in the Hana and Kula formations are quarried extensively. The largest quarry is east of Puunene in a massive Kula lava bed lying in Kalialinui Gulch at an altitude of 250 feet. This bed breaks into huge blocks, some of which were used to build the breakwaters at Kahului, Maui, and at Port Allen, Kauai. Residual boulders of Kula lava, gathered from adjacent cane fields, are crushed at Puunene, Paia, and Kihei. A heavy ledge of basalt suitable for quarrying is exposed half a mile east of the Kihei crusher in the south bank of Kulanihakoi Gulch. The valley-filling lava of Kula age at Honopou Gulch, and the Piinaau lava of Kula age at Keanae, are quarried extensively. Kula lavas were quarried for road metal in several places along the Kula and Haleakala Crater roads. A crusher was standing at the quarry in 1941 where the lower Kula road crosses the south fork of Kalialinui Gulch.

Loose aa clinker dug from road cuts is used extensively for surfacing unpaved roads. Many caves and short tunnels on the road to Hana originated in this manner. They are sometimes mistaken for natural lava tubes. Kaeleku Sugar Co. is surfacing its roads with a peculiar aa of late Hana age obtained north of Hana Bay. When pushed with a bulldozer the aa shatters into fragments ranging in diameter from ½ to 3 inches. The rock is used without crushing. The aa that is quarried lies above tide, but the lava poured into the sea at this place. Steam rising through the lava as it congealed may have shattered it. No similar aa is known elsewhere. It does not contain pillows, but pillows may exist in the part that congealed below sea level.

Cinders are quarried by the H. C. & S. Co. for road metal in Puu Hele, a cinder cone near Maalaea Bay.

Gravel and sand of good quality derived from lava are scarce. They are quarried from the mouth of Kulanihakoi Gulch near Kihei and from the beach of Honomanu Bay. Other beaches between Keanae and Nuu contain workable quantities of dense blue lava rock gravel. Some would justify crushing for road metal should there be construction nearby. Calcareous sand from Lower Paia beach is used for surfacing secondary roads in that vicinity. It is also burned for lime.

GROUND WATER IN EAST MAUI

BASAL WATER IN EAST MAUI LAVA ROCKS

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 of the island.[67] It is the unconfined ground water occurring in the lavas under all the island except the rift zones (pl. 12) and in the permeable sediments near the coast. Thus, the term is not used to include the water in the dike complexes.

PERMEABILITY OF THE LAVA.—The cavities and crevices within and between the lava flows form the greatest underground reservoir on Maui. In order of their potential yield, they are (1) interstitial spaces in clinker, (2) cavities between beds, (3) shrinkage cracks, (4) lava tubes, (5) gas vesicles, (6) cracks produced by mechanical forces after the flows have come to rest, (7) tree-mold holes.

Lava tubes 10 feet or less in diameter are common and have been encountered in many infiltration tunnels of the wells. They yield water so abundantly that they greatly reduce the length of tunnel necessary. A tube 6 feet high was encountered in well 28 about 35 feet above the water table. It proved very useful during the excavation of the infiltration tunnels. Water discharged into the tube from the pumps at the rate of 5 million gallons a day while dewatering did not fill it. Lights and a ladder have been installed to make it accessible from the pump room for visitors. The lower Waianapanapa cave at the shore near Hana is a lava tube filled with fresh water.

The Honomanu basalts are extremely permeable. They resemble the Lanai,[68] Koolau, and lower Waianae basalts[69] in this respect. H. C. & S. Co. wells 15, 18, 20, 22, 23, 25, and 26, however, have encountered the more massive andesitic types of lavas of the Kula formation in the zone of saturation. Well 25 required 1,000 feet of tunnel through massive rock to develop 20 million gallons a day, compared with well 16 in Honomanu basalt, which required only 548 feet of tunnel to develop 40 million gallons a day. Well 14 has 1,582 feet of tunnel which yields only about 7 million gallons a day. The balance of the yield is supplied by drilled wells. It has been found economical to drill test borings prior to the construction of Maui-type wells to determine whether the permeable Honomanu basalts rather than the less pervious Kula lavas lie just below the

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[67] Meinzer, O. E., Ground water in the Hawaiian Islands, in 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. 10, 1930.

[68] Stearns, H. T., Geology and ground-water resources of the islands of Lanai and Kahoolawe: Hawaii Div. of Hydrography, Bull. 6, p. 75, 1940.

[69] Stearns, H. T., and Vaksvik, K. N., Geology and ground-water resources of the island of Oahu, Hawaii: Hawaii Div. of Hydrography, Bull. 1, p. 93, 1935.

water table. In some wells, where dense lavas lie at the water table and more permeable basalt lies not far below, water is developed by drilling wells through the dense rock to the basalt.

When the pumps are running at well 15, some water pours into the sump from cracks 4 feet above the water level in massive Kula pahoehoe. This indicates lower permeability than is usual in most basalts. Additional data on the low permeability of the Kula lavas are given on pages 85 to 88.

RELATION TO UNDERLYING SALT WATER.—The lavas are always saturated with either fresh water or salt water or both for an unknown depth below sea level. The fresh water extends to different depths in different localities, depending upon the recharge and geologic structure. Test hole 108, altitude 120 feet, near the center of the Isthmus, started in water with 40 grains of salt per gallon and penetrated progressively saltier water until at a depth of 400 feet, where the hole ended, the water contained 1,950 grains of salt per gallon.

Fresh water floats on sea water and is separated from it by a transitionary zone of mixture. The salt content in all wells drilled into the basal zone of saturation in the other islands also increases with depth. Permeability of rocks, distance from coast, height of tides, rates of discharge and recharge, and other factors influence the rate the salt increases with depth and the thickness of the zone of mixture. The rate of increase with depth in test hole 106 at Kahului is shown by the following data.

Salt content in test hole 106

(Altitude, 5 feet; water level, 3.24 feet. Analyses made in laboratory of H. C. & S. Co. Samples obtained by R. E. Hughes by pumping from a pipe lowered progressively into the hole on May 22, 1936.)

Depth (ft.)	Grains per gallon	Depth (ft.)	Grains per gallon	Depth (ft.)	Grains per gallon
93	45.6	115	48.4	136	1,417.6
94	43.6	116	48.2	137	1,488.0
95	47.6	117	48.6	138	1,545.0
96	46.0	118	48.8	139	1,609.6
97	45.6	119	67.2	140	1,644.8
98	45.6	120	172.8	141	1,700.0
99	46.0	121	281.6	142	1,692.0
100	46.0	122	460.8	143	1,670.0
101	46.8	123	736.0	144	1,683.0
102	47.2	124	908.8	145	1,683.0
103	48.4	125	937.6	146	1,696.0
104	47.6	126	928.0	147	1,699.0
105	44.0	127	954.0	148	1,710.0
106	47.6	128	953.6	149	1,712.0
107	47.6	129	976.0	150	1,733.0
108	48.4	130	972.8	151	1,754.0
109	48.0	131	995.2	152	1,760.0
110	48.0	132	1,027.2	153	1,757.0
111	48.0	133	1,116.8	154	1,758.0
112	48.0	134	1,212.8	155	1,760.0
113	48.0	135	1,318.4	156	1,768.0
114	48.2				

The following statement about Oahu applies equally well to Maui:

> Salt water probably filled the interstices in the rocks concurrently with the building of the volcano above sea level. Rain water percolating downward through the porous lava floated upon the salt water because of its lower specific gravity. When the island was small this rain water percolated laterally and quickly discharged into the sea, but as the island grew larger the friction increased in proportion to the distance the water had to move to reach the sea. Moreover, because the salt water in the interstices of the island is not a rigid body, but is in hydrostatic equilibrium with the adjacent ocean level, the fresh water disturbed the equilibrium and caused the surface of the salt water to sag until the body of combined fresh and salt water in the rocks was in equilibrium with the sea.[70]

GHYBEN-HERZBERG PRINCIPLE.—The Ghyben-Herzberg principle[71] of the behavior of fresh water in contact with salt water in a pervious formation is illustrated in figure 16 and is expressed by the following formula:

> Let H equal total thickness of fresh water.
> h equal depth of fresh water below sea level.
> t equal height of fresh water above mean sea level.
> Then H equals h plus t.
>
> But the column of fresh water H must be balanced by a column of salt water h in order to maintain equilibrium. Wherefore, if g is the specific gravity of sea water and the specific gravity of fresh water is assumed to be 1, $H = h + t = hg$, whence
>
> $$h = \frac{t}{g - 1}$$
>
> In any case, $g - 1$ will be the difference in specific gravity between the fresh water and the salt water.
>
> The average specific gravity of the ocean adjacent to Maui is unknown, but off Oahu[72] it is 1.0262 at 22° C., using the specific gravity of fresh water at 22° C. as 1. Using this specific gravity, $h = 38.5t$. Other factors such as the change in density of the ocean with depth make this value approximate only, hence $h = 40t$ is in common use. If fresh water stands 2 feet above sea level in a well, the depth of fresh water below sea level will be theoretically about 80 feet. Because of diffusion and mixing, the actual depth of fresh water is less than the theoretical depth.

FORM OF THE WATER TABLE.—The basal water table lies near sea level and has only a slight gradient, as in other islands of Hawaii (pl. 12). The water table in the basalt rises from both sides of the

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[70] Stearns, H. T., op. cit. (Bull. 1), p. 237.

[71] Badon Ghyben, W., Nota in verband met de voorgenomen put boring nabij Amsterdam: K. inst. ing. Tijdschr., 1888-89, p. 21, The Hague, 1889.
Herzberg, A., Die Wasserversorgung einiger Nordseebader: Jour. Gasbeleuchtung und Wasserversorgung, Jahrg. 44, Munich, 1901.

[72] Wentworth, C. K., The specific gravity of sea water and the Ghyben-Herzberg ratio at Honolulu: Hawaii Univ. Bull., p. 12, 1939.

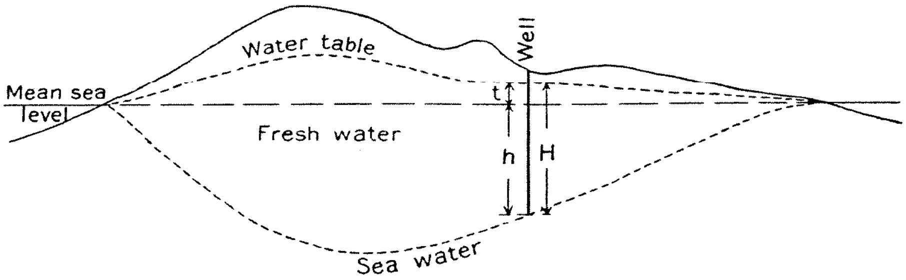

Figure 16. Section of the island of Norderney, Germany, showing the application of the Baden Ghyben-Herzberg theory. (From Herzberg.)

Isthmus toward the middle, where it reaches an altitude of 5.5 feet, equivalent to a gradient of 1.8 feet per mile. It rises 1.5 feet per mile to well 27 and 2 feet per mile to well 15. The gradient in the unconsolidated sediments along the coast is practically the same as in the basalt, indicating that these rocks also are exceedingly permeable.

The basal water table does not extend under the entire mountain but surrounds the dike complex, which contains confined water in many places several hundred feet above sea level (pl. 12). The altitude of the basal water table next to the dike complex is not known, but is probably only 15 to 20 feet higher than along the shore.

FLUCTUATIONS IN WATER LEVEL.—The water level in the wells fluctuates in response to changes in rainfall, tides, and draft, and under irrigated areas to changes in the amount of surface water applied to the land.

Annual fluctuations range from an inch to 2 feet, but fluctuations of more than half a foot are unusual and indicate tremendous changes in the volume of ground storage. The water level in the H. C. & S. Co. wells fell 10 inches during the dry year of 1935. Mr. R. E. Hughes reports that it was several inches lower during the drought of 1933 than during 1935. Annual static water levels on December 31, 1937-40, follow:

Water levels in H. C. & S. Co. wells at end of each year, 1937–40

U.S.G.S. number	H. C. & S. Co. number	Water level in feet above sea level			
		1937	1938	1939	1940
14	Pump 1	4.23	4.04	4.55	4.55
15	3K	6.83	6.61	6.95	6.67
16	7	5.85	5.67	5.93	5.54
18	6	5.13	4.92	5.30	5.37
19	5	4.50	4.34	4.57	4.53
21	3 old	4.52	4.43	4.45	4.08
24	4	3.17	3.02	3.47	3.32
25	2	5.25	5.14	5.06	5.20

The annual peak usually occurs in the early spring and the annual low in the late fall. The annual fluctuation results chiefly from cessation of pumpage, which is generally concurrent with increased rainfall. The immediate recovery in irrigated areas at the beginning of a wet spell is caused chiefly by cessation of pumping. A rise due to recharge from rainfall takes several days.

In addition to the annual fluctuation the water level rises and falls slowly over a period of several years. Such secular fluctuations are also in response to rainfall and draft. Thus, the water level fell from 1933 to 1935 due to a protracted drought, but recovered again in response to the wet years of 1936-38.

The amount of fluctuation due to pumping varies with the proximity of the observation well to the pump and the quantity of water being pumped. The water level in wells that are pumped heavily declines precipitously when the pump is started. The permeability of the rocks is so great and the reservoir so large that the decline is extremely slow after the first few minutes. Well 16 declines only 2.5 feet with draft of 40,000,000 gallons per day. The water table under the Isthmus declines from 0.5 to 1.0 foot annually from pumping, depending on the seasonal draft (fig. 17).

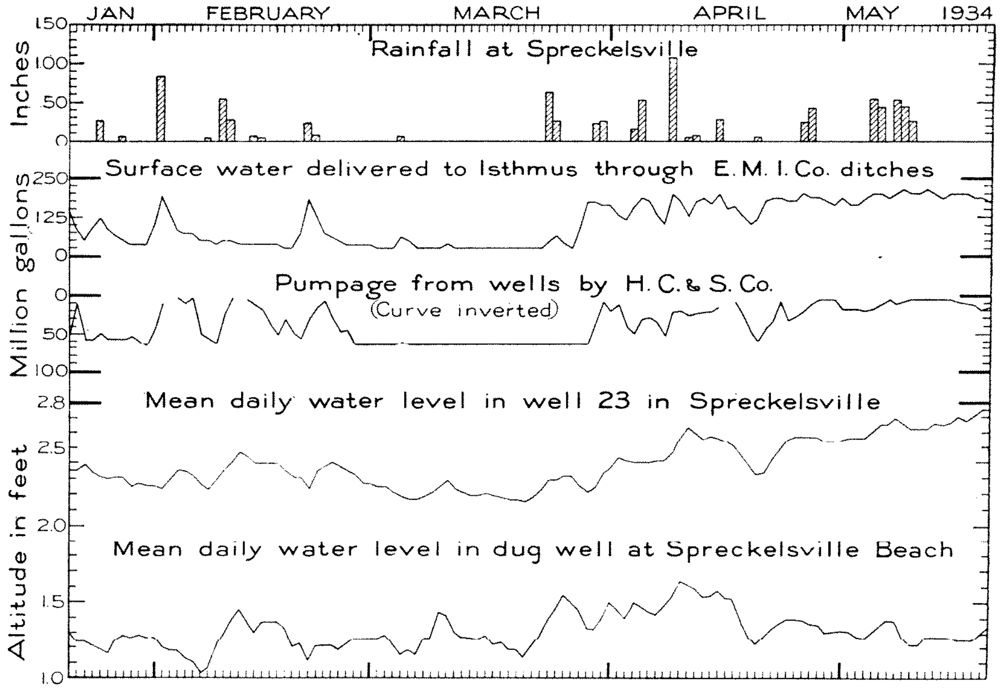

Figure 17. Graphs showing fluctuations of the water in well 23 at Spreckelsville on the Isthmus in relation to pumpage, rainfall, and ditch deliveries. The dug well is in loose sand at the beach where tidal effects are pronounced.

The tidal range of the ocean about Maui averages 2 feet. Tidal fluctuation in water levels in wells varies with the permeability of the rock and the distance from the sea. The tide causes fluctuations of about 1 foot only in wells in loose sand 100 yards from the beach. Automatic recorders were maintained during nonpumping periods in 1934 on the M. A. Co. wells. Tidal fluctuations were found to travel inland at the rate of 1,000 feet per 15 to 20 minutes, depending upon the magnitude and frequency of the tides. Typical tidal fluctuations are shown in figure 18. They are barely perceptible in wells 15,000 feet from the coast. The amount of movement of the water level as a result of certain tidal fluctuations moving inland is shown in figure 19. It was found that large fluctuations die out more slowly inland than small ones; also that large low tides pass inland as readily as large high tides. The large P fluctuation in figure 19 was 32 precent as large at well 28 as at well 30, compared with the small J fluctuation, which was only 18 percent.

Fluctuations due to recharge from rainfall and irrigation seepage are obscured by pumping and tidal fluctuations. Large ditch deliveries and heavy rains mean reduced pumpage, and because the water levels respond more rapidly to cessation of draft than to either rainfall or ditch deliveries, the effect is obscured (fig. 17). The E. M. I. Co. delivered more water to the Isthmus through its ditches in 1936 than in any year since 1879, when it was founded. Following the drought of 1935 the ditch water did much to bring the water level under the Isthmus back to normal. If 25 percent of the 91,309 million gallons[73] of ditch water delivered in 1936 was seepage, then 22,800 million gallons reached the zone of saturation. This is 50 percent of the average annual pumpage of 45,500 million gallons from wells on the Isthmus.

The M. A. Co. ran surplus ditch water into leaky reservoirs and down gulches near wells in 1935 to recharge the basin artificially. The company succeeded in decreasing the salt and raising the static level in that area.

Effect of draft on quality.—The salt content in every well responds to a greater or lesser degree to pumping. As pumpage has increased in the last decade, the salt content has risen to such an extent that most of the wells along the shore have been replaced with new ones dug farther inland. The infiltration tunnels in others have been lengthened to reduce the salt content. The average annual salt content in the table (p. 222) reflects, in addition to changes in

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[73] Includes H. C. & S. Co. ditch from Waihee Stream on West Maui but excludes all ditch water used by W. S. Co., a small part of which may find its way to the wells in the west side of the Isthmus.

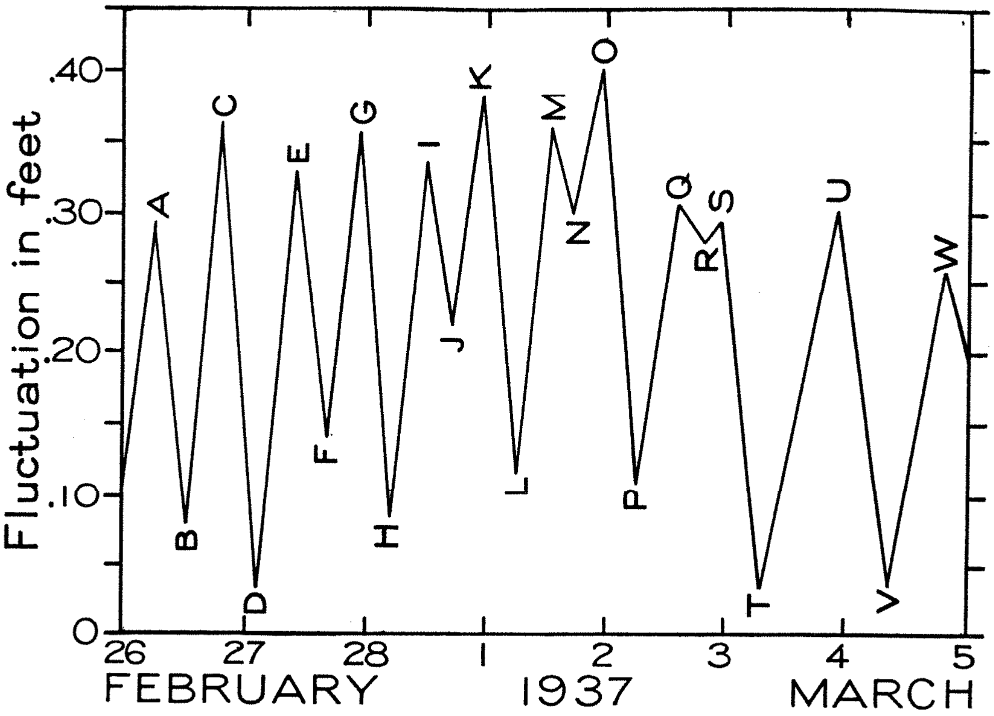

Figure 18. Tidal fluctuations in well 30 at Lower Paia.

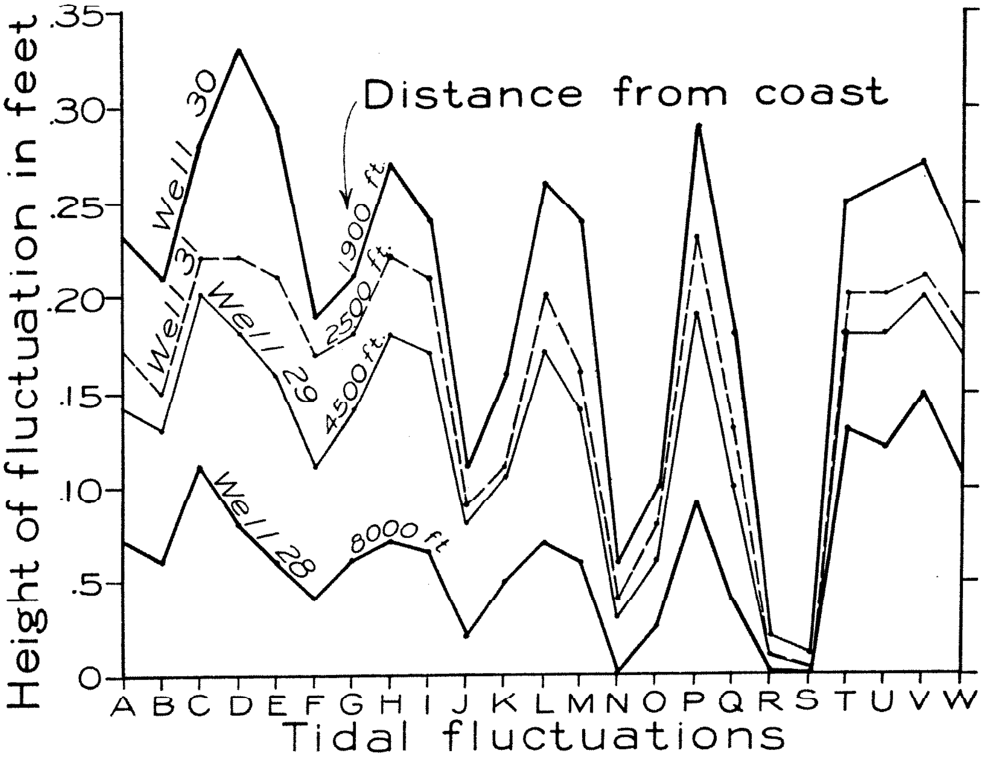

Figure 19. Graph showing decrease in tidal fluctuations moving inland, East Maui. Letters A to W designate successive crests and troughs of tidal fluctuations.

draft concurrent with variations in rainfall, the effect of these improvements. The average salt content in grains per gallon on the H. C. & S. Co. plantation rose with increased draft from a low of 59 in 1914 to a high of 83 in the dry year of 1926. It fell to an all time low of 39 in 1941, in spite of the fact that pumpage has been increased about six times since 1914 (fig. 20). This shows the success of the improved methods of recovering the water.

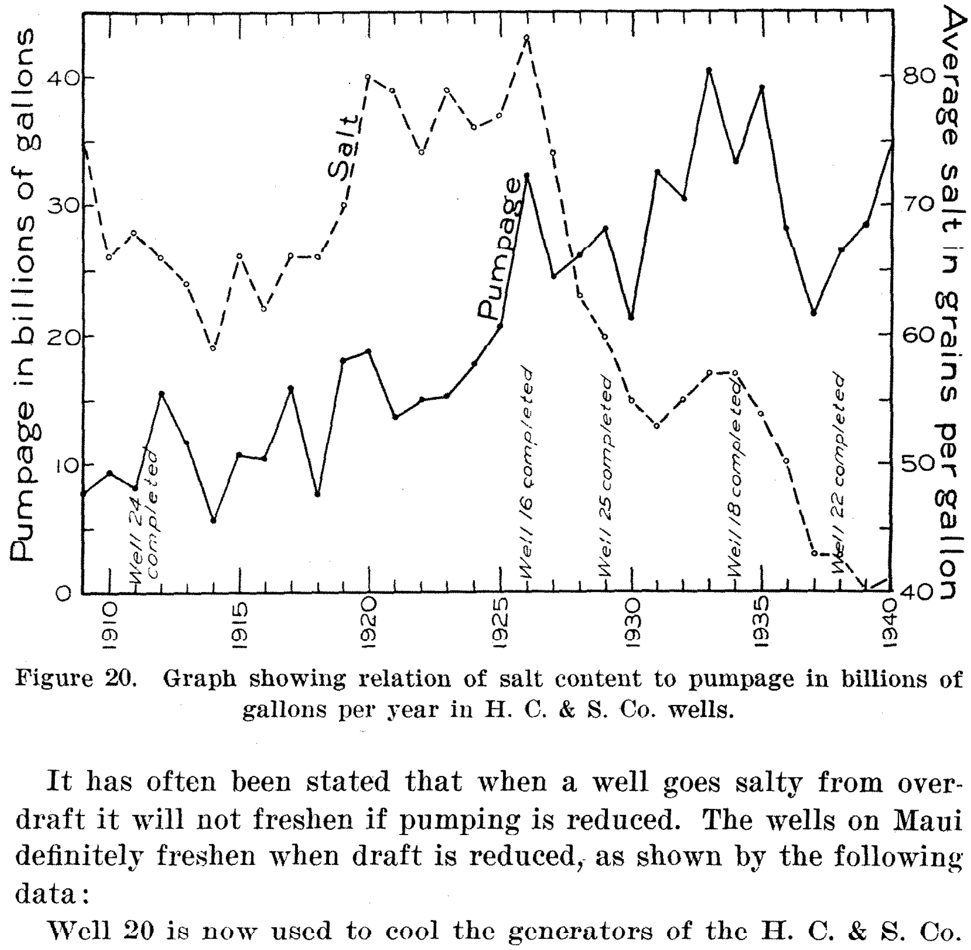

Figure 20. Graph showing relation of salt content to pumpage in billions of gallons per year in H. C. & S. Co. wells.

It has often been stated that when a well goes salty from overdraft it will not freshen if pumping is reduced. The wells on Maui definitely freshen when draft is reduced, as shown by the following data:

Well 20 is now used to cool the generators of the H. C. & S. Co. central power plant. Prior to 1916 it was equipped with a 4-m.g.d. steam pump. The water was formerly used for irrigation after it left the generators and averaged about 40 grains of salt per gallon. The station was converted, in 1916, to an electrically driven 12-m.g.d. pumping plant. The station then contained two wells that ended 50 feet below sea level in the sump and tunnels that extended 10 feet northward, and 75 feet southward. In 1916, an additional 40 feet were added to the south tunnel and at its new heading a well was drilled to a point 50 feet below sea level. The salt content slowly increased to 122 grains per gallon in 1920, when the water became too brackish for irrigation. A 5-m.g.d. circulation pump was added in 1925. In 1926, the south tunnel was extended 30 feet, and an east lateral 60 feet long and a west lateral 80 feet long, each with two drilled wells, were added to reduce the salt content. The pumpage was increased to 15 m.g.d. and the salt content rose to 150 grains per gallon. The water was not used for irrigation after 1929, but was wasted into the adjacent swamp. The well is still being pumped at various rates depending upon the demand but when pumped at the rate of 10 m.g.d. the salt content hovers about 90 grains per gallon. The well freshens even more when pumped at the rate of 5 m.g.d.[74]

The lower Paia pumping station of the M. A. Co. (well 30) has had a similar history. Tunnels have been extended during dry years to counterbalance increased draft from new wells sunk inland from the station. Finally one of the pumps was moved inland to well 27, thereby reducing draft from well 30. The relation of the salt content to the water level and to pumpage from well 30 is shown in figure 21.

The average salt content at well 19 varies from 60 to 73 grains per gallon with a draft of 24 m.g.d. The four supplemental drilled wells, that ended 40 to 45 feet below sea level in the sump, were plugged in 1926 as they yielded water containing 90 to 110 grains per gallon. Eighty feet of tunnel that yielded 8 m.g.d. with a salt content of 60 grains per gallon were substituted. A lava tube was encountered at the heading of the tunnel that yielded about 3.5 m.g.d. This inflow caused the water surface of the well to rise 2.5 feet during pumping.

Meinzer was told in 1920 that additional pumping sometimes decreased salt content[75] in the Isthmus wells. His informant probably failed to consider changes in draft from wells nearby, as careful observations do not support his statement. Well 24 was completed in 1911. The salt content dropped from 100 grains in 1911 to 78 grains in 1925, to 64 grains in 1929, and to 50 grains in 1932. Decreased pumpage from well 23 nearby and increased quantities of stream water delivered for irrigating the adjacent land were chiefly responsible for the change. One pump in well 23 was removed in 1920 and the other in 1929. Its salt content averaged 71 grains per gallon in 1929 and only 45 grains per gallon in 1931 after two years of disuse. The salt content dropped 12 grains in well 26 during the year following the shut down of no. 23. Well 23 was closer to the

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[74] Oral communication, R. E. Hughes, December 14, 1941.

[75] Op. cit., p. 14.

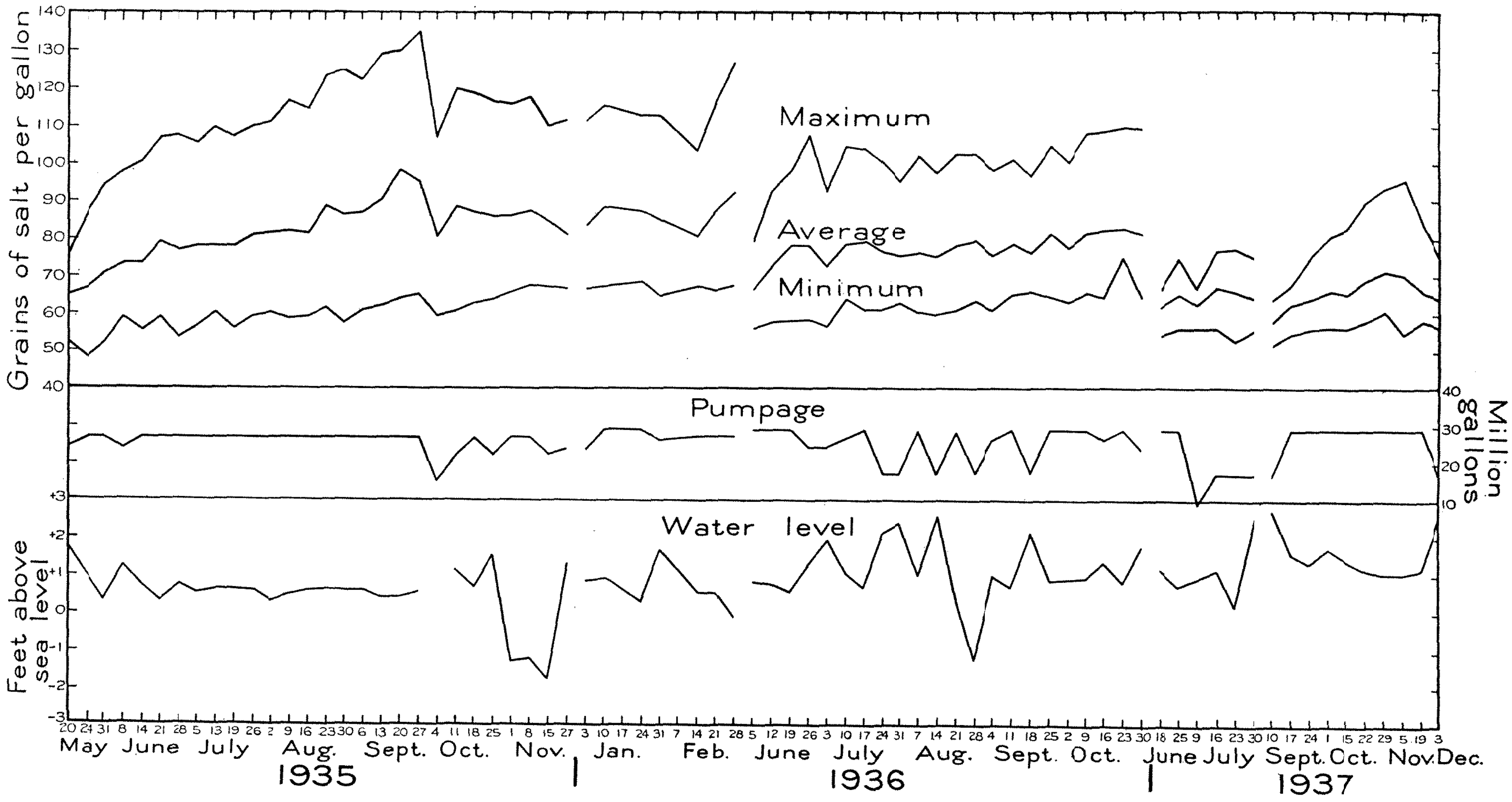

Figure 21. Graph showing relation of pumpage, salt content, and water level in well 30 at Lower Paia. (After H. J. Eby.)

beach than 26 and stirred up the underlying salt water. It probably also drew some of the water away from well 26.

Small clinker particles derived from the unlined floor and walls of the tunnels may gradually freshen wells by sealing cracks in the sump and tunnel floors, and thereby reducing the direct upward flow of saltier water from below. The particles may fall into drilled wells, thereby reducing their yield. The water discharged by the wells is usually saltier than the water being skimmed by the tunnel. A 12-inch drilled well in the sump of well no. 14 was yielding 2 million gallons a day with a salt content of 90 grains per gallon when the sump was pumped. The water from the drilled well forms a dome 6 inches above the water level of the sump and surges violently in its rush to escape. Mr. Hughes reports that because of its high salt content he plugged it temporarily to determine whether it could be abandoned. When the plug was pulled the loose clinker on the sump floor rolled into the well and stopped its flow. Later the well was cleaned out and made to flow again.

The average salt content at pump 25 when not in use is 15 grains per gallon. It rises to 50 grains per gallon or more when being pumped, and the adjacent test wells rise to 60 grains per gallon even when most of their flow is shut off.

MAUI-TYPE WELLS.—Maui-type well is the name applied throughout Hawaii[76] to a mine-like shaft to the basal water table with one or more infiltration tunnels skimming the fresh water off the underlying salt water. The first well of this type was excavated in 1900 on the old Kihei plantation. The fact that this well (no. 15) is still in operation and that wells of this type have been utilized so successfully, even to the extent of replacing the artesian wells in the Honolulu city supply,[77] establishes the soundness of this method for recovering basal water in Hawaii. Meinzer recognized the advantages of the Maui-type well two decades ago.[78]

Constructional and engineering difficulties inherent in the development of a unique well were costly. Expenses were carried by the Kihei Plantation Co. and are said to have led to its bankruptcy. Miners were brought from the mainland and paid $10 per day, a high rate at that time, to excavate the shaft and tunnels. The fly wheels for the pumps were 12 feet across. This size necessitated the construction of a special building at the factory on the mainland to make them. They were made in 6 sections so that they might be

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[76] Stearns, H. T., op. cit. (Bull. 1). pp. 324-325; Supplement to the geology and groundwater resources of the island of Oahu, Hawaii: Hawaii Division of Hydrography, Bull. 5, pp. 6-9, 1940.

[77] Idem (Bull. 5), pp. 26-29.

[78] Op. cit. p. 15.

lowered through the shaft. Remains of the old equipment still exist in the bottom of the well, and they make the present 1900-hp electrically driven pumps look puny indeed. Even though the coal-burning steam engines to drive the pumps were at the surface, the temperature in the underground pump room is reported to have been 120° F., due to lack of proper ventilating equipment. The pumping station is reported to have cost $1,000,000.[79]

Most of the technical improvements in this type of well have been made on Maui due to its extensive use there. It was early discovered that wells drilled 20 to 50 feet below sea level in the bottom of the Maui-type well shaft and at points along the infiltration tunnels would greatly increase the yield and reduce the amount of tunnel required. As draft has increased it has been found expedient to plug some of the deeper wells in order to reduce the salt content. It was soon found that wells yielding excessively large volumes of water would commonly have the highest salt content. This resulted from too great a local doming of the zone of salt water under the well.

The engineers on the Maui plantations found it advantageous, when the compact electrically operated equipment became available for deep shafts, to excavate new wells as far inland as possible also, where the water table was higher and the danger of salt-water encroachment less. C. A. Brown, engineer of the Pioneer Mill Co., was the first to use an inclined shaft in Hawaii as a means of reducing the cost of construction and equipment.[80]

Maui still holds the distinction of having the well with the largest yield in the Territory and the deepest vertical shaft. The well is no. 16 (H. C. & S. Co.) with a capacity of 40,000,000 gallons per day and the shaft is no. 27 (M. A. Co.) with a depth of 552 feet.

Records of the Maui-type wells both abandoned and in operation on East Maui are on page 216. Some of those listed with dates earlier than no. 15 were shallow dug wells and subsequently were made into Maui-type wells. Records of the annual pumpage and average salt content of water from these wells are on pages 218–222. Cost of pumping is given on page 216.

Ancient Hawaiian wells.—The ancient Hawaiians obtained water from springs, natural water holes, and wells near the beaches. They spread sheets of oiled tapa (cloth made from the bark of trees) to catch the dew and rain. The sites for wells were presumably located by noting springs at low tide along the coast or by tasting water in cracks along the coast. Two types of wells were made. One

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[79] Oral communication, F. F. Baldwin, December 19, 1941.

[80] Stearns, H. T., op. cit. (Bull. 5) for summary of advancements made in construction of Maui-type wells see pp. 11-13.

type was made by blocking crevices in the lava with rocks, mud, and straw on the seaward side to prevent the inflow of sea water. Large rocks were placed in position for steps to make access easier. The other type was made by excavating loose clinker in aa to the basal water near the beach, as shown in plate 27A. Such wells were lined with big boulders if necessary to keep the clinker from caving. The water in many Hawaiian wells is too brackish to drink, if one is not accustomed to it, but the Hawaiians are noted for their ability to drink brackish water.

Basal springs.—The sand beaches between Paia and Kahului and to a lesser extent along Maalaea Bay are cut by thousands of closely spaced rivulets each heading in a miniature cove a few inches to 1½ feet deep during very low tides (pl. 27B). The water is derived from the adjacent lavas. The discharge of the springs near Spreckelsville was estimated on such tides to be at the rate of 2,000,000 gallons per hour per mile of coast. They flow at this accelerated rate about 6 hours per day during such tides. The water is fresh to brackish and is basal water being lost from the Isthmus basin. Similar springs discharge from rocky stretches along the entire coast, but are less visible. Basal water runs into the sea at all times, but the rate of loss gradually increases as the tide goes down, and then slowly decreases as the tide rises.

About 5,000,000 gallons a day of spring water issues at the mouth of Honomanu Valley. The two largest springs are shown on plate 1. The western one issues 3 feet above the stream bed at an estimated altitude of 15 feet from coarse talus at the foot of a cliff of Honomanu basalt. It has a temperature of 64° F. most of the time and yields about 1,000,000 gallons per day. About 2,000,000 gallons per day seeps into the stream bed between this spring and the sea.

The eastern spring shown on plate 1 issues at an altitude of 15 feet as determined by levels run by David Summers. It yields about 2,000,000 gallons per day. An artificial terrace cut into the spring exposes a peculiar pyroclastic deposit composed of small irregular and vesicular fragments of aphanitic basalt containing scattered blocks reaching 8 inches across of porphyritic and nonporphyritic basalt coated with ¼ to 1 inch of aphanitic basalt. Such blocks are commonly formed by talus falling into liquid lava. The base of the deposit is not exposed. It is 30 feet thick above the valley floor and is overlain by porphyritic feldspar pahoehoe of the Honomanu series. The pyroclastics do not outcrop at the sea. They may be related to those exposed along the road nearby (p. 71).

The source of the Honomanu Springs is enigmatic. The water could be from the Honomanu series. If so, it is puzzling why the water does not escape at tide level in the adjacent sea cliffs where highly permeable basalts of this series are exposed. The springs may be supplied by water forced upward from the gravels in the valley-fill due to a decrease in permeability of the fill near the coast, or they may be due to some other cause.

RECHARGE.—The basal zone of saturation is recharged by direct percolation from rainfall, seepage from streams and ditches, and return flow from irrigated fields. About 15 percent of East Maui is composed of such permeable lavas and cinders that no water runs off, no matter how much rain falls. Streams do not reach the sea on about 80 percent of the mountain except during cloudbursts, which occur at most a few times a year and some years not at all. Most of the flood water finds its way to the basal water table. The average annual recharge is roughly estimated to be 300,000 million gallons from rainfall on East Maui, including recharge on the Isthmus from ditch water. The total annual recovery from wells and water-development tunnels is about 47,500 million gallons, indicating that vast quantities are escaping unused into the ocean. The steep slopes along the shore and the absence of a fringing caprock are largely responsible for the waste.

The Isthmus was without trees and covered with drifting sand prior to the planting of cane. Old residents report that red dust storms were nearly a daily occurrence. The climate, topography, and geology of the isthmus connecting East and West Molokai are quite similar to those of the Isthmus of Maui, but a test boring near the center of the Molokai isthmus indicated little ground water as the boring encountered a low water table and brackish water. Except during floods two perennial streams sank in the alluvium bordering the West Maui mountains on the Maui Isthmus prior to their diversion for irrigation. A considerable part of this seepage moved through the alluvium into the sea and did not reach the water table in the lavas under the Isthmus. By analogy with the hydrologic conditions on Molokai, it seems probable that very little water existed under the Maui Isthmus prior to irrigation. If so, the annual pumpage of 45,500 million gallons[81] represents mostly return flow from the 78,271 million gallons[81] of surface water imported for irrigation. The recovery from wells is about 58 percent of the surface-water deliveries. Some of the water pumped from the wells returns to the water table and is repumped.

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[81] Average last 10 years

UNDEVELOPED BASAL SUPPLIES.—The water under the Isthmus proper is too high in salt to be potable. The salt results from mixing due to heavy pumping, and from concentration of the salt by evaporation and transpiration in the seepage from the brackish irrigation water. So many changes have been made in the location of the pumping stations in the last few years that the safe yield of the Isthmus basin cannot be determined accurately. It seems improbable, however, that large additional quantities of water for irrigation can be safely developed there. It will be safe to sink isolated wells to irrigate small areas, such as lawns, airports, or athletic fields, or to supply barracks and camps with water for all purposes except drinking. Test hole 105 at the Baldwin High School encountered water in East Maui lavas 5 feet above sea level which contained 8 to 16 grains of salt per gallon. This water could be used to irrigate the school yard, thereby conserving mountain water for drinking.

Recharge is so small and discharge so rapid along the highly permeable dry rocky coast of the southwest end of Maui, and along the south coast as far as Kaupo, that drilled wells will probably encounter water too brackish for domestic use but satisfactory for stock use if sunk ¼ to 1 mile inland. Maui-type wells to recover potable domestic water would have to be much farther inland. The slope rises so rapidly inland that the great depth of such wells would make them too costly under present economic conditions for the small quantities of water required.

Anywhere east of Maliko Gulch and along the north and east slopes, wells drilled to shallow depths below the basal water table and also Maui-type wells, will recover ample water of excellent quality.

BASAL WATER IN EAST MAUI SEDIMENTARY ROCKS

The shores of the Isthmus are bordered with calcareous beach and dune sand, and unconsolidated earthy silts, sands, and gravels, chiefly delta and lagoon deposits. The silt yields water to wells slowly and is chiefly valuable in serving as a barrier to prevent the rapid escape to the ocean of ground water from the basaltic aquifers under the Isthmus and to prevent the rapid infiltration of sea water.

The well-sorted gravels that underlie Kahului yield water copiously, as shown by the large volumes that have been pumped from sewer trenches in the town. The water at the south and east sides of the town is not potable because it has a salt content of about 30 to 45 grains per gallon. Such water is valuable for air conditioning and industrial use. The water west of town, supplied by Iao gravels, is potable as it carries only 6 to 12 grains of salt per gallon. Test hole 107, near the middle of the Isthmus and 145 feet above sea level in the fan of Waikapu Stream, encountered water 5 feet above sea level with a salt content of 26 grains per gallon. Only loose sand, gravel, and cobbles were encountered.

Dug wells in the coarser earthy sediments along the south shore of the Isthmus obtain sufficient water for irrigating beach lots. The deposits laid down by the streams draining East Maui are fairly clean and well sorted, compared to those deposited by streams from the West Maui Mountains on the west side of Maalaea Bay. The salt content in the dug wells averages more than 50 grains per gallon, and the water table is only slightly above sea level.

Except for the part of the Isthmus next to the East Maui Mountains, the earthy sediments are saturated only for a short distance inland because they rise above the water table. The dune deposits west and northwest of Kahului are underlain by the conglomerates of the Pleistocene fan of Iao Stream. Water finds its way seaward through permeable ribbons of sand and gravel in sufficient quantity and quality to be of value for domestic use. It is supplied by seepage from Iao and adjacent streams, and from reservoirs, ditches, and irrigated lands of the Wailuku Sugar Company. Some of this water is probably not floating on salt water. Test hole 103 found fresh water to a depth of 177 feet below sea level 1¾ miles north of Wailuku. A well dug in 1936 upon the senior author's recommendation at the National Guard Camp, half a mile west of the mouth of Iao Stream, penetrated boulder clay containing water with 2½ grains of salt per gallon. The static water level was 17 feet above sea level. The yield of the alluvium is small, as shown by a pumping test made when the well was 4 feet below the water table. It yielded about 1 gallon per minute for each 11 square feet of wetted area.

Basal springs issue along the entire seaward base of the consolidated dunes between the mouths of Iao and Waiehu Streams. They are used for irrigating taro. They yield about 750,000 gallons per day. The water is probably seepage from irrigated fields inland of the dunes and from rainfall on the dunes. Samples collected on September 21, 1940, by the W. S. Co. showed 2.65 to 2.90 grains of salt per gallon.

The loose calcareous sand deposits yield water abundantly. This water is moving to the sea from the lavas under the Isthmus. Trees and shrubs remain green throughout droughts in low areas next to the coast because their roots reach the water table. The water is too brackish for domestic use but satisfactory for stock or irrigation. A few dug wells recover water from these sands to irrigate lawns between Kahului and Paia, where it is essential to conserve the domestic supply.

Water is less abundant and higher in salt in the sediments along the south shore of the Isthmus than on the north chiefly because more land is irrigated with stream water on the north side.

The conglomerates as a whole at the mouths of Kaupo and Keanae Valleys are probably too impermeable to allow sea water to move inland and establish the Ghyben-Herzberg lens. The small springs there issue from gravel lenses and are perched on silt beds. Brackish water is found in some of the narrow gravel beaches along the eastern end of Maui. This is basal water moving into the sea from the adjacent lavas. Mules and horses are sometimes seen pawing holes or digging their own wells in the gravel beach east of Kaupo. They apparently smell the fresh water and dig to it.

HIGH-LEVEL GROUND WATER IN EAST MAUI

General statement.—High-level ground water occurs appreciably above the basal water table and is separated from it by rocks that are more or less impermeable. All types of perching structures known in the Hawaiian Islands, except ice, are found in East Maui. They are intrusive rocks, ash beds, soil, and alluvium.[82] Water is apparently perched for short distances by dense very continuous sheets of steeply dipping andesitic or closely related lava in very wet areas. Several such sheets enclose permeable basalt and cause artesian water in the Nahiku area. Also interstratified clinker beds that have been decomposed by circulating water now perch water. The areas in which high-level water is known to occur are shown in plate 12. High-level water is exceedingly valuable, even though it is found in smaller quantities than basal water. It is used to irrigate lands too high to be supplied by pumped water, to provide domestic and stock water where no basal or surface water is available, to generate power, and to flume sugar cane. Also, it cannot be encroached upon by sea water.

Artesian water.—The perched aquifer containing water under an artesian head of 430 feet in the vicinity of Hanawi Gulch, East Maui, is an occurrence of artesian water of a type previously unknown in the Hawaiian Islands. It was discovered in 1941 by J. M. Heizer while drilling for the E. M. I. Co. to locate the aquifer of Big Spring (no. 26), the largest spring on Maui.

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[82] Meinzer, O. E., op. cit., p. 21.

The Hanawi artesian structure is described fully on pages 258 to 262. The water is confined under pressure in a permeable pahoehoe basalt between two or more dense aa lavas as shown in figures 39 and 40. Insufficient data exist to determine precisely the form of the artesian system but it is probable that the aquifer pinches out downslope between the confining lava flows as shown in figure 13. The lavas are transitional in composition between the primitive Honomanu basalt and the Kula differentiated lavas. It is believed that Big Spring is supplied chiefly by leakage from this artesian system.

The typical primitive lavas of Hawaiian volcanoes do not form dense continuous sheets of the type forming the Hanawi artesian system. The group of slightly differentiated rocks to which the confining lavas belong, are in sufficient abundance, however, in Mauna Kea and Kohala Mountain on Hawaii, in the Waianae Range on Oahu, and in West Molokai, to make similar artesian structures possible elsewhere in these islands. It is believed that such dense beds, to be effective as confining structures for artesian water, must lie in regions of high rainfall where frequent and rapid recharge to the aquifer will be sufficient to offset leakage. The rainfall on the recharge area of the Big Spring artesian aquifer exceeds 250 inches a year. It is possible that Puaaluu Springs (nos. 35 and 36) near Kipahulu, East Maui, are supplied by leakage from a similar artesian structure.

Artesian water floating on sea water in the basalts of Oahu and Kauai and capped with impermeable sediments has been known for many years. Artesian water underlain by dense intrusive rock and capped with impermeable sediments in the dike complexes of Oahu was recognized in 1935.[83]

WATER CONFINED BY DIKES.—Large supplies of water confined by dikes must exist in the north and east rift zones because of the great amount of rain that percolates downward there. However, most of it lies too deep for economic recovery. Test hole 101 at the Kula pipe line intake failed to reach confined water at a depth of 650 feet. It is believed that Kaupo, Kipahulu, Waihoi, and Keanae Valleys were eroded deeply into the east rift zone at the end of Kula time and were supplied by large perennial springs from the underlying dike complex (section B, fig. 22), and that these springs still flow through the permeable Hana lavas that cover them. The depth to the buried springs is unknown, but judging from the steepness and width of the valley walls, is probably 2,000 to 5,000 feet. The valleys

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[83] Stearns, H. T., op. cit. (Bull. 1), pp. 268-269 and (Bull. 5), pp. 34-35.

were cut nearly across the dike complex, hence the height of the water table in the dike complex will be largely controlled by the altitude of the buried springs on the ancient valley floors (section C, fig. 22). It is roughly estimated that the water table slopes eastward from an altitude of about 3,000 feet at the head of Keanae Valley, to 1,500 feet at the head of Waihoi Valley. Whether a sufficient number of dikes of Hana age cut through these large valleys to affect the altitude of the water table in the valley-filling lavas is unknown. If effective, they would raise the level of the water. All the dikes spread fanwise toward the east end of the island; hence the water table may be even lower than estimated, as diverging dikes allow the water confined between them to escape.

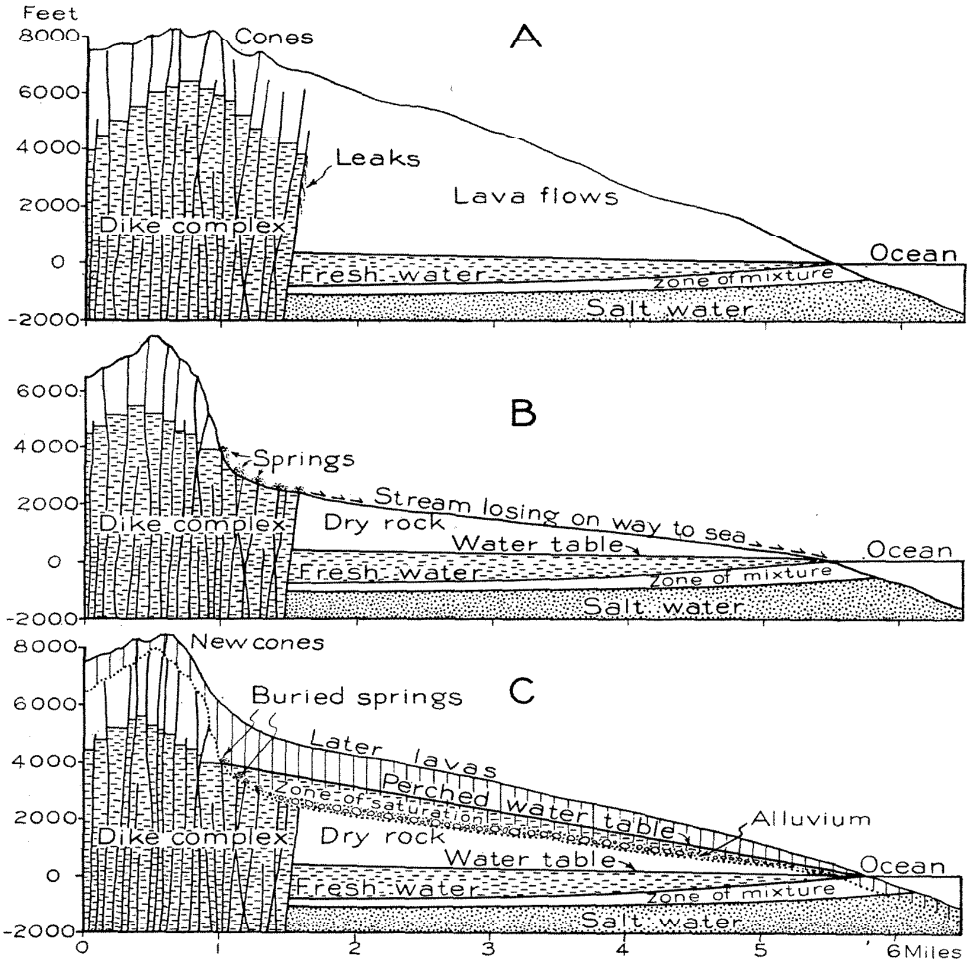

Figure 22. Diagrams showing the hydrology of canyons cut into a dike complex and later filled with permeable lava.

The rainfall in the dike complex underlying the southwest rift zone is too low to build a water table far above sea level.

WATER PERCHED ON ASH BEDS.—Ash beds perch water in two ways on Maui. Water is found above Ulupalakua moving along the base of coarse porous vitric ash layers where they lie on finer grained beds. The finer textured ash is usually weathered to waxy dark-yellow palagonitic tuff or to a brownish-red soil. Such products are much less permeable than the original ash and perch water. The quantity of water recovered from such structures is small, largely because they cover such small areas.

Water is commonly perched in lava by underlying fine-textured red or reddish-yellow vitric tuff beds (fig. 13). Many have been baked to a friable brick by the overlying lava and some weathered to a clay-like soil before burial. Every degree of weathering exists Some of the tuff beds are only partly altered and the glassy pumice particles are easily identified under a hand lens; others have been reduced to a red soil in which the particles are no longer recognizable. In places some of these soils are probably loess, dust blown from ash-covered lands to the windward. Tuff and ash beds abound in the Kula formation and are responsible for many small perched springs, notably in the sea cliff east of Maliko Gulch, and in the numerous deep gulches between Haiku and Kailua. A notable ashy soil horizon 2 to 24 inches thick perches the water in the Makapipi tunnel above Nahiku. Other tunnels and springs supplied by water perched by ash are listed on pages 212 and 213.

The extensive surface deposits of Hana and Kula ash shown on plate 1 are mostly too pervious to perch water. Some water may be moving along their less pervious beds, especially in wet weather, but the quantity is probably small. The ground in a few swales is swampy and the vegetation remains green during droughts, indicating seeps. Probably numerous concealed streamlets of ground water perched in lava flows by ash lie in the east rift zone. The dense jungle there makes exploration and development difficult and expensive; hence, this water will probably remain unused for a long time.

An instructive lesson in the relation of the amount of rainfall to the effectiveness of interstratified tuff or ash beds in perching water is found in East Maui. Numerous intercalated tuff beds are exposed in the canyons cut in the Kula lavas on the dry south slope, yet only a few perch water, and then only in quantities of a pint or less a minute. On the wet north slope, similar tuff beds in the same formation perch hundreds of small springs and give rise to perennial streams. This difference shows that the tuff beds are sufficiently permeable and discontinuous to allow great quantities of water to percolate through them. But when the rainfall exceeds about 40 inches a year, loss by seepage is exceeded by recharge, and sufficient water moves laterally along them to make perched springs.

Numerous tunnels at the contact of tuff beds and the overlying lava have shown that usually small amounts of water only can be recovered from such structures unless the ash mantled a terrane cut by shallow gullies or containing swales in which water will collect. Another essential is that the ash be buried by lava before it is cut through in too many places by streams. The water enters tunnels when they penetrate the bottom of such gullies (fig. 23). Wide buried plateaus mantled with ash yield little water to tunnels even in regions of high rainfall, as shown by Waikamoi (no. 32) tunnel, which followed such a buried surface for 2,000 feet and yields only 9,000 gallons per day soon after rains cease.

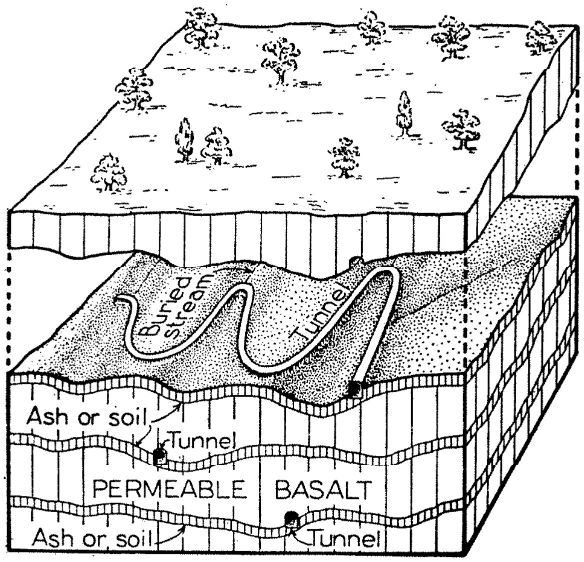

Figure 23. Diagram illustrating the position of tunnels driven to recover water from buried ash beds.

Spring 40 in Manawainui Canyon emerges in a steep cliff that could not be climbed. Viewed from the opposite rim, the spring appears to come from lava that fills a swale made impervious by tuff deposited from an adjacent cinder cone, as shown in figure 24. Spring 39 is similarly perched.

The total yield of the 2,400 feet of tunnels developing water perched by ash or tuff in East Maui is about 71,500 gallons daily, or 30 gallons per day per foot of tunnel. The total discharge from springs numbered on plate 1 perched on tuff in East Maui is estimated to be about 475,000 gallons daily.

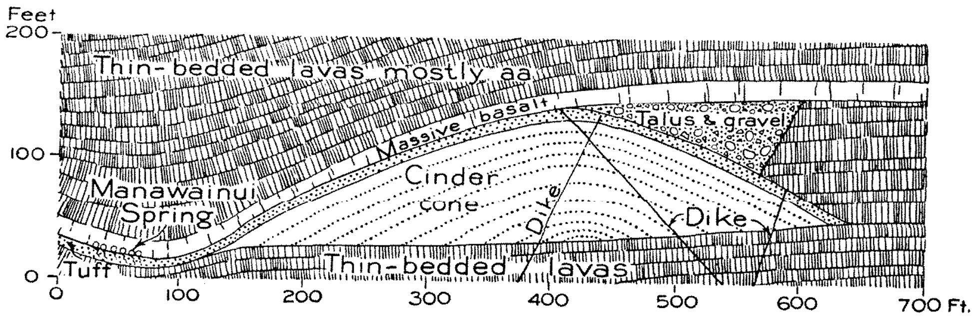

Figure 24. Geologic structure of Manawainui Spring (no. 40), East Maui, as sketched from the opposite canyon wall.

WATER PERCHED ON SOIL.—The principal soil horizon lies at the contact of the Hana and Kula lavas. No soils capable of perching water are known in the Honomanu basalts. Several soil horizons carrying water are known in the Kula formation.

Most of the buried lava flows that remained uncovered sufficiently long to decompose to a soil, received numerous ash showers. Also, many of the ash beds were weathered to a soil before burial. Thus, it is difficult to separate the occurrence of water perched on interstratified soil and ash in East Maui.

Waikaukane Spring (tunnel 59) above Ulupalakua issues from cinders resting on a baked black peaty humus bed. This spring and others nearby have small yields, but they do not dry up after weeks without rain, in spite of the few acres of drainage area above them. It seems likely that they are supplied during droughts by percolation from the dew and fog that condense on the coarse cinders and foliage in their drainage basins. They lie concealed in a fog bank a large part of the time. A steady drip from the leaves of the trees and shrubs was observed every foggy morning when camping in this area.

A water-bearing ashy soil may lie at the contact of the Kula and Hana lavas west of the village of Hana, but it will probably be located only by an expensive exploratory boring program. Most of the soil was eroded from the top of the Kula lavas in the erosional interval preceding the eruption of the Hana lavas on similar steep slopes. Hence the Kula soil may be only a few inches to a few feet thick, and the buried terrane may be so rugged that most of the water is following gulches cut through the soil.

Where the Kula soil is buried by the Hana lavas of the southwest rift zone, the rainfall is too low for water to occur in sufficient quantities on it to justify tunneling.

An investigation was made by John Hofmann for the E. M. I. Co. in the area between Keanae and Haiku to determine seepage losses from streams below the Haiku-uka boundary at 3,000 feet altitude. The early and middle Kula lavas in the area contain sufficient interstratified thin ashy soil beds, decomposed clinker beds, and dense sheets of rock to perch many small springs in this area of high rainfall. Thus, the streams gain as they flow downstream, with the exception of those that flow in gulches plastered with lava in late Kula time. The low flow of streams from the early and middle Kula series entering Wailoa Ditch at 1,000 feet altitude is approximately three times the flow at 3,000 feet altitude (fig. 25). Measurements of the gain in certain streams at various points along their channels are shown in figure 26. In contrast, Kailua Stream, typical of those plastered by late Kula lava, loses water progressively downstream (fig. 26).

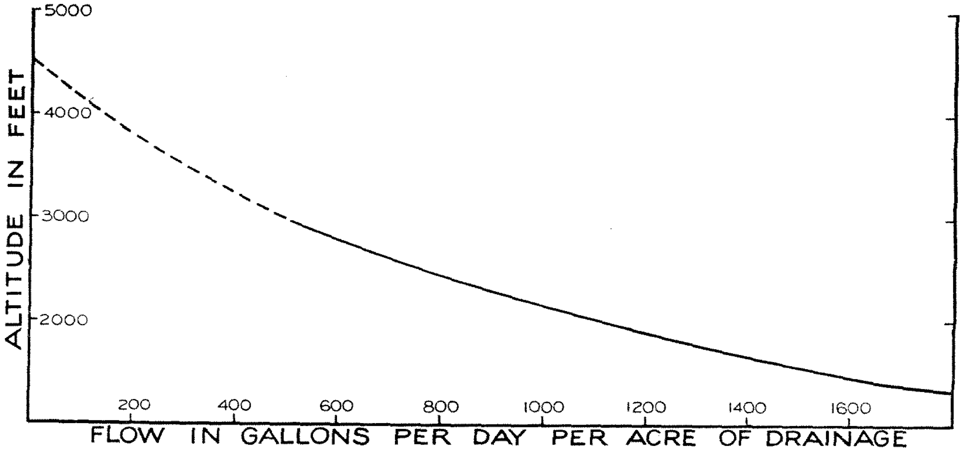

Figure 25. Graph showing rate of increase in flow with decrease in altitude of streams between Honomanu and Kailua Streams on East Maui. The streams are dry above 4,500 feet during droughts. (After J. H. Hofmann.)

An interesting experiment to determine seepage losses in Waikamoi Stream was made between December 22 and 27, 1928.[84] Salt (NaCl) in solution was added to the stream at the Haiku-uka boundary at an altitude of 3,000 feet at the rate of 200 pounds per hour until 10,000 pounds had been added. Samples were collected hourly

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[84] Carson, M. H., and Hofmann, J. H., Seepage tests by salt method in Waikamoi Stream, Maui: unpublished rept., U. S. Geological Survey files, Water-Resources Branch, Honolulu, Jan. 1929.

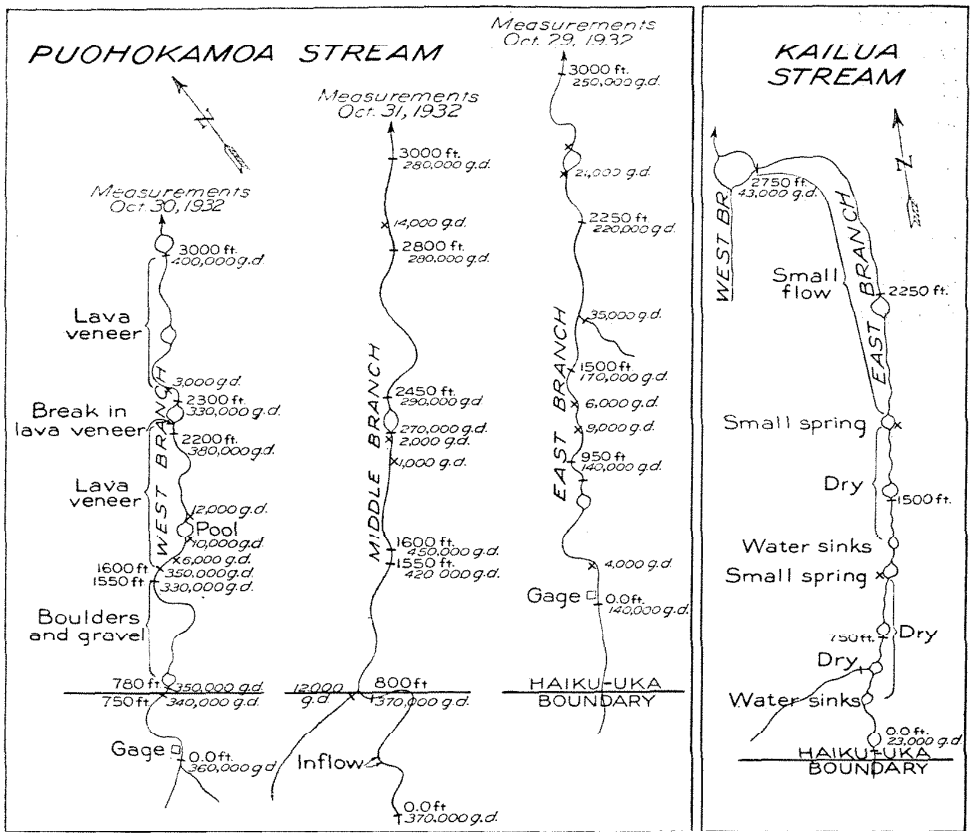

Figure 26. Map showing points of gain in gallons per day in Puohokamoa Stream and loss in Kailua Stream, East Maui. (After J. H. Hofmann.)

at the U. S. G. S. gage at an altitude of 1,250 feet. The normal salt content of the stream at the gage before the salt was added was 0.3 to 0.5 grains per gallon (3.12 to 5.20 p.p.m.). The total amount of salt that passed the gage was 6.8 percent greater than the amount added. It was found that during days of no rain, salt from ocean spray accumulated on the foliage and ground of the drainage basin. Following light showers heavy enough to wash the salt into the stream, as much as 3.5 grains per gallon (36.36 p.p.m.) was recorded at the gage. For these reasons it was concluded that seepage losses could not be determined by salt tests.

The chief gain from tunnels that failed to recover water in East Maui is the knowledge that only valleys containing perennial streams before burial by lava will yield water to tunnels in dry weather.

WATER PERCHED ON ALLUVIUM.—The poorly assorted partly consolidated older alluvium is sufficiently impermeable to perch water where recharge is rapid. A few seeps issue from younger alluvium where it rests on the older alluvium along the coast. Manawainui Stream sinks into younger alluvium. Part of this water might be recovered by a short tunnel at the contact of the older and younger alluvium part way up the canyon.

Water is found in valley-filling lavas in many places where they overlie older alluvium and silted stream beds. The water is recovered by tunnels driven to the floor of such buried valleys (fig. 27). Many of the tunnels in the Nahiku area recover water from such structures. (See Part 2.) Several small springs issue from the base of late lavas overlying alluvium in the sea cliff at the mouth of Keanae Valley. Waihi Spring (no. 37), 1¾ miles east of Kipahulu, issues from a similar structure. It is probable that the main underflow of Keanae, Kipahulu, Waihoi, and Keanae Valleys is perched on alluvium.

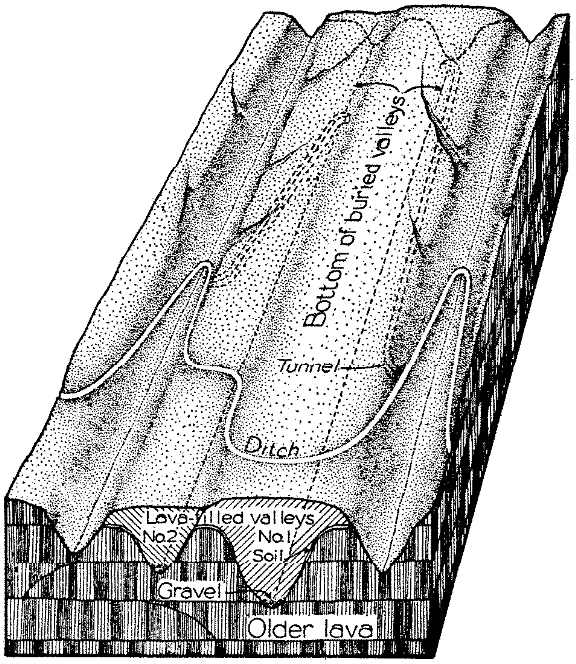

Figure 27. Diagram illustrating the position of tunnels driven to recover water from lava-filled valleys.

Some of the ribbons of gravel within the older alluvium carry water that is perched on underlying less permeable sedimentary beds. Store Spring (no. 19) and small springs along the coast of Keanae Valley can be seen tumbling from gravel lenses that rest on silt beds.

WATER PERCHED ON LAVA SHEETS.—The fact that small swift streams flow for long distances along the dense sheets of lava in the Kula formation and for short distances along channels plastered with dense Hana lavas, is evidence that dense rocks perch streams locally. How much water moves along similar structures in the ground where velocities are very low and the cracks unsilted, is unknown. Sheets of dense lava must perch water where the rainfall is heavy, as shown by the Hanawi artesian structure (fig. 13). The water in tunnels 60 to 62 on the slope of a cone above Ulupalakua discharges from the top of a dense sheet of lava about 1 foot thick, interstratified with thin-bedded tuffs. Lateral tunnels less than 10 feet long have been driven under the lava at these places but they failed to recover water. The water is obviously moving along the top of the lava. Were it not for the underlying ash, it is probable that every hundred yards or so the water would have found cracks and sunk. The chances of developing water by random tunneling along the top of dense lava sheets unless these sheets are underlain by ash, soil, or alluvium are small.

QUALITY OF PERCHED WATER.—Perched water in general is of good quality. Salt carried inland as spray amounts usually to less than 2 grains of salt per gallon. Analyses are not available, but in analogous perched springs on other islands, the total dissolved solids range from 50 to 175 parts per million in the windward springs and tunnels, and 150 to 250 parts per million in the smaller leeward springs.

TUNNELS.—Forty tunnels driven to develop water on East Maui are shown on plates 1 and 12. Pertinent data regarding the tunnels are on page 213. Tunnels 33, 34, 47, 49, 50, and 53 are exploratory only. The numerous tunnels, many of them long, driven to transport water through the great ditch systems are not listed. Tunnels 35 to 56 are listed on page 267. The total length of all East Maui water-development tunnels is about 23,850 feet, their combined low flow 6,000,000 gallons a day; and their yield per foot 250 gallons a day. Most of the tunnels were driven on soils at the base of Hana lava flows. Some of the lava flows fill canyons and locally rest on conglomerate. A few were driven where small springs formerly issued; hence the entire flow has not been developed by tunneling. No dike swarms were penetrated by tunnels, which accounts for their yield per foot being about one third of the yield of tunnels in West Maui.

SPRINGS.—Thirty-two important springs on East Maui and their perching formations are described on page 212. A few small ones that are valuable water sources are included. Some small springs and

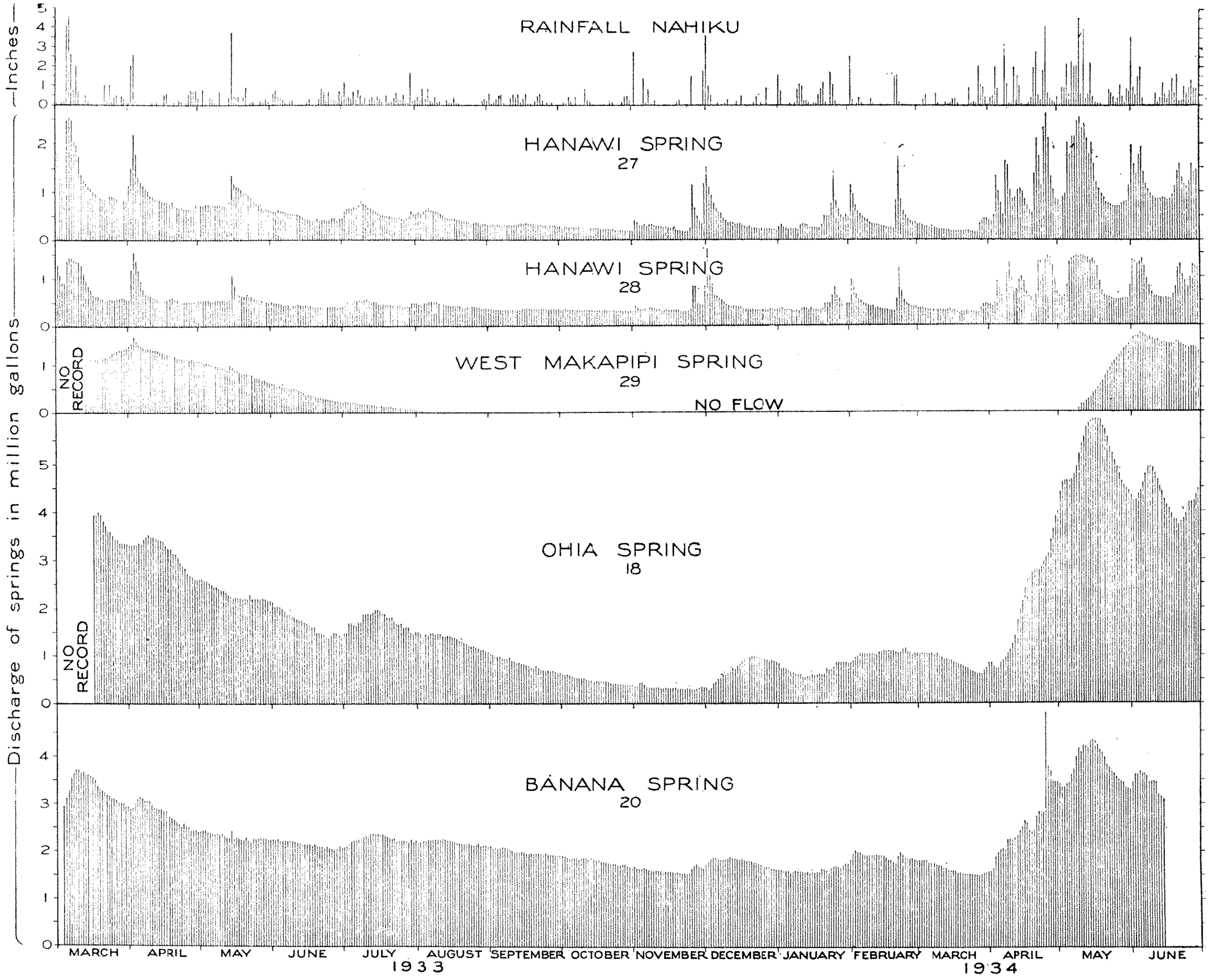

Figure 28. Graphs showing the discharge of several springs in East Maui in relation to rainfall at Nahiku camp. (Data furnished by E. M. I. Co.)

seeps shown on plate 1 have not been numbered as they are unnamed and not likely to be used. The number of small unmapped springs and seeps in the wet areas is legion. All springs for which records are available except Big Spring respond quickly to rainfall (fig. 28).

The total estimated low flow in gallons a day of all the springs numbered on plate 1 issuing from the Honomanu series is 15,370,000; from the Kula series is 390,000; and from the Hana series is 7,150,000. The total low flow in gallons a day from springs perched on mud flows is 15,000 and on alluvium is 2,200,000.

UNDEVELOPED HIGH-LEVEL SUPPLIES.—Studies of run-off water have been made by the E. M. I. Co. to determine the advisability of extending their Kooiau ditch to Kipahulu Valley. Such an extension would require many miles of ditch through very rough permeable Hana lavas. As an alternate plan, a tunnel could be driven about 5 miles southeastward from the intake near Makapipi Gulch to the head of Waihoi Valley. Probably dikes would be cut after 4 miles of tunneling, and perhaps sufficient water would be encountered before reaching Waihoi Valley. The ditch system is 1,300 feet above sea level; hence, the tunnel would probably tap the confined water now escaping into the Hana lavas at the head of Kipahulu and Waihoi Valleys. The altitude of the water table at the head of Waihoi Valley could be ascertained by test holes before starting the tunnel.

A tunnel 2 to 3 miles long extending due northward from the head of Manawainui Stream should encounter abundant water. It would start in a dike swarm and would probably develop water most of the way. It would tap water in the dike complex at the head of Kipahulu Valley at an altitude of about 2,000 feet. The water could be used to irrigate lands at the mouth of Kaupo Valley or for supplying consumers below 1,800 feet on the Kula system if conducted through a pipe line to Ulupalakua.

Large supplies of water must be confined in the dike complex under the north rift. Due to the lack of deep canyons in this area, it is doubtful if the water can be tapped by a tunnel. The 650-foot test hole (no. 101) at the Kula pipe-line intake failed to reach confined water; hence, water probably can not be recovered even by deep wells. Further, the cones on the north rift zone are scattered over a wide area (pl. 1), which indicates divergence of the dikes, and probably only basal water under the lower slopes of the rift zone.

The water supply is dependent upon a flashy stream; hence, the supply is frequently inadequate in dry weather. Many users have small storage tanks. It is now proposed to build a low-level system diverting water at an altitude of 3,000 feet from streams along the lower Haiku-uku boundary to supply Makawao and the Kula water users below this level. During droughts it is proposed to pump water to the upper system, a lift of about 1,300 feet. This project appears to be the only feasible plan to develop additional water. Since the Kula system was built, truck gardening has become profitable in that area. Year by year, more water has been used for irrigation.

The lack of satisfactory water supplies and the excessive cost of obtaining water so high on the mountain make it desirable to discourage farming in Kula. Unless the rates for water for irrigation are increased, the situation will become more acute each dry year and may soon lead to costly resettlement.

The rainfall on the southwest rift is too low to build a water table of any appreciable height above sea level in the underlying dike complex. If a deep well were sunk in this general region, it would be worth while to take advantage of the dikes for their damming effect upon the movement inland of salt water, thus utilizing the principle of the Oahu-type well.[85]

Numerous ash beds intercalated with lavas that probably carry perched water lie inland from Hana, but the high cost of exploring for these structures is prohibitive.

A promising prospect for developing water would be to drive a tunnel contouring the top of the buried soil at the contact of the Kula and Hana lavas between Opaeula Stream (the unnamed stream on plate 1 on the east side of Puu Hoolewa on the northeast side of Waihoi Valley) and the forest boundary above the village of Hana, at about the level of the abandoned Opaeula flume. An extensive sector-shaped remnant of Kula lavas is buried there by a very permeable Hana lava. The ashy Kula soil is 6 feet thick and rests on partly decomposed Kula lava in the northwest bank of this stream at an altitude of 2,000 feet. Numerous lava-filled valleys would probably be discovered and would probably carry more water than the plateau areas, as the rainfall exceeds 200 inches annually above the proposed tunnel.

Much unused spring water perched on soil and ashy soil beds issues between Muolea and Kipahulu. It was formerly diverted for irrigating and fluming sugar cane but is no longer used. A smaller quantity of spring water but more difficult to use because of the rugged terrane issues between Kipahulu and Kaupo. The large springs in the wall of Manawainui Canyon could be diverted to the

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[85] Stearns, H. T., op. cit. (Bull. 5), p. 10.

lands near Kaupo. Part of their flow was formerly piped to Kaupo for domestic use, but the pipe line was destroyed by the earthquake in 1938 and landslides have been so frequent since, that a pipe line is not feasible. A small tunnel in the canyon stretch would be safe from destruction. It is doubtful if the flow could be increased by tunneling at the springs, as the canyon effectively crosscuts the aquifer. Part of the underflow of Manawainui Stream could be recovered by a tunnel at the base of the younger alluvium, but much water in the stretch of channel above the alluvium seeps into the basalt floor and is lost.

Large quantities of undeveloped perched water are believed to exist in Keanae, Waihoi, and Kipahulu Valleys at the base of the Hana lavas. Test hole 100 was drilled 381.5 feet deep at the Koolau Ditch, altitude 1,240 feet, in Keanae Valley, but it failed to find water. Long expensive tunnels would be necessary to tap these supplies, because the pre-Hana basalt floors are probably far below ground. The water might be tapped by drilled wells should its value ever justify pumping. The large springs in Keanae Valley (nos. 18 to 21) would be extremely valuable if their supply could be tapped at an altitude of 1,200 feet. Exploratory drilling is necessary to trace them to ditch level, as the surface geology has been mapped in detail but gives little clue to the depth and location of the water at ditch level.

Much exploratory work has been done in the Nahiku area, and much valuable high-level water awaits development there. (See Part 2.)

It is probable that tunnels too long in relation to the quantity of water recoverable, would be required to tap the subterranean streams in Kaupo Valley. Tunnels 5 to 50 feet long would improve the pipe-line intakes of many of the seeps in the summit depression, in the gulches west of Kaupo, and above Ulupalakua, where it is obvious from adjacent water-loving vegetation that all the water is not collected. Waiu Spring in Kaupo Valley could be tapped a mile inland by a tunnel contouring the base of the small lava-filled valley supplying it. The springs issuing from the base of the lava fill in Honopou Gulch on the north rift indicate that some water could be collected by a tunnel driven to the base of this lava farther inland. Small quantities are probably recoverable from the other lava-filled gulches nearby (fig. 11).

INVENTORY OF GROUND WATER IN EAST MAUI

The following table summarizes the quantity of ground water discharged by wells, tunnels, and springs in East Maui in comparison with West Maui. The absence of caprock around Maui allows tremendous quantities of basal water to waste directly into the sea at tide level. This water cannot be measured and is not included. Crude estimates of such waste are 700 m.g.d. for East Maui and 100 m.g.d. for West Maui.

Average daily low-water discharge of ground water in gallons

	East Maui	West Maui
Basal water pumped from wells entering basalt[a]	125,000,000	45,000,000
Basal water pumped from dug wells and tunnels in sediments	50,000	[b]350,000
Perched and confined water discharged from tunnels	6,000,000	20,500,000
Perched water discharged in springs[c]	74,000,000	55,500,000
Total	205,050,000	121,350,000
Grand total	326,400,000	

[a] Average discharge 1932 to 1941 as reported by plantations, including cooling water for generators and a small amount for non-plantation wells. It excludes well 11 at Olowalu, listed in the next item, which averages 330,000 gallons per day.
[b] Includes Maui-type well 11 at Olowalu.
[c] Computed from the low-water flow of perennial streams at the mouths of canyons plus the flow of springs not tributary to such streams and minus the flow of tunnels listed above.

The average annual quantity of ground water discharged, based on the above table, is 119,136 million gallons. It is 11 percent of the average annual rainfall, as determined on page 202. This compares with 25.6 percent recovery of the rainfall on Oahu.[86]

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[86] Stearns, H. T., op. cit. (Bull. 1), p. 443.

Above: Plate 27A. Ancient Hawaiian well dug in aa clinker near Makena, East Maui, that is still in use. Kapu in Hawaiian means forbidden. The sign warns people not to pollute the water. The box is to keep livestock from drinking from the well.

Below: Plate 27B. Springs issuing from tiny coves of their own making during low tide at Spreckelsville beach on the Isthmus.


2
3
1

Opposite page: Plate 28. Head of Honokohau Canyon, 2,300 feet deep, nearly captured by Waihee Canyon (1). Puu Kukui (2), the highest and wettest peak on West Maui, is in the background. The light-colored interstream flats (3) radiating from Kukui are peat bogs resting on Honolua lavas. Photo by U. S. Army Air Corps.

GEOMORPHOLOGY OF WEST MAUI

VALLEYS.—West Maui is deeply dissected by streams, many of which rise in deep amphitheater-headed canyons. These canyons radiate from the summit like spokes from the hub of a wheel. The most famous is Iao Valley behind Wailuku with its Iao Needle (pl. 5). Several other canyons in West Maui are more scenic than Iao, but they are not accessible by auto. Waihee Canyon, north of Iao, is 4,000 feet deep and its head walls have dozens of spectacular waterfalls during each rain. Honokohau Canyon northwest of Waihee is the longest valley. It is about 2,300 feet deep (pl. 28). South of Iao are the deep gorges of Waikapu, Ukumehame, Olowalu, and Launiupoko Streams. All the other streams flow in canyons 200 to 1,500 feet deep, but canyons of this depth are commonplace on West Maui. The best views of the great canyons are obtained from the end of the trail that reaches the east rim of the head of Ukumehame Canyon from McGregor Point, or from the top of Puu Kukui. The Eke trail has been abandoned.

The great canyons are chiefly attributable to stream erosion, and their form results from certain conditions—an original steep surface, the presence of alternating resistant and nonresistant layers of rock dipping downstream, high rainfall at high altitudes and low rainfall at low altitudes on a conical mountain inducing active piracy in the upper parts of the drainage, and to plunge-pool action and landslides removing the divides between tributaries.[87] The effect of the original asymmetrical form of the West Maui dome on the rate of erosion is shown by the development of the deep box-headed canyons of Waihee, Iao, Waikapu, Ukumehame, and Launiupoko on the steep short slopes of the mountain, and the poor development of this type of canyon on the longer and gentler slopes between Launiupoko and Waihee Streams.

The outcrops of throat breccia at the head of Iao Valley indicate that this abnormally broad circular amphitheater probably was caused largely by the stream draining the former summit caldera of the West Maui volcano (pls. 23 and 24). How much of the amphitheater is due to the original caldera depression and how much is

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[87] Stearns, H. T., op. cit. (Bull. 1), pp. 24-26.

due to the weaker nature of the underlying rocks is unknown. However, since Waikapu Canyon headed in a similar mass of breccia without developing a circular amphitheater, it is probable that originally there was either a rather large volcanic depression tapped by Iao Stream or else sufficient fault blocks to concentrate the drainage as on Kohala Mountain in Hawaii.

Dome-shaped hills.—The profile of West Maui is characterized from almost any angle of view by pronounced bumps which differ genetically from the usual hill topography left by erosion in Hawaii. These bumps are composed of trachyte and closely related rocks. The most notable of these hills are Puu Koae and Puu Olai near Kahakuloa, Puu Anu and several unnamed hills on the ridge running down to McGregor Point, Puu Launiupoko and Puu Koai near Olowalu, Eke at the head of Waihee Valley, and several unnamed hills above Honokohau. They are bulbous domes made by viscous lava piling around a vent (p. 175 and fig. 32).

Several cones near the coast have a form somewhat similar to the domes described above but differ by being made of cinders. They are Puu Hele near Maalaea, two unnamed cones about 1½ miles northwest of Maalaea, Kilea half a mile north of Olowalu, Puu Laina one mile northeast of Lahaina, Puu Kekaa at Kaanapali, and Puu Kaeo at the mouth of Honokohau Valley.

Plains.—Three types of plains occur, namely, flow-slope plains, alluvial plains, and marine plains. The flow-slope plains are the most extensive and form valuable agricultural land. Most of the lands planted to pineapple and sugar cane are of this type (pl. 7). They are sloping plains with grades ranging from 200 feet per mile on the east side of Honokohau to 400 feet per mile between Lahaina and Kaanapali. Their surfaces conform very closely to the surfaces of the lava flows underlying them, but the scattered remnants of a former trachyte veneer indicate that the lava flows have been stripped layer by layer by erosion. Most of these plains become plateaus a short distance inland owing to the headward deepening of the stream channels crossing them.

The alluvial plains are formed by coalescing fans at the mouths of canyons. The slope of these plains ranges from about 100 to 400 feet to the mile and the most extensive one stretches from Waihee to Maalaea. It was caused by streams dropping their loads at the flat Isthmus because of the abrupt change in grade. Waikapu Stream has built the largest fan.

The marine plains are notably flatter and smaller than the flow-slope and alluvial plains. Their slopes are usually less than 25 feet

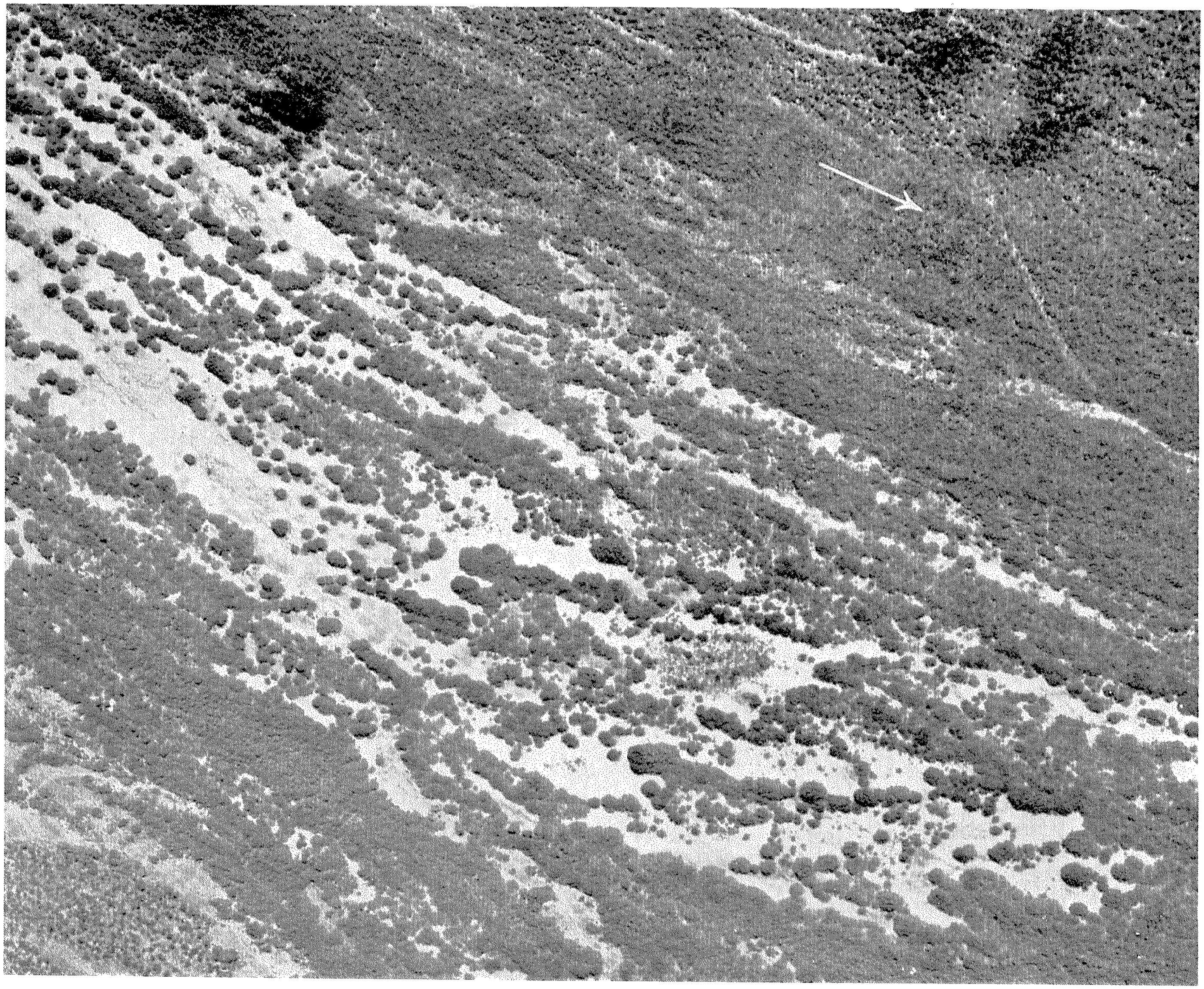
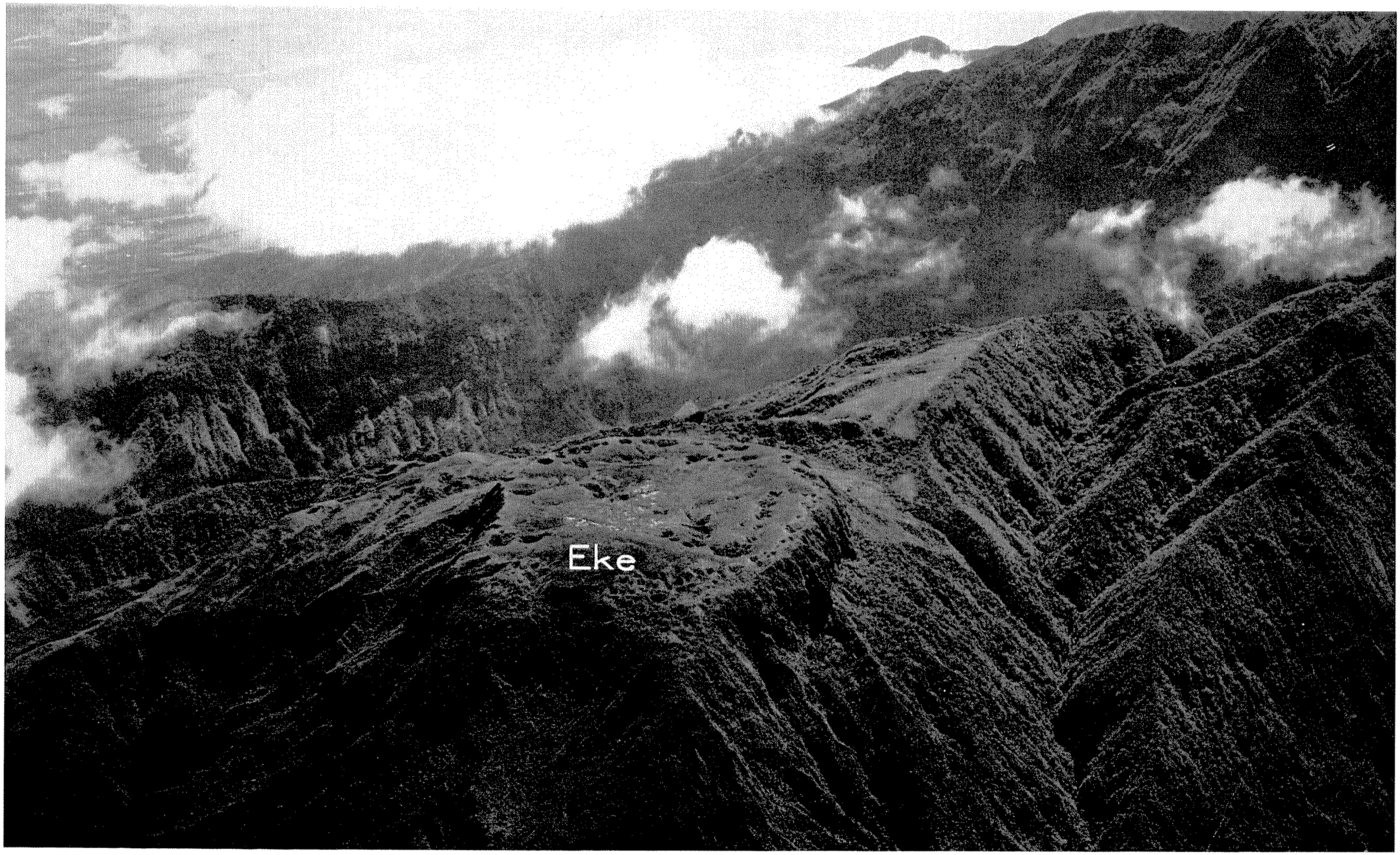


Plate 29. Vertical air view of longitudinal-type calcareous dunes and wind-swept algaroba trees southwest of Kahului on the Isthmus. Prevailing northeasterly winds indicated by arrow. Scale 1 inch equals 600 feet. Photo by U. S. Army Air Corps.


Eke

Opposite page: Plate 30. Mt. Eke, West Maui, a bulbous dome of massive trachyte that has withstood intense stream erosion. Sinkholes on its surface lie along concentric cracks. The small gleaming spots near its center are water holes. Photo by U. S. Army Air Corps.

to the mile. They are the result of a small recent emergence and deposition by the sea at its present level. The largest lie near Waihee, Olowalu, Lahaina, Kaanapali, and Honokowai. Some of these plains glisten with white salt incrustations and are unfit for agriculture.

EKE SWAMP AND SINK HOLES.—Eke is the name of a flat plateau 4,500 feet above sea level and half a mile across (pl. 30). It is the eroded and weathered summit of a bulbous dome. No enclosing rim exists. It was formerly designated a crater on the U. S. G. S. topographic map of Maui. A precipice 1,000 to 2,500 feet high bounds it except on the south side (pl. 1). Two knobs about 50 feet high, remnants of former rock pinnacles, project above the swamp on the plateau. A trail was cut to Eke from Waihee Valley during the investigation and a camp made on its summit. The former trail on the north slope is overgrown and has been abandoned.

Lying in the path of constant strong trade winds and receiving an average rainfall of 248 inches annually, Eke is rarely free from clouds all day except during clear kona weather. The plateau is covered with stunted, gnarled, and wind-tortured trees, low-lying shrubs, and acres of silversword. The bristling brilliant red pompon blossom of the native ohia lehua tree is found there, blooming on dwarfed trees less than 10 inches high and probably 100 years old. The whole scene reminds one of a Japanese garden of dwarfed trees. Arriving there in the cold wet fog of early morning, the plateau takes on a weird, uncanny aspect and one feels suddenly transported from a lush tropical jungle to a bleak Arctic tundra. The dreariness is relieved only by the glistening leaf-clusters of the endemic silversword,[88] that unique plant found only in Hawaii. Even it blooms rarely on Eke.

The surface of Eke is composed of spongy vegetation usually resting on black mud but acaulescent plants enable one to walk over it without difficulty. Scarcely any shrub rises above the top of one's boots. The greatest surprise, after sinking knee-deep into mud on the trail to the top, is to find that one sinks only a few inches at most in the swamp. The Eke uplands are a peat bog due to the extreme acidity of the soil. The peat is shallow and underlain with

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[88] *Argyroxiphium caligini* (C. N. Forbes) and *Argyroxiphium Grayanum* (Hillebrand) Degener are found only in the high swamps of West Maui. Degener, Otto, Flora Hawaiiensis: Family 344, vol. 3, 1937.

a few inches of soft yellow-gray limonitic-streaked clay resting on fairly firm trachyte. In some places a few inches of limonite are found under the bog. Here and there bedrock is exposed where pools of water stand 5 to 20 feet across and a foot or less in depth (pl. 30). Nearby there may be only a thin film of mud. On February 19, 1936, after a drought, some of the water holes were dry and the mud on the bottom had curled up. The smooth rock floors of the basins must be a result of solution, as they bevel steeply dipping platy structure. All the water holes are aligned along cracks and their rims consist of mud and vegetation. Apparently the water holes represent places where the water does not percolate through the rock fast enough. The plants are unable to bridge the holes until they become filled with mud. It is probable that the flat areas of the water holes are lowered progressively by solution, the water draining off the edge of the plateau when the pools overflow during the frequent periods of heavy rain.

Near the periphery of the plateau the pools are missing and deep narrow crevices are found (pl. 30). They make walking in the fog hazardous, as the narrower crevices are commonly bridged with vegetation. In addition there are holes 5 to 100 feet across and 10 to 75 feet deep. In the bottom of some are deep crevices. Rocks dropped in some crevices to unseen depths splashed into water. Small streams of water disappear in other crevices. The hypothesis is offered that the depressions are sink holes formed by rain-water solution. Concentric jointing is typical of the bulbous domes, and apparently near the rim of the plateau, gravity and incipient landsliding have opened the joint cracks enough for water to percolate down them and enlarge them by solution.

Trachyte is not usually considered a rock in which sink holes form by solution, but it appears that the hydrologic conditions on Eke are so unusual that the rock reacts like an impure limestone to the heavy rainfall. Similar sink holes were noted in the swamp on Puu Kukui and the swamp stretching northeastward from Eke, both of which are underlain with trachytic lavas. Pits have been formed in some bulbous domes in historic time by minor explosions. No explosion debris was found about the sink holes, but such minor features would have disappeared long ago from domes as old as Eke.

The silversword plant (*Argyroxiphium Sandwicense*), evolved during a long period of time, has efficient sun-reflecting leaves covered with silvery appressed hair to protect it from evaporation on the sun-drenched bare semi-arid cinder-covered summits of high volcanic peaks in Hawaii.[88a] This plant is found only on Mauna Loa, Mauna Kea, and Hualalai on the Island of Hawaii; Haleakala, Kukui, and Eke on the Island of Maui; and Waimea on the Island of Kauai. Even though somewhat depauperate, its presence on Kukui and Eke where 150 to 500 inches of rain falls annually may indicate a great change in climate, although some botanists doubt if silvery pubescence is evidence of xeromorphy. However, heavy stands of greensword grow in the swamps at an altitude of about 6,000 feet on the east rift-zone of Haleakala, a similar *Argyroxiphium* but minus the silvery pubescence, yet no silversword grows among them. Another greensword is also present on Eke and Puu Kukui.

The silversword plants were probably established prior to the great submergence of the Hawaiian Islands in the early Pleistocene (p. 157), when the summit of West Maui extended considerably above the wet trade wind belt. The climate then may have resembled that on Haleakala today. Whether the plant has survived since that time or whether its seeds were carried there by birds during some later period is unknown.

EFFECTS OF WIND WORK.—The wind-pruned trees along the southwest side of Kahului Bay and the longitudinal dunes stretching southwestward across the Isthmus are evidence of the strength of the prevailing trade winds (pl. 29).

The extensive dunes on the Isthmus are described on page 109. During the Waipio stand of the sea the dunes may have blocked Iao Stream, as its lower course is a canyon cut in consolidated dunes. An abandoned stream channel believed to be that of Waikapu Stream enters Kahului Bay. It is probable that the migrating dunes blocked the course of this stream and diverted it southward to the opposite side of the island at Maalaea Bay.

Wind erosion of steep ridges, especially since deforestation, has left numerous scars on exposed headlands. Combined effects of wind and water erosion have produced a bad-land topography in the deeply weathered rocks on the seaward ends of the north slope. Unusually regular benches have been cut by the wind in this area, as shown in plate 31. The soil involved is fine textured, chiefly of silt size, and when dry is filled with innumerable closely spaced irregular cracks. In some places the coarser grains form mounds 1 to 5 feet high on the leeward side of these benches, but in other places no trace of the removed soil was found, indicating that it had been blown away. The resistant layer forming the lower bench (pl. 31B)

[88a] Degener, Otto, Ferns and flowering plants of Hawaii National Park: p. 306, Honolulu, 1930.

seems too level to have been caused entirely by an original layer in the basalt. It appears to be a sort of hard pan at the base of the soil, perhaps controlled by a dense layer in the lava. The secondary bench above this layer is in the soil and may have been caused by some action of capillary moisture, as no difference in texture between the soil above and below this bench could be seen under a hand lens.

Highly developed fretwork weathering due to wind and spray extends several hundred feet above sea level in the trachyte at Puu Koae. Feldspathic lavas seem to weather in this manner much more readily than basalt.

SHORE FEATURES.—The most striking shore features are the high cliffs along the southernmost end of West Maui and along the windward coast between Waihee and Honolua (pl. 32). The latter cliffs reach heights of 500 feet and where cut in massive trachyte, are commonly vertical for several hundred feet. High surf breaks on them throughout most of the year because of the absence of protecting coral reefs and because they lie in the path of the prevailing trade winds. The cliffs are highest where they receive the brunt of the trade wind-whipped ocean and die out toward the protected points of Honolua and Waihee—a fact which substantiates their marine origin.

Southward from Honolua marine abrasion is gradually replaced by deposition as the coast passes to the lee side of West Maui. It is protected also from kona storms by the island of Lanai. A depositional coast continues until the cliffs on the southern tip of West Maui near Maalaea are reached. The southern tip is exposed to kona storms and as a result marine cliffs several hundred feet high are found. As usual in Hawaii, where no faulting has occurred, marine cliffs are higher on the trade-wind (northeast) side than on the opposite side, indicating that these winds probably dominated during glacial times as they do today.

At the foot of the cliffs in many places, especially near McGregor Point on the south coast, a bench 5 to 30 feet wide cuts across the bedding of the basalt, indicating a recent emergence of 5 feet.[89]

For such a long shore line, very few sand beaches occur on West Maui and they are small. Cobble beaches are numerous on the leeward side, and one, more than a mile long, lies south of Waihee Point.

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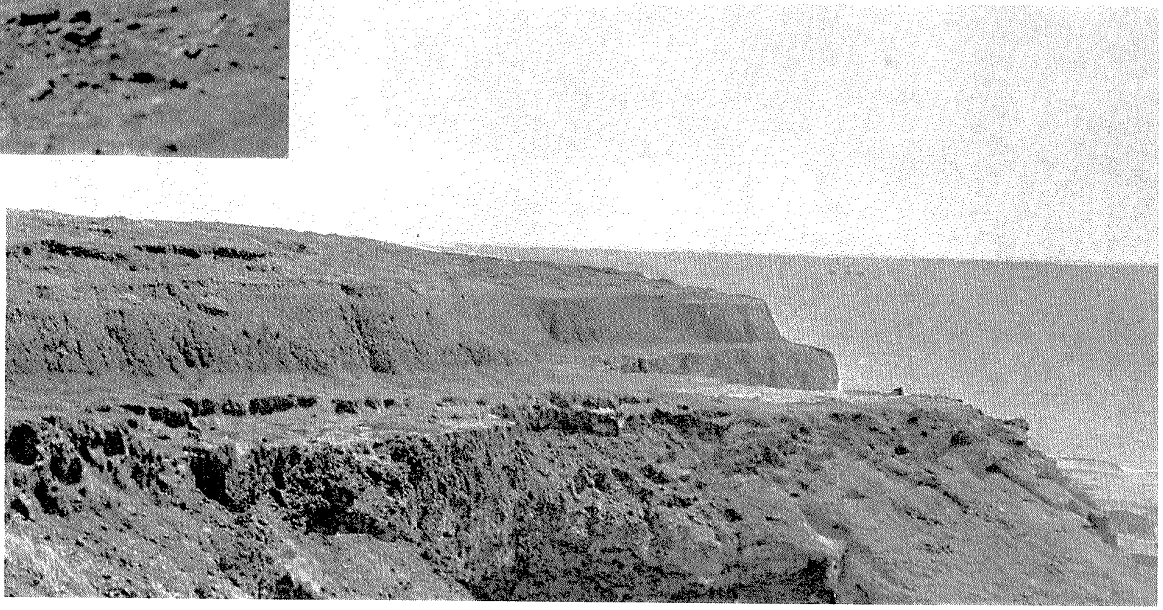
[89] Stearns, H. T., Shore benches on North Pacific islands: Bull. Geol. Soc. America, vol. 52, p. 779, 1941.

Below: Plate 31A. Bench cut by the wind in residual soil on Wailuku basalt near Nakalele Point on the windward coast of West Maui.

Above: Plate 31B. Close-up view of bench showing small secondary bench.



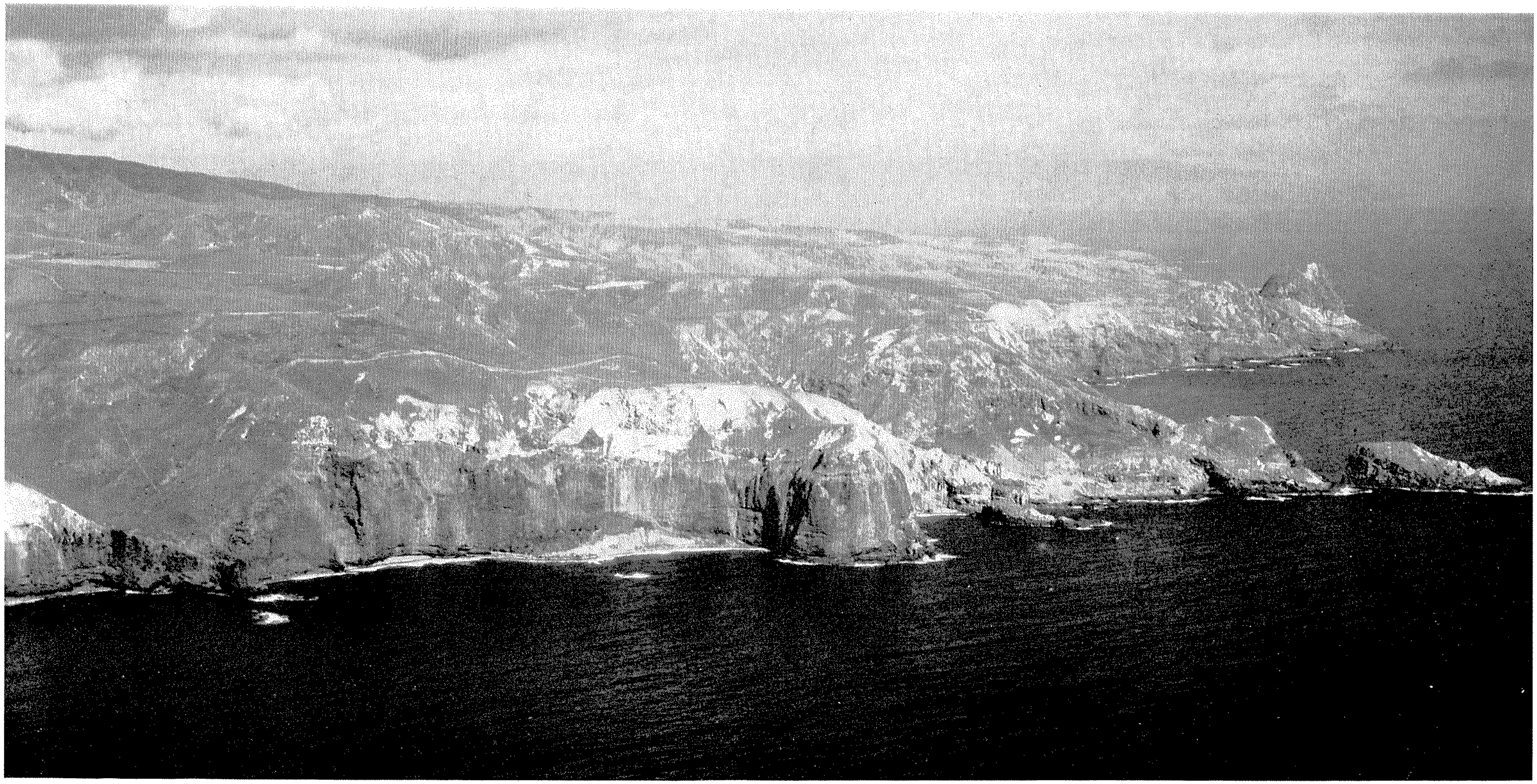


Plate 32. Massive trachyte flows cut by sea cliffs 500 feet high on the northeast coast of West Maui. The white scars are typical of the weathered exposures of Honolua lavas. Puu Koae, a bulbous dome, forms the second point. Photo by Hawaiian Airlines, Ltd.

A problem awaiting research is the paucity of fringing reef around West Maui as compared with Oahu. The sea off the leeward shore is clear and shallow, and insufficient fresh ground water enters it to affect coral growth. The absence of extensive reefs may be caused by the lack of food for reef-building organisms, by shifting sand, or by the steepness of the slope.

Evidence of emergence and submergence.—The evidence of emergence on West Maui consists of streams entrenched in their fans, marine plains, wave-cut benches above sea level, and deposits of marine fossils. The shore lines are described from oldest to youngest. (See list of shore lines and their altitudes on page 54.)

The deep drowning of the mouths of the canyons and the presence of a submarine shelf 3½ miles wide and 1,800 feet below sea level off Waihee (fig. 29) suggest that West Maui, like the islands to the northwest, was eroded during the *Lualualei stand* of the sea. Throughout the text a submergence of 1,200 feet below present sea level is assumed, similar to the measured amount on Oahu, but it may have been 1,800 feet or more if the shelf is a submerged coral reef or a wave-cut platform correlative with the long canyon-cutting epoch. The east side of the mountain was cliffed by the sea when the Isthmus was covered with water. Part of the cliffing may have been done before the Haleakala lavas built the Isthmus (pl. 23C).

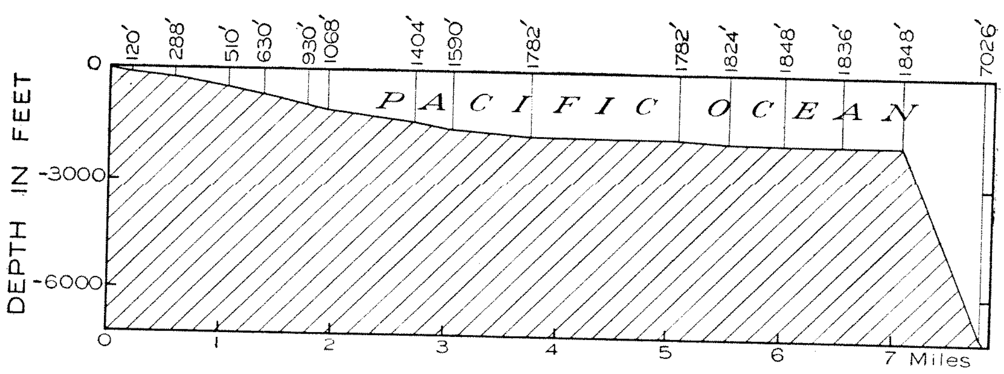


Figure 29. Profile of ocean floor N. 20° E. from Waihee Point, West Maui, showing the 1,800-foot submarine shelf. (From U. S. C. & G. S. chart 4130.)

In several places, particularly on the dry southeast end, the deep red soil has been stripped to about 1,200 feet above present sea level or to the level of the *Mahana stand*. The evidence is not conclusive, but the stripping is so similar to that on Lanai, it is probable that West Maui has emerged about 1,200 feet.

The soil is stripped so thoroughly below an altitude of 560 feet in many places that it is probable that the sea halted at this level, the

Manele stand, on its way down from the Mahana stand. The upper limit of the stripping on the southeast slopes near Maalaea is plainly seen from an airplane. Brown soil changes to red at this altitude on the slopes west of Lahaina, a condition caused, perhaps, by former submergence.

Well cemented marine fossiliferous beach conglomerate is exposed up Target Range Gulch one mile northwest of Olowalu to 240 feet above sea level. This is the highest known marine deposit on Maui. It is marked with an iron stake and a pile of rocks. Similar fossiliferous marine conglomerate is exposed in the gully due south of Launiupoko Peak at an altitude of 250 feet, as determined by a barometer. These deposits indicate a former shore line about 250 feet above the present, named the *Olowalu stand* from this locality.[90] It separated Maui into two islands (pl. 25A). Fossils from Target Range Gulch have been described by Ostergaard.[91] Some of the ancient well cemented high-level gravels in the larger canyons, such as Iao and Ukumehame, appear to have been graded to this sea.

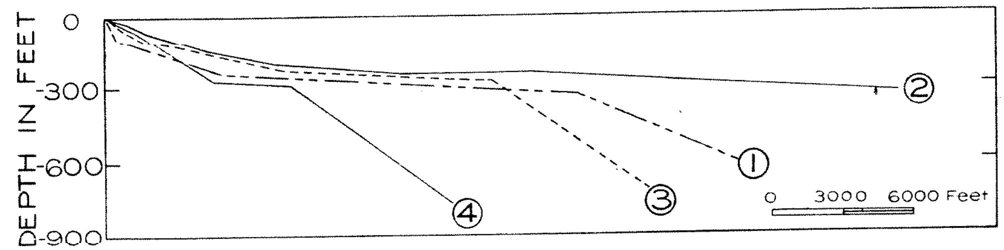


Figure 30. Four profiles offshore from West Maui showing 300-foot bench. (1) S. 12° W. from Papawai Point; (2) S. 40° W. from Launiupoko Point; (3) N. 67° W. from Honokowai; (4) north from Lipoa Point. (From U. S. C. & G. S. chart 4130.)

Four profiles off the shore of West Maui are given in figure 30. They show a distinct submarine shelf between 40 and 50 fathoms, the level of the *Kahipa stand,* apparently corresponding to the minus 300-foot Kahipa shore line off Oahu.[92] A broad shelf at this depth surrounds the Samoan Islands and is present on many Pacific islands. Perhaps it was formed by abrasion during the low levels of the ocean in glacial epochs. The lack of uniform depth of the shelf in the profiles is probably a result of subsequent deposition. Other evidence of this submerged shore line exists on East Maui (p. 107), which is younger than West Maui.

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[90] Stearns, H. T., Pleistocene shore lines on the islands of Oahu and Maui, Hawaii: Geol. Soc. America Bull., vol. 46, pp. 1927-1956, 1935.

[91] Ostergaard, J. M., Reports on fossil mollusca of Molokai and Maui: B. P. Bishop Mus. Occasional Papers, vol. 15, no. 6, pp. 67-77, May 1939.

[92] Stearns, H. T., op. cit. (Bull. 1), p. 39.

Several terraces, wave-cut platforms, and also fossil deposits near Puu Launiupoko at an altitude of 100 feet indicate the *Kaena stand* of the sea (pl. 33). Evidence of this shore line is well preserved on East Maui also.

A distinct gently sloping platform is cut in trachyte on the southwest side of Launiupoko Peak with its upper margin about 70 feet above sea level. The highest marine fossiliferous beach conglomerates exposed on this platform are in a gully at the upper edge of the 70-foot bench at an altitude of 69 feet, the level of the *Laie stand.* They are marked with an iron stake and a pile of rocks.

Partly drowned consolidated dunes overlying ancient dissected fans of Iao, Waiehu, and Waihee Streams along the north side of the Isthmus indicate that the sea stood lower than at present, following the Kaena and Laie stands. Test hole 104 (pl. 1) west of Kahului proves that the dunes extended at least 7½ feet below sea level. Valleys filled with lava on East Maui extend to about 60 feet below sea level. Although measurements are lacking of the exact depth of the submerged shore line when the oldest dunes were accumulating on the Isthmus, it is known on Oahu and nearby islands that similar dunes formed during the *Waipio stand* of the sea.

A few marine fossils have been found at the level of the *Waimanalo stand* of the sea near Maalaea (pl. 1). This shore line is a pronounced feature cut at the inner margin of the coastal plain. A distinct bench cut in rock reaching this height is found in several places, as at Makaluapuna Point near Honokohau Post Office and in the lithified dunes west of the mouth of Iao Stream. Most streams near the coast are bordered by gravel terraces graded to a sea about 25 feet higher than the present.

The last stand of the sea 5 feet above the present, the *Kapapa stand,* is recorded in benches cut into basalt at the base of many of the sea cliffs. They are reduced somewhat by erosion of the present sea.

GEOLOGY OF WEST MAUI

GENERAL CHARACTER, AGE, AND WATER-BEARING PROPERTIES OF THE ROCKS

West Maui volcano built first an oval shield-shaped dome of primitive olivine basalt laid down as highly fluid pahoehoe and aa flows averaging 15 feet thick. The flows came from two main rift zones and a central vent (23A). The volcano differs from most Hawaiian volcanoes by having a more circular form, steeper dips, more large intrusive bodies, wider dikes, radial dikes, and no recognizable third rift zone. Thin discontinuous vitric tuff beds and a few lithic tuff beds are exposed in the canyon walls, chiefly near the rift zones and the central vent. They are more numerous in the upper part of the geologic section than in the lower. Breccias indicate that a collapse caldera about 2 miles across indented the summit at the end of the epoch of basaltic extrusion (pl. 23C). The rocks of this basaltic dome are called herein the Wailuku volcanic series. The dome reached a height of about 7,000 feet above the sea during Wailuku time. The steep dips on the east side indicate that the lavas flowed into deep water and that Haleakala either did not exist or was not yet large enough to pond the lavas. The gentle dips in the northwest slope are evidence that West Molokai existed and dammed the lavas flowing from the north rift.

A relatively short period of quiescence followed the completion of the Wailuku dome, and a thin soil formed in many places from the decomposition of vitric ash and lava. A few lenses of conglomerate at the same horizon as the soil indicate that streams started to erode the mountain. During this rest period the composition of the magma changed to a more silicious type, and andesites and soda trachytes were erupted (pl. 23C). They issued chiefly as viscous flows from bulbous domes and cinder cones along fissures. They formed a veneer 50 to 500 feet thick over most of the basaltic dome. It appears from their remnants that they were thickest on the northeast slope and absent or very thin on most of the west and southwest slopes. This silicious group of rocks is named the Honolua volcanic series. The silicious lavas added probably 300 feet or less to the height of the Wailuku dome above sea level (section AA′, pl. 1).

Quiet reigned for a long time following the eruption of the Honolua volcanics. Steep-walled canyons 2,000 to 4,000 feet deep were cut into the dome and high sea cliffs formed on the shores exposed to strong wave attack (pl. 24C).

An epoch of great submergence followed the long erosion period. The submergence amounted perhaps to as much as 2,400 feet, and thick coarse conglomerates were emplaced on the canyon floors (pl. 25A). Remnants of these conglomerates now extend to the valley heads. Lesser emergences and submergences complicated the close of this epoch (pls. 25C and 26A). They are recorded by gravel terraces far above sea level, by soils swept away from smooth slopes, and by emerged fossiliferous marine conglomerates. Concurrently, feeble eruptions built isolated cones and poured out short flows along the southern and western shores. These lavas are picritic basalts and nepheline basanites and overlie or are interstratified with gravels. They are named the Lahaina volcanic series.

The age of the rocks is uncertain. The volcano probably began erupting above sea level in middle or late Tertiary time. Soils 10 to 30 feet deep may indicate that the dome of Wailuku and Honolua volcanics was completed in late Tertiary or early Pleistocene time. The Lahaina volcanics were erupted in late Pleistocene time, as shown by their relation to gravel and marine deposits of that age. Thermal water at Ukumehame Canyon in well 12 indicates that bodies of hot rock still exist underground. The gravels and fossiliferous conglomerates are chiefly middle to late Pleistocene in age and were deposited during a series of emergences and submergences.

The Wailuku basalts are very permeable and yield water freely. Swarms of dikes both in and outside the dike complexes confine water at levels far above sea level. All streams cutting such dike swarms are spring fed and are perennial. The interbedded tuffs carry little water. The massive rocks of the Honolua formation are much less permeable and carry relatively little water in most places, even near sea level. Interstratified soil, ash, and clinker beds in them give rise to a number of valuable perched springs. In the Lahaina volcanics only the Laina lava is extensive enough to carry water. It does so along the shore and the water is fit for irrigation only. A little water is recovered from the conglomerate at the mouths of valleys. It is mostly of good quality and as yet has been little developed. The loose gravels in the beds of perennial streams carry underflow that has been developed in Iao Valley.

The general character and water-bearing properties of the rocks of West Maui are given in the following table:

Stratigraphic section of West Maui

Major geologic unit	Rock assemblage	Thickness (feet)	Symbol on map (pl. 1)	General character	Water-bearing properties
Recent sedimentary rocks	Unconsolidated deposits	75±	Ra	Chiefly younger alluvium with brown silts, possibly in part marine, near the coast. Includes present gravel beaches.	Carries small quantities of water in perennial stream beds and supplies dug wells near the coast with fresh water, providing the lands inland are not irrigated with brackish water.
Erosional unconformity					
Middle(?) and late Pleistocene lavas and pyroclastics of the Lahaina volcanic series	Laina and Kilea volcanics, Kekaa and Hele cinder cones	10–60	Ql	Lava flow of picritic basalt from Laina cone and nepheline basanite from Kilea cone.	Laina lava yields brackish water to dug wells along the coast. The Kilea lava carries no water.
		150±	Qlc	Cones of cinders and spatter built by fire-fountains.	Carry no water.
Erosional unconformity					
Middle(?) and late Pleistocene sedimentary rocks in part contemporaneous with the Lahaina volcanic series	Consolidated calcareous dunes	1–200	Qd	Chiefly consolidated and partly consolidated cream-colored thin-bedded and cross-bedded eolian limestone deposits of uniform fine sand blown inland from ancient beaches. A Recent unconsolidated dune deposit near Honokohau P.O. included.	Very permeable but above the water table except along the north coast where they contain brackish water.
	Consolidated earthy deposits	10–200+	Pa	Chiefly weathered older alluvium, correlative talus breccia, landslide deposits, and probably some marine silt. The deposits form extensive fans and high terraces extending to the heads of the large canyons.	Carry small quantities of water at the mouths of main valleys and at their bases in the heads of large canyons.
	Consolidated calcareous deposits	10±		Angular, subangular, and rounded lava rock fragments in a calcareous matrix of fossil shells, coral fragments, and sand.	Too inextensive to carry water.

Great erosional unconformity					
Late Pliocene (?) or early Pleistocene volcanic rocks	Honolua volcanic series	15–1000	Th	Lava flows of massive soda trachyte and thinner oligoclase andesite. Individual flows reach 300 feet thick. All weather to white or gray.	Not very permeable, but some of the clinker beds supply perched springs in wet areas. Elsewhere they do not carry water.
		100–750	Thd	Bulbous domes of massive lava at the source of the flows.	Mostly impermeable and supporting swamps and water holes in wet areas.
		10–350	Thc	Cones of andesitic and trachytic cinders at the source of flows.	Permeable but lie above the water table; hence are dry.
		6–25	Orange lines	Dikes of dense andesite and trachyte filling fissures through which the Honolua lava erupted.	Confines water at high levels.
Probably Pliocene and early (?) Pleistocene volcanic rocks	Wailuku volcanic series	5500+	Tw	Lava flows of thin-bedded primitive olivine aa and pahoehoe 1 to 100 feet thick laid down in rapid succession and dipping 5° to 20° away from their source.	Extremely permeable and the chief aquifer of West Maui. They yield slightly brackish water to wells along the dry south and southwest coast.
		10–360	Twc	Cones of friable weathered basaltic cinders and spatter built along fissures at the source of the flows.	Very permeable and yield water freely where saturated but most of the cones are dry.
		1–50	Twf	Firefountain deposits of friable thin-bedded red and yellow weathered vitric tuff interbedded with the lavas.	Perch a few springs in wet areas.
		500±	Tpc	Pit crater deposits of talus breccia, shales and conglomerates filling small collapsed depressions.	Poorly permeable but yield water where saturated.
		200±	Tlc	Lava cones of thin-bedded highly scoriaceous lava and a little spatter.	Highly permeable and yield water freely where saturated, but the one shown on plate 1 contains sea water.
		1–50	Twp	Pyroclastic deposits of angular and subangular debris, chiefly blocks torn from crater walls by phreatic explosions. The beds are interbedded with the lavas.	Do not carry water, as all known beds lie in unsaturated zones.
		4000+	Tdc	Dike complex of swarms of closely spaced basaltic dikes mostly less than 4 feet wide.	Carries large volumes of water and supplies most of the springs, tunnels, and perennial streams. The water is confined in the intervening compartments of permeable lava flows at high levels.
		5000+	Tcc	Caldera complex of vent breccias, lava flows, bosses, talus, and pyroclastics that accumulated in the summit caldera. The vesicles in many of the rocks are filled with pneumatolitic secondary minerals.	Not very permeable but yields small valuable flows of water at high levels.
		1–24	Red lines	Dikes similar to those in the dike complex.	Confine water at high levels if in swarms.

WEST MAUI VOLCANIC ROCKS AND THEIR WATER-BEARING PROPERTIES

The West Maui volcanic rocks comprise all the lava flows, intrusives, pyroclastics, breccias, and interstratified soils in West Maui. They have been subdivided into the Wailuku, Honolua, and Lahaina volcanic series. The lavas of the lower or Wailuku volcanic series are separated from the lavas of the middle or Honolua volcanic series by a thin red soil, ashy in places. The lower Wailuku lavas are all primitive olivine basalts, and the Honolua lavas are all andesites and soda trachytes. (See Part 3.)

The upper member or Lahaina volcanic series does not in any place rest on the middle member. The Lahaina lavas are separated from the Wailuku lavas by a profound erosional unconformity and thick conglomerates, except near Lahaina, where they are separated in places by several feet of red residual soil. The Lahaina lavas are much fresher than those of either of the older series and their cones are loosely consolidated.

WAILUKU VOLCANIC SERIES

Lava flows.—The type locality of the Wailuku lavas is the 3,500-foot south wall of Iao Valley behind Wailuku. It is composed of thin-bedded pahoehoe and aa dipping 15° E. The Iao Valley road is at the base of the section. The pahoehoe is highly vesicular and is full of small tubes and slaggy masses. The aa is mostly highly vesicular and lies in jointed beds 2 to 10 feet thick, underlain, overlain, and in places mixed with clinker beds 6 inches to 4 feet thick. The clinker is mostly 1 to 4 inches in diameter and is sufficiently compacted to stand in vertical cliffs even though open and very permeable.

Small olivine and feldspar phenocrysts are common, but some lavas are nonporphyritic. A few lavas carry abundant olivines 1 to 3 mm. across. Rocks rich in olivine were noted in Iao tunnel (no. 7) and several places in Iao Valley, 1½ miles northeast of Olowalu, and 4 miles east of Honokowai Camp. Olivine segregations were found in boulders of augite porphyry a quarter of a mile west of the pit crater shown on plate 1 about 4 miles east of Olowalu, and in tunnel 2. Augite-olivine porphyries are common at the top of the series, notably on the slopes 3 miles northwest of Maalaea, 2 miles east of Lahaina, and inland from Kahakuloa.

As shown on plate 1, the Wailuku basalts are exposed at the surface on most of West Maui and in all deep canyons. In cliffs the

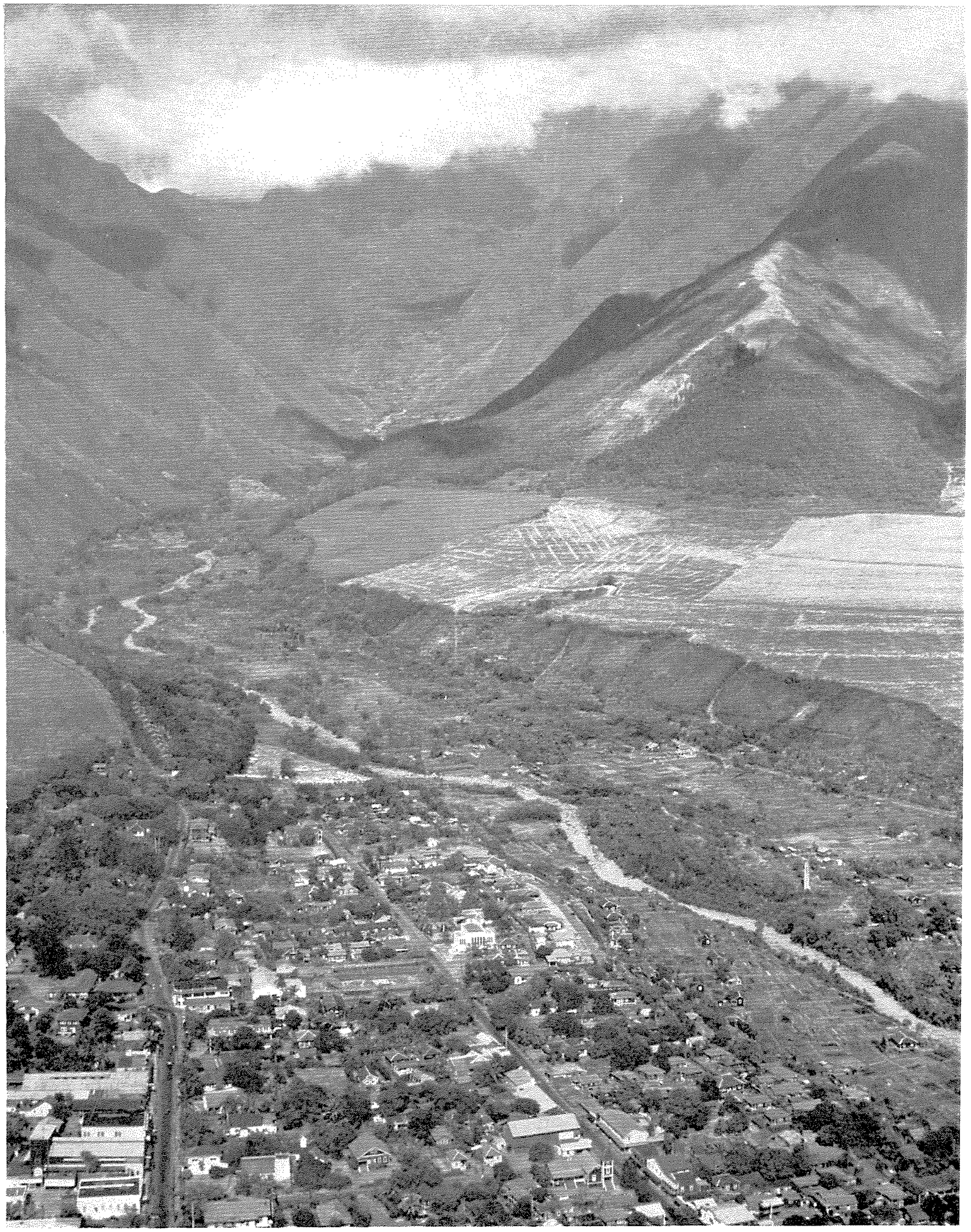
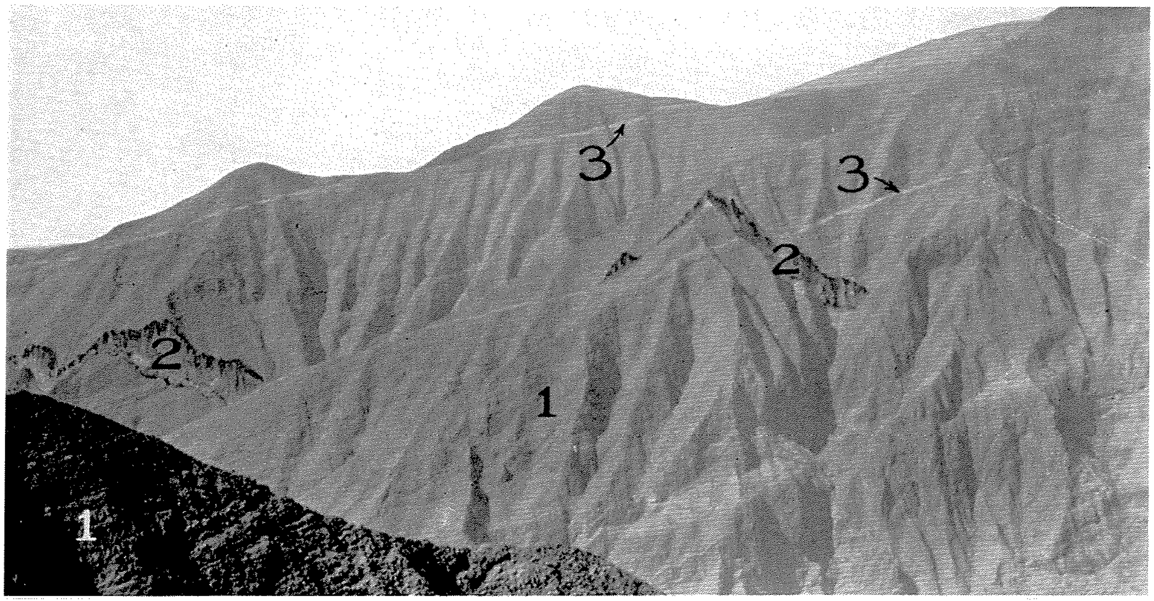


Plate 33. Air view of Iao Valley and Wailuku, West Maui. Stream terrace, planted to sugar cane and probably correlative with the 100-foot stand of the sea, borders the inner valley which contains a lower younger terrace. Photo by Fleet Air Base, U. S. Navy, Pearl Harbor, T. H.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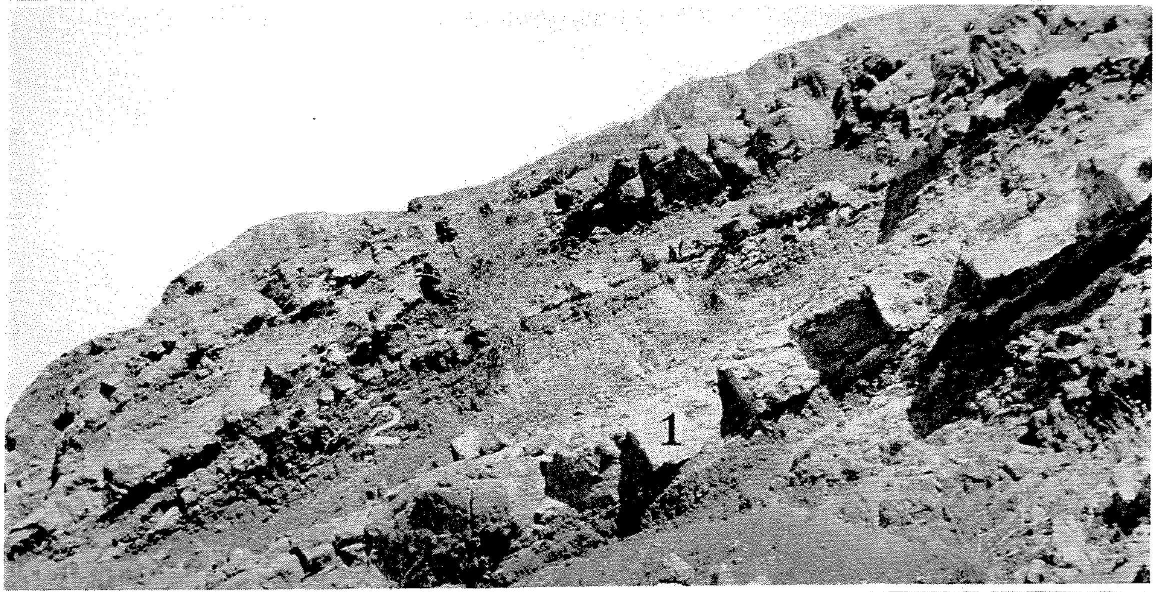
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Opposite page, top: Plate 34A. West wall of Ukumehame Canyon, West Maui, showing typical thin-bedded steeply dipping Wailuku basalts (1), trachyte dike (2), and beds of explosion breccia (3).
Middle: Plate 34B. Thin-bedded basalt (1) interbedded with vitric tuff (2) along the highway west of Maalaea, West Maui.
Bottom: Plate 34C. Banded basalt caused by selective weathering of parallel bands of vesicles separated by dense rock near Maalaea.

thin beds weather to dark-gray, red, red-violet, and brown, and stand in sharp contrast to the overlying Honolua lavas which weather to light-gray and white (pl. 32). Dark-red and reddish-brown soils characterize the undisturbed surface of the Wailuku basalts in contrast to light-brown soils on the feldspathic Honolua lavas. The basalts are almost completely decomposed to a depth of 100 feet on the slopes northeast of Kahakuloa and north of Lahaina where they were apparently never covered with Honolua lavas. Where the soils have been stripped away, jagged residual rock pinnacles remain.

Individual flows range from 1 foot to 100 feet in thickness and, in fresh specimens, from gray to blue in color. They dip from 5° to 20° away from their sources. Clinker near the original surface of the dome is loose and open, but in the bottom of cliffs 4,000 feet high it is more compact and coherent. The crusts of the billowy pahoehoe flow units are commonly oxidized to yellow or red. Many of the lava tubes and cracks are filled with intrusive rock in the vicinity of dikes. Amygdaloidal basalts are found in the caldera complex in Iao Valley, where hydrothermal action occurred.

Small lenses of gravel were found between the lavas at altitudes of 750 feet in the south bank and 500 feet in the north bank of Kahoma Gulch, and 250 feet in the north bank of Olowalu Gulch, and in Olowalu shaft. They were deposited by small streams near the close of Wailuku time, as all the gravel lies near the top of the series.

A local unconformity was found on the road crossing of Waipili Gulch, 1 mile south of Kahakuloa. There the lavas have a 26° dip and appear to cascade over a buried cone. Another local unconformity is exposed 1 mile northwest of Paupau Hill (Mt. Ball) in the south wall of Kanaha Canyon. It is indicated by a bed of very massive lava.

A conspicuous bed of banded basalt is exposed along the highway three quarters of a mile west of McGregor Point (pl. 34C). It is due to the selective weathering of parallel bands of small vesicles separated by dense rock. A little farther westward a laminated pahoehoe is exposed on the side of a secondary lava cone. The lamination is also a result of textural differences, layers of highly vesicular rock alternating with less vesicular layers. A similar lamination is produced in a dense basalt near the portal of Kahoma tunnel (no. 18).

The Wailuku basalts are extremely permeable owing to their vesicular slaggy, tubular, clinkery character (pl. 8A). The lavas in the south half of the mountain are exceedingly scoriaceous and thin-bedded because they flowed down steeper slopes than those on the north and are closer to their source (pl. 34A). As a whole, they are probably more permeable than the Koolau basalts on Oahu which yield freely to all wells drilled into them. Wells 1 to 12 obtain water from the Wailuku lavas. Huge quantities of basal water of excellent quality await development in these lavas in the north part of the mountain. In the south part, recharge is slow and numerous dikes cut off the underflow from the wet summit area. There, wells encounter a low water table and fairly high salt content.

Cones and vitric tuff deposits.—Most of the cones on the surface of the Wailuku dome have been destroyed by erosion but a few remnants are exposed in the southwest end (pl. 1). Many cones are exposed in the face of cliffs and when plotted on plate 1 had to be exaggerated to be distinguished from a vitric tuff bed. Many are spatter cones or cinder cones less than 100 feet high. A few are lava cones, or mixed lava and spatter cones. The thin extremely frothy lavas with many thin interbedded vitric tuffs in the southeast rift indicate that much of the Wailuku lava was extruded from narrow cracks, like the historic eruptions on Kilauea and Mauna Loa Volcanoes (pl. 34B).

The even-bedded lavas in the Iao type section, adjacent to the former West Maui caldera, with their sparse short thin lenses of tuff, stand in strong contrast to the thick section of Kula lavas in the west wall of the summit depression of Haleakala, with their numerous interbedded cinder cones and tuff beds.

The Wailuku cones are thoroughly consolidated and are generally palagonitized yellow or oxidized red. The most accessible large cone is at the mouth of Honokohau Valley (pl. 1).

Vitric tuff beds crop out as conspicuous discontinuous yellow or red layers a few inches to 50 feet thick. Only the more continuous and fairly thick beds have been shown on plate 1. Probably many are concealed by dense vegetation on the canyon walls, which accounts for more being shown in the leeward bare canyons than in the windward canyons. The tuff is composed of fine ash, lava ribbons, and pumice from the firefountains. The texture becomes coarser near vents where the fine ash grades into cinders and spatter.

Cross bedding or other evidence of being reworked by wind or water is scarce in the tuff.

Tuff beds are more numerous in the upper part of the formation and also next to the rift zones, but it is estimated that they make less than 1 percent of the Wailuku series. They are particularly numerous in Pohakea and Ukumehame Canyons, where beds 20 to 50 feet thick were noted. The thicker beds are sections of cones. Probably high winds blew across the southwest rift ridge, as they do today, and caused much debris to drift away from the fire-fountains during eruptions.

Only small quantities of water are perched on vitric tuff beds interstratified with primitive basalts on West Maui as elsewhere in Hawaii. The beds in the dry southern part of the mountain do not carry water, but small springs issue from them in the northern part. Water issues from basalt underlain by vitric tuff in tunnels 21 and 22. No prospects were found for developing water on tuff in the Wailuku formation.

INTRUSIVES.—Two great systems of dikes spread from Iao Valley like ribs of fans, one to the north and the other to the south-southeast, but dikes are abundant in the intervening sectors.

The finest exposure of a dike complex known in the Hawaiian Islands can be seen in the head of Ukumehame Canyon from the trail along the east rim. Exposed in this great amphitheater are hundreds of nearly parallel dikes, all of which terminate before they reach the rim or the ancient surface of the dome. All are conspicuously thin except two that trend southward to bulbous domes of the Honolua formation. A large stock or boss 3,000 feet long lies in the bottom of the canyon (pl. 1).

The dikes of the Wailuku series with a few exceptions range from a few inches to 10 feet wide and average 1½ feet. Their widths are shown in the following table:

Dikes on Maui

Width (feet)	West Maui[a] (number)	East Maui[b] (number)
Less than ½	60	2
½ - 1	196	5
1 - 1½	101	5
1½ - 2	123	13
2 - 3	69	7
3 - 6	57	12
6 - 12	14	1
12 - 24	11	0
More than 24	1	0
Total	632	45

[a] 762 additional dikes noted but not measured, mostly ½ to 2 ft. Most dikes more than 8 ft. wide belong to the Honolua series.

[b] 178 additional dikes noted but not measured.

A few dikes swell locally to 24 feet and still retain cross jointing that easily separates them from the wider and more massive bosses and stocks. Multiple dikes indicative of parallel intrusion at different times are common. Most have ⅛- to ½-inch glassy selvages; those that cooled at considerable depth are usually dense and cross-jointed, and those that cooled at shallower depths are platy and vesicular.

All petrologic types represented in the flows, ranging from fine-grained basalt to olivine-rich porphyries, are found among the dikes. (See Part 3.)

Most of the dikes found are plotted on plate 1, but many hundreds more exist that were not mapped, either because they are concealed with vegetation, are not on the lines of traverse, or are too close together to be shown. For example, 152 dikes were cut in 2,200 feet by Waihee tunnel (no. 1).

Large intrusive bodies are exposed in Kahakuloa, Black Gorge, Iao, Waikapu, Ukumehame, and Kahoma Canyons (pl. 1). More stocks, bosses, and plugs are exposed in West Maui than in any other mountain in the Hawaiian Islands so far studied in detail. This may be largely due to the loose character of the flows which made them easily stoped and to the abundance of deep exposures penetrating rift zones. The larger bosses are shown on plate 1 and are described in Part 3. Some are dikes locally swollen, to fill roughly oval cylindrical cavities. No disturbance is found in the adjacent bedding to indicate forceful intrusion; hence, the country rock probably either sank into the magma or was carried upward by it. If assimilation played a part, no evidence remains.

The stocks are mostly very dense basalt with the texture becoming coarse and holocrystalline near the center. Some are gabbros. A few are porphyritic. Some definitely decrease in size downward. Their diameters range from 100 to 3,000 feet. The Black Gorge intrusive, illustrated by Daly,[93] has been found not to extend far into the wall, as tunnel 7 passes within 600 feet of it.

Some of the bosses, when intruded, probably made pit craters, deep circular pits stoped in the land without lava being extruded.

Two sets of joints cut the huge Ukumehame stock. One set is vertical and trends east and west. The other trends N. 45° E. and dips 45° E. The other bosses and stocks are variously jointed.

Sills are scarce in comparison with dikes. A columnar-jointed sill 100 feet thick crops out in Waihee Valley. Several are well ex-

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[93] Daly, R. A., Igneous rocks and their origin: fig. 136, p. 281, N. Y., 1914.

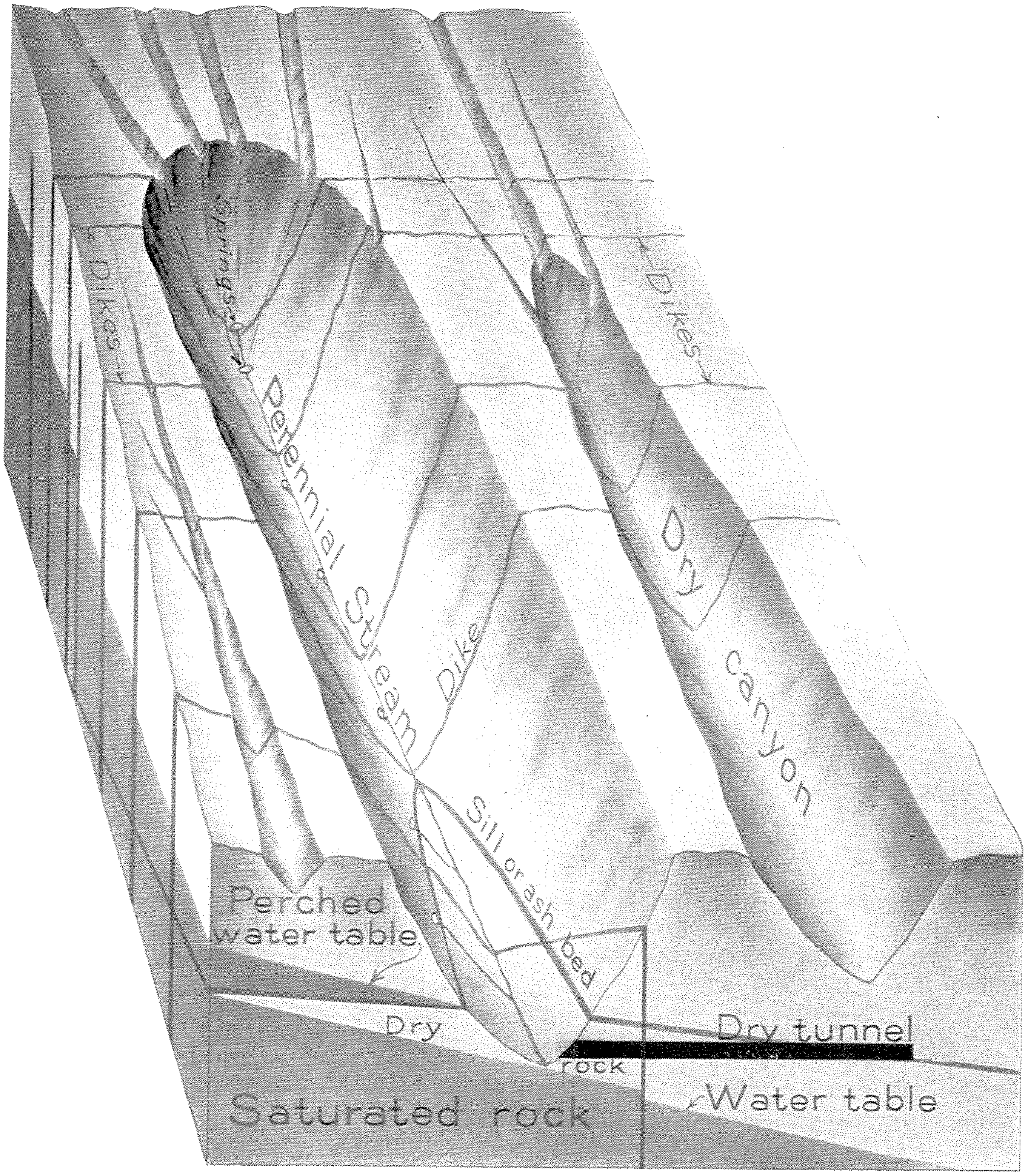
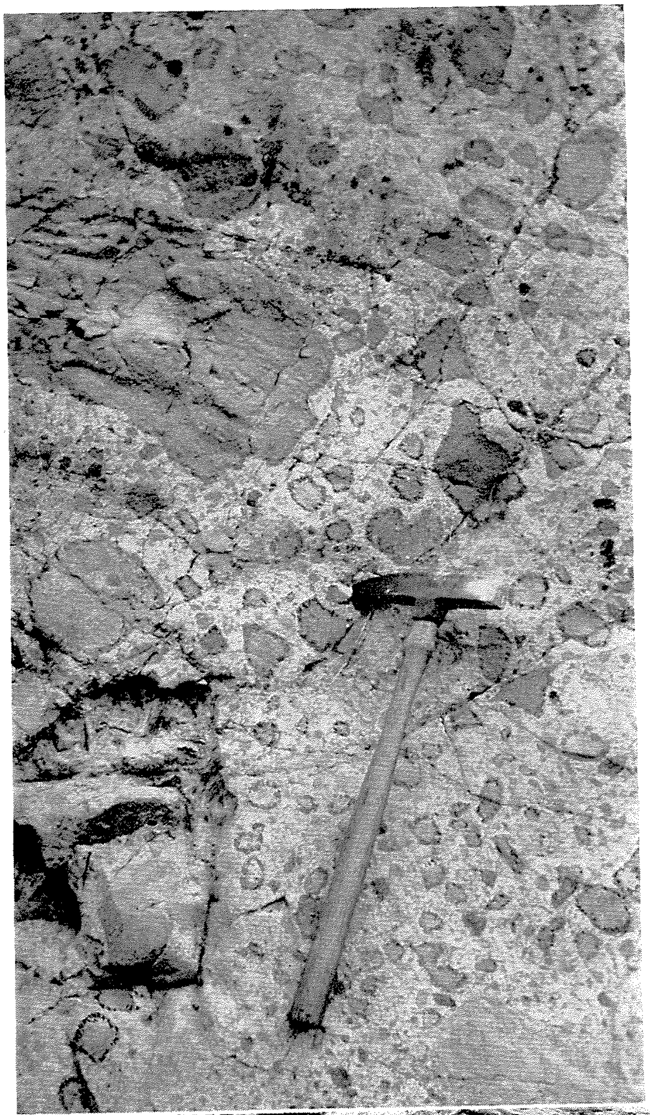


Plate 35. Diagram showing why some springs issue high above the floor in valleys heading into a saturated dike complex. Tunnels driven into the wall away from the recharge area fail to recover water, as they are above the water table.



Left: Plate 36A. Weathered clinker in Honolua lavas along the road to Kahakuloa, West Maui. Hammer is 14 inches long.

Below: Plate 36B. Honolua aa andesite resting on Wailuku basalt in road cut near McGregor Point, West Maui. The hammer is pointed at a 6-inch bed of soil at the contact.

posed in Ukumehame Canyon. They are not separated from dikes on plate 1.

The dike complexes and dike swarms are the great water bearers of West Maui. The abundance of water in the dike swarms is due to the high rainfall in the mountains, the extraordinarily high permeability of the intervening Wailuku lavas, and the radial divergence of the dikes from the area of high recharge, thereby dispersing water in all directions. The dikes crop out at the head of every major valley and supply practically all the perennial streams, or a total low flow of 75,000,000 gallons a day (fig. 9). Only in the dry south tip of the mountain do the canyons expose dikes which, due to the low level of the water table in that area, do not supply perennial streams. The successful tunnels derive their flow from dike swarms. They yield about 20,000,000 gallons a day.

Most of the water issues between dikes at or close to stream level. But in a few places, as at spring 8 in Waihee Valley, or in the heads of deep canyons, it issues several hundred feet above the stream. Such high springs are generally due to the outside retaining dike of the saturated compartment being only partly cut away by erosion. The two dikes bounding the compartment supplying spring 8 are both exposed, and the water escapes from a low place in the outside dike (pl. 35). Some high springs are due, however, to more or less horizontal, fairly impermeable bodies of rock between the dikes, such as other dikes with low dips, heavy beds of extrusive lava, sills, or ash beds (pl. 35).

All springs entering Launiupoko Stream issue from its north wall, and if tunnels were driven into the south wall they would not yield water. This is due to the canyon cutting obliquely across a swarm of dikes that are recharged entirely from the wet northern side and not from the dry southern side.

Some dikes are sufficiently fractured to yield water as in tunnel 7 and in several of the canyons. The water moves gradually seaward through such cracks, losing static head on the way. The dikes spread fanwise seaward so widely that all high-level water between them drops to the basal water table before it reaches the coast. Inland from Lahaina, many dikes are nearly parallel to the coast. They probably divert water that would otherwise reach the wells near Lahaina.

The plugs and other large intrusive bodies of rock are so dense and the joints so tight that they are poor water bearers. An exception was found at an altitude of 2,480 feet at the base of the canyon wall in the northwest corner of Iao Valley, where water was seen percolating from the joints of a large massive body. Water probably stands under great pressures in the cliff behind this body.

Caldera complex.—A caldera complex is defined as the rock assemblage underlying a caldera. It comprises all the 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 volcanic product laid down in a caldera. It is a convenient map unit because the individual rock details are too small, diverse, and close together, to be shown on plate 1. Furthermore, the eroded caldera of the West Maui volcano lies in deep valley heads covered with dense vegetation, the only outcrops being in steep inaccessible cliffs or in stream beds. Much of the detail is masked also on the valley floors by extensive thick deposits of older alluvium (pl. 1).

The faults bounding the caldera are poorly exposed, but the eroded fault cliffs are major topographic features. The rocks of the complex are not transitionary to the rocks outside the caldera. A marked change occurs at the main bounding fault. There, the lavas have essentially undisturbed bedding and plainly dip away from the caldera, even though cut by numerous dikes. In the caldera, the bedding in the lavas is either horizontal, warped, or shattered beyond recognition. It is seldom continuous for long stretches, and the flows are usually more massive than those elsewhere. Dikes that are very numerous in one outcrop may mostly disappear a short distance along their strikes due to being replaced by later lavas that congealed in a pit perforating the dikes. Breccias of all sorts dominate the assemblage and in places form large masses nearly circular in ground plan. Large bodies of dense rock, either intrusive plugs or pod-shaped crater fills, are conspicuous.

Only a few of the details in the complex are shown on plate 1. Vent breccias and dike swarms form most of it. Comparative studies of the ancient calderas on Lanai, Kahoolawe, Molokai, and Oahu show that intrusive rock and breccia increase with depth below the former surface, and extrusive rock decreases.

The caldera complex yields little water, considering that it lies where 200 to 350 inches of rain falls annually. This is due to its low permeability and crisscross dike structure, its large dense intrusive bodies, and its nearly impermeable vent breccias. The bodies of permeable extrusive basalt are too disconnected to serve as water bearers. Practically all the springs issue from lava flows cut by dikes at the base of the cliffs bordering the caldera. As the streams cross the complex, they gain water chiefly from the base of the overlying alluvium. Thus the floor of Iao Valley is a poor place to develop water by tunneling. The same hydrologic conditions were observed in the head of Waikapu Valley where tunnel 12 failed to encounter water in vent breccia.

VENT BRECCIAS.—Vent breccias may be classified according to the manner of emplacement, the size and shape of the deposit, and the type of fragments. The term breccia is used so loosely in scientific literature[94] that a detailed description of the formation of those on West Maui follows. Possible modes of emplacement can be ascertained from active vents, but criteria for distinguishing breccias in ancient eroded vents are not well known nor well established. In some places in West Maui it is difficult to distinguish them from the old firmly cemented talus breccia on the canyon walls, and in a few places they are identical in appearance, having originated in the same way from the same type of rocks. Some breccias contain interbedded shales and other water-laid deposits. The deep canyons on West Maui adjacent to the slightly dissected carapace remnants of the volcano expose vent breccias formed in deep craters near breccias of the same age formed in shallow craters. Although the shallow and deep-seated breccias may have been deposited in a similar manner, they are vastly different in appearance, due to the range of rock types in the vent walls. Deep-seated breccia are composed largely of dense fragments derived chiefly from intrusive bodies in the wall, whereas the surficial breccia is composed chiefly of fragments of vesicular lava flows. Similar breccias are being made now in Kilauea Volcano, Hawaii. Talus that fell into Halemaumau, the active fire-pit, in 1924, is 1,800 feet below the rim of the caldera and contains a great deal of dense rock. Steam passing through it has probably firmly cemented it. About 4 miles away is the small Devil's Throat pit crater, in which talus of very vesicular lava flows is slowly accumulating. If this talus escapes erosion, it may remain unconsolidated even after the volcano has been extinct long enough to become deeply eroded.

Caldera breccia may contain fresh fragments of cinders, dikes, sills, stocks, frothy or dense aa or pahoehoe flows, or any other volcanic product present. Hot gases commonly invade such a breccia, fill its interstices with secondary minerals, and cement it firmly. Lying in the path of repeated intrusion, it is usually invaded with numerous dikes and dikelets.

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[94] Williams, Howel, Notes on the characters and classification of pyroclastic rocks: Liverpool Geol. Soc. Proc., vol. 14, p. 235, 1926.

A small pit crater a few hundred feet deep stoped in the slope of a volcano near the close of activity may have a very different history from a vent in a caldera. The pit crater will slowly fill up with talus from its own walls, with ash from nearby cones, or with pumice and sandy ash drifted across the slope before the wind—a slow process compared to the filling of an active vent in a caldera. Sufficient time lapses for weathering to attack the walls, and fragments in the talus may show various amounts of decomposition. Small flashy streams may find their way into it, bringing angular, subangular, and subrounded fragments of lava flows, sand, cinders, pumice, ash, and perhaps gravel. Temporary ponds may form on the crater floor, and mud may be deposited between falls of talus. Submergence may cause the sea to invade it and marine organisms may be added to the floor debris. Later emergence may start terrestrial deposition again. Lava may erupt in the pit and bury it, or the whole vent-fill may collapse and lose its original structure. Also, lava may flow into the pit from the slopes above and completely fill it, burying the debris. Vents with such diverse histories are certain to form on volcanoes, but only two such histories have been deciphered on West Maui.

Vent breccias of the caldera type crop out over much of the area shown as caldera complex in the heads of Iao, Waikapu, and Ukumehame Canyons on plate 1. They are composed largely of varicolored, varitextured, angular and subangular, extrusive and intrusive rock fragments firmly cemented in a matrix of silt- and sand-sized rock powder. The fragments range from tiny particles to blocks more than 5 feet across, but 2- to 6-inch blocks appear to dominate. Bedding is scarce except in the upper part of the vents, but where observed, dips 20° to 32° away from the vent walls. Some of the breccias in Iao Valley resulted from the collapse of dense crater fills and intrusive masses and are composed of dense angular fragments. The degree of consolidation and the abundance of intrusive rock fragments increase notably with depth below the former caldera rim. In the Waikapu-Iao Valley divide breccia attains a thickness of more than 1,000 feet. It is exposed up the floor of Waikapu Valley from an altitude of 1,800 feet to the crest at the head.

At an altitude of 1,500 feet in the bed of the middle fork of Iao Stream near the end of the trail shown on plate 1, is a laminated amygdaloidal basaltic mass 100 feet long striking N. 20° E. and dipping 13° E. It is imbedded in a firmly cemented breccia composed of dense basaltic fragments. The fragments have not moved far and the breccia makes a nearly vertical but not very definite contact with the laminated basalt.

In the first gully east of Black Gorge along the road and unconformably below well cemented talus breccia is a breccia even more firmly cemented. The fragments project from the matrix only slightly. They are mostly vesicular gray basalt containing scattered olivine phenocrysts. The rock types are not very diverse (pl. 40A). The breccia is cut by several dikes and was formed in a vent. One 12-inch dike cutting the breccia and striking N. 80° W. and dipping 78° N. changes near Black Gorge to a vesicular olivine-rich basalt without regular flow bedding and with numerous pockets of clinker. At the gorge wall this lava contains irregular streaks of yellow palagonite, probably in part altered glassy crusts. However, one layer thickens to a 6-inch lens composed of distinct pumice fragments, some of which have not yet palagonitized, showing beyond doubt that some of the yellow material is vitric tuff. The peculiar mixture is unlike any lava flow seen elsewhere. Some of the lava masses that were floating islands in the former lava lake of Halemaumau at Kilauea Volcano[95] are known to have been engulfed during sinking periods of the lava column. They may make a breccia like the mixture described above.

Vent breccias in weathered exposures are easily confused with the older talus breccias that accumulated in the present valleys. The two types are separated with certainty when dikes are present, as dikes do not cut valley talus. In fresh exposures the absence of weathering on the fragments and the presence of rock particles instead of soil in the interstices, are indicative of vent breccia. These criteria fail in dry areas where the present canyon cliffs shed fresh rock talus practically free of soil.

A few coarse lithic tuff and agglomerate beds interstratified with the upper Wailuku lavas indicate that small portions of the vent breccias are probably due to disruption of lava beds by explosions. These portions are not distinguishable on Maui from a vent breccia composed of talus.

A shallow type of vent breccia is found in the pit craters shown in plate 1. The pit 4 miles south-southeast of Olowalu is well exposed. It is 1,000 feet across and is filled with talus and hillwash nearly to the rim. This pit, originally more than 200 feet deep, indented the steep slope of the south rift zone near the close of activity. It is similar to the pit craters in the southeast rift zone of Kilauea

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[95] Jaggar, T. A., Jr., Volcanologic investigations at Kilauea: Am. Jour. Sci., 4th ser., vol. 44, p. 171, 1917.

Volcano.[96] It slowly filled up with talus from the crater wall, debris washed over the rim from the steep slopes above it during heavy rains, and ash and cinders blown and washed from nearby cones. The conspicuous feature of the deposit is the fairly well defined bedding. The talus next to the crater walls dips 50° to 60° and parallels the contact. The dip decreases to 35° a short distance away from the wall. Unconformably on the talus but in places interfingering with it near the seaward side of the crater are nearly horizontal beds of tuffaceous friable sandstone 6 to 12 inches thick alternating with coarse hillwash. These beds have a dip of 6° next to the inland wall, indicating that they are probably a fan deposit. The hillwash was at first mistaken for a bed of explosion breccia. It is composed chiefly of vesicular clinker, fragments of vesicular pahoehoe 2 to 6 inches across, red cinders, and a few larger blocks of basalt. The slopes above the pit crater are strewn with similar debris as a result of weathering and erosion of the surface lava flows. Floods have carried into the crater chiefly the very light frothy fragments.

Many of the blocks are porphyritic and carry olivine and euhedral pyroxene crystals, the latter reaching ½ inch across. A few augite crystals were found in the sandy beds, evidently having weathered free from their matrix before being washed into the crater. Some of the fragments in the layers near the top are fairly well rounded. This deposit is puzzling even though it is well exposed, because it occupies a crater in a dry part of a rift zone where talus and hillwash contain much pyroclastic and highly vesicular volcanic material. The sandy beds resemble lithic tuffs and the coarse beds are easily confused with phreatic explosion debris. When the deposit was found in 1933 it was the only one known in the Hawaiian Islands. Since then several similar deposits have been found in Lanai[97] but they contain more pumice.

The process of accumulation makes such a deposit hard to classify. All the rocks therein are volcanic, fragmental, and in part pyroclastic. By the usual criteria, such a deposit of angular material filling a crater, should be a vent breccia either due to explosion or collapse, or both. It is, of course, sedimentary, but so are all other vent breccias in the Hawaiian Islands. A crater that persists as a depression from the cessation of volcanic activity through a long period of erosion, may contain a deposit grading upward from a typical vent breccia at the bottom, probably firmly cemented and

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[96] 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. 127-129, 1930.

[97] Stearns, H. T., op. cit. (Bull. 6), pp. 48-51.

perhaps even cut by dikes, to friable hillwash and talus, with perhaps conglomerate at the top.

The ancient pit crater in Kanaha Valley contains even-bedded laminated black lacustrine silts, coarse conglomerates, talus, and lava flows, the latter having flowed accidentally into the crater and filled it near the close of volcanic activity (fig. 31). Some of the pumice and cinders deposited with the hillwash show water-worn surfaces. Such pit craters might conceivably contain interbedded cinder cones, lava flows, or explosion deposits from later eruptions within the crater. Thus, crater fills may have a complicated history and contain almost any type of volcanic or sedimentary deposits. One in Lanai contains fossiliferous marine sediments.[98]

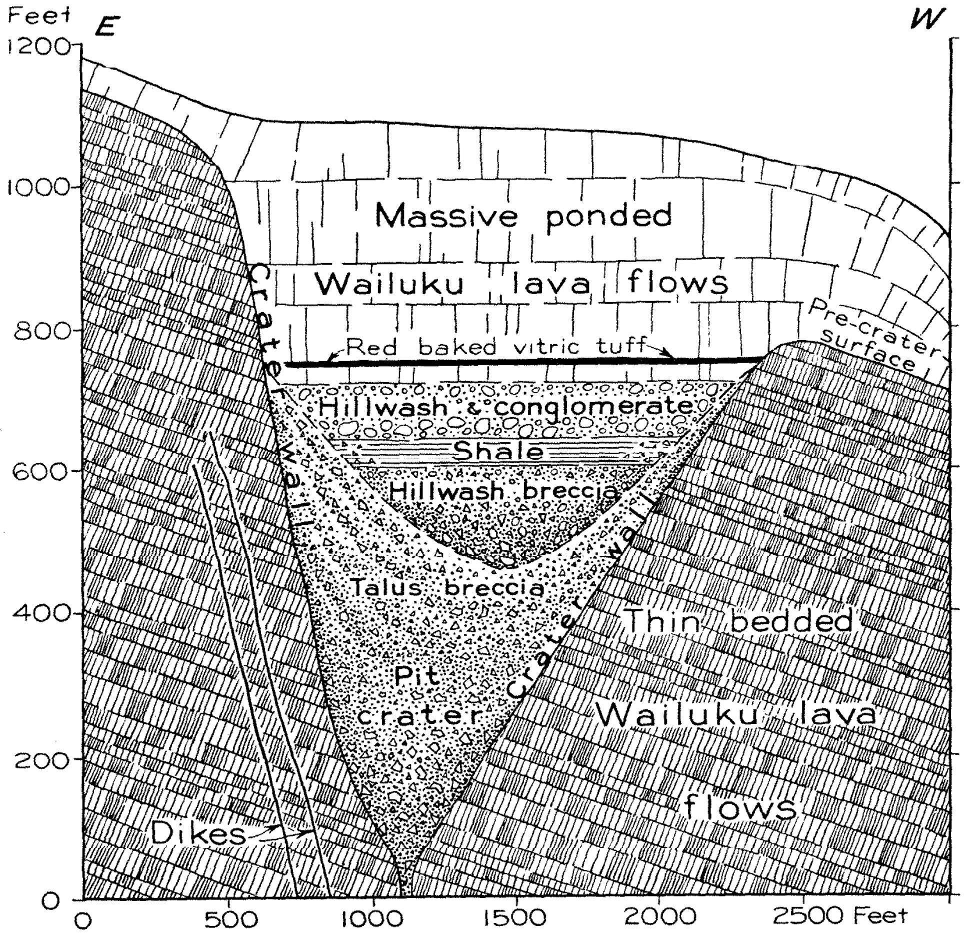

Fig. 31. Section of pit crater in Kanaha Valley near Lahaina, West Maui.

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[98] Idem, p. 19.

The permeability of vent breccias changes with the degree of consolidation and size of fragments. As a whole those on Maui have low permeability and those firmly cemented do not yield any water. Breccia, shattered bedrock, and fault gouge yield about 1 million gallons a day in tunnel 2, but much of the water comes from rocks other than breccia. Tunnel 12 yields only 5 gallons per minute from 1,650 feet of breccia. Its low flow is partly due to the tunnel running parallel to and slightly above the river. Streams crossing long stretches of breccia in Iao and Waikapu Valleys gain little or no water.

EXPLOSION BRECCIA AND LITHIC TUFF.—Several beds of explosion breccia and lithic tuff are interstratified with the upper Wailuku lavas on the flanks south of Iao Valley (pl. 34A). The two main layers are separated by 300 to 500 feet of bedded basalt. A 6-foot bed crops out at the portal of tunnel 19 in Kahoma Valley. Others may be hidden by vegetation on the north side. The deposits thin rapidly seaward, indicating that the explosions took place in or close to vents in the south end of the caldera.

The beds range from a few inches to 50 feet thick and contain angular and subangular blocks of Wailuku basalts reaching 3 feet across in a gray comminuted rock matrix, all typical accessory ejecta torn from the crater wall. The bed on the ridge 2½ miles inland from Olowalu contains an interstratified yellow vitric tuff layer 2 inches to 1 foot thick indicating that firefountains played between explosions. The deposit is poorly bedded and in places thickens locally to form short lenses. This stratigraphy resembles that found at Kilauea Caldera, Hawaii, where phreatic explosions have been interspersed with normal firefountains.[99] The explosion breccia is an infinitesimal part of the bulk of the volcano, but it establishes the fact that catastrophic phreatic explosions occurred during the collapse or mature phase. This fact suggests that, at times of rapid subsidence of the lava column, ground water can find ingress to vents through cracks induced by collapse and cause steam explosions from contact with bodies of hot rock.

The beds of lithic tuff and explosion breccia are poorly assorted and fairly impermeable. They might perch water in a wet area, but those explosed in the dry southern end of the mountains do not carry water.

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[99] Stearns, H. T., op. cit. (Water-Supply Paper 616), pp. 143-153.

HONOLUA VOLCANIC SERIES

Lava flows.—The Honolua volcanic series is named after the little village of Honolua on the northwest coast. The village is on a bay bounded on both sides by cliffs of andesitic lavas 100 to 150 feet high. Lipoa Point, north of the village, is a peninsula built by a massive flow from vents 5 miles inland. The soil separating the light colored andesites of the Honolua series from the underlying dark colored Wailuku basalts is well exposed in the road cuts at Honolua.

The Honolua lavas are andesites and soda trachytes characterized by platy cleavage. Along the cleavage faces, small uniform feldspars gleam in reflected sunlight like minute fish scales. The gleaming crystals are generally sufficient to identify these rocks in hand specimens. Most of them are nonporphyritic but some carry feldspar and hornblende phenocrysts. (See Part 3.) In the field the Honolua lavas are easily separated from the Wailuku basalts by their massiveness and by their white and gray surfaces when weathered. Their soils are thin, seldom exceeding 5 feet. They are never lateritic and are always buff to ochre in contrast to the dark reds and red-browns of the soils on the Wailuku basalts.

Individual flows have dips of 3° to 20°, depending on the slope on which they congealed. They range from 25 to 300 feet in thickness and may reach 500 feet near their vents. The average thickness of the andesitic flows is about 40 feet and of the trachytes about 150 feet. All of the trachytic and most of the andesitic flows are aa, but in an andesitic flow 42 feet below the ground in well 1, a lava tube 4 feet high was encountered with stalactites reaching 2 feet in length. The stalactites differ in form and texture from those in tubes in basalt, as shown in plate 44B. Other andesitic flows show incipient ropy structures. Smooth-walled oval cavities 1 to 5 feet across indicate that large bubbles of gas were trapped in some of the flows.

The massive part of most of the flows is columnar-jointed and breaks into huge blocks as the joints are usually 5 feet or more apart. The clinker beds are usually not less than 10 feet thick and reach 50 feet in some places. The clinker weathers into subrounded and rounded nodules in a gray powdery matrix that resembles a conglomerate except for the homogeneity of the mass (pl. 36A).

The Honolua lavas attain a maximum thickness of about 750 feet near Eke, but average about 75 feet elsewhere. They form a protective veneer or armor over the easily eroded dome of Wailuku basalts. Apparently the veneer was thickest on the northern flank because in spite of the high rainfall there, only Kahakuloa and Honokohau Streams have succeeded in cutting deep canyons (pl. 1). The rest of the dome was incompletely veneered, but scattered remnants indicate that the Honolua lavas were more extensive before erosion. Streams on the intervening basaltic areas have cut deep canyons. Thus two physiographic ages are found in the topography: The valleys or stretches of valleys in the trachyte are in youth and those in the basalt are in maturity. The trachyte cones also influenced the stream pattern established at the close of volcanic activity. Waihee Stream makes a distinct bend to the east as a result of the Lanilili vent.

No erosional unconformities were found between the Honolua flows, but thin interbedded soil and ashy soil beds are fairly common. The Honolua lavas usually are separated from the Wailuku lavas by several inches of soil (pl. 36B). If vitric ash is present, the soil may thicken to 5 feet or more. In a few places soil is absent; in others gravel is present. The long narrow flow of andesite that reaches the coast half a mile west of McGregor Point spilled over a cliff 40 feet high cut into Wailuku basalts. In places along this local unconformity 1 foot of hillwash separates the two formations, but in other places it is a nonconformable rock-to-rock erosional contact. On the north side of Puu Anu 3.5 miles inland, 15 feet of stream-laid conglomerate lies between the Honolua and Wailuku lavas.

The following section was recorded in well 1 during its excavation. It shows an erosional unconformity between the Honolua and Wailuku lavas.

Log of well 1 near Honokohau, West Maui

	Thickness (feet)	Altitude of top of bed (feet)
Massive andesite	37	244
Clinker and base of first Honolua flow	4	207
Massive andesite	14	203
Clinker and base of second Honolua flow	2	189
Conglomerate with cobbles reaching 10 inches across derived from Wailuku basalts	3	187
Compact coarse red sand	1	184
Base of eroded vesicular Wailuku basalt flow	1	183
Red soil	1	182
Aa and pahoehoe of Wailuku formation with no soil streaks	181	181
Bottom of hole in pahoehoe	...	0
	244	

The dense massive beds of the Honolua lavas have low permeability, but the clinker beds are permeable where not too weathered. All the lavas on the south end are too discontinuous and receive too little rain to carry water. Along the northwest coast between Mailepai and Punalau Points they carry some basal water along the shore, but they are more valuable there as a caprock to prevent the invasion of sea water than as water bearers. These Honolua lavas are underlain at depths of 25 to 200 feet by highly permeable Wailuku basalts. Wells to recover large supplies should be sunk ½ to 1 mile inland in order to encounter water in the basalts.

Seeps were noted at several places on the thin intercalated soils in the higher wet areas. Three springs between 2,100 and 2,250 feet altitude, 2 miles west of Waihee, are of this type (pl. 1). The clinker bed between two massive beds of trachyte supplies springs 5 and 6 and all of the low flow of Makamakaole Stream, which is about 1 million gallons a day. All the areas indicated by the swamp symbol on the West Maui Mountains are peat bogs underlain with dense Honolua lavas (pl. 1).

CONES AND TUFF DEPOSITS.—Many of the Honolua lavas issued in a very viscous state and formed dome-shaped masses, herein called bulbous domes. Similar domes have been found on other basaltic island volcanoes.[1] Before erosion they are characterized by deep concentric shrinkage fissures and loose blocky surfaces. A few domes were preceded by firefountains that laid down cinders and pumice around the vent, but no deposits of catastrophic explosions were found. Figure 12 shows the distribution of the 30 vents found. Only the cone 1½ miles northwest of Olowalu is composed entirely of cinders (pl. 1). The largest well preserved bulbous domes are Puu Launiupoko and the hill just inland 2 miles northwest of Olowalu (pl. 1). Puu Launiupoko is half a mile across, exhibits typical concentric jointing caused by the viscous lava moving outward from the vent, and lacks firefountain deposits (fig. 4 and pl. 9). Eke is a similar bulbous dome with deep pits apparently due to solution by rain water along the main circular joint cracks (pl. 30). Other domes filled craters in cinder cones (fig. 32).

Excellent exposures of dikes joining bulbous domes or flows prove that the Honolua lavas were erupted from fissures. The bulbous domes lie in definite lines along fissures radial from the summit, chiefly in the two rift zones of the Wailuku Volcano (fig. 12).

Two partly eroded bulbous domes inland of Olowalu show that the Honolua lavas were sufficiently viscous when emplaced to warp the adjacent Wailuku basalts near the surface. A narrow zone of crushed Wailuku basalt borders Puu Koai in the west wall of

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[1] Daly, R. A., The geology of Ascension Island: Am. Acad. Arts Sci. Proc., vol. 60, pp. 23-38, 49-63, 1925; The geology of Saint Helena Island: Am. Acad. Arts Sci. Proc., vol. 62, pp. 54-56, 66-75, 1927.

SECTIONS OF TYPICAL BULBOUS DOMES

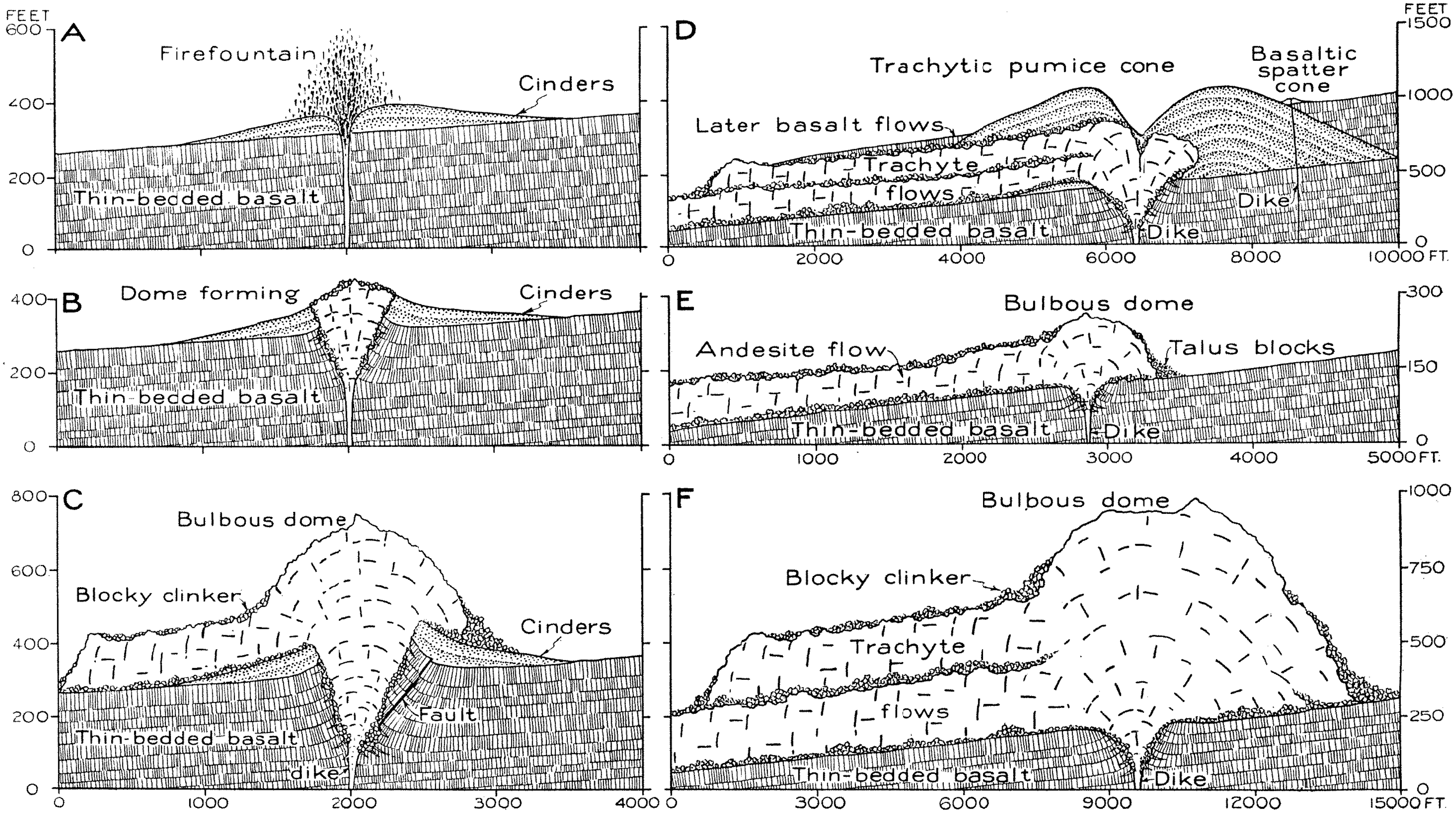

Figure 32. Diagrammatic sections of typical bulbous domes of trachyte and andesite in the Hawaiian Islands. **A**, Firefountain building trachytic cinder and pumice cone. **B**, Formation of a bulbous dome. **C**, Completed bulbous dome of trachyte with short flow. Basalt beds are pushed upward and faulted. Puu Koai near Olowalu on West Maui formed in this way. **D**, Trachytic pumice cone contemporaneous with flows and burying the bulbous dome at the source. It is surrounded by later basalt flows, one of which erupted through the trachytic cone. Puu Waawaa on Hualalai Volcano, Hawaii, formed in this way. **E**, Small bulbous dome of andesite with thin long flow and no cinders, similar to Puu Anu on West Maui. **F**, Large dome of trachyte with two thick stubby flows and little or no pumice, similar to Eke dome on West Maui.

Ukumehame Canyon. The basalt has been pushed upward and outward on the southwest side for a distance of 200 feet and the dip changed from 16° to 75°. The rock is oxidized red by heat only about 10 feet from the plug. The rock on the north and west sides faulted slightly, developing a friction breccia zone 18 inches wide. The feeding dike is exposed. Evidence of forceful intrusion is not seen in connection with the plugs of primitive basalts because of their great fluidity.

The magma in these plugs was so viscous and it moved upward so slowly that fragmentation at the top and margins, where chilling was most rapid, sometimes occurred while the magma was still in the open vent below the level of the mountain flank. In places the viscous lava squeezed vertically upward through the brecciated mass similar to the rise of the spine of Mont Pelée on the island of Martinique in 1902.[2] Such protrusion results in a dense rock bordered by breccia with nearly vertical contacts (pl. 38A).

The great mass of trachyte with Eke at its summit is underlain at the head of the north fork of Waihee Canyon by about 30 feet of decomposed ash. The ash is probably largely if not entirely basaltic, but a sample could not be obtained because of the inaccessibility of the outcrop. The seaward sloping basal contact of the trachyte with the Wailuku basalts is well exposed on the east wall of Honokohau Canyon. The mass is deeply eroded and weathered. It appears to consist of three flows, each about 200 feet thick and each shorter than the underlying one. An amphitheater 1½ miles northeast of Eke with Keahikauo Peak on its north rim is poorly represented by the contour lines on plate 1. It may be an eroded crater.

Puu Paupau (Mt. Ball), a dome-shaped hill 2½ miles east of Lahaina, may be a dome in the Wailuku lavas warped by an andesitic intrusion that failed to break through on top but discharged from the east side (pl. 1), but no evidence of distortion of the lava beds was found.

Puu Koae near Kahakuloa consists of a large trachyte mass partly surrounded by bedded cinders. The trachyte apparently filled a crater in a cinder cone. Subsequent erosion and weathering have removed most of the weak cinders and left the strong resistant mass of trachyte standing as a dome (pls. 37A and 37B).

Sections of the several types of bulbous domes on West Maui in contrast to the Puu Waawaa type in Hawaii are given in figure 32.

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[2] Lacroix, M. A., La montagne Pelée et ses eruptions: figs. 28-34, 1904.

It is possible that erosion has removed the cinders from many of the domes, but it is known from domes formed in historic time elsewhere that cinders and pumice are not always erupted.

Vitric tuff beds of sufficient extent to map were not found in the Honolua volcanics. A few remnants of cinder cones near Kahakuloa and on the slopes north of Olowalu are shown on plate 1.

No water was found in the cones and tuffs. A few small pools stand in holes perched on the dense rock of Eke (pl. 30).

INTRUSIVES.—The bulbous domes of the Honolua volcanics are partly intrusive. Sufficient exposures exist to show that the plugs of the Honolua bulbous domes in West Maui formed close to the surface and that, at shallow depths, the plugs contract to normal looking dikes 8 to 25 feet wide. At an altitude of 2,000 feet, 2 miles northeast of Olowalu, is a trachyte dike connected to a flow (pl. 1). Half a mile to the east lies another dike joining a bulbous dome. An excellent example may be seen 2¼ miles east of Olowalu in the west wall of Ukumehame Canyon, where a dike 2 miles long and about 25 feet wide expands into a bulbous dome about 600 feet high.

The dikes of the Honolua volcanic series range from 8 to 25 feet in width. During the first few months of field work, dikes of this series were not mapped separately from the basalt dikes; hence, several may exist in Iao and Waihee Valleys that are not shown in plate 1. The trachyte dikes are easily identified in the field, but some of the andesite dikes of the Honolua volcanic series are not; hence, some may have been overlooked. A few wide inaccessible dikes in canyon walls have been mapped with the Honolua dikes even though they were not sampled.

The same range of petrologic types found in the Honolua lavas are found in the dikes. They are mostly coarse-grained nonvesicular rocks. A few carry feldspar phenocrysts. Some dikes are jointed into narrow vertical plates, having been formed at shallow depths. Closely spaced cross-joints are scarcer in Honolua andesite dikes than in basaltic dikes of equal width. The wide Honolua dikes resist erosion and stand in many places as high walls that can be seen cutting across country (pl. 34A). Several dikes inland from Olowalu were traced for 2 miles before they became lost in the forest (pl. 1).

The wide dense Honolua dikes extending unbroken for several miles through the mountains are too few in number to store large volumes of water between themselves, but as part of the Wailuku dike swarms, they are valuable for confining water at high levels.

LAHAINA VOLCANIC SERIES

The Lahaina volcanic series comprises the firefountain deposits and lava flows emitted after erosion approached the present stage. They usually lie on gravel deposits and appear to be late Pleistocene or Recent. The Lahaina volcanic series corresponds in age to the secondary eruptives on Oahu, such as Diamond Head and Punchbowl, and to the late Hana lavas on East Maui. They comprise picritic basalts and nepheline basanite. (See Part 3.)

They are named from the town of Lahaina near which most of them occur. All lie on the dry leeward side of West Maui. Possibly some erupted on the windward side but have been subsequently removed by the greater erosion there. They are described below in order of their occurrence from north to south and all are shown on plate 1.

Kekaa cinder cone.—A cinder cone 86 feet high, composed of picritic basalt, forms Kekaa Point and shelters the small port of Kaanapali 4 miles north of Lahaina. The absence of a bench 25 feet above sea level makes it probable that this cone was formed after the 25-foot stand of the sea in Recent time. It is mapped with the Lahaina volcanics because of its fresh state of preservation, in comparison with the deep weathering of the adjacent Wailuku lavas. The cinders are very permeable but being on the coast would contain brackish water only.

Laina volcanics.—One mile northeast of Mala is Puu Laina cinder cone, altitude 650 feet. Its crater is used for a reservoir, but it leaks badly. The lava erupted through the fan of Kahoma and Kanaha Streams, displacing these streams southward with a voluminous picritic basalt flow (pl. 1).

Exposed along the road to well 5, on the north bank of Kahoma Stream, is 10 feet of vesicular thin-bedded pahoehoe resting on 8 inches of firefountain debris and 3 feet of alluvial soil. The soil overlies 30 feet of bouldery conglomerate, which in turn rests on Wailuku basalts. A few thin flows are intercalated with cinders in the cone, and on the north side 2 feet of pahoehoe overlies 8 feet of fine cinders, which in turn rests on 4 feet of soil and partly decomposed feldspar olivine Wailuku basalt. The Laina lavas are covered with 1 to 1½ feet of soil underlain with a few inches of partly decomposed rock. They form a valley-fill 60 feet thick on the inland side of the cone, where they pooled in the pre-eruption valley of Kahoma Stream. In the Martinsen well, half a mile north of Mala, the basalt is 30½ feet thick and is underlain by 3 feet of red soil.

The dense feeding dike of Laina cone is cut 700 feet from the east portal of the tunnel through which the discharge pipe of well 5 connects with Crater reservoir. The east side of the dike was not found, as the dike seems to merge with lava flows. The west side sharply cuts the cinders of the cone.

The alluvial fan on which Laina cone rests is middle or late Pleistocene. After it was displaced, Kahoma Stream cut a canyon nearly 200 feet deep in weak rocks.

The Laina basalt lies above the zone of saturation, except along the coast where it yields water to domestic wells with more than 50 grains of salt per gallon. The supply is probably chiefly water that percolates from the adjacent sugar cane fields. They are irrigated with water fairly high in salt content. A dome of water about 6 feet across breaks the ocean surface when waves pass over a point about 150 feet offshore, 1¾ miles north of Mala. It was reported to be a large spring supplied presumably by the Laina basalt. A sample collected by a diver from near the bottom tasted as salty as sea water, however, and was not titrated. The dome of water may be formed by a submarine spouting horn caused by sea water rushing through a cavern in the lava and squirting up through a hole in the roof.

KILEA VOLCANICS.—A cinder cone called Puu Kilea, altitude 260 feet, lies half a mile north of Olowalu on the south bank of Olowalu Stream. It produced a fine-grained nepheline basanite flow 15 feet thick that rests on the consolidated older alluvial fan of this stream. Much of the lava has been cut away by stream erosion. These volcanics appear to be as old as the 25-foot stand of the sea. The cone and lava lie above the zone of saturation, hence carry no water.

HELE CINDER CONE.—Puu Hele cinder cone, altitude 217 feet, lies 1½ miles north of Maalaea on the east side of the highway across the Isthmus. The cone rises 60 feet above the alluvial fan of Pohakea Stream through which it projects. Puu Hele appears to be younger than most of the fan and is a picritic basalt. The small amount of erosion and weathering of its surface is evidence of its youth. Most of the south side has been quarried away for surfacing secondary roads. If a lava flow erupted with the cinders, it has been buried by gravel.

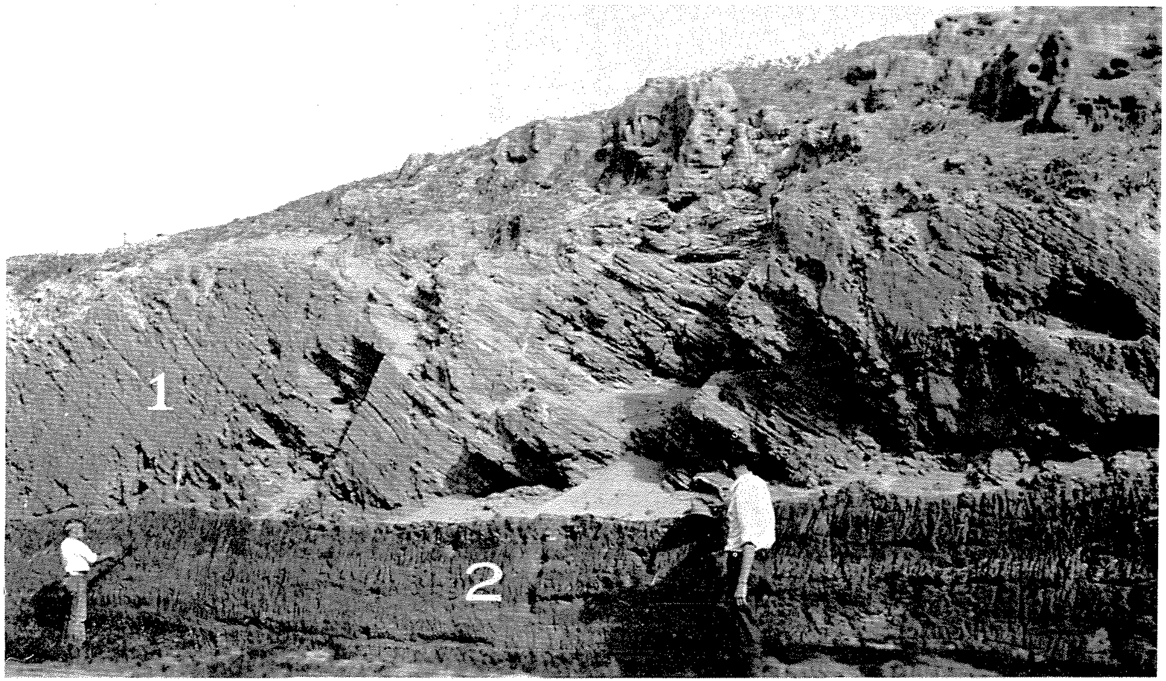
The cone is above the zone of saturation, but if a lava flow exists interstratified with the gravel, it may carry slightly brackish water near sea level.

QUATERNARY SEDIMENTARY ROCKS

CONSOLIDATED EARTHY DEPOSITS.—The exposed consolidated earthy or noncalcareous deposits on West Maui are shown on plate 1. They also underlie most of the areas of unconsolidated earthy deposits. The consolidated deposits consist chiefly of older alluvium and correlative talus. Part of the deposits near the coast may have been deposited beneath the sea. The alluvium is composed of mottled ochre to red-brown deeply weathered poorly sorted friable conglomerates. Near steep valley walls it grades into blocky landslide deposits and talus breccia. The alluvium is 200 feet thick in some exposures, but on the Isthmus it may be 1,000 feet thick or more. Many of the included boulders show onion-skin weathering. In wet areas the conglomerate is usually decomposed and may be cut with a shovel, but in the drier areas it is less rotted and is firmly cemented. In places it is strong enough to cause waterfalls. Blocks 10 feet or more across are common in some of the large valleys. Fossil trees were found in conglomerates in the south wall of the old Waihee ditch intake.

The fact that the older alluvium forms two terraces one above the other indicates that it was not all laid down at once (pl. 33). Most of it was laid down during the 100- and 250-foot stands of the sea. It was trenched during the minus 60- and minus 300-foot stands of the sea. Deep narrow inner gorges have been cut into it by the canyons on the south side of the mountain. They have not yet cut down to their former bedrock channels, nor have they removed the extensive deposits at their heads (pl. 1). In places streams have been superimposed on bedrock and now flow in deep gorges separated by thin rock divides from their former alluviated channels. (See valley cut by Waihee tunnel p. 196.) The tremendous amount of conglomerate preserved in the valleys indicates that the interval since the high stands of the sea was probably short compared to the period of accumulation. Other factors which affect the evaluation of the time interval are changes in climate and run-off, porosity of the conglomerate in comparison with the bedrock channel, and rates of aggradation versus degradation by streams carrying the same volume of water.

Several kinds and ages of breccias are exposed along the road in Iao Valley. The contacts indicate that they are talus on canyon walls, but varying degrees of consolidation indicate difference in age. The younger is well exposed just seaward of Black Gorge (pl. 40B); the older is in the portal of the irrigation ditch tunnel on the wall opposite the road a little downstream. The older type consists



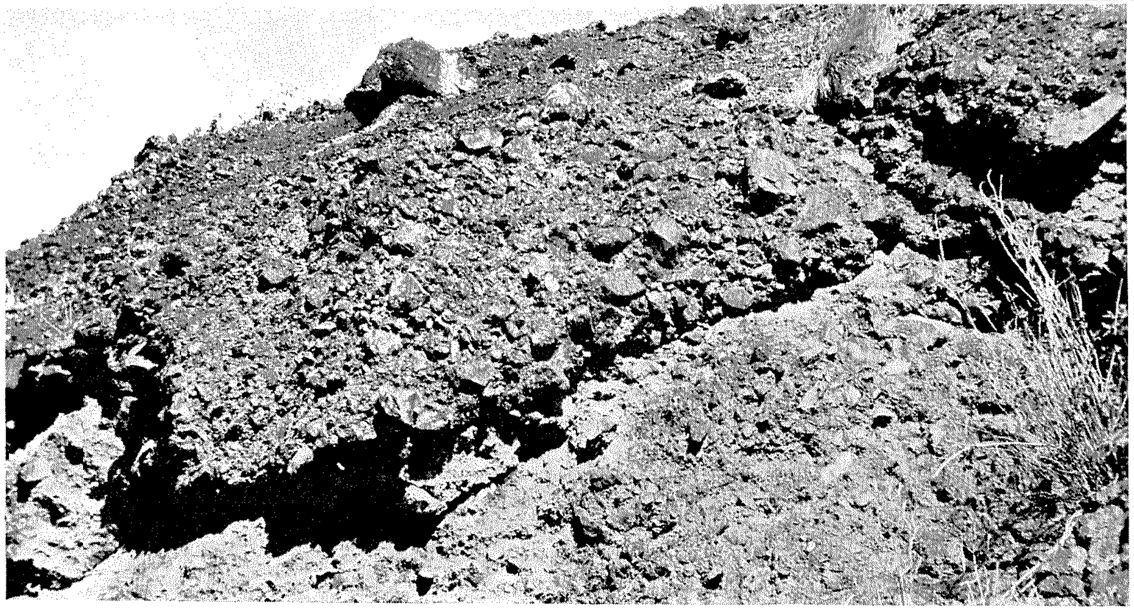
Above: Plate 39A. Consolidated calcareous dunes or eolianite (1) overlying unconformably older alluvium (2) in the fan of Waiehu Stream, near Waihee, West Maui.

Right: Plate 39B. Laina columnar-jointed basalt resting on stream-laid conglomerate in Kahoma Canyon, West Maui.

Above: Plate 40A. Vent breccia along Iao Valley road, West Maui.

Above: Plate 40B. Older alluvium in the east bank of Black Gorge along Iao Valley road.

Below: Plate 40C. Firmly cemented talus breccia in the older alluvium in Iao Valley seaward of Black Gorge.



of firmly cemented gray breccia with angular and subangular blocks up to 5 feet across with an abundant matrix of sand-sized particles. It rests on slightly weathered pahoehoe and aa of the Wailuku series with a nearly vertical contact. The fine-grained beds have dips of 32° toward the present canyon and strike parallel to its walls. The deposit contains cracks 4 to 8 inches wide, which in turn are filled with a similar breccia. A dike terminates at the contact of the lavas with the breccia, additional evidence that this breccia is an ancient talus fan of the present canyon. The breccia is wedge-shaped and pinches out upward. The breccia extending up the east wall of Black Gorge from a point 50 feet higher than the bridge is this type, although it is weathered uniformly black (pl. 40C).

The younger type lies lower than the black breccia and also extends up Black Gorge. It contains subangular and angular blocks mixed with water-worn boulders in a light-brown earthy matrix. It is a hybrid between a breccia and a conglomerate. It is less consolidated than the higher and older breccia but is sufficiently coherent to stand in a cliff 100 feet high. It rests unconformably on slightly decomposed Wailuku lavas. The contact dips 60° W. This younger and less consolidated variety is typical of the older alluvium in the canyon floors of West Maui.

Most of the consolidated earthy sediments have low permeability, but their coarse bouldery phases in stream valleys and their cleaner gravels near the coast carry small volumes of water. The deposits in the heads of the large canyons carry water commonly at their base. The youngest parts of the deposits are the best water bearers as they are not so thoroughly compacted and decomposed. Tunnel 3, well 11, and the dug well at the National Guard Camp northwest of the mouth of Iao Stream obtain water from older alluvium. Small domestic supplies could be developed in them in many places.

Consolidated calcareous deposits.—The marine calcareous conglomerates are thin and cover too small an area to be mapped. The important localities are indicated on plate 1. They consist of angular, subangular, and rounded lava rock fragments cemented in a matrix of fossiliferous limestone. They do not carry water. No emerged coral reef was found.

The consolidated calcareous dunes on the Isthmus in part overlie the fans of West Maui streams (pl. 39A). They are described on page 109. Mapped with them are a few recent unconsolidated dunes near Honokohau Post Office.

UNCONSOLIDATED DEPOSITS.—The areas of unconsolidated deposits are shown on plate 1. They consist chiefly of poorly sorted lava rock gravels, in part derived from the older earthy deposits. The thin strips extending up the river beds are too small to be shown on plate 1. Along the shore they include beach gravels and silt deposits in part laid down by the present sea and in part during the 5- and probably the 25-foot stands of the sea.

They carry water in perennial stream beds and along the coast below irrigated lands. Below lands irrigated with slightly brackish water, they supply wells with water unfit for human consumption, but satisfactory for other uses.

GEOLOGIC STRUCTURE

The West Maui Mountain is an asymmetrical dome elongated northwest-southeastward and built about Iao Valley as a center with the lava beds having centrifugal or quaquaversal dips of 2° to 20° away from it. The apex of the dome is missing, due to collapse and erosion. The only folding observed was adjacent to bulbous domes of the Honolua volcanics. The Wailuku caldera complex is bounded by normal faults (pl. 1). They truncate the Wailuku basalts and the downthrown block is covered usually with throat breccia. Hawaiian calderas, as shown by all studied, including Iao caldera, form during the waning phase of primitive olivine basaltic eruptions and before differentiation has proceeded far in the magma reservoir.[3] Some geologists think that lateral draining causes Hawaiian calderas, but this theory does not seem well founded, as fissure eruptions on the flanks characterize the entire growth of such basaltic domes. Collapse proceeds at an accelerated rate near the end of the very hot fluid primitive basalt phase when the rate of stoping exceeds building. The Hawaiian caldera is the Glen Coe type.[4]

A few faults radial from Iao caldera but lying chiefly in the two main rift zones were found, in spite of the extensive cover of soil, alluvium, talus, and vegetation. They are described below.

Tunnel 2 in Waihee Valley is crossed by several faults, probably associated with the pit crater it cut. (See table page 196.)

Waikapu Canyon is crossed at 1,400 feet altitude by a vertical fault striking N. 45° W. (pl. 1). A dike along the fault has been ground to powder. A shear zone 1 foot wide is exposed on both walls. The displacement could not be determined, but the east side

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[3] Stearns, H. T., Four-phase volcanism in Hawaii: Geol. Soc. America, Bull., vol. 51, no. 12, pp. 1947-1948, Dec. 1940.

[4] Williams, Howel, Calderas and their origin: California Univ. Publ., Dept. Geol. Sci., Bull., vol. 25, no. 6, p. 246, 1941.

appears to be downthrown. Eight dikes ½ to 2 feet wide parallel the fault. A sheared dike was found 350 feet from the portal of tunnel 12 in this canyon.

Olowalu Canyon is crossed at 920 feet altitude by a vertical fault striking N. 65° E. along the side of a 6-inch dike that has a downthrow of 2½ feet on the north side (pl. 1). An earlier 2½-foot dike is displaced by the fault.

An irregular fault striking N. 60° W. to N. 80° E. and dipping 70° S. is exposed half a mile below tunnel 17 on the ditch trail up Kahoma Valley (pl. 1). A band of breccia 1 foot wide lies along the fault plane. The southwest side is downthrown 12 feet. Another fault intruded with a 2-foot dike crosses the trail ¼ mile below the tunnel. It is vertical and strikes N. 50° W. The downthrow is 6 feet on the northeast side. About 500 feet from the tunnel a 2½-foot dike striking N. 55° W. appears to be displaced 10 feet horizontally and dropped 3 feet on the southwest side, but a fault, if present, is poorly exposed. A streak of powdered rock on the side of a dike in tunnel 18 may be indicative of a fault.

The lava beds 1 mile east of the top of Laina cone in the north wall of Kahoma canyon strike N. 10° W. and dip 40° W. The normal dip is 8° at this place. The local steeping of the dip indicates a buried cliff or cinder cone. A declivity exists in the flank of the mountain for about a mile to the north. Such features in Hawaii commonly indicate a fault cliff buried by lava flows.

The effect of so few faults on the movement of ground water is probably not great. They may lower the level of confined water where they have been shattered or displaced by dikes. They probably do not affect the movement of basal water.

GEOLOGIC HISTORY

PROBABLY LATE TERTIARY AND EARLY PLEISTOCENE(?) TIME

1. Building of a steep-sided shield- or dome-shaped island of highly fluid primitive olivine Wailuku basalts around a north rift and a south rift with a vent at their intersection (pl. 23A). Numerous dikes radiating from the apex of the volcano indicate that fissure eruptions were not confined exclusively to these rifts.
2. Collapse stage with the formation of a caldera on the summit 3 miles across and several hundred feet deep.
3. A relatively short rest period during which a thin soil formed and differentiation took place in the magma reservoir.

4. Outpourings of the thick soda trachyte and thinner oligoclase andesite Honolua flows, chiefly from bulbous domes located along fissures. These lavas formed a veneer over part of the great Wailuku volcanic dome. Starting of streams, especially in areas not covered with the Honolua lavas (pl. 23C).

EARLY(?) PLEISTOCENE TIME

5. Cessation of volcanism followed by a long epoch of weathering and erosion. Canyons as much as 4,000 feet deep were carved and high cliffs were made on shores exposed to strong wave action (pl. 24). The lava flows from East Maui joined West Maui to form a single large island.
6. Submergence of an unknown but large amount, perhaps as much as 2,500 feet, drowning the mouths of the valleys and alluviating their floors. East and West Maui again became two islands.
7. Culmination of the submergence in a short halt at about 1,200 feet above present sea level.
8. Gradual emergence of about 950 feet with a short halt at the Olowalu shore line 250 feet above present sea level (pl. 25A). The larger streams partly filled their canyons to their heads with alluvium.

MIDDLE(?) PLEISTOCENE TIME

9. Fairly rapid emergence of 550 feet or more with several short halts and the development of the Kahipa shore line about 300 feet below present sea level. Rivers cut deeply into their alluvial fans and the sea cliffed the exposed parts of the coast. East and West Maui were again joined (pl. 25C).
10. Resubmergence of about 400 feet to the Kaena 100-foot shore line and the deposition of thick conglomerates in the valleys, especially at their mouths. East and West Maui became separated again by the ocean flooding the Isthmus.

LATE(?) PLEISTOCENE TIME

11. Re-emergence of about 160 feet to the Waipio minus 60-foot strand with a short halt at the Laie shore line 70 feet above the present sea. East and West Maui were joined for the final time. The wind blew great quantities of sand shoreward from the emerged reef flats to form extensive calcareous dunes on the Isthmus. Valleys were cut into the alluvium laid down during the 100-foot stand of the sea. Scattered eruptions pro-

duced the short flows and cinder cones of the Lahaina volcanic series about this time (pl. 26A).

12. Resubmergence of about 85 feet and the formation of a shore line about 25 feet above present sea level, during which some of the dunes were drowned and others cliffed.
13. Re-emergence of about 20 feet with the formation of a fringing shore bench about 5 feet above the present strand.

RECENT TIME

14. Further emergence to the present strand (pl. 26C).

ROAD METAL

Residual boulders from the Wailuku and Lahaina lavas are crushed 1½ miles north of Mala. Cobbles are crushed near the mouth of Iao Stream. A massive bed of Honolua lava is quarried near the mouth of Alaeloa Gulch half a mile north of Kahana Camp. During the first World War trachyte was quarried near Launiupoko Hill and made into cement at Paia. The Honolua lavas have been quarried in several places especially near McGregor Point. Many are too platy for high quality crushed rock. Wailuku lavas are generally too thin-bedded and vesicular to make good quarries. Large boulders in the alluvial fans and river beds are crushed at times for road metal. Some of the massive andesitic flows of the Honolua series along the northeast coast are good quarry sites. Sand and gravel derived from lava are fairly abundant at the mouths of the large streams. Calcareous sand is hauled from the dunes near Wailuku for various purposes.

GROUND WATER IN WEST MAUI

BASAL WATER IN WEST MAUI LAVA ROCKS

OCCURRENCE AND PERMEABILITY OF WATER-BEARING ROCKS.—Basal ground water floats on salt water in West Maui in the same way as in East Maui. It underlies a peripheral belt 1½ to 4 miles wide, inland of which is water confined considerably above sea level by the dike complex (pl. 12). The highly permeable Wailuku basalts are characterized by cavities similar to those in the basalts of East Maui (p. 116). It is probable that the average permeability of the Wailuku basalts in the south rift is greater than elsewhere because of their very frothy character and exceptionally thin bedding. The rock is so jointed and friable in the infiltration tunnel of well 12 that it was excavated without blasting. The cost of tunnels in Wailuku basalts is appreciably less than in the Kula lavas due to this friable character.

The Honolua lavas are far less permeable than the Wailuku, but fortunately they lie above the basal water table in most of the belt of basal water where wells are needed. The massive Honolua lavas could be avoided in most places along the northeast shore by sinking wells inland in gulches that have been cut through into Wailuku basalt (pl. 1). The clinker in the upper part of the Honolua lavas has become impermeable by weathering (pl. 36A), but water moves through the deeper, less altered beds (springs 5 and 6). Water percolates through the open joint cracks of the massive Honolua beds, but much less freely than through similar cracks in the underlying Wailuku basalts, because the cracks are spaced farther apart and are less open. Consequently, much longer infiltration tunnels will be required to develop water in them than in the basalts. Tubes are absent in the trachytes and scarce in the andesites.

The lavas of Maui rank as follows in order of permeability, the most permeable being named first: (1) Hana lavas, (2) Honomanu and Wailuku basalts, (3) Kula lavas, (4) Honolua andesites, and (5) Honolua trachytes.

Waipuna is the name of a dome of water about 8 feet across that breaks the ocean surface as waves pass over a point about 100 feet offshore, 1½ miles north of Waihee. It is locally believed to be a large spring issuing undersea from the Honolua lavas. A sample collected by a diver at half tide on January 13, 1942, from the bedrock floor under the dome and titrated by the W. S. Co. contained 2,005 grains of salt per gallon. It is suspected that Waipuna is an undersea spouting horn similar to the one described on page 181 and to the one in Manele Bay, Lanai.[5]

FORM OF THE WATER TABLE.—The basal water table stands about 1 foot above mean tide near the coast and rises at the rate of 1½ to 2½ feet per mile inland for the first 2 or 3 miles. Alluvium skirts the coast for 4 miles near Olowalu and retards the discharge of basal water into the sea, as shown by the slightly higher heads in wells 10 and 12 than in the wells farther north. Sufficient wells exist to determine the 5-foot water-table contour in plate 12, except on the north and northeast side of West Maui, but the 10-foot contour is entirely conjectural. Test hole 102 indicates that the water table stands at 30 feet behind Wailuku due to an alluvial caprock. It is probable that the 10-foot contour is very irregular, and in places where confined water lies not far inland of the 5-foot contour, the basal water table may not reach 10 feet. It may be farther seaward than shown in areas where scattered dikes increase friction but do not enclose bodies of confined water. If dikes are absent, the water table probably continues inland on the same grade as below the 5-foot contour as far as the dike complex. The basal water table ends 2 to 4 miles inland, as shown by springs confined by dikes at high levels in all the major valleys. The change must come abruptly at one or more nearly impermeable dikes, as the high-level water table crops out at altitudes of 700 to 1,200 feet within a mile of wells where the water stands a few feet only above sea level (section AB, plate 12).

The coalescing alluvial fans that flank the east side of the West Maui Mountains impound the basal water and cause much of it to move northward to discharge into the sea. The salt content in test boring 110 is 30 grains per gallon, which is unusually high for a static head of 7 feet in a well 2 miles from the nearest coastal outcrop of basalt. It indicates that the quantity of ground water is small and the movement sluggish. Dikes may shut off recharge from the wet area to the north, so that diffusion and mixing with the underlying salt water plus percolating rain water carrying salt spray are effectual. The adjacent fields are irrigated with fresh stream and tunnel water, but they lie on alluvium; hence deep percolation from them probably does not reach the adjacent lavas encountered in the boring.

FLUCTUATIONS.—The basal water table fluctuates with the tide, and changes in rates of recharge and draft. During dry years the water level in the P. M. Co.'s wells will decline 1 to 2 feet and the salt

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[5] Stearns, H. T., op. cit. (Bull. 6), p. 84.

content will rise 20 to 60 grains per gallon. Pumping lowers the water levels only ½ to 1½ feet in the wells in spite of heavy draft, indicating that the adjacent rocks are highly permeable. The tide causes fluctuations of as much as half a foot, depending upon the nearness to the coast and the permeability of the intervening rock. Some of the wells have no tidal fluctuations because of the alluvial barrier between them and the sea. A few of the wells show a definite freshening during low tide. This results from the increased gradient seaward causing fresher water to flow from inland.

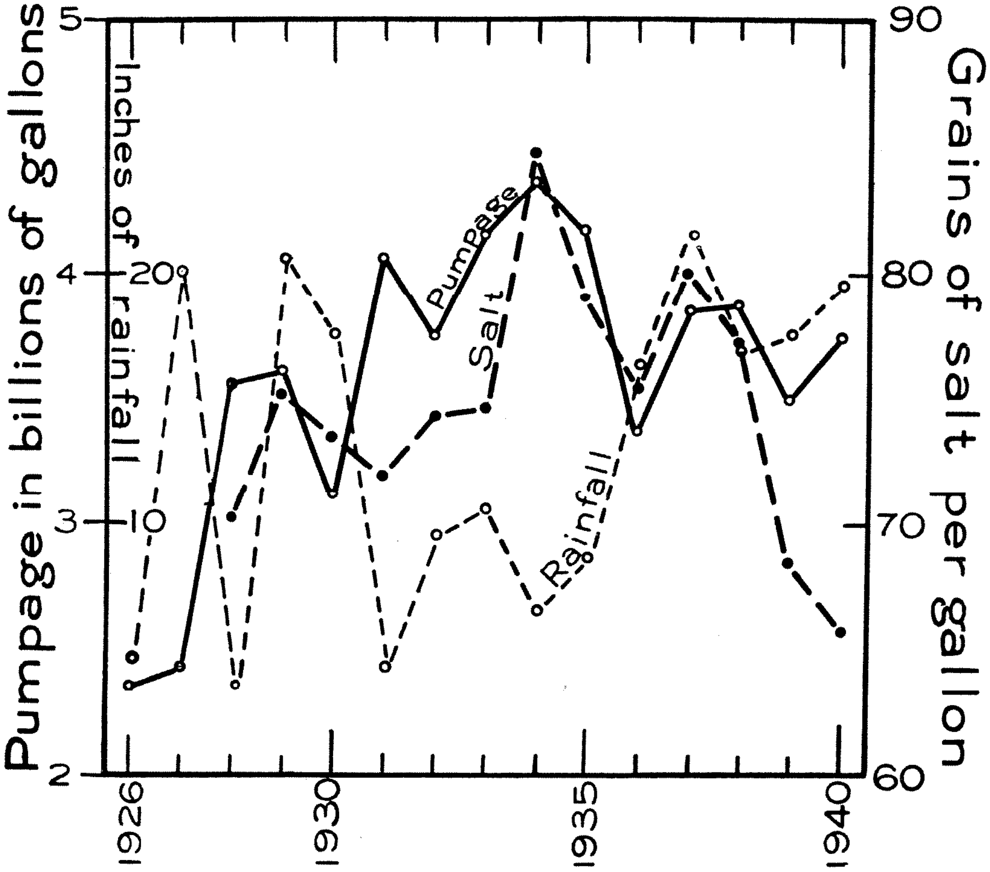

Figure 33. Graph showing relation of pumpage in billions of gallons per year to salt content in well 3 and rainfall at Kaanapali, West Maui.

Effect of draft on quality.—The salt content of the water is greatly influenced by the rate of draft, as graphically illustrated for well 3 at Kaanapali (fig. 33).

The factors affecting the salt content are: (1) Depth of pump sump below sea level. (2) Length and yield of infiltration tunnels. (3) Height above sea level of floors of infiltration tunnels. (4) Proximity of the well or its tunnels to the sea. (5) Presence of sediments between the basalt and the sea and their permeability. (6) Continuity of pumping. (7) Rainfall in the recharge area. (8) Quality of irrigation water used in adjacent fields. (9) Depth of tributary drilled wells in the sump or tunnels. (10) Presence of dikes, and their trends and permeability. (11) Permeability of the rocks penetrated by the drilled wells and tunnels.

The importance of these factors varies from place to place, but it is always advantageous in West Maui to be far from the coast and to have the infiltration tunnels and sump as little below the water table as possible. Many of the drilled wells were too deep and have been plugged or the lower part has been sealed. In some Maui-type wells, the infiltration tunnels have been too short for the amount of water pumped, causing excessive drawdown and high salt. Thus, 280 feet of additonal tunnel in well 7 reduced the maximum salt content about 200 grains per gallon. Records of draft and salt are given on pages 218 and 219.

Recharge.—The basal zone of saturation under the sugar lands of the P. M. Co. is supplied by (1) water percolating through the outermost dikes of the high-level body of water, shown in plate 12; (2) water percolating from fields irrigated with surface water; total ditch deliveries average 20,800 million gallons annually; (3) rainfall on the lands underlain by basal water; and (4) seepage from floods on their way across rocks underlain by basal water.

All factors tend to reduce the basal supply in dry years. Low rainfall decreases direct recharge, run-off, and amount of surface water available for irrigation. Deficiencies in surface supplies have to be met by increased draft from wells. The lands of the P. M. Co. lie on the lee side of the West Maui Mountains, where the rainfall is low, but the streams behind the plantation reach back to the crest of the mountains and are supplied chiefly by trade-wind rains. Heavy kona rains fall on the lands in some years of low trade-wind rainfall, which makes up for the deficiency in surface supplies in those years. Thus, the water level in the wells on this plantation gained in 1940, when most others in the Hawaiian Islands declined.[6]

The absence of continuous caprock along the shore causes a low water table and little opportunity for storage in wet years. Since 1932 several new wells have been driven farther inland than the old wells and some of the old wells have been abandoned or improved.

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[6] Stearns, H. T., Chapter entitled Hawaii in Water levels and artesian pressure in observation wells in the U. S. in 1940: U. S. Geol. Survey Water-Supply Paper 910.

The quality of the ground-water supply has improved in spite of the increased draft.

THERMAL WATER.—The only thermal water known in the inactive Hawaiian volcanoes was encountered in well 12 at the mouth of Ukumehame Canyon. The temperature of the water is 95° F. when the well is being pumped at the rate of 5 m.g.d. The water level stands about 6 feet above sea level, and the salt content ranges from 33 to 48 grains per gallon. The temperature in well 8 not far away as reported by C. A. Brown is 73° F. The higher temperature is apparently acquired from underlying hot intrusive rock. The intrusives may be correlative with the younger Lahaina volcanic series, but the warm gaseous tunnels in the older rocks farther inland suggest that the heat is derived from intrusives of either the Wailuku or Honolua series. Perhaps a large stock similar to the one in the head of the canyon exists not far below well 12.

WELLS.—The records of the quantity and quality of the water pumped from all irrigation wells are given on pages 218–222.

The record of Maui-type wells on West Maui is on page 216. The history of the early wells drilled in connection with the shafts has been summarized by McCandless.[7] The first inclined shaft in the Territory was excavated under the direction of C. A. Brown at Olowalu (well 10) in 1933. A much deeper and less accessible vertical shaft would have been required to reach the aquifer than an inclined one, because of the steepness of the mountain front. If a vertical shaft had been excavated on the flat accessible land, it would have penetrated alluvium only and a section of nearly nonwater-bearing tunnel at the bottom of the shaft would have been required to reach the aquifer. This is the type of place where an inclined shaft is preferable to a vertical shaft. However, the increase in efficiency of vertical centrifugal pumps and deep-well turbines in the last few years has now made it more economical to excavate vertical shafts in most places and put the pumps at the surface.[8] Moisture is sufficient in some shafts to cause motors to burn out when started after several months of idleness. This is overcome by keeping them dry with electric heaters when not in use.

An unusual experience during the construction of well 5 was to descend the shaft in a steel bucket and ride to the heading of the dimly lighted infiltration or skimming tunnel in the flat-bottomed boat used to transport rock to the hoist. The boat was pushed by two Filipinos wading noiselessly in water to their chests. The boat

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[7] McCandless, J. S., Artesian water in Hawaii: p. 65, Honolulu, 1936.

[8] Stearns, H. T., op. cit. (Bull. 5), p. 12.

glided along nearly half a mile to the heading in semi-darkness and in deep silence. Occasionally the boat would grate raucously against a projecting rock and break the silence like a clap of thunder. The loose clinker and highly fractured lava rock looked as if ready to tumble down with a mighty splash at any moment, but they are too rough to slide and will probably stand for centuries without support. Often a layer of red doughy lava was passed or the boat glided between ragged rock walls gleaming with tiny specks of light, reflected from thousands of olivine crystals. In other places the walls were covered with pearly drops of water. Out of the darkness like a phantom came another boat laden with broken rock. We passed at special sidings where the tunnel had been widened for this purpose. Finally the boat rounded a bend, and the sound of the air drills warned of the approach to the heading. There two more Filipinos were rapidly drilling holes into the rock face, to be filled later with sticks of dynamite. Blasting is done every 8 hours. We talked to these gnomes in pidgin English and found that they preferred work underground to work in the hot cane fields above. Our guide stated, however, that the native Hawaiians would not work underground because of superstitions about caves. The air was fresh and cool in contrast with the hot humid day outside, in spite of the absence of the usual air ventilating pipe. The rock is so cavernous and jointed that the powder smoke disappears rapidly after each blast, partly as a result of circulation set up by the moving water.

Unlike water-development tunnels driven into a dike complex where water pours down from the roof and squirts from the drill holes, the heading of this tunnel was dry. The only evidence of water being encountered was the decreased drawdown on the chart at the bottom of the shaft which records the water level automatically while the pumps are operating. Water was encountered so gradually that the record showed an increased yield only after several weeks of tunneling. In dry seasons the salt content of the water averages 50 grains per gallon, and the water surface stands only 1½ feet above sea level. Consequently only the freshest water must be skimmed from the top, just as cream is skimmed from a pan of milk.

The boat trip back to the shaft was faster because the boat moved with the current. The boys walked faster and faster as the current increased near the shaft. Finally the whir of the motors and pumps pushing 10,000,000 gallons a day through 322 feet of pipe to the surface was heard. The water is clear as a crystal in the pump sump, as the comminuted rock from blasting at the heading settles to the bottom of the tunnel before it reaches the sump. Again in the hoist bucket, a cord was jerked to signal the operator above, and up we went to the top. Out in the brilliant tropical sunlight, surrounded by high mountains, green fields, and a wide expanse of blue ocean, one felt suddenly hoisted into reality again, and the journey under the mountain seemed a fantasy.

UNDEVELOPED BASAL SUPPLIES.—It is estimated that about 100,000,000 gallons of basal water of excellent quality wastes into the sea daily from West Maui lavas. Nearly all is lost between Honokowai and Iao Stream. Shafts judiciously spaced around West Maui 1 to 2 miles inland could recover most of it. They would not need to be very deep if sunk in the gulches. The land is now used for growing pineapple or for grazing, but much of it could be used for irrigated crops. However, before Maui-type wells are constructed in these areas, Lanai-type wells developing high-level water in the dike swarms not much farther inland should be considered. Test hole 102 proved the presence of water with less than 2 grains of salt per gallon 30 feet above sea level 1 mile up Iao Valley from Wailuku. This water has potential municipal and irrigation use due to its proximity to the Isthmus.

BASAL WATER IN THE WEST MAUI SEDIMENTARY ROCKS

About 500,000 gallons daily of basal water is pumped from four tunnels totaling 670 feet in well 11 at Olowalu. The infiltration tunnels penetrate poorly permeable coarse boulder conglomerate except in the seaward branch where 3 feet of red and brown clayey silts were cut. The water is probably in part return irrigation water. Eight drilled wells about 60 feet deep supplement the flow of the tunnels. The salt content ranges from 2.4 to 38 grains per gallon.

The first well drilled outside Oahu in Hawaii was at Waikapu about 1881 by W. H. Cornwell, who brought a rig from California.[9] The well failed to find water. It must have penetrated alluvium only, as the fan of Waikapu Stream is very thick. Its exact location is unknown. The well may have been considered a failure because of its low yield, as irrigation supplies were being sought at that time. Test boring 103 penetrated alluvium for 177 feet near Waihee, but the movement of water was so slow through the sediments that dye placed in the well did not move away for months. Water will be found a little above sea level in relatively small quantities in all the sedimentary rocks bordering the West Maui Mountains. The less permeable the sediments, the higher will be the head. Recharge is

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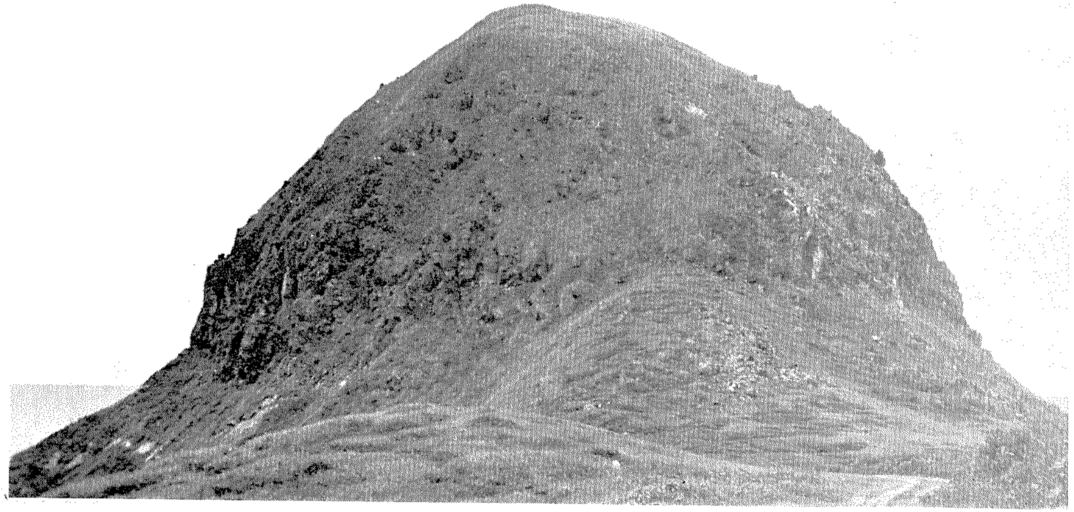
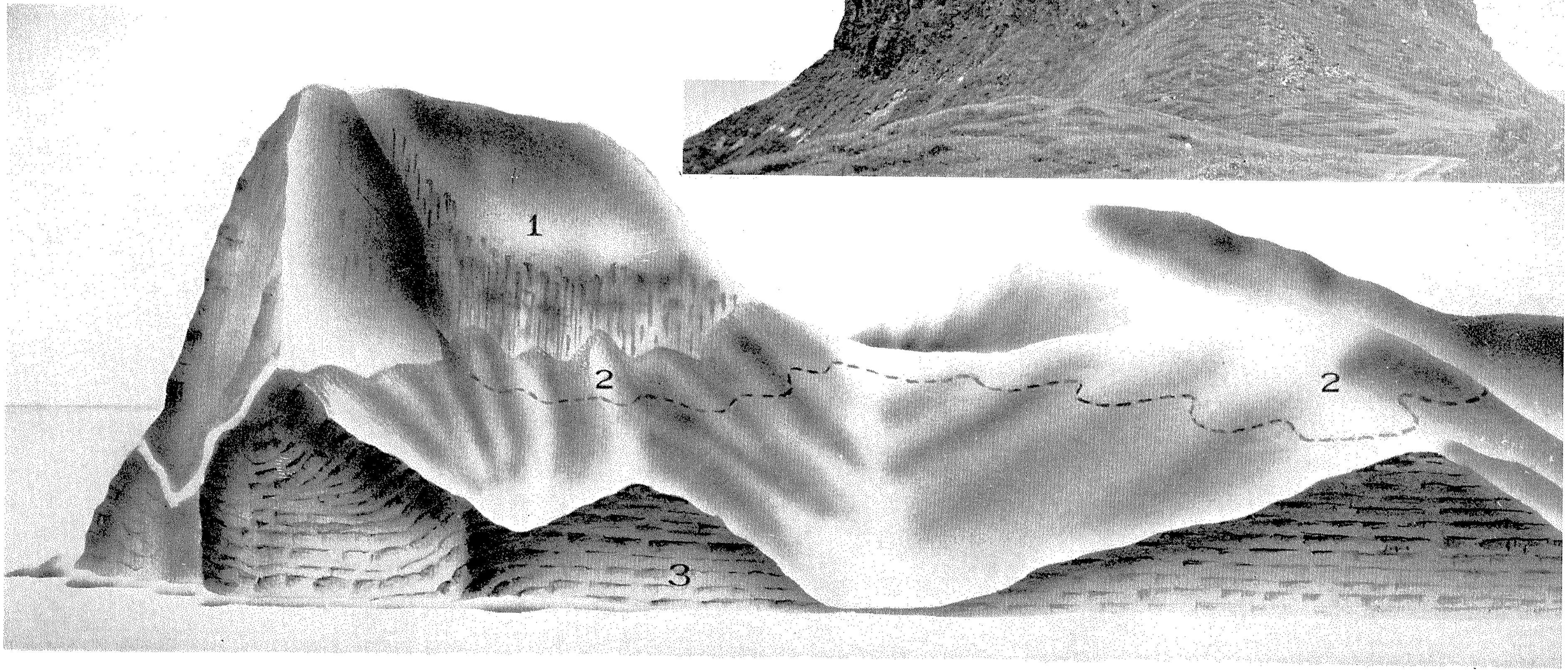
[9] McCandless, J. S., op. cit., p. 65.

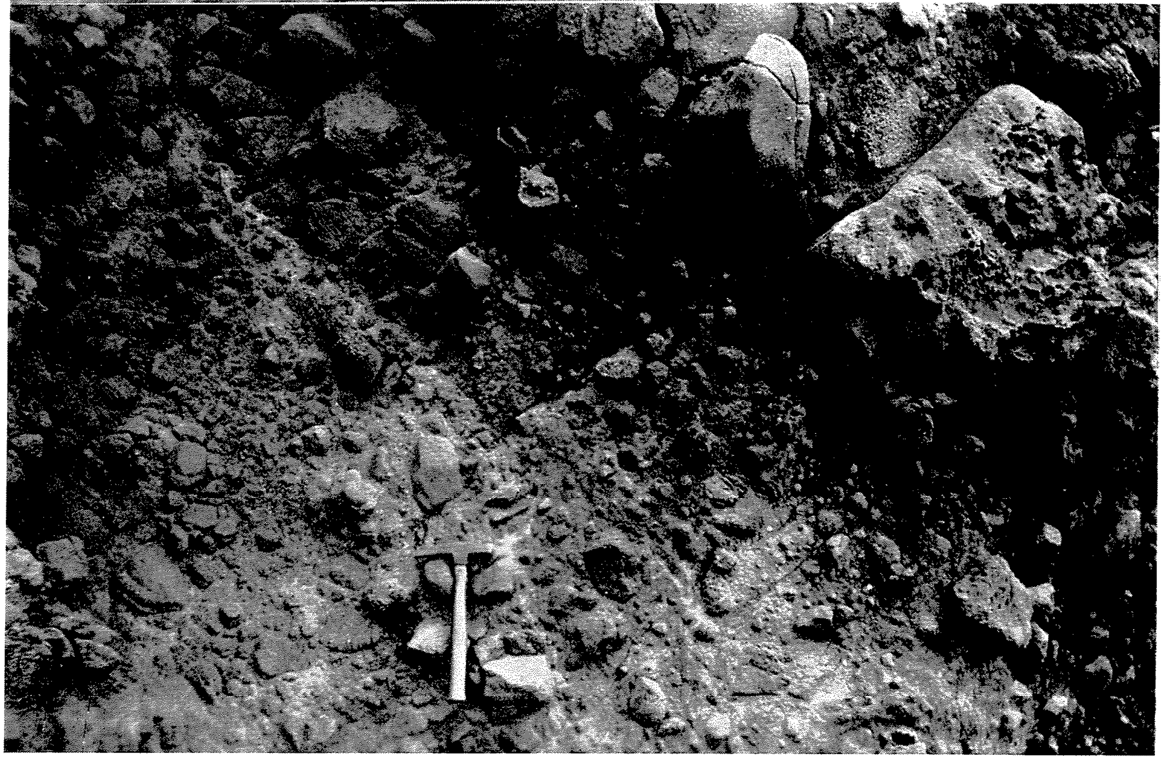
Right: Plate 37A. Puu Koae near Kahakuloa, West Maui.
Below: Plate 37B. Looking southeastward to Puu Koae, a bulbous dome of trachyte (1), resting on cinders (2) and thin-bedded basalts of the Wailuku volcanic series (3).





Left: Plate 38A. Contact of massive trachyte and breccia in Puu Koae.

Below: Plate 38B. Breccia resulting from fragmentation during the protrusion of the bulbous dome, Puu Koae, West Maui.



chiefly from streams sinking on their way to the sea during floods and from water percolating from irrigated fields. The salt content of water in the West Maui sediments between Maalaea and Waihee should be low because fresh stream water only is used for irrigation in this area. Fertilizers used on the fields may cause the water to carry nitrates, but probably not in harmful quantities. Shafts developing water in the sediments should be sunk considerably below the water table, and infiltration tunnels should be driven along the most permeable layers. Timbering may be necessary in some tunnels.

HIGH-LEVEL GROUND WATER IN WEST MAUI

WATER CONFINED BY DIKES.—Dikes confine water in the enclosed compartments of permeable lava flows. The radial dike structure in West Maui has resulted in an egg-shaped area of high-level water underlying most of the mountain. It is skirted with a fringe of basal water (pl. 12). Such a form is unusual. In all other Hawaiian mountains studied to date, the confined water is in longitudinal belts along rift zones, as in East Maui (pl. 12). The surface of the body of confined water in West Maui, as indicated by springs, rises from about 700 to 1,200 feet along its periphery to 3,500 feet or more under the high, wet ridges near its center. All deep canyons cut into this great zone of saturation serve as open drains to lower the high-level water table, as shown in section AB, plate 12. All perennial streams on West Maui shown in figure 9 except Makamakaole depend on ground water confined by dikes for their supply.

HIGH-LEVEL WATER-DEVELOPMENT TUNNELS.—The 22 high-level tunnels in West Maui are listed on page 213. Two are dry. Sixteen develop water in the dike complex. They total 28,666 feet in length and yield about 700 gallons per foot per day. The history of the West Maui tunnels is largely lost. They were excavated between 1900 and 1926, but it appears from their manner of construction and their location that they were driven with little consideration of the geologic structure and its bearing on the movement of water. They are shown on plates 1 and 12.

Tunnel 1 has the greatest yield of any tunnel in West Maui and is driven at the proper angle to the dikes to develop the maximum flow. This seems to be accidental, as tunnel 2, driven at the same time, nearly parallels the trend of the dikes. F. F. Baldwin, manager of the H. C. & S. Co., states that he often visited tunnel 1 during its excavation. He doubts whether the low flow of Waihee Stream was materially increased at the ditch intake at an altitude of 665 feet after the storage had been depleted. As most of the dike compartments cut by the tunnel were drained by the North Fork of Waihee Stream not far seaward of the tunnel at a considerably lower altitude, it is understandable why the flow at the ditch may not have been appreciably increased.

The dike compartments cut by tunnel 2 nearby are also drained by Waihee Stream at a lower altitude; hence it is probable that much of the flow of both tunnels formerly appeared in the stream. These tunnels could be made more useful by the installation of bulkheads at several dikes and by storing water in the ground during wet periods. A log of tunnel 2 follows:

Log of South Waihee tunnel no. 2

(Starts 80 feet above stream; yields 1 million gallons a day. Examined August 31, 1933.)

	Distance from portal (feet)	Thickness of dike (feet)	Trend
Wailuku basalt cut by two dikes striking NE......	0–30	—	—
North wall of earlier Waihee Valley............	30	—	—
Older alluvium	30–300	—	—
South wall of earlier Waihee Valley............	300	—	—
Dike	300	1.5	N. 70° E.
Beginning of volcanic breccia..................	305	—	—
Hardened fault plane dip 15° N. with sheared dike above and water dripping from it. Forms smooth roof to tunnel for about 25 feet and then cuts floor. Has 5 inches of gouge along it..........	425	—	N. 25° W.
Dike	500	2	N. 45° W.
Sheared dike	535	—	—
Breccia filling V-notch 20 feet wide............	535–555	—	—
Fault dipping 70° N. with 4 inches of sand-textured gouge yielding water; collected dunite specimen nearby	700	—	E.–W.
Dike	725	3	N. 10° E.
Dike	750	2	N. 10° E.
Fault with 4-inch streak of sandy gouge yielding water	850	—	—
Rock gradually becoming less brecciated and in part recognizable as lava flows...............	850–900	—	—
Dike	925	2	N. 5° E.
Tunnel is driven S. 23° E. to this point and starts turning	925	—	—
Shattered dike dipping N. 45° N.; strike indeterminable but more than 10° E................	1,040	5	—
Dike	1,125	—	N.–S.
Breccia yielding a little water................	1,125	—	—
Definitely breccia without dikes..............	1,200–1,700	—	—
Dike	1,725	4	N. 20° E.
Water practically ceases	1,760	—	—
Dike	1,775	—	N. 10° W.
Tunnel runs S. 25° E. at this point............	1,775	—	—
Dike	1,825	3	N. 10° W.
Dike	1,890	2	N. 10° W.
Dike	1,945	2	N. 45° W.
Dike	1,995	2	N. 30° W.
Dike	2,010	1.5	N. 40° W.
Dike	2,100	5	N. 25° E.
Dike	2,105	2	N. 25° E.
Tunnel runs S. 20° W.	2,105	—	—
Dike	2,180	—	N. 20° E.
Dike	2,195	—	N. 20° E.
Dike with slickensides	2,200	—	N. 20° E.
8 dikes between 2,200 feet and end; tunnel direction at heading S. 20° W....................	2,500	—	N. 30–45° E.

Tunnel 3 was driven in older alluvium near the mouth of Waiehu Canyon, but it developed very little water. Tunnels 4 and 5 probably did not develop any water that did not percolate into Iao Stream above the ditch intake. Tunnel 6 is properly driven but was stopped just when it began to encounter saturated rock not already drained by Black Gorge (fig. 34). The proposed extension of tunnel 7 will probably drain tunnel 6, otherwise bulkheads could be built to store water in 6. Tunnel 7 will probably divert most of the water from the springs and tunnel in Black Gorge, but when driven another 4,000 feet and equipped with bulkheads, it should make more water available than is now entering Iao Stream from this area. Also, the

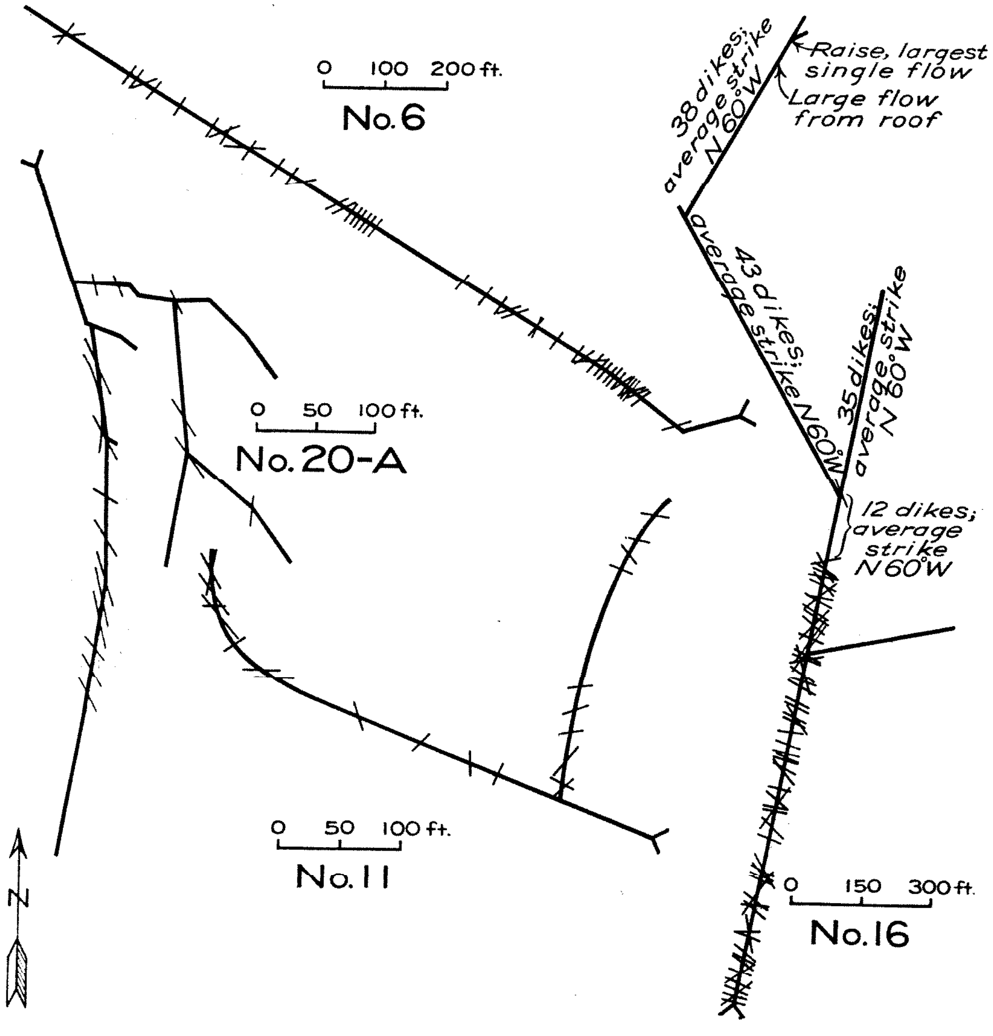


Fig. 34. Maps showing dikes cut by tunnels in Black Gorge (no. 6), Waikapu (no. 11), Kauaula (no. 16), and Honokowai (no. 20A) Canyons, West Maui.

present supply for Wailuku and Kahului is subject to pollution and this tunnel will yield water free from such a danger.

Tunnels 8, 9, and 10 appear to recover underflow of Iao Stream that would otherwise be lost. Additional water can be recovered from the alluvium of Iao, Waihee, and other West Maui streams by similar tunnels. Except where special conditions exist, tunnels driven under the younger alluvium with a hook form will recover the most water.

No. 11, a successful tunnel, is reported to have been started in dry rock (fig. 34). The quantity of water that formerly discharged from the valley and was diverted by the tunnel is unknown. But it may not have been large, as the tunnel cuts saturated compartments between dikes that would normally discharge eastward underground and be lost. The mistake in this tunnel was to drive a lateral cutting the dikes already cut by the main tunnel at a slightly higher level. The last 89 feet of the lateral is dry for this reason. The dominant dike trend is N. 40° to 80° W. More water could be recovered probably by extending the lateral 3,000 to 5,000 feet N. 30° E. at right angles to the average trend, keeping the grade as flat as possible. Bulkheads could be installed to conserve water for dry periods. A longer tunnel driven from a lower altitude in Waikapu Stream through these same dikes would recover more water.

Tunnel 12 was driven parallel to and about 50 feet above Waikapu Stream. The water confined between the dikes penetrated by the tunnel finds its way to the stream under the tunnel; hence it is dry. Further, the vent breccia penetrated is too well cemented to be a good water bearer. The yield of tunnel 13 is small because it is driven into well-cemented vent breccia cut by dikes. Tunnel 14 is dry because it cuts at a slightly higher level dike compartments already drained by Olowalu Stream.

Tunnel 15 probably recovered some water that did not reach Launiupoko Stream above the ditch intake. Most of the water comes from the drill holes in the heading of the main tunnel. The two laterals were a mistake, as they cut the same dikes as the main bore. The rainfall on the ridge above the tunnel is low, otherwise the tunnel might be extended farther northward to encounter dikes and saturated compartments not cut by any stream.

Tunnel 16 is located effectively and intersects sufficient dikes not cut by Kauaula Stream to recover a considerable quantity of water that would otherwise be lost. If the tunnel were extended at right angles to the average dike trend and equipped with bulkheads, more water probably could be recovered. The laterals were a mistake, as little water, if any, is gained by cutting the same saturated compartments twice (fig. 34).

Tunnel 17 failed because it cut compartments between dikes already drained by Kahoma Stream. If extended in a northeasterly direction it would finally reach compartments not drained by any stream. Tunnel 19 is nearly dry for the same reason as 17, and likewise if extended would finally cut undrained compartments. Tunnel 18 has a good yield but too many laterals. The tunnel cuts dikes before they are cut by the stream. Probably a large part of water recovered reached the stream farther seaward. The advantage of the tunnel is that it collects the water above the ditch intake. If extended and equipped with bulkheads water could be stored in it when the stream fills the ditch and the flow from the tunnel is not needed.

Tunnel 20A has too many laterals; a single straight bore would have been just as effective (fig. 34). Its geologic setting is much like 18, as it recovers water from compartments above the ditch intake that probably largely entered Honokowai Stream farther downstream. If the tunnel were extended at right angles to the average dike trend and equipped with bulkheads, it would yield more water.

Tunnels 21 and 22 with their various laterals typify the hunt for water on West Maui. Two serious mistakes have dominated all the tunneling: (1) driving tunnels into compartments between dikes already drained by the adjacent stream, and (2) trying to follow veins of water underground by numerous laterals. When the tunnels are first driven, water squirts from crevices in the roof, heading, and walls, and its quantity varies with the head and permeability of the rock at that particular place. As the tunnel is continued and storage drains out, the water table generally falls to the level of the tunnel floor. The tunnel men, lacking technical supervision, too often followed the large water-bearing crevices with laterals without waiting for the water table to fall.

High-level springs.—The important high-level springs on West Maui are listed on page 212 and shown on plate 1. Their aggregate low flow is about 9,000,000 gallons a day. Springs 5 and 6 issue from clinker beds in the Honolua series; all others listed issued from the Wailuku dike complex. Many more unlisted springs issue in the beds of the streams draining the dike complex. The low flow of all springs in West Maui aggregates 76,000,000 gallons daily.

Undeveloped high-level supplies.—The West Maui Mountains are cut by so many deep canyons that few large supplies remain undeveloped. A tunnel driven from an altitude of 1,350 feet from the amphitheater-headed canyon of the North Fork of Waihee Valley about a mile northwest should cut a broad saturated dike complex confining water which does not reach any stream. The rainfall above it averages 247 inches annually, but the recharge will be less than might be expected, owing to the capping of fairly impermeable trachyte. Tunnel 1 might be extended under Eke, but it is above much of the recharge area.

A tunnel driven from 1,500 to 1,800 feet altitude in Honokohau Canyon for a mile or more westward and gradually curving southward to cut the dikes radiating from Iao Valley should be highly successful. It would recover water for a distance of three or four miles, as an extensive saturated body of rock high above sea level lies under the area. The water developed would then flow down Honokohau Stream and through the Honokohau ditch tunnel to P. M. Co.'s plantation. A better plan might be to tunnel about 3 miles from an altitude of about 1,600 feet behind Lahaina in Kahoma Canyon directly northeastward to Honokohau Stream. Two adits would be possible, thereby halving the haul. The water could be used for power and for irrigating high lands. Stored water released from both portals during excavation could be used for irrigation on the same plantation.

Bulkheads in all the tunnels mentioned above would increase the supply in dry weather. The possibility of developing water by extending existing tunnels and bulkheading them is described in the chapter on tunnels.

Lanai-type wells[10] could be sunk successfully in most West Maui canyons above altitudes of 500 feet. If such wells were dug at the intakes of the ditches on the various streams, they would be of great value during droughts. Flood waters could be stored in them also. A revision of the present method of recovery of water on West Maui is essential to the beneficial use of its ample ground-water resources. Ownership is vested almost entirely in four companies and the government; hence, adoption of a master plan benefiting the area as a whole should be possible. An example of undesirable use is the flow of Waihee Stream, seven-twelfths of which is carried through a ditch all the way across the high lands of the W. S. Co. to be used on the low Isthmus lands of the H. C. & S. Co., where ample water can be obtained from shallow wells.

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[10] Stearns, H. T., op. cit. (Bull. 5), p. 10.

WATER PERCHED ON TUFF AND SOIL BEDS.—A few small springs are perched by tuff beds in the wet areas, but they have no value. In the dry south end of the mountain where small springs have value the beds do not perch water.

Soil and ashy soil beds perch many small springs at the base and between flows of the Honolua series. A few are shown on plate 1, namely on the east bank of Kahakuloa and on the spur south of Waihee Valley. The latter were used once for supplying a mountain house. Springs exceeding 5 gallons a minute in dry weather are scarce.

Makamakaole Stream heads in springs 5 and 6, which issue from clinker beds. They are probably perched on weathered clinker and dense trachyte.

QUALITY OF HIGH-LEVEL WATER.—The quality of most high-level water is good but no analyses are available. The total dissolved solids is very low in other analyzed high-level waters in the Hawaiian Islands, owing to the high rainfall and insoluble character of the rocks. The small quantity of water produced by tunnel 12 is an exception. It deposits sufficient solids to form miniature cream-colored terraces of a soft clay mineral on the tunnel floor. The solids are probably magnesium aluminum silicates derived from the breakdown of minerals in the basalts by the slowly percolating water en route to the tunnel.

INVENTORY OF GROUND WATER IN MAUI

The inventory of ground water in West Maui in comparison with East Maui follows:

Average discharge of ground water in million gallons per day from rock structures in Maui and its relation to the rainfall

Item	1	2	3	4	5	6	7	8
Source of water	Perched springs (numbered on pl. 1)	Spring-fed streams[b]	Tunnels	Wells	Sum items 2 to 4	Estimated undeveloped ground-water	Rainfall	Relation item 5 to 7
East Maui								
Honomanu series	[a]15.37	[c]18.63	0.00	[g]70.00	88.63			
Kula series . .	0.39	43.55	0.09	[g]55.00	98.64			
Hana series . .	7.15	9.74	5.90	0.00	15.64			
Alluvium . . .	2.20	2.20	0.00	0.05	2.25			
Total	25.00	[d]74.00	6.00	125.00	205.00	700.00	2,360.00	9%
West Maui								
Wailuku series .	9.03	54.50	19.85	45.00	120.35			
Honolua series .	0.16	1.00	0.00	0.00	1.00			
Alluvium . . .	0.00	([e])	0.65	0.35	1.00			
Total	9.19	[f]55.50	20.50	45.00	121.00	100.00	580.00	21%
Island of Maui								
Total	34.00	129.50	26.50	170.00	326.00	800.00	2,940.00	11%

[a] Excludes 5 m.g.d. from springs at mouth of Honomanu Valley that may be perched.
[b] Includes all springs listed in item 1.
[c] Excludes flow of 1.75 m.g.d. from Plunkett Spring that sinks and may reappear in Store Spring.
[d] Excludes 5.9 m.g.d. from tunnels tributary to the Koolau ditch.
[e] Small springs issue from the alluvium in many valleys but their flow is not separable from the water derived from the Wailuku volcanic series.
[f] Excludes 20.5 m.g.d. from tunnels tributary to the streams.
[g] Segregation as to rock formation approximate only, as formations are transitional in the Isthmus.

GROUND-WATER STATISTICS

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Water supplies of towns and villages on Maui[a]

(Data compiled from county, plantation, and original surveys)

Place	Population[b] 1941	System[c]	Consumption[b] 1941 (million gallons)	Source of supply	Geologic structure
West Maui plantations					
Baldwin Packers (Systems 1–3):					
Honokahua	633	1	69.6	Honokohau ditch	Surface water
Kahawihi Camp and golf course	125	2	13.8		
Kahana subdivision	25	3	2.8		
Mala cannery	....	7	....	Kanaha ditch[d]	
Pioneer Mill Co. (Systems 4–10):					
Mahinahina	79	[e]4	8.7	Honokohau ditch	do.
Kahana	80		8.8		
Honokowai	91	5	10.0	Honokowai ditch	
Puukolii Power House village	48		5.3		
Puukolii	900		99.0		
Kaanapali Power House village	48		5.3		
Kaanapali Landing	45		5.0		
Crater village	159	6	17.5	Kahoma Stream	
Lahaina (Plantation residences only and Makila village)	714	[f]7	78.5	Kanaha ditch	
Keawe village	156		17.2		
Kapunakea village	262		28.8		
Kelawea village	219		24.1		
Kuhua and mill villages	452		49.7		
Mala	153		16.8		
Puunoa village	100		11.0		
Wainee	418		46.0		
Kauaula	82	8	9.0	Kauaula Stream	
Lunaville	42		4.6		
Launiupoko	75		8.3		
Olowalu	182	9	20.0	Olowalu Stream	
Ukumehame	3	10	0.3	Ukumehame Stream	
Sugar mill	....	....	....	Well 7 (pl. 1)	Wailuku basalt

See footnotes page 206.

Water supplies of towns and villages on Maui[a]—*Continued*

Place	Population[b] 1941	System[c]	Consumption[b] 1941 (million gallons)	Source of supply	Geologic structure
Wailuku Sugar Co. (Systems 11, 13, 14):					
Maalaea[g]	[h]90	11	10.0	S. Waikapu ditch	Surface water
Puuhele	165		18.0		
Waikapu	525		58.0		
Wailuku camps	986	12	99.5	Iao Stream[i]	
Hopoi	83		4.4		
Puuohala	265		27.8		
Waiehu	215	13	[h]23.0	N. Waiehu ditch	
Waihee	590	14	[h]60.0	Waihee ditch	
Waihee Beach	31		[h]3.0		
Sugar mill	......	......	......	Tunnels 9 and 10 (pl. 1)	Iao gravel

[a] The chloride (Cl) content in parts per million ranges from less than 10 to about 40 for all streams, ditches, and tunnels depending upon the weather and the amount of spray carried inland by the wind. The following tests of the chloride (Cl) made by the Wailuku Sugar Co. on Dec. 11, 1941, are in parts per million: Waihee ditch 9.4; north Waiehu ditch 8.3; Iao Stream 11.4; and south Waikapu ditch 10.4.

[b] The population for the large towns listed under the plantations is the number of resident employees. The population of the towns served by the County systems is estimated from the number of meters and does not include the employees of plantations listed separately. The consumption is estimated at the rate of 300 gallons per person per day except for the W. S. Co. and Maui County systems which are metered. The large per capita consumption is due to the water being free and to many users irrigating small gardens. This rate of consumption has been verified by J. H. Foss and other engineers who have charge of the plantation water systems.

[c] Numbers assigned to distinguish the various pipe line systems.

[d] Two brackish dug wells on the premises are pumped for washing purposes only.

[e] 2" pipe line from adit No. 29 of the Honokohau ditch tunnel. Included with the population of Mahinahina village are 2 persons at Mahinahina ditchman's house supplied by a separate pipe line from the south portal of Honokohau ditch tunnel.

[f] One pipe line jointly owned by Lahainaluna School, P. M. Co., and the County. Some of the plantation's properties are supplied through the county distribution system, especially the ice works, beach residences, and Wainee.

[g] Village does not belong to plantation.

[h] Estimated.

[i] Tunnel 10 (pl. 1) supplies 7 families not included.

[j] Census made by the company, Dec. 31, 1941.

[k] Two main systems. No. 15 diverts from ditch at northeast corner of plantation to supply divisions 1 and 10 (Spreckelsville) and the water is chlorinated only. No. 16 diverts from the same ditch near reservoir 5 where it is chlorinated and filtered.

[l] Also connected to the Wailuku Waterworks of the County (system 12).

[m] Uses a drilled well containing 400 p.p.m. of chloride for washing purposes only.

[n] Pipe diverts from portal of Wailoa ditch tunnel and water comes from forest reserve; hence the water is neither filtered nor chlorinated.

[o] See ranches in this table.

[p] About 15,000 gallons a day used for washing purposes only comes from a spring half a mile above the cannery on the Mitchell property in East Kuiaha Gulch.

[q] Included in consumption data for this system listed under Maui County.

[r] Goes dry in droughts.

[s] Rates are: 6¢ per 1,000 gallons for domestic use and 10¢ per 1,000 gallons for commercial use except in the Makawao Waterworks where the domestic rates are 15¢ per 1,000 gallons for the first 20,000 gallons and 16¢ thereafter. The commercial rate is 16¢ per 1,000 gallons regardless of quantity. Huelo and Kahakaloa do not pay for water.

[t] Tunnel 7 (pl. 1) being excavated to supply this system.

[u] The Kula system is shown in figure 9. The water is distributed from Olinda reservoir where one main goes to Kula and the other to Makawao.

[v] Supplied also from system 16.

[w] This system in times of drought uses water from the Opana-Awalaau Gulch system of the M. A. Co. Tunnels 27–31 (pl. 1) supply most of the water at such times. The County pays $75.00 a million gallons for this water whereas it pays $10.00 a million gallons diverted by the Kula system.

[x] Diverts from tailrace of the Kaheka power plant of the H. C. & S. Co.

[y] Also short tunnel at spring on red ashy soil in the Kula volcanics on the west bank of Wailuanui Stream above the road, altitude 750 feet.

[z] Supplemented by the Kula system No. 25.

[aa] Tunnels 27–31 (pl. 1) supply most of the dry weather flow.

[bb] Supplemented with water from Helani Stream via Kaupo Ranch pipe line.

[cc] Supplemented with water from Kalepa Stream.

[dd] Supplemented with water from dug well.

East Maui plantations

Hawaiian Commercial and Sugar Co.[j] (Systems 15–16):					
Camp 1 division:					
Baldwin Ave.	80	[k]15	8.8	Lowrie ditch	Surface water
Camp 2	290		31.9		
Central Power Plant[l]	108		11.9		
Codfish Row	99		10.9		
Hawaiian Camp	160		17.6		
Hospital Camp	168		18.5		
Japanese Camp 1	254		27.9		
Lower Camp 3	423		46.5		
Middle Camp 3	98		10.8		
Upper Camp 3	87		9.6		
Russian Camp	77		8.5		
Camp 10 division:					
Camp 10	179		19.7		
Camp 11	70		7.7		
Camp 5 division:					
Ah Fong Camp	137	16	15.1		
Alabama Camp	684		75.2		
Camp 5	180		19.8		
Camp 8	53		5.8		
Dairy[l,m] and bean mill	104		11.4		
Green Camp	143		15.7		
Kahului Store Camp[l]	76		8.4		
McGerrow Camp	807		88.8		
Puunene Ave.	266		29.3		
Sam Sing Camp	274		30.1		
Spanish A	326		35.9		
Spanish B	746		82.1		
Wells 5 and 6 Camps	19		2.1		
Young Hee Camp	407		44.8		
Airport division:					
Airport village	226		24.9		
Camp 7	64		7.0		
Kihei division:					
Kihei Camp 1	95		10.5		
Kihei Camp 3	107		11.8		
Camp 12	52		5.7		
Camp 13	183		20.1		
Kaheka	30		3.3		
Sugar mill	....	....	....	Well 17 (pl. 1)	Honomanu basalt

See footnotes page 206.

Water supplies of towns and villages on Maui[a]—*Continued*

Place	Population[b] 1941	System[c]	Consumption[b] 1941 (million gallons)	Source of supply	Geologic structure
Maui Agricultural Co. (Systems 17, 18, 37, 46):					
Lime Kiln	32	[n]17	3.5	Wailoa ditch	Surface water
Semi-skilled	479		52.7		
Orpheum	445		49.0		
Nashiwa	642		70.6		
Below Store	285		31.4		
Above Store	518		57.0		
Hawaiian-Spanish	402		44.2		
Stable	62		6.8		
Lower Paia Pump	20		2.2		
1,000-Up	96		10.6		
Kaheka	621		68.3		
Paholei	72		7.9		
Grove Ranch	53	([o])	5.8		
Kailiilii	14	17	1.5		
Kailua Camp	158		17.4		
Keahua	453		49.8		
Pulehu	247		27.2		
Hamakuapoko	739		81.3		
Maliko	9		1.0		
Haiku	13		1.4		
Sugar mill	......	......	......	Well 29 (pl. 1)	Honomanu basalt
Maui Pineapple Co.:					
Corn Mill Camp	187	18	20.6	Tunnels 27–31 (pl. 1)	Kula soil and ash beds
Haliimaile	493	17	54.2	Wailoa ditch	Surface water
Kahului cannery	......	......	......	Well 13 (pl. 1)	Honomanu basalt
Libby, McNeil & Libby:					
Pauwela cannery	([p])	26	......	Wailoa ditch	Surface water
Hawaiian Pineapple Co. (System 19):					
Haiku cannery	......	19	......	Spring 17 (pl. 1)	Kula interbedded ashy soil
Kaeleku Sugar Co. (System 20):					
Hana	806	30	([q])	Wailua Stream	Surface water
Kaeleku	215	[r]20	23.7	Honomaele Stream	

Maui County systems[s] (12, 21-32, 49)

Wailuku Waterworks:					
Wailuku	[h]6,350	12	471.9	Iao Stream[t]	Surface water
Kahului	[h]1,000		213.0		
Kahakaloa	[h]50	21	5.5	Kahakaloa Stream	
Lahaina Waterworks:					
Honokohau	[h]65	22	2.0	Honokohau ditch	do.
Honokowai	[h]150	23	6.9	Honokowai ditch	
Kahana	[h]90	24	1.0		
Lahaina	[h]3,000	[f]7	163.0	Kanaha Stream	
Makawao Waterworks:					
Upper Kula division	[h]930	[u]25	52.5	Waikamoi and Haipuaena Streams	do.
Koheo					
Waiohuli					
Keokeo					
Kula Sanatorium					
Kamaole					
Ulupalakua					
Makena					
Kanaio					
Lower Kula division	[h]1,670	[u]25	63.8	do.	do.
Omaopio					
Pulehu					
Kamehameiki					
Kealahou					
Waiakoa					
Naalae					
Kaomoulu					
Kihei division[v]	[h]300	[u]25	6.4	do.	do.
Makawao division[w]	[h]2,000	[u]25	44.8	do.	do.
Pukalani					
Olinda homesteads					
Haleakala homesteads					
Maluhia					
Pookula					
Kokomo					
Kaupakalua					

See footnotes page 206.

Water supplies of towns and villages on Maui[a]—*Continued*

Place	Population[b] 1941	System[c]	Consumption[b] 1941 (million gallons)	Source of supply	Geologic structure
Haiku-Pauwela division	[h]2,100	26	29.7	Wailoa ditch	do.
Kuiaha					
Ulumalu					
Peahi					
Midway					
Naikuna					
Paia-Kuau division	[h]1,700	[x]27	25.9	.... do.	do.
Hana Waterworks:					
Keanae and Wailua	[h]280	28	3.9	Wailuanui Stream[y]	do.
Nahiku	[h]100	29	1.2	Tunnel 51 (pl. 1)	Hana lavas and soil
Hana	[h]2,000	30	13.6	Wailua Stream	Surface water
Hamoa					
Kakio					
Puuiki					
Muolea					
Kaupo	[h]175	31	2.0	Kalepa Stream	do.
Huelo	20	32	2.0	Hanehoi Stream	
Pohookipa Park	......	......	......	Dug well	Probably Honomanu basalt

Large ranches

Haleakala Ranch (Systems 33–36):					
Dairy Camp	150	[z]33	[r]25.0	Awalaau Gulch[aa]	Surface water
Headquarters		34		Tunnels 25 and 26 (pl. 1)	Partly buried Kula cinder cone
Makawao division					
Kamaole division	12	[z]35	[r]5.0	Tunnel 61 (pl. 1)	Kula ash and lava
Waiopae division	1	[bb]36	[r]2.0	Tunnel 57 (pl. 1)	Kula interbedded soil
Rice Ranch	......	[z]33	......	Awalaau Gulch[aa]	Surface water
Grove Ranch:					
Paia section	......	37	......	.... do.	do.
Haiku section	......	26	......	Wailoa ditch	
Ulupalakua Ranch (Systems 38–39):					
Ulupalakua division	([q])	[z]38	......	Tunnels 58–60, and 62 Springs 47 and 48 (pl. 1)	Kula ash and lava Soil interbedded with Hana cinders
Kipahulu division	[h]70	39	......	Oheo Stream	Surface water
Kaupo Ranch	[h]25	[cc]40	......	Helani Stream[r]	

Miscellaneous

Haleakala National Park (Systems 41–44):					
Ranger station	....	41	....	Rain catch and Waikamoi Gulch	Surface water
Observatory	....	....	....	Roof	Rain
Old Rest House	....	....	....		
Paliku Cabin	....	....	....		
Kapalaoa Cabin	....	42	....	Spring 43 (pl. 1)	Top of partly buried Kula cone
Holua Cabin	....	43	....	Spring 44 (pl. 1)	Kula tuff bed between dikes
Keanae CCC	40	44	5.0	Pohokuokane Stream	Surface water
U. S. Army:					
Summit Haleakala Station	....	....	....	Roof	Rain
Lower Haleakala Station	....	41	....		
National Guard Camp	....	[dd]12	(q)	Iao Stream	Surface water
U. S. Navy	....	[v]45	....	Maui-type well and drilled well	Honomanu basalt
Large schools:					
Lahainaluna	[h]200	[f]7	20.0	Kanaha ditch	Surface water
Baldwin High	....	12	(q)	Iao Stream	
Hamakuapoko	....	27	(q)	Wailoa ditch	
Maunaolu	80	17	8.8		
Baldwin Home	20		2.2		
Kula Sanatorium	....	25	(q)	Waikamoi Stream	
Maui Airport	....	16	....	Wailoa ditch	
Maliko Gulch	40	46	4.4	Tunnel 23 (pl. 1)	Contact Kula and Honomanu lavas
East Maui Irrigation Co. (Systems 47–48):					
Kailua	50	47	5.5	Wailoa ditch	Surface water
Nahiku Camp	12	48	1.3	Tunnel 39 (pl. 1)	Hana lava and soil
Boy Scout Camp	....	49	....	Makamakaole Stream	Surface water

See footnotes page 206.

Perched springs on Maui

(Only those numbered on plate 1)

No. (pl. 1)	Name	Valley or area name	Altitude (ft.)[a]	Average daily discharge (gals.)[b]	Perching formation
West Maui springs					
1	Lower	Honokohau	1,300	100,000	Wailuku dike complex
2	Middle	do.	1,350	150,000	do.
3	Upper	do.	1,900	1,000,000	do.
4	Kapuna	Kahakuloa	550	[c]2,230,000	do.
5	West	Makamakaole	2,350	75,000	Clinker bed in Honolua series
6	East	do.	2,400	35,000	do.
7	Waikulu	Alaeloa	1,400	50,000	Soil in Honolua series
8	Waipuka	Waihee	1,100	100,000	Wailuku dike complex
9	North	N. Waihee	1,600	1,250,000	do.
10	Lower	N. Waiehu	1,500	150,000	do.
11	Upper	do.	2,050	1,500,000	do.
12	Lower	S. Waiehu	1,000	200,000	do.
13	Middle	do.	1,325	500,000	do.
14	Upper	do.	1,500	1,000,000	do.
15	Black Gorge	Black Gorge	[d]1,200	600,000	do.
16	Needle	Iao	1,100	250,000	do.
				9,190,000	
East Maui springs					
17	Pukalani	Maliko	1,000	10,000	Interbedded ash soil bed in Kula series
18	Ohia	Keanae	230	[e]3,040,000	Older alluvium under Ohia lava
19	Store	do.	245	[e]2,200,000	Older alluvium
20	Banana	do.	750	[e]2,880,000	Unknown; issues from Honomanu basalt
21	Plunkett	do.	1,000	[f]1,750,000	do.
22	Ogino	Paakea	1,237	[e]200,000	Soil at base of Paakea lava
23	Pali	Kapaula	950	500,000	Soil and decomposed clinker at base of Waiaaka lava (?)
24	Silveno	do.	1,171	[e]180,000	do.
25	Kapaula	do.	1,113	[e]440,000	Soil at base of Paakea lava (?)
26	Big	Hanawi	546	[g]10,400,000	Artesian structure 200 feet below in the Honomanu lavas
27	Hanawi 1	do.	767	[e]1,170,000	Soil at base of Makaino lava
28	Hanawi 2	do.	660	[e]880,000	do.
29	West Makapipi	W. Makapipi	1,185	[e]490,000	Soil at base of Big Falls lava
30	Ulaino	Ulaino	200	100,000	Soil between Hana lavas
31	Clark or Kinney	Kawaipapa	2,900	[h]100,000	Ash interbedded with Hana lava
32	Waihoi	Waihoi	2,300	75,000	Clinker bed in Kula series
33	Lower	Hahalawe	2,280	75,000	Thin soil on a clinker bed in Kula series
34	Upper	do.	2,760	30,000	do.
35	E. Puaaluu	Puaaluu	1,100	100,000	Clinker bed in Kula series
36	W. Puaaluu	do.	1,120	75,000	do.
37	Waihi	Kukuiula	25	15,000	Soil and talus at base of Hana lavas
38	Panainai	Maalo	1,972	15,000	Thin soil at base of Kula lava flow
39	Upper	Manawainui	2,150	200,000	Vitric tuff in Honomanu series
40	Lower	do.	1,940	[i]140,000	do.
41	Waiu	Kaupo	50	[h]15,000	Kaupo mud flow
42	Paliku	Haleakala Crater	6,550	[h]200	Decomposed surface of buried Kula cone
43	Kapalaua	do.	7,400	[h]25	do.
44	Holua	do.	7,250	[h]500	Interbedded Kula vitric tuff
45	Punakeaka	Kahalulu	3,250	[h]8,000	Side of lava-filled valley in Kula series
46	Wailaulau	Wailaulau	2,900	[h]4,000	Interbedded Kula vitric tuff
47	Waikaalu	Ulupalakua	5,400	750	Interbedded peaty soil in Hana cinders
48	Waihoi	do.	4,750	20,000	Interbedded ash soil in Hana cinders
				25,113,475	
Total West and East Maui...........				34,253,475	

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[a] Mostly determined by barometer. [b] Estimated on basis of one or two observations unless footnoted otherwise. [c] Discharge determined by measuring Kahakuloa Stream above and below spring on May 23, 1939. [d] The stream gains rapidly between altitudes of 1,200 and 1,300 feet and below 1,200 feet loses. [e] Average of recorded measurements. [f] Ground-water flow from the Kano re-entrant. Plunkett Spring yields about 1,000,000 gallons per day except in droughts, when it goes dry. Plunkett Spring sinks in Palaukulu Gulch and may supply part of the flow of Store Spring (No. 19). [g] Calculated from readings of gaging stations at 500 and 650 feet altitude on Hanawi Stream and at Hanawi Spring No. 27. [h] Goes dry in dry weather. [i] Measured at old Kaupo intake, altitude 1,050 feet, on Aug. 16, 1939.

Tunnels driven for perched ground water in Maui

No. (pl. 1)	Owner	Valley or name	Altitude[a] (ft.)	Yield[b] (g.d.)	Length (ft.)[c]	Geologic structure and perching formation
			Water-development tunnels in West Maui			
1	H.C. & S. Co. and W.S. Co.	Waihee[d]	1,625	[e]4,600,000	2,200	Older alluvium and Wailuku dike complex (cuts 152 dikes)
2	Do.	do.	1,650	1,000,000	2,500	Older alluvium, Wailuku dike complex, and pit crater breccia (cuts 30 dikes)
3	W.S. Co.	Waiehu	300	250,000	500	Alluvium
4	Do.	Iao	1,425	[f]75,000	[g]2,500	Dikes in Wailuku caldera complex
5	Do.	do.	1,475	75,000	caved	do.
6	Do.	Black Gorge	[h]1,305	600,000	1,413	Wailuku dike complex (cuts 47 dikes)
7	County	Iao[i]	787	[j]2,050,000	2,630	do. (cuts 85 dikes)
8	W.S. Co.	Field Gorge[d]	700	100,000	caved	Alluvium and Wailuku basalt
9	Do.	Iao[d]	440	150,000	1,000	Alluvium (underflow Iao Stream)
10	H.C. & S. Co.[k]	do.[d]	240	250,000	2,000	do.
11	Do.	Waikapu	1,800	1,000,000	2,943	Dike swarm in Wailuku basalt (cuts 26 dikes)
12	Do.	do.	1,770	7,000	[l]1,650	Vent breccia of Wailuku caldera complex cut by dikes
13	P.M. Co.	Olowalu[m]	1,710	100,000	[n]3,000	do.
14	Do.	do.	775	dry[o]	......	Dike swarm in Wailuku basalt
15	Do.	Launiupoko	1,425	100,000	1,320	do. (cuts 20 dikes)
16	Do.	Kauaula[m]	2,920	2,000,000	656	do. (cuts 194 dikes)
17	Do.	Kahoma[m]	[h]1,923	dry	2,500	do. (cuts about 19 dikes)
18	Do.	do.	[h]1,984	[p]1,900,000	3,080	do. (cuts 47 dikes)
19	Do.	do.[m]	2,350	10,000	739	do. (cuts 16 dikes)
20A	Do.	Honokowai[m]	1,700	2,000,000	1,250	do. (cuts 18 dikes)
20B	Do.	do.[m]	1,600	500,000	1,050	do. (cuts 7 dikes)
21	B.P.	Honokohau	880	[q]1,350,000	720	Dike swarm in Wailuku basalt and cinder cone (cuts 7 dikes)
22	Do.	do.	900	[q]2,400,000	1,015	do. (cuts 10 dikes)
			Water-development tunnels in East Maui			
23	M.A. Co.	Maliko[m z]	50	10,000	130	Ashy soil and gravel between Kula and Honomanu lavas
24	H.P. Co.	Kaiwaikoa (Maliko)	10	[r]5,000	[r]100	do.
25 26	H.R. Co.	Waihoi[s]	3,350	15,000	[r]50	Soil-covered cinder cone in Kula lavas
27	M.A. Co.[t]	Awalaau	2,300	[u]5,000	(?)	Thin soil beds interbedded with Kula lavas
28	Do.	do.	2,340	(?)	375	do.
29	Do.	do.	2,300	[u]4,000	30	do.
30	Do.	do.	2,300	3,000	(?)	do.
31	Do.	do.	2,300	(?)	(?)	do.
32	County	Waikamoi	[h]4,277	9,000	1,901	Ash interbedded with late Kula lavas
33	E.M.I. Co.	Piinaau[v] (Keanae)	1,200	50,000	248	Soil interbedded with Hana lavas
34	Do.	Keanae[w]	1,250	dry	190	Contact of Hana and Honomanu lavas
35 to 56	Do.	Nahiku	......	....	......	See page 267
57	H.R. Co.	Kao (Pahihi)	4,180	1,500	[x]95	Interbedded thin red baked soil on Kula clinker
58	U.R. Co. and T.H.	Polipoli (Ulupalakua)	6,200	7,000	75	1 foot of soil interbedded with Kula ash
59	Do.	Waikaukane (Ulupalakua)	5,750	[y]1,900	[r]50	Two 1-foot beds of black shale interbedded with coarse Kula ash
60	U.R. Co.	Cornwall (Ulupalakua)	4,850	7,000	40	Lava bed 1 foot thick and fine-grained ash beds interbedded with coarse Kula ash
61	H.R. Co.	Morton (Ulupalakua)	4,850	1,500	60	Similar to no. 60
62	U.R. Co.	Waikaahi (Ulupalakua)	4,600	15,000	15	Similar to no. 60

See footnotes on next page.

(Footnotes: Tunnels driven for perched ground water in Maui)

[a] Determined by barometer unless otherwise indicated.

[b] Mostly estimated.

[c] Includes laterals, if any.

[d] H. B. Penhallow, former manager of Wailuku Sugar Co., reported that tunnels 1 and 2 were driven in 1909; no. 3 about 1902; nos. 4 and 5 about 1906; no. 6 in 1926 under direction of W. O. Clark; nos. 8, 9, and 10 about 1900; no. 11 for about 300 feet before 1900 and abandoned because it was dry, continued again about 1906 when about 7 m.g.d. was encountered but soon dropped to 1½ m.g.d.; and no. 12 about 1905.

[e] Measurement by John Hofmann in Aug. 1933 of Waihee Stream above and below tunnel inflow indicated that tunnels 1 and 2 had a combined discharge of 5.6 m.g.d.

[f] F. G. Duarte who was working for W. S. Co. at the time this tunnel was dug states that the tunnel diverted a spring, but that the tunnel flow exceeds the spring.

[g] Tunnel is caved in at 650 feet from portal. Length reported by F. G. Duarte; cuts 21 dikes in first 650 feet; 3-inch deposit of montmorillanite(?) on the floor; brown silt lens 18 inches thick striking N. 60° W. and dipping 25° NE. at cave-in; olivine-rich basalt above it.

[h] Reported altitude as determined by level line.

[i] First 641 feet driven under direction of H. A. Powers, yield about 50,000 gallons daily; remaining 1,989 feet on County property under direction of H. T. Stearns; tunneling stopped because of agreement reached with W. S. Co. whereby the plantation would extend the tunnel under its property in exchange for certain water rights.

[j] Measured discharge on Dec. 27, 1940, prior to tunneling by W. S. Co. Records of discharge kept during excavation show maximum flow of 4,000,000 g.d.

[k] On property of W. S. Co. Part of flow is used in W. S. Co.'s mill, balance piped to H. C. & S. Co.'s Waihee ditch.

[l] Length reported by S. Mochizuki, tunnel worker. Caved at 1,500 feet; terraces of montmorillanite(?) 1 foot thick on floor. Water slightly thermal and gas present. Another tunnel not found reported to be in this area.

[m] Surveyed by G. A. Macdonald.

[n] Water thermal; gas in tunnel prevented examination. Length reported by P. M. Co. Driven 1907–11.

[o] Shown on plate 1 but portal is buried by landslide. Driven 1911–12. A tunnel driven in 1898 on the east bank at an altitude of 600 feet was not found.

[p] Measured. See p. 231, Planning Board Rept. "Water Resources," 1939.

[q] Measurement Jan. 24, 1924 by U. S. Geological Survey.

[r] Reported.

[s] Short third tunnel.

[t] M. A. Co. and Haleakala Ranch Co. divert this water through two pipe lines. In times of drought surplus water is sold to the Makawao Waterworks of Maui County.

[u] Not in use, goes dry often.

[v] Hole has been bored through the roof to allow a surface stream formerly flumed to the ditch to discharge through the tunnel. Tunnel was driven where seepage discharged from the face of a cliff. Dye tests show the seepage is largely from pools in the stream bed.

[w] Exploration tunnel.

[x] Tunnel A, 15 feet; tunnel B, 60 feet with 20-foot caved-in dry lateral.

[y] An additional 3,900 gallons daily drips from 20-foot cliff at portal to form Waikaukane Spring; 4 gallons per minute measured from spring and tunnel on June 18, 1934.

[z] Driven to supply boiler water for the Maliko pumping plant; now used to supply 8 families with domestic water. Never goes dry.

Test holes in Maui

(Logs of test holes 1–86 in the Nahiku area shown in figure 36. Nos. 87–99 reserved for new holes in East Maui)

No.	Location (See pl. 1)	Owner	Driller	Year drilled	Diameter (in.)	Altitude (ft.)	Depth (ft.)	Water level (feet above sea level)	Rocks penetrated
100	Keanae Valley	E. M. I. Co.	J. M. Heizer	1938	1.5	[a]1,240	381	920.6	Hana lavas mostly dense 0–327.7 ft.; red clay or soil with boulders 327.7–334.9 ft.; Hana clinker 334.9–348 ft.; alluvium 348–368 ft.; Honomanu basalt 348–381 ft.
101	Waikamoi Gulch	County and U.S.G.S.	do.	1940	1.5	[a]4,300	650	Dry	Kula lavas[b]
102	Iao Valley	U.S.G.S.	J. V. Crews	1940	6.5	454	475	32.9	Alluvium 0–40 ft.; probably talus 40–150 ft.; Wailuku basalt 150–475 ft.
103	Near Waihee	W. S. Co.	J. M. Heizer	1933	1.5	[a]80	177	[a]65.0	Alluvium
104	Do.	U.S.G.S.	do.	1935	1.5	14	22	[a]2.0	Lithified dune
105	Baldwin High School	County	do.	1939	1.5	120	131	5.9	Dune sand, alluvium, Honomanu basalt[b,c]
106	Kahului	County	do.	1936	1.5	7	157	3.2	Sand 0–26 ft.; soil 26–55 ft.; Kula(?) and Honomanu lavas 55–157 ft.
107	Near H.C. & S. Co. pump 7	H.C. & S. Co.	H.C. & S. Co.	1926	6.0	[a]145	185	[a]5.0	Earthy conglomerates 0–185 ft.
108	Do.	U.S.G.S.	J. M. Heizer	1938	1.5	120	400	[a]5.0	Earthy conglomerates 0–56 ft.; Kula(?) and Honomanu lavas 95–400 ft.[b]
109	Do.	H.C. & S. Co.	H.C. & S. Co.	1926	6.0	106	146	5.5	Soil 0–30 ft.; residual boulders 30–45 ft.; Kula(?) and Honomanu lavas 45–146 ft.
110	Near Puu Hele	W. S. Co.	J. M. Heizer	1933	1.5	313	325	6.5	Talus 0–15 ft.; Honolua lava 15–49 ft.; Wailuku basalt 49–325 ft.[d]
111	Near pump 3, H.C. & S. Co.	H.C. & S. Co.	H.C. & S. Co.	1936	8.0	193	204	[a]5.0	Soil 0–10 ft.; Kula and Honomanu (?) lavas 10–204 ft.

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[a] Approximate.

[b] Core stored at Honolulu Board of Water Supply.

[c] Dune sand 0–18 ft.; red soil 18.5–27.4 ft.; boulder conglomerate 27.4–48 ft.; red soil with a few pebbles 48–59.5 ft.; dune sand 59.5–75 ft.; boulder conglomerate 75–98 ft.; brown soil 98–104.4 ft.; basalt probably from Haleakala 104.4–131 ft.

[d] Bottom of Honolua lava not certain as core has not been seen. Core is stored by owner.

Records of Maui-type wells

(Data furnished by R. E. Hughes, C. A. Brown, H. J. Eby, and R. Bradley, engineers in charge of pumps for the several plantations)

U.S.G.S. number[a] (See pl. 1 and fig. 9)	Plantation number	Name of plant	Owner	Date installed	Date abandoned	Altitude of shaft collar (ft.)[b]	Depth of shaft (ft.)	Number of tunnels	Length of tunnels (ft.)	Number of supplemental drilled wells	Average depth of wells (ft.)	Number of pumps[c]	Capacity (m.g.d.)	Number of hp of each motor[d]	Number of booster pumps	Hp of booster motors	Average pumping lift, 1940 (ft.)	Average operating cost of pumping each million gallons, 1940 (dollars)[e]	Altitude of static water level (ft.)	Average drawdown (ft.)	Average salt while pumping, 1940 (gr.p.g.)[f]	Chief aquifer[g]
1	....	Alaeloa	B.P.	1934	....	244	245	1	30	0	....	1	0.03	15	0	......	400	.....	2.0	0	24	Wailuku basalt
2	F	Honokowai	P. M. Co.	1921	....	65	65	0	......	12	85	1	5.00	400	0	......	340	12.08	2.0	2.0	50	do.
3	D H	Kaanapali	do.	1897	....	27	25	2	1,561	[h]11	50	1 2	5.00 10.00	50 400	1 2	50 40 & 60	85 390	4.65 11.70	2.0	0.7	80	do.
4	G	Hahakea	do.	1923	....	14	12	1	187	0	....	1	5.00	500	0	......	390	13.40	1.5	0.5	70	do.
5	M	Kahoma	do.	1933	....	322	323	2	3,801	0	....	2	10.00	500	0	......	430	14.65	2.2	0.7	30	do.
6	L	Wahikuli	do.	1897	....	26	27	1	215	12	60	1	5.00	200	0	......	185	9.18	1.5	0.7	60	do.
7	C	Mill	do.	1897	....	34	39	1	768	3	85	1 1	3.00 7.00	50 200	0	......	100	.....	3.0	3.0	100	do.
8	B									0	....	1	10.00	250	0	......	102	4.44	2.0	1.0	60	do.
9	A E	Lahaina (Wainee)	do.	1897	....	30	31	1	1,094	[i]10	50	1 1	11.30 2.60	850 400	0 0	....	280 535	9.28 22.87	2.0	1.0	80	do.
10	N	Olowalu	do.	1933	....	165	[j]300	1	239	0	....	1	5.25	150	0	......	135	4.28	3.5	1.0	30	do.
11	O	do.	do.	[k]1905	....	20	20	4	670	8	60	1	3.00	30	0	......	20	1.81	2.0	2.0	18	do.
12	P	Ukumehame	do.	1934	....	79	[j]143	1	428	0	....	1	4.75	100	0	......	85	3.20	6.0	0.7	45	do.
13	....	Cannery[l]	M. P. Co.	1926	....	20	28	1	75	1(?)	....	2	2.23 1.80	100 60	0	......	75	.....	3.0	5.0	11	Honomanu basalt
[m]14	K1	Kihei	H.C.&S. Co.	1900	....	26	23	1	1,582	6	65	1	10.00	600	0	......	215	3.23	4.0	5.5	70	do.
15	K3	do.	do.	1900	....	303	323	2	350	5	350	2	11.00 11.00	1,000 1,000	1	150	403	4.34	6.0	12.5	52	do.
16	7	Waikapu	do.	1926	....	126	129	2	548	1	168	2	20.50 19.50	500 500	1	150	[dd]148	2.06	5.5	2.0	[n]42	do.
17	8	Mill	do.	1939	....	72	80	1	190	0	....	3	5.00 5.00 5.00	125 125 125	..	......	117	0.26	4.7	3.5	47	do.
18	6	Mauka of hospital	do.	1934	....	182	176	2	1,000	0	....	2	[o]15.00 10.00	700 400	1	275	[dd]219	2.31	5.0	3.0	38	do.
19	5	Makai of hospital	do.	1899	....	40	48	3	[p]145	[q]6	85	1	11.00	550	0	......	227	3.55	4.5	6.0	67	do.
20	Old 2	Central power plant	do.	1894	....	20	23	1	150	4	50	3	5.00 5.00 5.00	50 50 30	0	......	30	.....	2.9	8.0	90	do.

21	Old 3	Camp 3	do.	1898	1937	50	61	1	20	[r]5	90	...	....	.....	0	......	215	.....	3.5	8.0	67	do.
22	3	Haiku ditch	do.	1938	....	207	202	1	800	0	....	1	15.00	[s]700	1	600	[dd]296	3.91	5.0	3.0	31	do.
23	1	Spreckelsville	do.	1895	1930	....	....	...	......	...	....	...	....	.....	..	......	.....	.....	...	....	....	......
24	4	East of Spreckelsville	do.	1911	....	30	38	1	150	11	65	1	[t]12.00	650	0	......	242	3.59	4.4	2.5	47	do.
25	2	Camp 2	do.	1929	....	125	130	2	1,400	[u]1	167	2	10.00 10.00	320 320	1	200	[dd]150	2.17	5.4	10.5	46	Probably Kula basalt
[v]26	Old 4	Kailua gulch	do.	1899	1911	18	25	1	250	0	....	1	1.00	40	0	......	.....	.....	4.5	0	....	Kula basalt
27	3 4	Kaheka	M. A. Co.	1938	....	552	548	2	250 50	0	....	2	7.35 6.65	800 750	0	......	[dd]525	.....	5.0	2.0	30	Honomanu basalt
28	7	JapaneseSch.	do.	1932	....	295	300	2	[w]850	0	....	1	12.00	800	0	......	320	.....	4.0	2.0	32	do.
29	8 13	Mill	do.	1923	....	155	150	3	800	0	....	2	6.00 8.60	300 250	1 1	[x]300 150	180 360	....	5.0	2.5	45	do.
30	1 5 6	Lower Paia	do.	1899	....	25	30	4	[y]1,710	5	55	3	[d]4.25 5.58 [d]12.00	400 75 2,000	0	......	(z)	.....	4.5	3.0	48	Kula and Honomanu basalt
31	12	Kuau	do.	1933	....	156	150	2	[aa]325	0	....	1	7.50	250	0	......	150	.....	4.2	2.0	32	Honomanu basalt
32	10 11	Maliko	do.	1898	....	30	25	2	[bb]350 125	[cc]10	(?)	2	[d]4.20 3.10	400 250	0	......	[dd]390	.....	4.0	....	60	do.

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[a] A new Maui-type well with a 6 x 9-foot vertical shaft was under construction by the U. S. Navy in January 1941, at about 50 feet altitude at the Puunene Airport. Two tunnels, each 45 feet long, one of which encountered a lava tube full of water, exist at the bottom of the shaft. A deep-well turbine with a capacity of 2,000 gallons per minute and 150 hp electric motor will be installed. The shaft penetrated soil 0–5 feet; dense basalt 5–35 feet; loose black lapilli firefountain debris 35–41 feet; basalt 41–53 feet. The aquifer is probably pahoehoe of the Honomanu volcanic series.

[b] Altitudes divisible by 5 were determined from the U.S.G.S. topographic map. The others were determined by level lines run by the owners.

[c] All are horizontal centrifugal pumps except 3 deep-well turbines at well 17.

[d] All are electric except pumps 1 and 6 at well 30 and pumps 10 and 11 at well 32 which are steam.

[e] Usual operating costs including repairs. Also booster pumps, if any. Data furnished by owners.

[f] To convert grains per gallon NaCl to parts per million of Cl multiply by 10.39.

[g] Some of the shafts on East Maui end in Kula basalt but the drilled wells in them penetrate the Honomanu basalt which yields most of the water.

[h] Number reported as now in use by owner. 36 wells were drilled at this plant; 1 in 1883, 9 in 1896, 14 in 1900, and 12 in 1921. See McCandless, J. S., A brief history of McCandless Brothers and their part in the development of artesian well water in the Hawaiian Islands 1880–1936: p. 65, Honolulu, 1936.

[i] McCandless reports 26 wells 100 to 300 feet deep that were cased through clay, gravel, and boulders for depths ranging from 30 to 115 feet. See reference above.

[j] 30° inclined shaft. No. 12 replaces the former Ukumehame well (alt. 6 feet) which was a pit 5 feet deep with a 6-inch drilled well 12 feet deep in the bottom. It was drilled about 1908, filled in 1936 and was equipped with a pump with a capacity of 1¼ m.g.d.

[k] Estimated.

[l] Annual pumpage estimated to be 100,000,000 gallons.

[m] The Kihei Plantation Co. had McCandless Brothers drill 2 or 3 wells on the north side of reservoir K2 at the discharge end of the present pipe line of well 14 at an altitude of about 165 feet. The company failed before the pumping station was built. It would have been the K2 plant.

[n] One pump running, salt content drops to 35 grains per gallon.

[o] Formerly unit A in well 19; moved to this well in 1934.

[p] East tunnel 80 feet long driven in 1926 increased the yield 8 m.g.d. with a salt content of 60 grains per gallon.

[q] Four of the wells plugged in 1926. Salt content prior to plugging, 100 grains per gallon.

[r] One well not connected to sump.

[s] Temporary motor in use 750 hp.

[t] Electrified in 1925 and capacity increased from 10 to 12 m.g.d.

[u] Partly plugged, salt content 60 grains per gallon during pumping.

[v] Present equipment operated by the Maui Country Club for irrigating its golf course.

[w] Two tunnels, 250 and 600 feet long.

[x] Booster pump No. 9. Other is No. 14.

[y] Four tunnels, 100, 160, 700, and 750 feet long, radiating from the sump.

[z] Four lifts, 46, 214, 416, and 671 feet.

[aa] Two tunnels, 75 and 250 feet long.

[bb] Tunnels do not develop water; contain header connecting wells only.

[cc] McCandless Brothers report 8 wells drilled in 1897 and 1899.

[dd] Maximum lift of the following pumps differs from the average: well 16=200 feet; 18=305 feet; 22=387 feet; 25=238 feet; 27=566 feet; and 32=435 feet.

Water pumped by the Pioneer Mill Co., 1918 to 1941, in millions of gallons

(Data furnished by the Pioneer Mill Co.)

U.S.G.S. No. (pl. 1 and fig. 9)	2	3	4	5	6	7	8 & 9	10	11	12	Total
P. M. Co. No.	F	D & H	G	M	L	C	A B E	N	O	P	
1918					721.60	777.56	4,309.35				5,809
1919		1,195.55			2,657.65	303.30	4,779.01				8,936
1920		1,476.80			2,792.28	1,800.04	4,898.89				10,968
1921		710.37			2,042.72	1,583.58	4,502.36				8,839
1922		1,312.12			2,349.79	2,132.22	5,103.39				10,898
1923	215.80	1,291.90			2,206.32	2,117.05	4,745.76				10,577
1924	528.73	1,613.95			2,395.19	2,876.92	5,476.21				12,891
1925	685.22	2,861.43	690.46		2,164.72	2,369.89	5,463.77				14,235
1926	1,372.27	2,372.04	1,121.34		2,871.05	1,756.45	7,343.37				16,837
1927	1,038.33	2,443.72	935.40		2,003.63	1,955.11	5,896.27				14,272
1928	1,078.15	3,572.64	921.72		1,052.24	1,985.01	6,034.20				14,644
1929	1,258.36	3,608.11	1,028.43		1,651.19	1,828.80	5,721.25				15,096
1930	1,055.33	3,131.86	886.94		1,024.58	2,784.40	4,903.47				13,787
1931	1,439.21	4,048.94	1,365.03		1,747.45	2,433.49	7,349.47				18,384
1932	1,238.30	3,773.75	1,096.58		1,357.39	2,559.06	6,126.50		173.47		16,325
1933	1,357.39	4,175.64	1,407.23	1,189.96	1,228.96	2,434.12	6,536.51	443.41	208.86		18,982
1934	1,587.66	4,394.08	918.40	1,353.73	1,159.14	2,308.13	6,423.67	624.95	136.92	130.90	19,038
1935	1,253.93	4,184.52	1,231.16	2,541.55	414.86	2,435.72	5,791.14	893.23	176.56	582.52	19,505
1936	959.88	3,396.41	954.08	1,886.80	369.64	2,582.80	4,451.20	624.50	94.90	312.53	15,633
1937	767.40	3,854.62	711.17	1,006.34	235.77	2,591.55	4,390.82	193.55	38.93	163.03	13,953
1938	890.07	3,882.83	942.43	1,150.18	241.94	2,680.60	4,558.87	538.11	0.0	464.64	15,350
1939	528.86	3,506.66	810.61	1,036.25	186.74	2,107.34	4,173.82	334.59	45.52	172.57	12,903
1940	850.86	3,742.84	933.12	1,597.11	261.61	2,410.42	5,085.85	640.57	165.31	510.73	16,198
1941	501.83	3,785.24	859.38	1,661.63	216.08	2,597.52	5,447.30	737.05	174.25	400.38	16,381

Salt (NaCl) content in grains per gallon of water pumped by the Pioneer Mill Company, 1926 to 1940[a]

(Data furnished by the Pioneer Mill Co.)

U.S.G.S. No. (Pl. 1 & fig. 9)		2	3	4	5	6	7	8	9	10	11	12[b]
P. M. Co. No.		F	D	G	M	L	C	B	A	N	O	P
1926	Max.	56.0	49.6	65.6		126.4	310.4	92.8	84.1			
	Min.	38.5	36.7	47.4		88.6	105.6	57.3	38.4			
	Mean	49.9	46.2	60.0		113.9	199.0	72.9	58.5			
1927	Max.	59.2	67.2	70.4		127.8	395.2	102.4	83.2			
	Min.	30.4	46.4	49.6		83.2	76.8	40.0	41.6			
	Mean	53.6	56.5	65.7		108.5	164.5	83.7	54.1			
1928	Max.	67.2	81.6	70.4		108.8	76.8	118.4	70.4			
	Min.	44.8	51.2	59.2		67.2	52.8	44.8	43.2			
	Mean	56.6	70.2	62.2		81.3	66.6	69.6	55.2			
1929	Max.	81.6	89.6	81.6		104.0	76.0	73.6	83.2			
	Min.	54.4	59.2	64.0		62.4	49.6	46.4	49.6			
	Mean	60.8	75.2	75.2		82.5	65.6	64.5	57.3			
1930	Max.	75.2	80.0	80.0		80.0	76.8	76.8	81.6			
	Min.	48.0	64.0	59.2		59.2	30.8	44.8	43.2			
	Mean	57.6	73.6	74.3		68.5	64.4	55.7	65.6			
1931	Max.	72.0	81.6	81.6		92.8	86.4	72.0	86.4		29.6	
	Min.	43.2	62.4	68.8		56.0	74.4	36.8	49.6		....	
	Mean	54.3	72.0	73.6		65.2	76.8	49.6	76.8		....	
1932	Max.	62.4	78.4	76.8	33.6	91.2	96.0	54.4	89.6		25.6	
	Min.	46.8	67.2	51.8	8.0	60.8	52.8	41.6	67.2		14.4	
	Mean	55.6	74.3	74.0	28.0	66.2	73.5	51.6	76.3		20.8	
1933	Max.	64.0	88.0	81.6	62.4	97.6	112.0	70.4	83.2	22.4	28.8	
	Min.	44.8	51.2	64.0	17.6	32.0	67.2	49.6	70.4	8.0	12.8	
	Mean	56.0	74.6	72.0	38.4	73.6	92.8	54.4	78.2	19.6	21.3	
1934	Max.	73.6	92.8	91.2	58.6	94.4	132.8	76.8	115.2	38.6	38.4	48.0
	Min.	57.6	76.8	65.6	19.2	68.8	70.4	60.8	83.2	14.4	20.8	40.1
	Mean	68.8	84.8	76.0	41.6	81.6	107.2	68.8	94.4	26.4	31.8	42.4
1935	Max.	82.4	92.8	81.6	81.6	90.4	153.6	75.2	111.2	49.6	32.0	41.6
	Min.	52.8	72.0	59.2	24.0	51.2	82.4	49.6	64.0	17.6	16.0	33.6
	Mean	58.4	79.0	64.0	50.4	57.6	114.4	60.8	91.0	24.0	27.5	40.8
1936	Max.	74.4	91.2	82.4	74.4	88.8	120.0	76.0	116.8	50.4	30.4	48.8
	Min.	49.4	68.0	76.0	31.2	57.6	82.4	56.0	70.4	22.4	2.4	40.0
	Mean	64.4	75.2	79.2	45.6	72.8	138.4	68.8	94.2	22.5	21.8	43.1
1937	Max.	64.8	84.8	79.2	28.8	58.4	123.2	68.0	105.6	23.2	....	43.2
	Min.	57.6	76.0	75.2	8.0	50.0	75.2	58.4	67.2	8.4	....	41.6
	Mean	60.0	80.0	76.8	20.0	54.0	100.0	64.0	83.0	19.0	....	41.6
1938	Max.	56.0	80.0	77.6	32.8	42.6	104.8	63.2	108.4	21.2	....	42.0
	Min.	41.2	74.4	71.2	11.8	35.8	74.4	58.8	76.6	17.2	....	42.0
	Mean	50.5	77.2	74.4	18.5	38.3	88.4	61.4	81.5	19.0	....	42.0
1939	Max.	54.0	72.8	72.4	26.8	47.2	91.6	68.0	89.2	29.6	....	45.0
	Min.	46.4	66.0	66.8	12.4	38.0	56.0	54.0	68.8	15.0	....	42.0
	Mean	50.0	68.6	69.6	19.6	40.0	73.8	61.0	79.0	22.3	....	44.3
1940	Max.	49.2	69.6	80.0	33.6	56.8	112.0	64.0	86.0	39.2	....	45.2
	Min.	40.4	62.0	64.8	17.2	42.0	62.8	50.0	61.2	18.0	....	40.0
	Mean	46.4	65.8	74.0	24.8	49.4	84.0	57.0	72.8	28.6	....	43.2

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[a] The number of salt determinations are variable for each pump and for each year. The mean is the average of all determinations and has no relation to the volume of the water pumped.

[b] The salt (NaCl) content in the water pumped from the former Ukumehame drilled well from 1932 to 1936 ranged from 4.8 to 83.2 grains per gallon.

Water pumped by the H. C. and S. Co., 1899 to 1941, in millions of gallons, and average grains of salt (NaCl) per gallon
(Data furnished by Hawaiian Commercial and Sugar Co.)

U.S.G.S. No. (pl. 1 & fig. 9)	14		15		16		17		18		19		20 & 25[a]		21 & 22[b]		23		24 & 26[c]		Total	Average
H.C. & S. Co. No.	K1		K3		7		8		6		5		Old 2 & new 2		Old 3 & new 3		Old 1		New 4 & old 4			
Year	Water	Salt	Water	Salt	Water	Salt	Water	Salt	Water	Salt	Water	Salt	Water	Salt	Water	Salt	Water	Salt	Water	Salt	Water	Salt
1899....																					[d]3,228	
1900....																					[d]4,579	
1901....																					[d]6,369	
1902....											854		51		664		734		854		[d]4,450	
1903....											574		68		775		256		574		[d]3,602	
1904....											1,124		590		1,295		1,616		1,124		[d]7,673	
1905....											637		160		1,111		557		637		[d]5,812	
1906....											835		265		1,195		2,761		835		[d]9,826	
1907....											304		0		258		1,361		304		[d]4,748	
1908....											.....		.....		.....		.....		.....		[d]12,437	
1909....	794	46	774	64							3,266	55	159	28	687	50	1,509	112	770	165	7,959	75
1910....	1,422	48	1,040	61							3,324	60	262	31	1,146	51	1,448	107	569	113	9,211	66
1911....	88	45	1,131	57							3,327	52	248	32	960	50	1,329	97	1,185	117	8,268	68
1912....	1,803	43	2,373	57							4,874	56	546	37	1,575	52	2,674	103	1,804	96	15,649	66
1913....	1,636	49	1,963	55							3,830	55	492	40	1,231	65	1,442	92	1,248	100	11,842	64
1914....	9	42	1,189	53							3,305	60	0	...	910	52	223	91	214	81	5,851	59
1915....	837	69	2,191	54							4,188	60	540	39	1,072	56	890	109	1,239	92	10,957	66
1916....	1,464	55	1,375	48							3,492	55	410	36	1,261	57	1,294	101	1,102	77	10,399	62
1917....	1,955	55	2,316	52							5,438	54	731	41	1,295	57	2,244	104	1,981	96	15,960	66
1918....	856	57	1,202	55							2,614	61	677	55	720	55	856	109	715	86	7,641	66
1919....	2,230	59	3,203	56							5,723	63	1,679	78	1,023	58	1,871	110	2,284	89	18,013	70
1920....	2,317	58	3,205	58							5,561	77	2,239	122	1,030	63	1,799	100	2,468	90	18,619	80
1921....	1,885	56	1,751	50							3,953	78	1,965	117	1,108	84	1,608	109	1,622	89	13,892	79
1922....	1,680	59	2,665	55							4,324	72	1,375	92	2,075	90	1,313	100	1,596	73	15,028	74
1923....	1,765	64	2,678	57							4,197	79	1,648	110	2,117	94	1,364	100	1,657	82	15,425	79
1924....	1,946	67	3,284	57							4,397	76	1,957	102	3,059	84	1,642	90	1,591	76	17,876	76
1925....	2,723	71	3,447	55							4,622	78	2,462	102	2,881	83	2,251	87	2,596	78	20,983	77
1926....	3,326	74	6,000	58							8,335	95	2,828	122	5,153	87	2,414	83	4,025	73	32,082	83
1927....	2,026	73	3,846	58	5,681	45					5,131	86	264	112	3,003	91	1,788	84	2,775	78	24,515	74
1928....	1,868	71	5,119	54	7,630	42					4,861	74	0	...	2,776	77	1,300	77	2,578	66	26,132	63
1929....	2,264	75	5,129	57	7,346	47					4,145	72	2,364	46	3,179	75	1,745	71	2,243	64	28,415	60
1930....	1,659	71	3,747	51	6,497	45					3,516	66	3,087	51	1,656	70			1,042	52	21,203	55
1931....	2,598	72	5,850	49	9,709	44					5,571	62	4,407	48	2,861	68			1,790	54	32,786	53
1932....	1,925	80	5,194	50	9,476	45					4,971	67	4,353	53	2,700	66			2,017	50	30,637	55
1933....	3,044	80	6,373	49	11,534	45					7,260	71	5,377	57	3,971	65			3,102	56	40,661	57
1934....	1,825	81	5,581	48	9,406	48			1,186	35	5,524	73	4,171	52	3,170	71			2,423	58	33,285	57
1935....	2,359	80	6,119	48	10,122	48			6,056	45	2,786	58	4,979	54	3,946	70			3,019	55	39,386	54
1936....	1,026	75	5,882	46	8.364	47			4,247	43	1,899	56	2,772	52	2,586	72			1,593	55	28,368	51
1937....	1,040	68	4,970	44	6.768	39			3,697	37	1,079	50	2,473	43	353	60			1,160	44	21,540	43
1938....	1,335	71	4,882	43	7,676	39			4,432	36	1,434	47	2,600	51	2,386	32			1,434	49	26,179	43
1939....	1,398	69	5,141	41	7,321	35	1,785	48	4,762	36	1,455	45	2,827	44	2,209	32			1,306	44	28,204	40
1940....	1,959	66	5,959	41	6,624	33	3,135	47	6,013	34	1,902	45	3,607	46	3,004	31			2,204	48	34,407	41
1941....	1,403	59	5,204	31	6,169	31	3,494	40	5,124	34	1,724	43	3,328	29	2,514	28			1,605	42	32,500	39

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[a] No. 20 (old 2) was discontinued for irrigation in 1928 and replaced with No. 25 (new 2) in 1929. No. 20 is still in use for cooling the Central power plant. No records of quantities pumped for cooling until 1940 when 2,191.37 million gallons were pumped. Pumpage in 1941 was 1,933.03 million gallons.

[b] No. 21 (old 3) was discontinued in 1937; subsequent records are for No. 22 (new 3).

[c] No. 26 (old 4) was discontinued in 1911; subsequent records are for No. 24 (new 4).

[d] Data for 1899–1901 from large ledger in Puunene office; 1902–1908 from published annual reports; totals in ledger for these years slightly different from the published totals.

Water pumped by the Maui Agricultural Co., 1913 to 1941, in millions of gallons[a]

(Records furnished by Maui Agricultural Co.)

U.S.G.S. no. (pl. 1 & fig. 9)	27 (Kaheka)		28 (Upper Paia)	29 (Mill)		30 (Lower Paia)						31 (Kuau)	32 (Maliko)		Total
M. A. Co. pump number[b]	3	4	7	8	13	1	2	3	4	5	6	12	[c]10	[c]11	
1913						896	1,324	441	204	208	490		721	529	4,813
1914						903	692	62	167	0	0		154	465	2,443
1915						889	0	134	306	0	0		724	0	2,053
1916						583	572	443	59	89	658		232	163	2,799
1917[d]						1,293	839	777	342	150	258		1,036	608	5,303
1923						536	577	0	308	0	1,515		590	260	3,786
1924						754	747	423	240	0	1,561		766	598	5,089
1925						789	692	256	436	166	1,929		610	583	5,461
1926						1,655	1,323	1,242	682	532	3,448		1,438	1,161	11,481
1927						977	989	173	321	200	1,547		669	638	5,514
1928						766	732	534	500	412	1,618		682	621	5,865
1929						823	1,044	921	572	414	2,601		1,024	945	8,344
1930						580	596	452	330	224	882		546	530	4,140
1931						833	987	1,009	507	355	1,846		751	802	7,090
1932			277			1,028	999	1,132	472	315	1,995		919	772	7,909
1933			3,903			1,364	1,215	1,405	668	369	2,725		1,261	993	13,903
1934			3,088			742	804	1,084	465	[e]332	1,671		550	465	9,201
1935			3,601			716	841	1,485	381	0	3,098	1,216	859	568	12,765
1936			2,962	[f]1,197		622	718	1,276	478	0	1,936	1,194	713	604	11,700
1937			2,248	1,289		400	490	817	481	0	869	981	335	286	8,196
1938	785	[g]668	2,483	1,563	149	742	627	[h]94	340	0	1,379	1,178	653	362	11,023
1939	774	1,497	2,658	1,502	[i]1,689	601	509		[e]371	0	1,081	1,249	559	304	12,794
1940	[h]1,306	1,595	2,508	1,958	2,308	662	[j]293			[e]449	2,081	1,096	765	504	15,525
1941	1,136	979	2,298	1,957	2,339	644				390	1,746	1,169	502	410	13,570

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[a] Some of the amounts pumped from 1937 to 1940 differ from those published in U.S.G.S. Water Supply Papers (No. 840, p. 64; No. 845, p. 61; No. 886, p. 86; No. 911, p. 147) because the plantation reports are confused by the numerous changes in pump numbers during these years.

[b] Pumps 9, 14, and 15 are booster pumps.

[c] Pump 10 formerly Haiku 1 and 11 formerly Haiku 2.

[d] Records for 1918–1922 are missing.

[e] Pump 5 was abandoned in 1934 and after the new pump in Kaheka was numbered 4, pump 4 at Lower Paia was renumbered 5.

[f] Pump was installed in 1923 but records were not kept until 1936.

[g] Newly purchased pump started in Sept. 1938 at Kaheka well. Record prior to that time for another pump No. 4 at Lower Paia well. Started as No. 14, then in Aug. 1939 numbered 5 and in Jan. 1940 numbered 14.

[h] Moved to Kaheka well in July 1938. Formerly was No. 3 at Lower Paia well. Was designated No. 13 in July 1938 and renumbered 3 in Aug. 1939.

[i] Called No. 9 from Aug. to Dec. 1939.

[j] Abandoned in July 1940.

Salt (NaCl) content in grains per gallon of water pumped by the Maui Agricultural Co., 1929 to 1941[a]

(Data compiled from records of H. J. Eby and R. Bradley, pump engineers, Maui Agricultural Co.)

U.S.G.S. number (Pl. 1 & fig. 9)		27	28	29	30					31	32	
M. A. Co. number		3 & 4	7	8	Sump	2	3	4	6	12	10[b]	11[c]
1929......	Max.				....	....	47	....	....		52	52
	Min.				....	....	30	....	....		28	32
	Mean				....	....	40	....	....		33	37
1930......	Max.				....	....	....	....	....		28	32
	Min.				....	....	....	....	....		25	28
	Mean				....	....	....	....	....		27	29
1931......	Max.				....	87	79	62	110		69	81
	Min.				....	69	57	60	66		52	56
	Mean				69	76	59	61	80		59	67
1932......	Max.				....	....	87	....	105		58	59
	Min.				....	....	....	....	57		42	46
	Mean				....	....	....	....	85		51	55
1933......	Max.		40	39	....	....	226	85	198		82	88
	Min.		25	31	....	....	54	50	58		53	55
	Mean		31	36	103	....	113	66	129		69	77
1934......	Max.		45	55	....	....	120	70	151	31	78	90
	Min.		19	30	....	....	42	43	46	15	63	69
	Mean		30	41	83	....	86	59	105	24	68	83
1935......	Max.		42	50	....	58	111	66	125	32	86	88
	Min.		9	30	....	45	42	42	43	7	57	67
	Mean		28	42	71	52	77	58	96	26	69	80
1936......	Max.		36	52	....	63	94	65	118	30	94	117
	Min.		10	26	....	56	58	46	69	13	58	66
	Mean		29	40	74	59	74	54	94	25	74	86
1937......	Max.	22	34	55	62	....	....	....	....	32	....	....
	Min.	16	25	30	48	....	....	....	....	20	....	....
	Mean	19	30	39	55	....	....	....	....	25	....	....
1938......	Max.	34	32	40	54	....	....	....	....	28	....	....
	Min.	12	22	23	39	....	....	....	....	20	....	....
	Mean	26	28	32	49	....	....	....	....	25	....	....
1939......	Max.	29	34	40	50	....	....	....	....	28	....	....
	Min.	17	16	22	41	....	....	....	....	15	....	....
	Mean	24	26	33	46	....	....	....	....	28	....	....
1940......	Max.	28	28	43	....	....	....	....	....	26	....	....
	Min.	15	17	32	....	....	....	....	....	19	....	....
	Mean	23	24	37	....	....	....	....	....	22	....	....
1941......	Max.	23	33	45	50	....	....	....	....	25	....	....
	Min.	16	17	34	43	....	....	....	....	19	....	....
	Mean	19	23	38	47	....	....	....	....	22	....	....

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[a] The number of salt determinations are variable for each pump and for each year. The mean is the average of all determinations and has no relation to the volume of the water pumped.

[b] Also called Maliko 1 or Haiku 1.

[c] Also called Maliko 2 or Haiku 2.

PART 2

GEOLOGY AND GROUND-WATER RESOURCES OF THE NAHIKU AREA, EAST MAUI

By Gordon A. Macdonald

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FOREWORD

By Harold T. Stearns

The Nahiku area has been the site of diverse hydrologic investigations for about 12 years. Its economic importance, geologic complexity, and unique Big Spring have challenged scientific research. Much of the work has been concentrated in a search for the origin of Big Spring which discharges in Hanawi Canyon at an altitude of 540 feet. The geologic search was started about 1930 by W. O. Clark, who has continued to date as consulting geologist for the East Maui Irrigation Co.

In 1932, the Geological Survey employed H. A. Powers, who spent the major part of two years studying the geology of the Nahiku area, especially trying to locate the source of Big Spring.

Joel Swartz and his associates of the geophysical section of the Geological Survey made an extremely detailed electric resistivity survey of the area over a period of 23 months between 1936 and 1939, to locate, if possible, the structure responsible for the spring. He made also a magnetometer survey of the area. He believes that he found, by resistivity, a shallow valley in the vicinity of the spring.[11]

G. A. Macdonald spent the last 4 months of 1939 and the first month of 1940 making an intensive search in the field for water-bearing structures. He completed a detailed geologic map (insert B, pl. 1) and made comprehensive petrographic studies of the lavas in the Nahiku area. His work has been of considerable value in deciphering the complicated succession of lava flows in the northeastern slope of East Maui volcano, and the numerous intervening erosional epochs. He did not succeed in locating the deeply buried artesian structure supplying Big Spring but his mapping confirmed the relation of the cycles of valley cutting and subsequent filling with permeable lavas to the perched springs and high water tables.

Between December 1934 and February 1942, J. M. Heizer drilled about 17,000 feet of diamond drill holes, recovering very complete cores and making excellent records of interbedded soils and perched water tables. All drilling was done for the East Maui Irrigation Company under the direction of W. O. Clark to determine the origin of Big Spring and the geologic structure and occurrence of perched water in the Nahiku area. In January 1941, while drilling a deep hole (No. 85) to locate supporting members that might perch Big Spring, Mr. Heizer encountered artesian water 395 feet above sea

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[11] Press release, U. S. Dept. Interior, Geol. Survey, Sept. 10, 1941.

level.[12] The water was directly below the spring in a permeable basalt between two dense lavas with sufficient head to rise 825 feet above sea level, or more than enough for it to rise through cracks to supply the spring.

The discovery of artesian water after 11 years of exploration came as a surprise to scientific workers in the area, all of whom had accepted the ruling hypothesis of a buried valley filled with permeable lavas as the aquifer. It is true that geologists were handicapped by the fact that none of the rocks making up the artesian structure are exposed and further by the fact that no diamond drilling equipment suitable for drilling to the depth required was available until 1938. It must be admitted however that our greatest handicap was a unanimous failure to consider an artesian hypothesis.

The important lesson gained from the discovery of the source of Big Spring is the addition of the artesian hypothesis to studies of high-level springs issuing from stratified lavas in the Hawaiian Islands. Unfortunately, however, the discovery of the origin of Big Spring has not simplified the problem of recovering at the level of the Koolau ditch the water supplying the spring. For this reason, recommendations made prior[13] to the senior author's knowledge of the artesian aquifer remain unchanged. They were (1) that search for a buried valley be abandoned; (2) that holes be drilled to locate a body of rock above the Koolau ditch saturated with water with the low temperature of the Big Spring; and (3) that such water be recovered by one or more tunnels. Macdonald's recommendation that the Hanawi tunnel (No. 46) be extended to the zone of saturation probably offers the most economical procedure (p. 262).

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[12] Letter from J. H. Foss dated Feb. 13, 1941.

[13] Geological Survey memorandum by H. T. Stearns dated February 5, 1941 sent to J. H. Foss.

GEOLOGY AND GROUND-WATER RESOURCES OF THE NAHIKU AREA, EAST MAUI

By Gordon A. Macdonald

ABSTRACT

The Nahiku area has been mapped and studied in detail. The upper part of the Honomanu volcanic series, exposed in the sea cliffs, in petrographic character is transitional into the overlying Kula lavas. Kula and Hana time were characterized by a long succession of valley-cutting episodes, each valley being filled by lava erupted from the east rift zone. The lavas include olivine basalts, picritic basalts, and basaltic andesites.

In the Nahiku area basal ground water occurs largely in the Honomanu basalts. Perched water occurs in many of the later lavas, generally following the axes of buried valleys. The members which perch the water are mostly ashy soil beds, although an unusually extensive, thick layer of much decomposed clinker also appears to be a supporting member. Most of the water travels through the basal clinker members of aa lavas. Artesian water is encountered in the upper, transitional part of the Honomanu volcanic series. The aquifer is permeable porphyritic pahoehoe; the confining members are relatively impermeable nonporphyritic aa.

INTRODUCTION

The Nahiku area lies on the northeastern slope of Haleakala Volcano, as shown on plate 1. It has been intensively investigated by the United States Geological Survey in cooperation with the Territory of Hawaii, and in addition the East Maui Irrigation Co., Ltd. has explored extensively with test borings, tunnels, and geologic work. The company has cooperated generously with the Geological Survey by making available all of their data and at times rendering other material aid. A detailed geologic map of the Nahiku area is shown in insert B, plate 1. The mapping was done on a scale of 1,000 feet to the inch, on aerial photographs taken by the U. S. Army Air Corps. Statements contained in the present report pertain only to the Nahiku area as shown in insert B, plate 1.

The Nahiku area is crossed at an altitude of 1,250 to 1,300 feet by the Koolau ditch (pl. 42), which collects the flow of the surface streams and of several tunnels that intercept perched ground water. Basal ground water and perched water that emerge below the Koolau ditch have no value at present, although it is possible that if cheap enough power ever becomes available, such low-level water may be pumped to the ditch. In an effort to locate perched water the East Maui Irrigation Co. has made over 70 diamond-drill borings. It has also driven 20 tunnels, a few to get geological information, but most to develop ground water. Nearly all of the water tunnels have been successful.

PREVIOUS WORK AND ACKNOWLEDGMENTS.—The region was previously partly mapped and studied for the Geological Survey by H. A. Powers, and for the East Maui Irrigation Co. by W. O. Clark, geologist for the Hawaiian Sugar Planters' Association. A geologic map was prepared by D. S. Summers, engineer for the East Maui Irrigation Co., under Clark's direction. The earlier maps have been available during the present work and have been of great aid. The earlier investigators have given willingly of their time for discussions of various problems.

It is difficult to credit the individual contributions which make up our present knowledge of the geology of the Nahiku area. Although the work has been in progress more than a decade, little has been written on the area and nothing published. The record of progress is stored almost entirely in the memories of the investigators. It is difficult to be sure who first recognized a given feature, such as a particular valley-filling lava flow. However, most of the contributions undoubtedly were made by W. O. Clark, who recognized most of the buried valleys, and developed the method of tunneling along a contour on the old valley wall until the buried stream was intercepted. Powers appears to have been the first to recognize the Big Falls lavas and the ancient valley they occupy. Several springs were discovered by Summers. The discovery of the artesian water, and much of the success in deciphering the subsurface structure should be attributed to the ability of J. M. Heizer, whose keen observation and understanding of the problems, coupled with his ability as a diamond driller and his careful notes, have resulted in an excellent record of the rocks and hydrologic conditions encountered by the drill holes.

It is a pleasure to express appreciation to the officials of the East Maui Irrigation Co., including J. H. Foss, J. H. Hofmann, and D. S. Summers, for courtesies extended during the investigation. Flow records and engineering data for the tunnels, and driller's logs for the test holes were supplied by the company. Mr. Summers has kindly checked the names and locations of the springs. John Plunkett and William Lonokapu lent valuable assistance in the field. James Y. Nitta prepared the illustrations. The study was made under the supervision of H. T. Stearns, geologist in charge of Hawaiian ground-water investigations. The manuscript has been read and criticized by W. O. Clark, and by H. T. Stearns and C. S. Ross of the U. S. Geological Survey.

GEOLOGY OF THE NAHIKU AREA

GENERAL FEATURES

The rocks of the Nahiku area are all volcanic, and by far the greater proportion are lava flows. Both aa and pahoehoe lavas are present, and range in composition from picritic basalts through basalts to basaltic andesites. Individual aa flows are generally thicker and in their central parts denser than the pahoehoe flows. Clinker forms moderately persistent layers at the tops and bases of aa flows, and in places forms irregular masses within the flows. Pyroclastic rocks are of little volumetric importance, but many of the intercalated soil layers, which perch ground water at high levels, are tuffaceous, containing fine ash drifted by the wind from fire-fountains along the east rift zone. The quantity of ash would be greater were it not that the prevailing northeast winds blew such ash away from the Nahiku area. A single bed of lithic-vitric tuff is exposed in the sea cliff in the upper part of the Honomanu volcanic series.

The geologic history is one of a long succession of lava flows, covering surface drainage systems in various stages of evolution. (See fig. 35.) Many of the buried valleys support subterranean streams which move seaward through fractures and other apertures in the overlying lava as shown by the Big Falls and Makaino lavas in figure 35. Stearns has divided the lava flows of East Maui into three groups—the Honomanu, Kula, and Hana volcanic series (Part 1). In the Nahiku area the Honomanu lavas grade in petrographic character into the Kula lavas, and the line of demarcation has been arbitrarily placed at the top of the transition zone at a surface marked by minor erosion. All the rocks in the Honomanu volcanic series at Nahiku belong in the transition zone. The stratigraphic succession in the Nahiku area is shown in the table on page 230.

INTRUSIVE ROCKS.—The only dike found in the area is exposed in the sea cliff 300 feet west of Kapaula Stream. The rock is a basaltic andesite, similar in petrographic character to several flows in the Hana and Kula volcanic series. It is dense and nonporphyritic, with prominent platy jointing parallel to the walls. It averages 4 feet thick and is essentially vertical, although in detail its course is somewhat sinuous. It cuts Honomanu basalts in the lower part of the cliff, and passes upward into Kula lavas, where it is lost under a cover of soil and vegetation. Other dikes may be present, but have

Stratigraphic section of the Nahiku area, East Maui, Hawaii[a]

Geologic age	Formation			Symbol on insert B, pl. 1	Maximum thickness (feet)	General character	Water-bearing properties
Recent	Talus, landslide deposits, and beaches (the latter not shown on the geologic map)			T		Two small areas of talus along the coast, and a small landslide on the West Branch of Makapipi Creek: unsorted, uncemented breccias, consisting of angular blocks in a finer matrix.	Highly permeable, but of too local extent to have any importance as water bearers. One spring issues from talus, but the water is probably derived from the base of the Kula lavas beneath the covering of talus.
Recent and late Pleistocene	Hana volcanic series	Probably nearly contemporaneous	Hanawi basaltic andesite	H	100±	Aa lava filling the ancient valley of Hanawi Stream.	Its small area makes it unimportant as a water bearer. A few small springs and seeps issue from the base of the flow.
			Paakea basalt	Pa	150±	Olivine basalt of aa type; a thin sheet in the southwestern part of the area divides to form two branches following ancient valleys of Kapaula and Paakea Streams.	Yields water from its basal part in several tunnels; several springs issue from it along Paakea Stream.
			Kuhiwa basaltic andesite	Ku	75±	Aa lava; the main flow covers much of the eastern part of the mapped area, and a minor branch lies farther west; the only post-Kula lava found to contain biotite.	Yields water copiously in tunnel 55, where the water is perched by impermeable stream gravel and soil; also yields small amounts of water in tunnels 52 and 53, and in several small springs along Makapipi Stream.
		Local					
		Mossman basalt		Mo	80±	Picritic basalt, containing abundant phenocrysts of augite and olivine, and consisting of many thin layers of pahoehoe.	Unimportant as a water bearer, although a number of seeps and small springs emerge from it at various localities, and small amounts of water issue from it in tunnel 56 and the main transportation tunnel of the Koolau ditch.
		Local					
		Probably nearly contemporaneous	Makaino basaltic andesite	Ma	125±	Aa lava filling an ancient valley which followed a course approximately parallel to and east of the present Hanawi Gulch.	Yields water copiously in tunnel 46 which contours the ancient valley; Hanawi Springs 1 and 2, and other smaller springs also issue from this lava.
			Kapaula basaltic andesite	K	85±	Aa lava filling an ancient valley which followed approximately the present course of Kapaula Stream.	Yields water in tunnels 40, 41, and 42, and a number of small springs issue from it.

Recent and late Pleistocene	Hana volcanic series	Local				
		Waiaaka basaltic andesite	W	120±	A widespread thin flow of aa characterized by well-developed platy jointing in its basal part lies on an eroded surface but fills only small valleys.	Nearly everywhere carries water, but the amount yielded at any single place is not large. The water is perched by soil and underlying widespread decomposed clinker at the top of the Makapipi lavas.
		Local				
		Makapipi basalts	M	155±	Several flows of andesitic basalt, containing small phenocrysts of olivine, and separated locally by thin layers of soil.	Unimportant as water bearers, although several small springs and seeps emerge from them.
		Local				
		Big Falls basalts	B	134±	Picritic basalt, containing many phenocrysts of olivine and augite. Two flows are present, locally separated by soil; each is composed of several thin layers of pahoehoe.	Several small springs emerge from these lavas in the sea cliff, at Big Falls on Hanawi Stream, and in the plunge pool at the mouth of Makaino Stream.
Great erosional unconformity						
Probably early and middle(?) Pleistocene and Pliocene	Kula volcanic series		N	575+	Several thick, massive aa flows of basaltic andesite, separated locally by thin layers of soil, and local erosional unconformities.	The largest spring in the region, Big Spring on Hanawi Gulch, issues from the clinker phase of a Kula lava, and small springs emerge from Kula lavas at other localities.
	Local					
	Honomanu volcanic series		Ho	190+	Typically thin flows of olivine basalt, of pahoehoe type; intercalated in the upper part are aa flows of andesitic basalt, forming a zone petrographically transitional into the overlying Kula lavas.	Basal ground water is abundant; perched artesian water occurs in the upper, transitional lavas.

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[a] Each member in the Hana volcanic series is underlain by a local erosional unconformity, but superposition in the table does not necessarily mean superposition in the field.

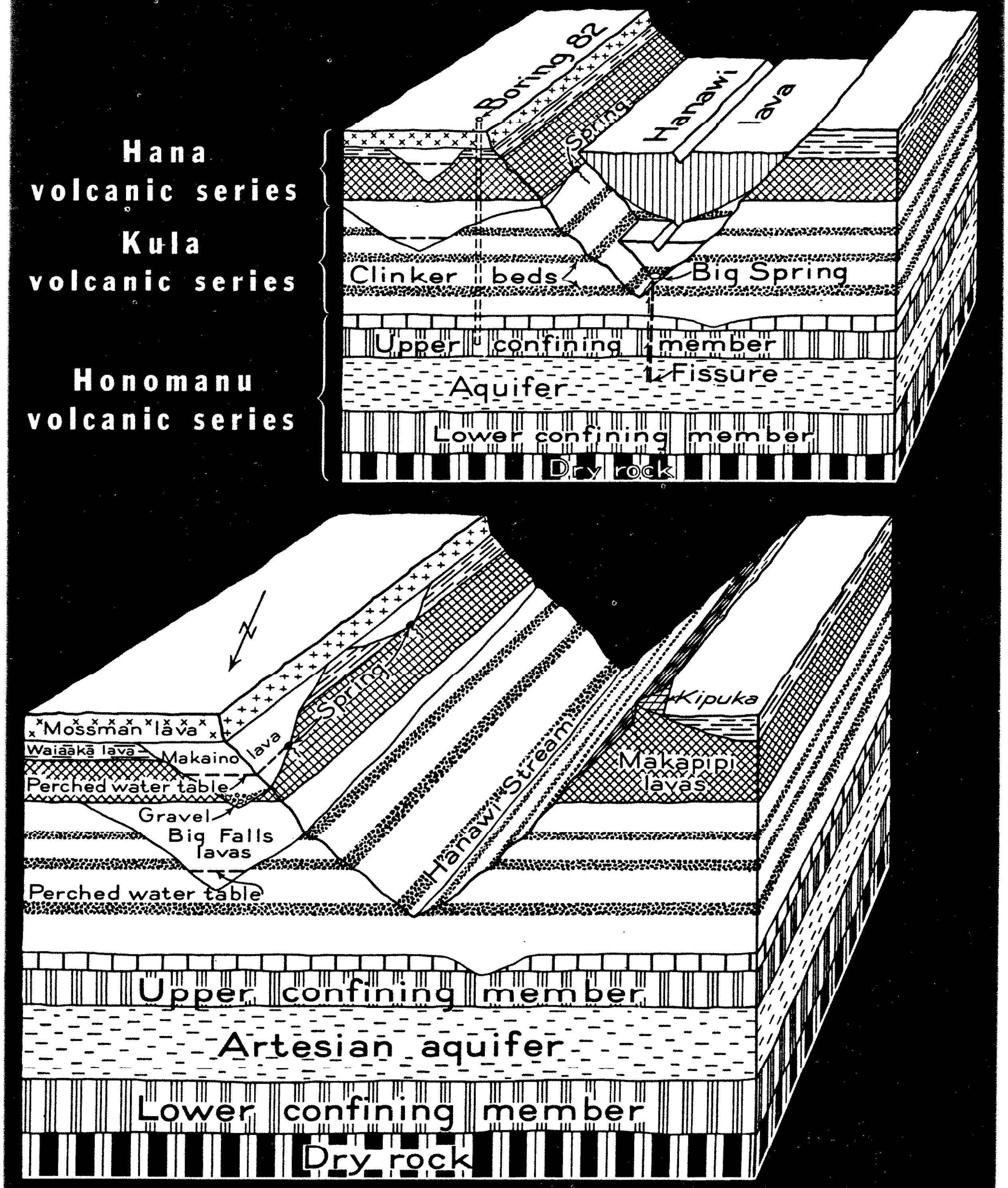

Figure 35. Diagram showing geologic conditions and the occurrence of perched ground water at Hanawi Gulch, in the Nahiku area, East Maui.

not been detected. They are certainly so few in number that they can have no important effect on the movement of ground water.

GEOLOGIC STRUCTURE.—The structure of the area consists essentially of a series of irregular sheets and prisms of lava sloping toward the sea. Folding and important faulting are absent. Minor slickensides are present in several of the cores from the drill holes, but probably do not indicate any great amount of movement. They probably were caused by the slipping of blocks of lava during adjustments accompanying the compaction of the intercalated layers of loosely integrated clinker, caused by the weight of overlying rocks. No other evidence of faulting has been observed.

HONOMANU VOLCANIC SERIES

DISTRIBUTION AND CHARACTER.—Lavas of the Honomanu volcanic series are exposed in the sea cliffs west of Hanawi Stream and in the lower walls of Hanawi Gulch (pl. 1, insert B). They are truncated 500 feet east of Hanawi Gulch by a buried valley filled with Big Falls lavas. Honomanu lavas are encountered in several borings east of Hanawi Gulch (fig. 36). The maximum thickness exposed in the sea cliffs is 150 feet, but the base of the series is nowhere exposed. The upper contact slopes gently northeastward and appears to be essentially the upper surface of the lava dome at the close of Honomanu time. In the sea cliff just west of Hanawi Stream a small valley cut into the upper part of the Honomanu lavas is filled by Kula lava (section C-C′, pl. 1). A small valley at the same stratigraphic horizon, and probably representing the mountainward continuation of the valley exposed in the sea cliff, has been demonstrated by geophysical studies to underlie the area between Big Spring and the highway west of Hanawi Gulch.[14] Such minor irregularities represent local erosion, and several inches of baked soil is commonly present at the upper contact of the Honomanu lavas, but no period of large-scale valley cutting intervened between the eruption of the Honomanu and Kula lavas in this area.

The typical Honomanu lavas of the lower part of the section are thin pahoehoe flows of olivine basalt. Most contain phenocrysts of olivine, and many have tabular phenocrysts of plagioclase. (See Part 3.) The uppermost part of the series, the only part exposed in the Nahiku area, is transitional to the Kula volcanic series in containing both picritic basalts and nonporphyritic andesitic basalts. These uppermost Honomanu lavas are in petrographic character

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[14] Swartz, J. H., Press release, U. S. Dept. Interior, Geol. Survey, Sept. 10, 1941.

more nearly like the Kula lavas than like the typical Honomanu rocks. Traces of soil are present at several horizons, but the only distinct stratigraphic break in the Nahiku area is an erosional surface marked by minor gullies and 0 to 8 inches of red soil at the base of the thick, massive basaltic andesites. This horizon has consequently been taken as the base of the Kula volcanic series, and the underlying transitional lavas are included in the Honomanu volcanic series.

Individual lava flows range from 15 to 75 feet thick, but few exceed 40 feet and most are less than 30 feet. The surfaces of the pahoehoe flows often show thin reddened crusts, which in places are ropy. The andesitic basalts are aa, with thin layers of clinker at top and base. Filled and partly filled lava tubes are abundant in the pahoehoe. These openings, together with numerous vesicles and columnar and cross joints, make the rock exceedingly permeable. The rocks are further described in Part 3.

WATER-BEARING PROPERTIES.—The abundant openings in the Honomanu lavas in general permit the easy circulation of water. Several basal springs emerge near sea level from Honomanu lavas along the coast (pl. 1, insert B). A spring issuing from talus a few feet above sea level 300 feet northeast of Waiaaka Stream may be a basal spring supplied from Honomanu lavas, or may be water which entered the talus at the base of the Kula lavas where a thin soil bed acts as a perching member. Permeable porphyritic pahoehoe basalt with numerous phenocrysts of olivine and augite in the upper part of the Honomanu volcanic series contains water under artesian pressure. The confining members are overlying and underlying relatively impervious aa basalts, nonporphyritic or containing only scattered feldspar phenocrysts. The artesian water will be discussed further in the chapter on ground-water resources.

KULA VOLCANIC SERIES

DISTRIBUTION AND CHARACTER.—The Kula lavas are exposed along the coast and in the walls of Hanawi, Kapaula, and Waiaaka Streams, and have been encountered in drill holes east of Hanawi Gulch and along Makapipi Stream (fig. 36).

The Kula lavas are typically thick, dense, medium- to light-gray aa, sparingly vesicular to almost nonvesicular, with clinkery base and top and local streaks of clinker within the flow. The basal and upper clinkers are very persistent, but the inter-flow clinker masses are small and discontinuous. The rocks are basaltic andesites and for the most part are nonporphyritic, but locally they contain a few small phenocrysts of feldspar. Columnar jointing is poorly to moderately well developed, and in many places there is a weak platy jointing roughly parallel to the surface of the flow. When broken on the platy joints, many specimens show a distinct sheen resulting from the orientation of innumerable minute tabular feldspar crystals parallel to the flow planes.

The upper surface of the Kula lavas is one of profound erosion, representing a series of valley-cutting episodes extending from the close of Kula volcanism to the present. Throughout most of the area the Kula lavas were buried by later flows, but the hill near the coast between Kapaula and Waiaaka Gulches and the ridge west of Waiohue Gulch are kipukas, or eminences of Kula lavas never overridden by later flows. In these two kipukas respectively, the total thickness of the lavas is 450 and 575 feet, but elsewhere it is less, and locally the Kula lavas are completely absent where later valley-filling lavas are superimposed directly on the Honomanu basalts.

In the walls of Hanawi Gulch the Kula volcanic series consists of four flows. The lower one is exposed from the coast to Big Falls, where it is overlain by the third flow which fills a shallow valley exposed in the fall. The base of the second flow is seen at the foot of a fall at 540 feet altitude, and from its basal clinker issues Big Spring. The base of the third flow is exposed 50 feet above Big Spring, and can be traced along the west wall of the gulch where it overlaps the second flow. The base of the fourth flow is exposed on the east wall of the gulch near the top of the waterfall above Big Spring, and the flow is overlain higher up the canyon wall by Makapipi basalt. At that locality the upper flow is 80 feet thick, the third flow 65 feet, the second 50 feet, and the lower flow, judging from the position of its base in adjacent drill holes, about 50 feet.

WATER-BEARING PROPERTIES.—The dense, massive central parts of the Kula lavas are poor water bearers. Movement of water is possible only along joints and locally through masses of interflow clinker. The tightness of most of the joints together with their rather wide spacing minimizes the importance of even those channels. The basal clinker phases, however, form good channels for water circulation, provided there is beneath them a bed sufficiently impermeable to perch the water. The soil at the top of the Honomanu lavas is a relatively impermeable bed of this sort, and several small springs emerge along it in the walls of Hanawi Gulch and in the sea cliff between Kapaula and Waiaaka Streams. No well de-

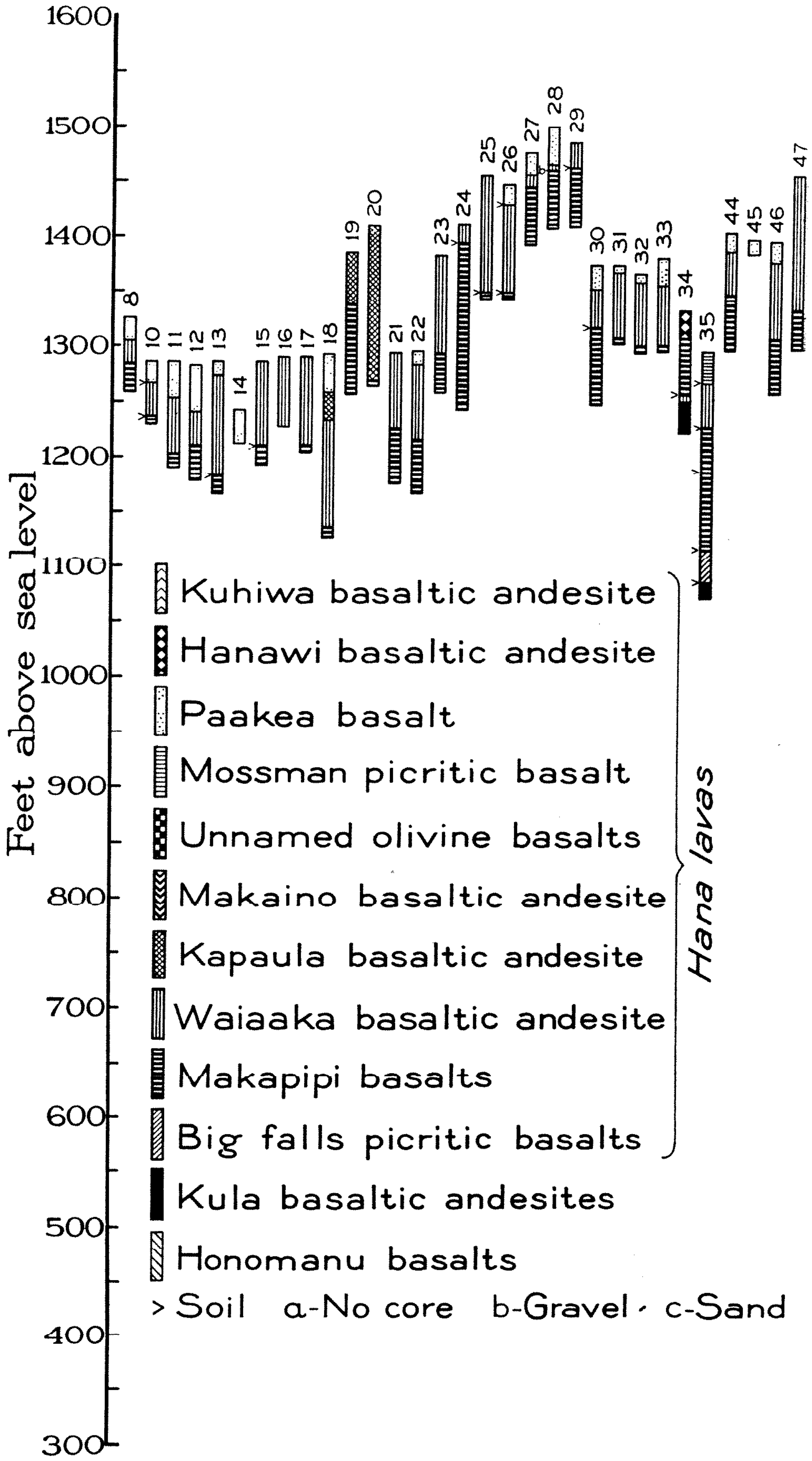
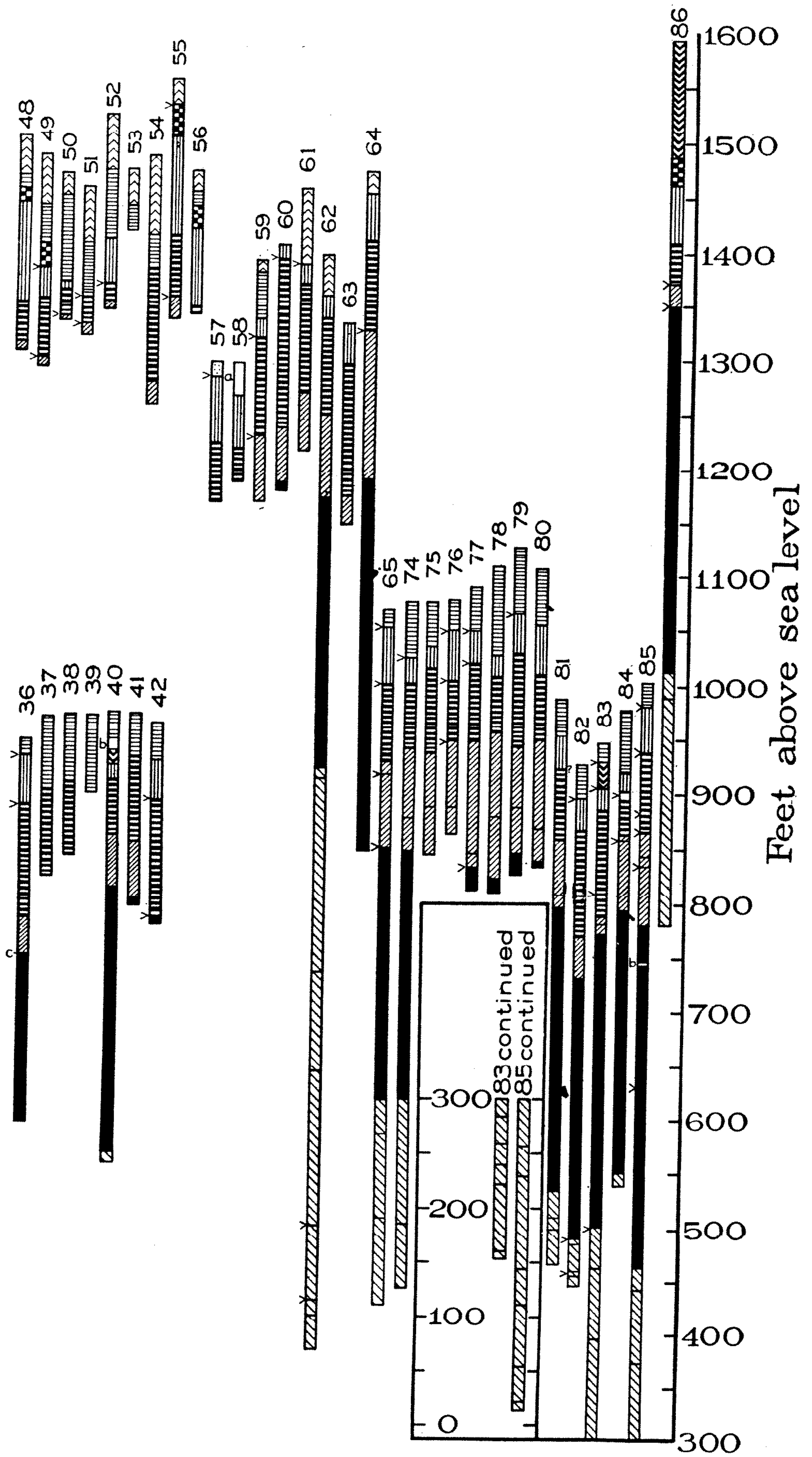


FIGURE 36.—GRAPHIC LOGS OF TEST



BORINGS IN THE NAHIKU AREA, EAST MAUI

veloped drainage system was formed on this surface, however, and nowhere has the water been sufficiently concentrated to form a large spring. Moreover, the soil is not continuous, and wherever it is absent water can move down through the highly permeable Honomanu lavas to the basal water table. Big Spring issues from the basal clinker of the second Kula lava. It will be discussed in a later section.

A small spring emerges at the base of the third Kula lava a few feet east of the axis of a buried valley exposed in the face of Big Falls. Still another small spring issues from the base of the fourth Kula lava in the west wall of Hanawi Gulch near Big Spring.

HANA VOLCANIC SERIES

BIG FALLS PICRITIC BASALTS

Distribution and character.—The Big Falls lavas are named for their occurrence at Big Falls on Hanawi Stream. Local workers have called them the "Turkey Egg lavas" because the rounded pebbles, spotted with cross-sections of phenocrysts, resemble turkey eggs. The designation "Wild Turkey lavas" was later coined to differentiate them from the similar Mossman lava, which was called the "Tame Turkey lava." The Big Falls lavas are picritic basalts, characterized by prominent phenocrysts of augite and olivine. They are nearly everywhere very vesicular pahoehoe, although locally they are aa. Partly or completely filled lava tubes are numerous. Typically, the lavas consist of many thin flow units ranging in thickness from 1 or 2 feet to 20 feet. Columnar jointing is moderately well developed, and there are many irregular joints. All these openings permit water to circulate freely through the rock.

At least two separate lava flows are represented, for a thin layer of baked soil is found within the section in several drill holes, and in tunnel 55, where it is locally as much as 24 inches thick. In general, augite phenocrysts are considerably less abundant in the lower lava than in the upper one, and olivine phenocrysts, although more abundant than in the upper lava, are smaller. The total phenocrysts average about 20 percent in each. In the upper lava, augite phenocrysts range from 5 to 10 percent and average 3 mm. long; the olivine phenocrysts range from 5 to 15 percent and average 2 mm. In the lower flow the olivine phenocrysts average only between 1 and 1.5 mm. across, and in all specimens are more than twice as abundant as the augites, which in some are nearly absent.

The Big Falls lavas lie on the eroded surface of the Kula lavas, and in the sea cliff 500 feet east of Hanawi Stream fill a gorge cut completely through the Kula lavas into the Honomanu basalts (section C-C′, pl. 1). This gorge is 300 feet wide at sea level and 600 feet wide at the top of the cliff. If the sides continue downward at the same angle shown in the cliff, the valley extends about 75 feet below sea level, indicating that it was cut during a stand of the sea at least 75 feet lower than the present. On the east side of the valley at sea level the Big Falls lavas rest on a thick zone of buff soil, baked brick red for a few inches at the top, which contains partly decomposed fragments of Kula lava.

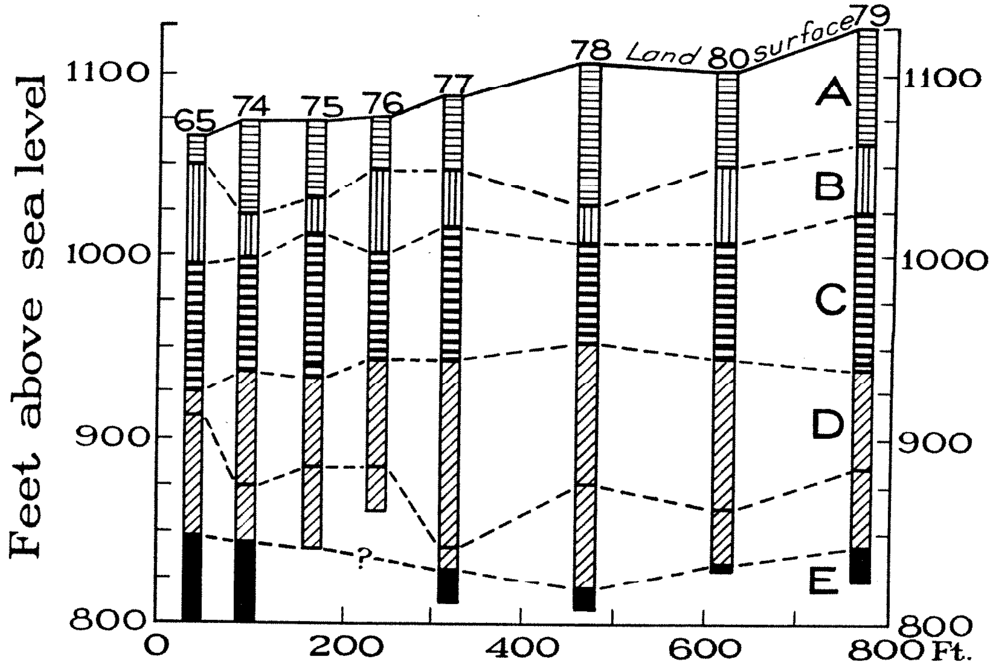


Figure 37. Graphic logs of test borings showing the absence of a deep valley buried by the Big Falls lavas near the highway in the Nahiku area. The location of the borings is shown on insert B, plate 1. A, Mossman basalt; B, Waiaaka basaltic andesite; C, Makapipi basalts; D, Big Falls basalts; E, Kula basaltic andesites.

This valley continued southward approximately parallel to and just east of the present Hanawi Gulch, and the lateral recession of the wall of Hanawi Gulch has exposed the Big Falls lavas in a series of windows. Just south of the highway the Big Falls valley seems to have nearly disappeared (fig. 37 and section D-D′, pl. 1). It is possible that it may lie west of boring 65, but if so, it should appear in boring 34, where instead the Big Falls lavas are absent. The trend of its western edge in the windows along Hanawi Gulch, if continued to the line of the section would place the valley within the line of drill holes east of boring 65. The base of the Big Falls lavas in the drill holes indicates a broad swale-like feature, but no such gorge as that at the beach. Like many of the present-day streams, the Big Falls valley probably decreased rapidly in size between the coast and the 1,000-foot contour.

The Big Falls lavas cross Hanawi Gulch at the head of Big Falls in a small filled tributary trending nearly at right angles to the main buried valley. They are found on the west wall of the gulch also nearly opposite Hanawi Spring no. 2, where they appear to represent a westward swing of the main valley. Big Falls lavas are exposed on Makapipi Stream south of the highway, and were encountered in tunnel 55 (fig. 43) and in several test holes (fig. 36). A rock petrographically similar and occupying the same stratigraphic position crops out on the west side of Kapaula Gulch midway between the highway and the sea. It has been mapped as Big Falls lava despite the presence of feldspar phenocrysts. (See Part 3.) The outcrop may mark the position of the tributary valley which crosses Hanawi Gulch at Big Falls.

WATER-BEARING PROPERTIES.—Numerous vesicles, partly filled lava tubes, cavities along the surfaces of flow units, and joints of various sorts combine to make the Big Falls lava easily permeable; and soil layers at the base and within the section which might act as supporting members make them potentially important as a bearer of perched water. However, no large springs emerge from them. Several small springs with an estimated aggregate flow of 20,000 gallons a day issue from local bodies of clinker near the center of the valley fill in the sea cliff about 20 feet above sea level, and a seep is located at the same level on the west wall of the valley. Springs may occur at the base of the valley below sea level, but no evidence of them is known, and the drill holes have not revealed any large flow of water in the lavas filling the Big Falls valley farther south. Small springs emerge at the base of the Big Falls lavas on the east side of the plunge pool at Big Falls, and this water probably represents leakage from the main valley, because no springs were seen at the base of the lava-filled tributary. Water issues from Big Falls lavas below stream level in the plunge pool below the hanging mouth of Makaino Gulch, and also in tunnel 55, but at neither place does the amount much exceed 100,000 gallons a day. West Makapipi Spring issues from Kuhiwa lava, but dye introduced into test hole 63 seeped through leaks in the Big Falls lavas and reappeared in the spring, indicating that the Big Falls lavas are probably the source of the water. The constancy of the discharge and the low temperature of the water also point to the Big Falls lavas as the source of the water, rather than the surficial Kuhiwa lava.

MAKAPIPI BASALTS

DISTRIBUTION AND CHARACTER.—The Makapipi basalts are a group of lavas stratigraphically between the Big Falls picritic basalts and the Waiaaka basaltic andesite. They are named for exposures along Makapipi Gulch, but are best exposed along Hanawi Gulch from Makaino Stream to Hanawi Spring no. 1. Several separate lava flows are present, the surfaces of individual lavas being marked by thin layers of red soil but showing little evidence of erosion. The soil beds are probably tuffaceous. The greatest measured thickness of the Makapipi lavas is 155 feet in test hole 27, but the average thickness is about 75 feet. A section down the east wall of Hanawi Gulch at the intermediate step of the double waterfall above Big Spring follows:

Geologic section of east wall of Hanawi Gulch, East Maui

	Thickness (feet)
Mossman basalt	
Dark-gray pahoehoe, with abundant phenocrysts of olivine and augite	15
Waiaaka basaltic andesite	
Medium-gray nonporphyritic aa, with well-developed platy jointing parallel to the flow planes in its basal part	12
Makapipi basalts	
Partly decomposed clinker, with 0 to 10 inches of red baked soil at top	27
Medium-gray aa with a few small phenocrysts of olivine; platy jointing parallel to flow planes is present locally	15
Partly decomposed clinker, with 0 to 3 inches of red soil at the top	9
Medium-gray aa with a few small phenocrysts of olivine; platy jointing is locally present	10
Partly decomposed clinker	3
Massive medium-gray aa	5
Partly decomposed clinker	6
Massive medium-gray aa	7
Partly decomposed clinker; base poorly exposed	10±
Big Falls picritic basalts	
Absent here, but exposed 0.1 mile farther north	0
Kula basaltic andesite	
Massive medium-gray nonporphyritic aa; Kula flow no. 4, largely hidden by talus	80±

Two large areas of Makapipi lavas near the coast east of Hanawi Gulch fill an old valley, a cross section of which is exposed in the sea cliff (section C-C′, pl. 1). They show platy jointing near the base, and rest on 6 to 10 inches of baked soil developed on Kula lavas. Between Waiaaka and Waiohue Streams, Makapipi lavas fill a large valley cut into Kula and Honomanu lavas. Projected downward the walls of this valley intersect 500 feet below sea level, indicating that it was cut when the land level was relatively far above that of the present.

The Makapipi lavas are fine-grained olivine basalts tending toward basaltic andesites. The feldspar averages close to andesine-labradorite, but is decidedly subordinate in amount to the mafic constituents. Both pahoehoe and aa are present, with aa predominant. The lavas have moderately distinct fluidal structure, and in many places the aa shows near its base platy jointing parallel to the flow planes. A few small phenocrysts of brownish-green olivine, seldom exceeding one millimeter in diameter, are present at many localities.

Along Hanawi Stream south of the highway and in tunnels 44, 45, and 46, the upper 10 to 20 feet of Makapipi lava consists of highly decomposed clinker. This clinker bed is everywhere remarkably persistent. Notwithstanding its extensive decomposition the outlines of the angular fragments are still clearly visible. The color has been altered from gray to pale-buff, brown, reddish-brown, and yellow, and an originally highly pervious member is now very impervious. A layer of red soil a few inches thick is commonly present at the top, and in tunnel 47 reaches a thickness of 2 feet. Near the heading of tunnel 51, from 2 to 8 inches of soil grades downward into decomposed Makapipi clinker. In a few places where it rests on dense lava it is thin, and the contact with the lava is sharp, indicating that soil formed more rapidly on the clinker, and that the soil resting on lava is largely transported. Locally the soil is overlain by Waiaaka clinker, which generally is nearly as much decomposed as the Makapipi clinker, showing that much of the decomposition took place following burial, probably by the action of circulating ground water.

WATER-BEARING PROPERTIES.—The Makapipi lavas are mostly dense, and even where broken by joints they appear only slightly permeable. A few small springs emerge from the clinker phases. Several springs with an aggregate flow estimated on October 3, 1939, to be 300,000 gallons a day, emerge at the high waterfall on Makapipi Stream, 1,000 feet south of Nahiku village. The stream above the falls gradually disappeared through leaks in its bed, until it was completely dry, and much of the spring water was probably derived from these leaks. A spring estimated on November 18, 1939, at

Below: Plate 41B. Jungle-covered Hanawi Gulch showing dry waterfall over terminus of Hanawi lava fill (1) and location of Big Spring (2).

Above: Plate 41A. Big Spring discharging 10,400,000 gallons daily issues from Kula aa clinker in Hanawi Gulch, East Maui.

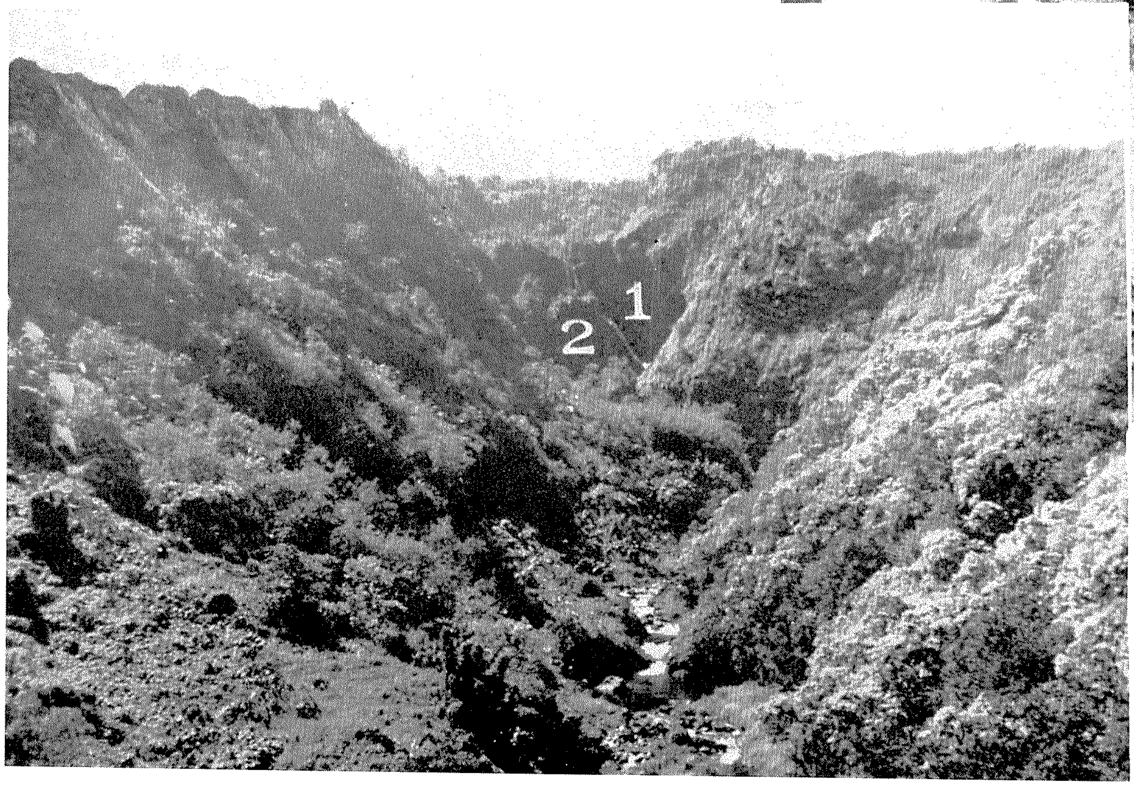


Plate 42A. Spring no. 27, Hanawi Gulch, East Maui. Photo by Max Carson.

Plate 42B. Koolau ditch in the Nahiku area, East Maui. Photo by Ray Baker.

250,000 gallons a day, issues from Makapipi clinker in a waterfall half a mile from the mouth of the unnamed stream between Hanawi and Makapipi Streams. Small springs emerge at the base of the Makapipi basalt on both sides of Hanawi Gulch near Big Spring, and several small basal springs are located near sea level between Waiaaka and Paakea Streams.

WAIAAKA BASALTIC ANDESITE

DISTRIBUTION AND CHARACTER.—The Waiaaka basaltic andesite is a remarkably persistent thin lava flow overlying the Makapipi basalts. It is named for its occurrence along Waiaaka Gulch, but is best exposed in Hanawi Gulch north of the highway. It appears to be a single flow, although in places clinker layers interbedded with the dense lava may indicate two or more flow units. It is almost everywhere aa, except in the extreme southwestern part of the area, where it is pahoehoe. In the small gulch between Hanawi and Kapaula Streams, 1,600 feet south of the Koolau Ditch, it exhibits numerous subspherical vesicles up to 1 cm. across, many of which contain mammilary masses of calcite. In many places the aa has prominent platy jointing parallel to the flow planes. The platy jointing is especially well developed in the lower part of dense layers where basal clinker is absent. It is found in other flows, but is very characteristic of the Waiaaka lava, and is responsible for the name "shaly lava" applied to this bed by local workers.

The thickness of the Waiaaka lava varies greatly from place to place owing to both original form and later erosion. It is absent along Makapipi Stream and between Makapipi and Hanawi Streams near the sea. Whether it was never present there or was removed by erosion is uncertain, but the latter seems more probable. The greatest thickness is 120 feet in test hole 47, but the average thickness along the east wall of Hanawi Gulch is 30 feet. In the west wall of the West Branch of Makapipi Stream, 100 feet south of the landslide shown as talus on insert B, plate 1, the exposed section is as follows:

Mossman basalt: dark-gray pahoehoe, with abundant phenocrysts of olivine and augite; 70± feet
Baked red soil: 6 to 10 inches
Waiaaka lava: nonporphyritic medium-gray aa; 25 feet
Baked red soil: 1½ to 3 feet
Makapipi basalts: medium-gray nonporphyritic aa; 10+ feet (base not exposed).

A small amount of local erosion occurred during the interval between Makapipi and Waiaaka time. Waiaaka lava fills a shallow valley exposed in the high waterfall of Kapaula Stream, 6,000 feet south of the highway. In tunnel 46, about 1,500 feet from the portal, it is underlain by gravel containing stream-rounded boulders and angular talus blocks, which in turn rest on Kula basaltic andesite, the Makapipi basalts having been removed by erosion. In tunnels 51 and 56, pockets of stream gravel containing angular to subrounded pebbles up to $2\frac{1}{2}$ inches in diameter are found at the contact of the Waiaaka lava with Makapipi clinker.

WATER-BEARING PROPERTIES.—The Waiaaka basaltic andesite nearly everywhere rests on the soil and decomposed clinker at the top of the Makapipi basalts, and these form an impervious member which perches water in the Waiaaka lava. Elsewhere underlying gravel also is relatively impervious owing to its poor sorting. The base of the lava is in many places clinkery, but water moves more freely through the numerous platy joints than through the clinker.

Many small springs occur at or near the base of the Waiaaka lava. About 300,000 gallons a day issue from it in the waterfall on Kuhiwa Stream 2,000 feet south of the highway; and several small springs, the largest estimated as 30,000 gallons a day, issue near the base of the shallow valley filled with Waiaaka lava in the waterfall on Kapaula Stream 6,000 feet south of the highway. A spring with a flow of about 250,000 gallons a day issues at the base of the lava 500 feet from the coast just west of Paakea Stream. The Waiaaka lava is the source of all or part of the water developed in tunnels 41, 44, 45, 46, 51, 55, and 56. (See table, p. 267.) About 150 feet from the portal of tunnel 56 water issues from the platy jointed base of the lava, where it is perched by an underlying bed of gravel a few inches to 3 feet thick. Also, about 25,000 gallons a day emerges from the base of the lava in the roof of the main transportation tunnel of the Koolau ditch system, 325 feet east of tunnel 52.

Although the Waiaaka lava is quite generally an aquifer, most springs issuing from it are small, probably because no large pre-Waiaaka valley existed. Further tunneling along its base would undoubtedly develop more water, but there appears to be no reason to expect a large yield at any point.

KAPAULA BASALTIC ANDESITE

DISTRIBUTION AND CHARACTER.—The Kapaula basaltic andesite is a narrow valley-filling lava flow which followed the valley of the ancient Kapaula Stream. It is a single flow of aa. Interflow clinker is found locally, and in such places more than one flow unit may be present, but elsewhere above the basal clinker the entire thickness is composed of dense rock. Columnar and other jointing is present but not prominent. Platy jointing is rare, and phenocrysts are seldom present. In many places the rock contains numerous minute irregular vesicles into which project laths of feldspar.

The Kapaula basaltic andesite is exposed from the coast to 2,000 feet south of the Koolau ditch, where it disappears beneath the later Paakea lava. It closely resembles the Makaino lava in petrographic character, and occupies approximately the same stratigraphic position. The two may be branches of the same lava flow, or separate flows erupted simultaneously from different points on the same fissure. A cross section of the buried valley is exposed in the sea cliff on the western side of Kapaula Stream (section C-C′, pl. 1). It is 190 feet wide at sea level, and projection of the valley walls at the same angle as that observed in the cliff, places the bottom of the valley about 45 feet below sea level. Allowing for some recession of the shore line, the ancient Kapaula valley may have been graded to the Waipio, or minus 60±-foot, stand of the sea.[15] The upper part of the prism of Kapaula lava is notched in the sea cliff by a later shallow valley filled with Paakea lava.

The ancient Kapaula valley was cut more than 400 feet below the surface of the Waiaaka lava in the ridge between Kapaula and Hanawi Streams. Near the coast the course of the valley was probably determined by the edge of the Waiaaka lava along the east side of the kipuka of Kula lavas (insert B, pl. 1). The west wall of the buried valley is exposed in the west fork of Kapaula Stream near its junction with the east fork, the lava resting on thoroughly decomposed Makapipi clinker. Near the heading of tunnel 40, Kapaula lava is underlain by poorly sorted gravel containing subangular to subrounded pebbles and cobbles in a matrix of sand and silt. A few inches of gravel is present beneath the lava in the west branch of tunnel 43 also, where it rests on Waiaaka lava, and elsewhere along this tunnel several inches of baked soil intervene between the two lavas.

The exposed thickness of Kapaula lavas in the sea cliff is about 40 feet, and if the valley extends 45 feet below sea level the total thickness at the coast is 85 feet. The greatest measured thickness is 140 feet in test hole 20. Approximately 50 feet of Kapaula lava, comprising alternate layers of massive lava and clinker, is exposed in a waterfall a few feet south of the highway.

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[15] Stearns, H. T., Ancient shore lines on the island of Lanai, Hawaii: Geol. Soc. America Bull., vol. 49, p. 625, 1938.

Water-bearing properties.—Several small springs emerge from the Kapaula lava. One is located in a plunge pool just below the highway. Several issue just above the base of the lava and from higher clinker beds in the sea cliff west of Kapaula Stream. There some have veneered the cliff with thin deposits of calcareous tufa. Pali Spring, which emerges at the western edge of the lava in the west fork of Kapaula Stream, has an estimated flow of 500,000 gallons a day. However, test holes penetrating the Kapaula lava south of the Koolau ditch and tunnels contouring its base failed to affect appreciably the discharge of the spring, and the water probably does not flow through the Kapaula lava at the level of the holes and tunnels. The buried valley was cut through the Waiaaka lava, and it seems likely that the water of Pali Spring enters the Kapaula lava along the base of the Waiaaka lava. Prior to the eruption of the Kapaula lava the water probably issued as small springs along the side of the ancient valley.

Water issues from fractures and clinker near the base of the lava in tunnels 40, 41, and 42. The total average flow from these tunnels is only about 700,000 gallons a day, however, and tunnel 41 is nearly dry. Near the heading of tunnel 40 the water is perched by relatively impervious gravel.

The Kapaula lava appears favorable as a water bearer, and a soil bed which might act as a supporting layer is present locally at its base. The small amount of perched water actually yielded by this lava is probably the result of the absence of the soil layer in many places, permitting the water to escape downward, and possibly also due to the smallness of the drainage basin tributary to the buried stream.

MAKAINO BASALTIC ANDESITE

Distribution and character.—The Makaino basaltic andesite is a single narrow lava flow which filled a small gulch, east of the present Hanawi Gulch, formed by erosion after the extrusion of the Waiaaka lava. It is named for exposures along Makaino Stream. The rock is a nonporphyritic aa with poorly to moderately well defined fluidal structure. Abundant minute plates of feldspar are megascopically visible and in places their common orientation produces a sheen on surfaces parallel to the flow planes. North of the highway the Makaino lava was buried by Mossman picritic basalt, but erosion has re-exposed it in small windows. The rock in several windows along the small stream just east of Hanawi Stream may be Makaino lava, but its characteristics are not sufficiently distinct from those of the Waiaaka lava to make its recognition certain. Its positive identification is possible only where its structural relations can be determined. The ancient Makaino valley is not exposed in the sea cliff. Provided the rock in the windows mentioned above is Makaino lava, the lower part of the valley probably diverged eastward from the present Hanawi Gulch, and followed approximately the same course as the small northwestern branch of the Mossman basalt. Whether the Makaino lava stopped before it reached the sea, whether it is present beneath the Mossman lava, or whether it was once present but was removed by erosion before Mossman time, is not known.

The edge of the Makaino lava flow, along Hanawi Gulch, has a maximum exposed thickness of 125 feet. At the two southern windows the ancient valley was cut through the Waiaaka and into the Makapipi lava; at the northern window it was cut through both the Waiaaka and Makapipi lavas and into the Big Falls basalt. At this northern window the Makaino lava rests on poorly sorted gravel up to 7 feet thick containing boulders as much as 3 feet in diameter. The ancient valley is approximately contoured by tunnel 46 at a point where it had been cut through the Waiaaka and Makapipi members into the Kula lavas.

WATER-BEARING PROPERTIES.—The lower part of the Makaino basaltic andesite is a copious water bearer. Several small streams emerge from it and from the underlying gravel and talus breccia in tunnel 46. Near the heading a stream estimated at 500,000 gallons a day cascades down a disinterred waterfall. Hanawi Springs 1 (pl. 42A) and 2 and a smaller spring 300 feet farther north, issue from Makaino lava in windows along Hanawi Gulch, and still another small spring emerges at the lateral contact of the lava near the east end of the highway bridge.

MOSSMAN PICRITIC BASALT

DISTRIBUTION AND CHARACTER.—The Mossman picritic basalt forms the surface of most of the area between Hanawi and Makapipi Streams and along the coast east of Nahiku (insert B, pl. 1). It is named for Mossman's Spring, which issues from it. The rock was formerly known by local workers as the "Tame Turkey lava." Along the highway it overlies Makaino basaltic andesite at Makaino Stream, and is overlain by Kuhiwa basaltic andesite east of Makapipi Stream. A boulder similar in appearance to the Mossman picritic basalt was found in a fork of the West Branch of Hanawi Stream, 2,300 feet south of the Koolau ditch, indicating that Mossman or a similar lava must be exposed in the West Hanawi drainage farther south. A similar picritic basalt underlies the Makaino lava in drill hole 86 (fig. 36), but has been recognized nowhere else in the area.

The Mossman lava is a single widespread flow of pahoehoe, composed of numerous thin flow units. Aa is found in places, but is decidedly subordinate. The rock is a moderately vesicular picritic basalt, rather uniform in composition over the entire area, and resembling the picritic basalt of the upper Big Falls lava. Phenocrysts of augite and brownish-green olivine are abundant, and the augite phenocrysts generally exceed the olivine in size and number. Augite phenocrysts commonly attain a maximum diameter of 5 mm., but olivine phenocrysts seldom exceed 3 mm.

In drill holes 48, 49, and 56 the Mossman lava is underlain by an olivine basalt not elsewhere recognized. This unnamed olivine basalt, which overlies the Waiaaka lava, is a sparingly vesicular aa, with many large phenocrysts of olivine and a few of feldspar, but only rare phenocrysts of augite. It is quite distinct from the more mafic Mossman picritic basalt, which everywhere contains abundant phenocrysts of augite.

The Mossman lava reaches a maximum thickness of 80 feet in test holes 50 and 78, but elsewhere averages about 35 feet. Its contact with the underlying lavas appears to mark an erosional surface which was probably formed partly at the same time as the ancient Makaino and Kapaula valleys. In most places, however, the erosion was slight and the surface is only gently undulating. Throughout most of its extent it was probably an only slightly dissected interstream area. Along the coast it passes below sea level, indicating that the Mossman lava probably was extruded during a stand of the sea lower than the present—possibly that during which the ancient Kapaula valley was cut.

A conglomerate composed of subrounded to rounded pebbles in a soft yellowish-brown clay matrix is exposed beneath the Mossman lava in the western distributary of Makaino Stream just south of the highway. Gravel and clay were reported beneath the lava in test hole 40.[16] In many places the lava is underlain by several inches of baked soil; but elsewhere, as in tunnel 56, soil is absent.

WATER-BEARING PROPERTIES.—In spite of its general high permeability, the Mossman picritic basalt is not an important water bearer. The soil and decomposed clinker beneath it are apparently too dis-

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[16] Heizer, J. M., in driller's log submitted to the East Maui Irrigation Co.

continuous to form a good supporting member. Moreover, the drainage buried by the lava appears to have been for the most part poorly defined, so that water moving through it remains as small streams.

Several small springs emerge at or close to the base of the lava along Makapipi Stream, and in the roof of the main Koolau ditch tunnel 250 feet from the portal of the Makapipi section. The flow of the latter springs was estimated on January 19, 1940, to be 15,000 gallons a day. A larger stream issues from Waiaaka clinker in the roof of tunnel 56, about 165 feet from the east portal, but its source is probably Mossman lava a few feet above. The tunnel tapped a spring which formerly emerged from Mossman lava in Makaino Stream half a mile south of the Koolau ditch. The largest spring issuing from this lava is Mossman's Spring, which is located at the contact with a small kipuka of Waiaaka lava. The yield was estimated on November 27, 1939, as 150,000 gallons a day, but it decreases considerably in dry weather.

KUHIWA BASALTIC ANDESITE

DISTRIBUTION AND CHARACTER.—The Kuhiwa lava is named for exposures along Kuhiwa Gulch near the highway. It occupies most of the area east of Makapipi Stream. A narrow tongue between the east and west forks of Makaino Stream is similar in composition and stratigraphic relations and is probably a branch of the same lava flow.

The Kuhiwa basaltic andesite appears to be a single aa flow, although two or more flow units separated by clinker are present in places. Basal clinker is in general thin or absent. The rock is sparingly vesicular, locally nonporphyritic, but usually with a few phenocrysts of brownish-green olivine up to 1.5 mm. across. Platy jointing parallel to the base is found in only a few localities. Vertical jointing is abundant, but seldom regular enough to be classed as columnar. The maximum thickness in drill holes east of Makapipi Stream is 75 feet.

The lava buried a series of small gullies and overflowed the flat divides between them. Cross sections of one of these valleys are exposed along the Middle Branch of Makapipi Stream, and three of the valleys are contoured by laterals from tunnel 55 (fig. 43). In the tunnel and along the stream near the portal the lava is underlain by poorly sorted fluvial gravel containing subrounded boulders reaching 3 feet in diameter (fig. 38). Along Makapipi Stream south of the highway and at the coast, the Kuhiwa lava rests on Mossman basalt, generally with several inches of soil at the contact.

Kuhiwa lava overlies Mossman basalt nonconformably in the western wall of the plunge pool on Kuhiwa Stream, 2,300 feet south of the highway. It rests on an erosion surface which dips more steeply seaward than the underlying lavas, truncating not only the Mossman, but also the Waiaaka and part of the Makapipi lavas. Similar but less extreme cross-cutting relationships exist at the same locality between the Mossman and Waiaaka lavas. The present high waterfall appears to occupy nearly the same position as an older declivity which existed in pre-Kuhiwa time.

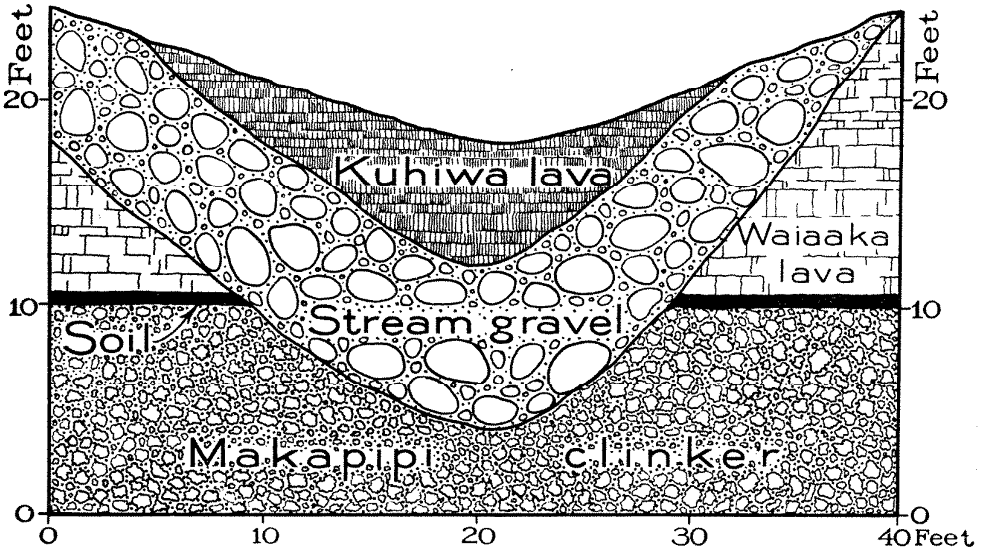

Figure 38. Diagrammatic section across the Middle Branch of Makapipi Stream at tunnel 55. The scale is approximate.

WATER-BEARING PROPERTIES.—The Kuhiwa lava yields a small amount of water in tunnels 52 and 53, and most of the water (2 m.g.d.) in tunnel 55. Small springs issue from its base along Makapipi Stream 300 and 900 feet north, and a larger one 1,600 feet south of the highway. A small spring emerges from it in the West Branch of Makapipi Stream 100 feet north of the Koolau ditch trail, and West Makapipi Spring issues 350 feet farther downstream. However, the water of this latter spring probably circulates through Big Falls lavas, because fluorcene dye introduced into test hole 63 escaped through leaks in the Big Falls lavas and colored the spring. Moreover, the discharge shows less fluctuation and the temperature of the water is lower than at tunnel 55, which derives its water largely from the Kuhiwa lava.

The land surface buried by the Kuhiwa lava was characterized by many small gullies but no large valleys. Therefore the perched water moving through the base of the lava is distributed in many small streams. Further tunneling at the base of the lava east of the Middle Branch of Makapipi Stream would almost certainly yield additional small streams, but it is unlikely that any single large stream would be encountered.

PAAKEA BASALT

DISTRIBUTION AND CHARACTER.—The Paakea olivine basalt appears to be a single aa lava flow, although locally inter-flow clinker may indicate two flow units. Platy jointing is almost absent, but columnar jointing is well developed, especially at the mouths of Paakea and Waiohue Gulches and in Moku Huki Island. The rock is generally sparsely vesicular, with scattered phenocrysts of olivine, a few up to 2 mm. across but most less than 1 mm., in a microcrystalline groundmass. Feldspar phenocrysts as much as 0.75 mm. long are found locally, and an augite phenocryst 2 mm. across was noted in a core from test hole 28.

The Paakea basalt is named for its occurrence along Paakea Gulch. The lava flow entered the area from the southwest, and divided into two branches which advanced to the coast along the valleys of Kapaula and Paakea Streams. Along Kapaula Stream for over 1,000 feet north of the highway it has been removed by erosion. Lava which is identical in petrographic character occupies the lower 1,000 feet of Waiohue Gulch, but has not been recognized higher up that gulch. Inasmuch as there is little likelihood of a lava flow which extended down Waiohue Gulch being completely removed by erosion, the lava occupying the mouth of the gulch probably backed up into it from Paakea Gulch. The present lava surface in Paakea Gulch is lower than that in Waiohue Gulch, but remnants of lava are found on the walls of Paakea to levels as high or higher than the surface in Waiohue. The fluid middle part of the lava in Paakea Valley drained away, allowing the surface to drop to a lower level. But the lava in Waiohue Valley, being a "backwater" of the flow, received less additional lava as the flow continued, and cooled more quickly, so that its central part did not drain away.

Paakea basalt fills a shallow valley cut into the Kapaula lava, exposed in cross sections in the sea cliff near Kapaula Stream (section C-C′, pl. 1). The base of the valley is about 10 feet above sea level. The base of the ancient Paakea valley at the mouth of Paakea Stream passes below sea level, projection of the exposed valley walls indicating its depth below sea level to be about 25 feet. The valley therefore was cut when ocean level was relatively 25 feet or more lower than it is now.

In the western section of tunnel 43, Paakea basalt is underlain by stream gravel containing subangular to subrounded pebbles and cobbles from 2 feet to less than an inch in diameter in a matrix of sand and clay. Along the incline between the lower and upper tunnel levels the gravel is 1 to 3 feet thick. Near the top of the incline it rests on decomposed clinker with up to 10 inches of reddened immature residual soil. Where the incline joins the adit leading to the upper tunnel, the clinkery base of the lava contains fragments of charcoal from a fraction of an inch to 3 inches across. Red soil underlies the lava at many other places, and in the first small gulch west of Hanawi Gulch just south of the Koolau ditch it is 2 to 9 inches thick and grades down into buff clayey subsoil derived in place from Waiaaka clinker.

The thickness of the Paakea lava in test hole 12 is 41 feet, and in most places it ranges between 10 and 20 feet. The easternmost of the two tongues which cross the highway at Kapaula Gulch is only a thin veneer 1.5 to 5 feet thick. Such very thin late lavas have been termed by local workers "plastering lavas." The exposed thickness of the lava at the mouth of Paakea Gulch is approximately 150 feet. This illustrates well the effect of topography on the thickness of a lava flow. Where a flow is confined to valleys it is thick, but where it is free to spread out over areas of low differential relief it is thin, as is the Paakea lava south of the highway.

WATER-BEARING PROPERTIES.—Several small springs issue from Paakea basalt along Paakea Stream. Tunnels 35, 36, and 37 were driven along the base of the west branch of the lava, and the eastern section of tunnel 43 contours the base of the east branch. All of these except tunnel 37 recover small amounts of water. Tunnel 37 is dry probably because the water is intercepted by tunnel 36, which follows the base of the lava directly up-slope from tunnel 37. The relatively small yield from the Paakea lava is probably the result of an underlying drainage system of youthful development and limited extent, and of a poor supporting member. In a few places the lava is underlain by relatively impervious gravel, but elsewhere it is underlain by a layer of soil which, although also relatively impervious, is everywhere thin and in many places absent. Most of the water entering the Paakea basalt probably moves down to lower supporting formations or to the basal water table.

HANAWI BASALTIC ANDESITE

DISTRIBUTION AND CHARACTER.—The Hanawi basaltic andesite forms a single narrow band of aa along Hanawi Gulch. It completely filled the valley south of the Koolau ditch, but only partly filled it farther north where the valley was deeper (pl. 41B). It appears to have terminated near its present northernmost exposure. Vertical jointing is prominent in the lava, but in few places is it regular enough to be called columnar. Platy jointing is present in places near the base, but is not well developed. Where it is present, fluidal arrangement of tabular feldspar microlites results in a sheen on the joint surfaces. Vesicles are generally sparse and in places are almost totally lacking. Small phenocrysts of olivine, commonly less than 1 mm. across but rarely as much as 5 mm., are found in most places, but are not abundant. A few of the tabular feldspars attain a length of 0.7 mm.

The valley of Hanawi Stream was in approximately the same stage of development before it was flooded by the lava as at present. The waterfall at Big Spring was located in nearly the same place. Both the base and top of the lava north of Big Spring are much lower than the same horizons to the south (section E-E′, pl. 1). The lava must have cascaded over this cliff, producing large volumes of clinker which were easily removed by the stream in re-establishing the waterfall. Another pre-lava waterfall or abrupt cascade was located near the present waterfall 250 feet upstream from the Koolau ditch trail. There the buried Hanawi valley, cut into Waiaaka lava, is exposed in cross section. The lava rests on a zone of reddened soil 8 inches thick, but along the Koolau ditch trail at the western edge of Hanawi Gulch soil is absent at the contact.

Test hole 34 penetrated 23 feet of Hanawi lava, but the surface there has been lowered several feet by erosion. At the highway the visible thickness is 30 feet, but the base is not exposed. South of the highway the surface of the lava probably approximates the original surface, for the aa channels are still clearly visible. The remnant of Hanawi basaltic andesite north of Big Spring has a thickness of about 100 feet, which is probably close to its original thickness.

The relative ages of the Hanawi, Kuhiwa, and Paakea lavas cannot be accurately determined. They are nowhere in contact. However, their topographic position and degree of erosion are similar, and they are regarded as approximately contemporaneous.

WATER-BEARING PROPERTIES.—The Hanawi basaltic andesite is unimportant as a water bearer. The valley filled by the lava is too small to accumulate much water. In the second plunge pool south of the Koolau ditch a small spring is located at the contact of the Hanawi lava with the underlying Waiaaka lava, and seeps occur at the same horizon at other localities.

Several small springs emerge at the base of the lava in the plunge pool just north of the Koolau ditch. Additional springs must issue from Makapipi clinker below water level, to account for the volume of water leaving the pool. The temperature of the water averages 16.8° C. Boring 34, about 300 feet upstream, revealed no water flowing through the Hanawi lava, and so much of the filled valley is exposed in waterfalls upstream that it appears unlikely that there could be any such amount of water moving through the lava as issues in the springs. It is equally unlikely that the water moves far through the Makapipi clinker, which nearly everywhere is extensively decomposed and impervious. The water is probably derived from the base of the Waiaaka lava, which is there cut across by the Hanawi lava, in the same way that water from the base of the Waiaaka lava is believed to supply Pali Spring. (See p. 246.)

GROUND-WATER RESOURCES OF THE NAHIKU AREA

GENERAL STATEMENT

The water-bearing properties of each formation have already been discussed. In this section general features of the occurrence of ground water in the Nahiku area are reviewed, and a few examples are described in detail.

Basal ground water, even though abundant, is at present of no value, because it lies at sea level, 1,200 feet below the Koolau ditch (pl. 42B), which transports water to irrigable lands on the Isthmus. Basal springs occur along the coast, but elsewhere the springs are fed by perched water. The rainfall of the region is high, 219 inches a year at the Nahiku ditch camp on the highway, and 387 inches a year at Kuhiwa Camp at an altitude of 3,100 feet, south of the area shown in insert B, plate 1. It is therefore not surprising that all the lavas are to some extent water-bearing, although some carry much more water than others. Most of the bodies of perched water occur in aa lavas, but as these are much more numerous than pahoehoe lavas, it does not follow that aa constitutes a better aquifer than pahoehoe. The basal water appears to move freely through highly pervious pahoehoe, and a pahoehoe aquifer in the upper, transitional part of the Honomanu volcanic series contains perched artesian water with a head of several hundred feet. This aquifer is believed to supply Big Spring in Hanawi Gulch, and if so has a capacity of at least 10 million gallons daily. The artesian water constitutes a special, unusual type of occurrence, and will be discussed further at a later point.

Most of the bodies of perched water move through clinker and fractures in the basal parts of aa lavas, and are perched there by relatively impervious underlying rock. The supporting members are soil, decomposed clinker, gravel, or dense lava. The most extensive supporting member in the Hana volcanic series is the thick decomposed clinker at the top of the Makapipi basalts; but springs from this horizon, although numerous, are generally small because of the absence of extensive buried valleys to concentrate the water. Gravel, where present, is relatively impervious, but it occurs only as discontinuous narrow bands along ancient stream beds and hence does not perch much water.

Perched water does not always follow the base of the lava. The course of the water is determined by the distribution, size, and interconnection of the openings in the lava, and the bottom of a lava flow may be sufficiently impermeable to flume water over a tunnel driven at its base. This probably happens only rarely, because the base of the lava is generally crossed by numerous cracks which allow most of the water to drain downward. It appears to happen, however, at tunnel 46. This tunnel follows the west side of the valley filled with Makaino lava to its center, and then turns back for a short distance along the east side of the valley, thus approximately contouring the base of the lava (fig. 41). The tunnel collects a large amount of water from the basal part of the lava, the largest yield being encountered at the buried stream bed, but some water must pass by the tunnel and on toward the sea, for Hanawi Springs nos. 1 and 2 and a small spring near the east end of the highway bridge over Hanawi Gulch issue from the Makaino lava farther seaward. Water emerging in these springs may be carried across the tunnel in openings in the middle or upper part of the lava, but it is also possible that some unknown structure is responsible, such as a tributary of the buried valley entering between the tunnel and the springs, and hidden by the later Mossman lava.

The same principle is demonstrated by springs on the walls of lava-filled valleys considerably above the lowest exposed part of the valley, such as Hanawi Spring no. 2 and Pali Spring. The former discharges on the east side of Hanawi Gulch where erosion has exposed the edge of the buried Makaino valley. No water emerges at the lowest point of the window. The spring is located near the south side of the window 100 feet above the lowest exposed Makaino lava. (See section E-E′, pl. 1.) Pali Spring issues from Kapaula lava on the West Branch of Kapaula Stream. The base of the valley-filling prism of Kapaula lava is exposed in the wall of a nearby plunge pool at least 40 feet lower than the spring.

Principal springs in the Nahiku area, Maui

No. pl. 1	Name	Location	Average discharge (m.g.d.)	Average temperature of water, °C	Lava from which spring issues
22	Ogino	Paakea Stream, between highway and Koolau ditch	0.20	16.9	Paakea
23	Pali	West Kapaula Stream, near junction with East Kapaula Stream	[a]0.5		Issues from Kapaula lava, but water probably derived from Waiaaka lava
24	Silveno	West Kapaula Stream, 150 feet north of highway	0.18	16.5	Waiaaka
25	Kapaula	Kapaula Stream, just below highway	0.44	17.4	Issues from Kapaula lava, but water probably derived from base of adjacent Paakea lava
26	Big Spring	Hanawi Gulch, at 540 feet altitude	10.4	14.9	Kula (second lava flow) ; but water probably derived from artesian structure in Honomanu lavas
27	Hanawi no. 1	East wall of Hanawi Gulch, 2,500 feet northeast of highway bridge	1.17	17.6	Makaino
28	Hanawi no. 2	East wall of Hanawi Gulch, 2,900 feet northeast of highway bridge	0.88	18.1	Makaino
29	West Makapipi	West Makapipi Stream, 450 feet north of Koolau ditch	0.49	15.8	Issues from Kuhiwa lava, but water probably derived from Big Falls lava

[a] Estimated, Nov. 1, 1939.

Average discharge of springs, Nahiku area, Maui, in million gallons a day
(Data furnished by East Maui Irrigation Co.)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Avg.
No. 22 (Ogino Spring)													
1933								[a].16	.15	[a].14	.15	.14	.15
1934	.19	.18	.16	.20	.23	.21	.19	.18	.18	.18	.23	.19	.19
1935	.19	[b].18+	[a].16	.18	.16	.13	.13	.14	.14	.25	[a].42	.38	.20
1936	.39	.21	.27	.33	.35	.22	.39	.27	.23	[a].21	.22	.30	.28
No. 24 (Silveno Spring)													
1934	.14	.16	.15	.20	.22	.22	.20	.18	.17	.18	.24	.19	.19
1935	.19	.14	[a].17	.18	.15	.16	.15	.15	.15	.13	.16	.13	.15
1936	.14	.12	.24	.20	.20	.16	.22	.22	.22	[a].16	.20	.26	.20
No. 25 (Kapaula Spring)[a]													
1934	.07	.38	.29	.64	.53	.53	.61	.38	.44	.40	.62	.38	.44
No. 26 (Big Spring)[c]													
1933			[a]12.16	[d]11.87	11.72	11.88	11.96	[d]12.13	[d]11.99	11.25	10.78	10.59	11.63
1934	[a]10.36	[d]10.16	9.29	[a]10.02	[a]9.77	10.16	10.05	9.66	9.75	10.31	[a]10.68	10.70	10.08
1935	10.80	[a]10.68	12.41	10.76	9.26	9.91	9.95	10.05	9.72	9.14	[a]8.96	8.42	10.00
1936	7.76	7.43	7.98	7.76	[a]8.01	7.89	[a]8.55	[a]8.97	[a]8.79	8.99	8.92	[a]8.65	8.31
1937		[a]9.00	[a]10.03	[a]10.63	[a]11.53	12.26	[a]13.36	[a]13.58	13.19	12.67	[a]12.66	[a]13.13	12.00
No. 27 (Hanawi Spring no. 1)													
1931	1.81	1.64	1.10	.42	1.70	1.68	1.97	2.14	2.24	1.68	[a]1.87	3.22	1.79
1932	3.25	[a]3.38	2.04	2.49	2.39	1.70	1.11	.82	.84	.52	.48	.76	1.65
1933	[a]1.17	[a]1.06	1.17	.93	.85	.48	.59	.48	.32	.24	.33	.48	.67
1934	.41	.53	.26	1.16	1.35	1.25	1.10	.70	.57	.53	1.28	.79	.83
1935	1.03	.81	.84	1.00	.61	.58	.49	.51	.47	.33	.51	.25	.62
1936	.29	.19	.55	.79	1.09	.47	.65	.75	.79	.50	.58	1.58	.69
1937	1.91	1.99	2.20	1.42	1.76	1.15	1.65	2.02	1.37	1.34	1.50	1.47	1.65
1938	1.41	1.09	1.82	1.72	2.13	1.62	1.07	1.22	.78	.95	1.15	1.37	1.36
1939	2.01	1.42	1.42	1.70	1.36	1.28	1.14	1.02	1.03	.66	1.36	.94	1.28
No. 28 (Hanawi Spring no. 2)													
1933	[a].67	[a].74	.82	.59	.58	.43	.48	.45	.35	.32	.38	.49	.52
1934	.42	.50	.33	.89	.95	.97	.78	.57	.48	.46	.96	.66	.66
1935	.80	.59	.67	.84	.56	.60	.52	.55	.52	.43	.55	.35	.58
1936	.40	.31	.56	.75	1.04	.55	.55	.78	.77	.55	.65	1.44	.70
1937	1.83	1.76	1.95	1.22	1.65	.96	1.38	1.83	1.14	1.07	1.29	1.19	1.44
1938	1.19	.99	1.50	1.49	1.84	1.41	.81	.99	.69	.83	1.03	1.17	1.16
1939	1.76	1.20	1.22	1.44	1.14	1.07	.98	.85	.81	.58	1.24	.85	1.10
No. 29 (West Makapipi Spring)[e]													
1932							.69	.71	.68	.23	[d].10	.004	.40
1933	.03	.80	1.22	1.26	.84	.36	.10	.002	0.0	0.0	0.0	.0003	.38
1934	0.0	0.0	0.0	.0003	.54	1.44	1.24	1.01	.66	.27	.26	.88	.53
1935	1.05	[d]1.43	[d]1.17	1.13	1.12	.79	.32	.16	.20	.11	.04	0.0	.62
1936	0.0	0.0	0.0	.007	.66	1.16	.81	.83	.99	.86	.58	.55	.54

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[a] Record incomplete.

[b] Part of the time water level was too high to be registered on the recorder.

[c] Calculated from flow records of Hanawi Spring No. 1 and Hanawi Stream at 650 feet altitude, furnished by East Maui Irrigation Co., and flow records of Hanawi Stream at 500 feet altitude, published in U. S. Geol. Survey Water-Supply Papers 795, 815, 835, and 865.

[d] Partly estimated.

[e] Data from U. S. Geological Survey Water-Supply Papers 795 and 815.

HANAWI ARTESIAN STRUCTURE

Several test holes have encountered artesian water, which rises as much as 695 feet above the level of the aquifer. The artesian water was first found in hole 85, and subsequently confirmed in 62, 74, and 83. An artesian aquifer is clearly shown by the behavior of the water levels in the holes during drilling. The water levels dropped intermittently as new leaks in the walls were reached by the drill in the Hana and Kula lavas and the uppermost part of the Honomanu lavas. However, when the holes penetrated the first dense aa

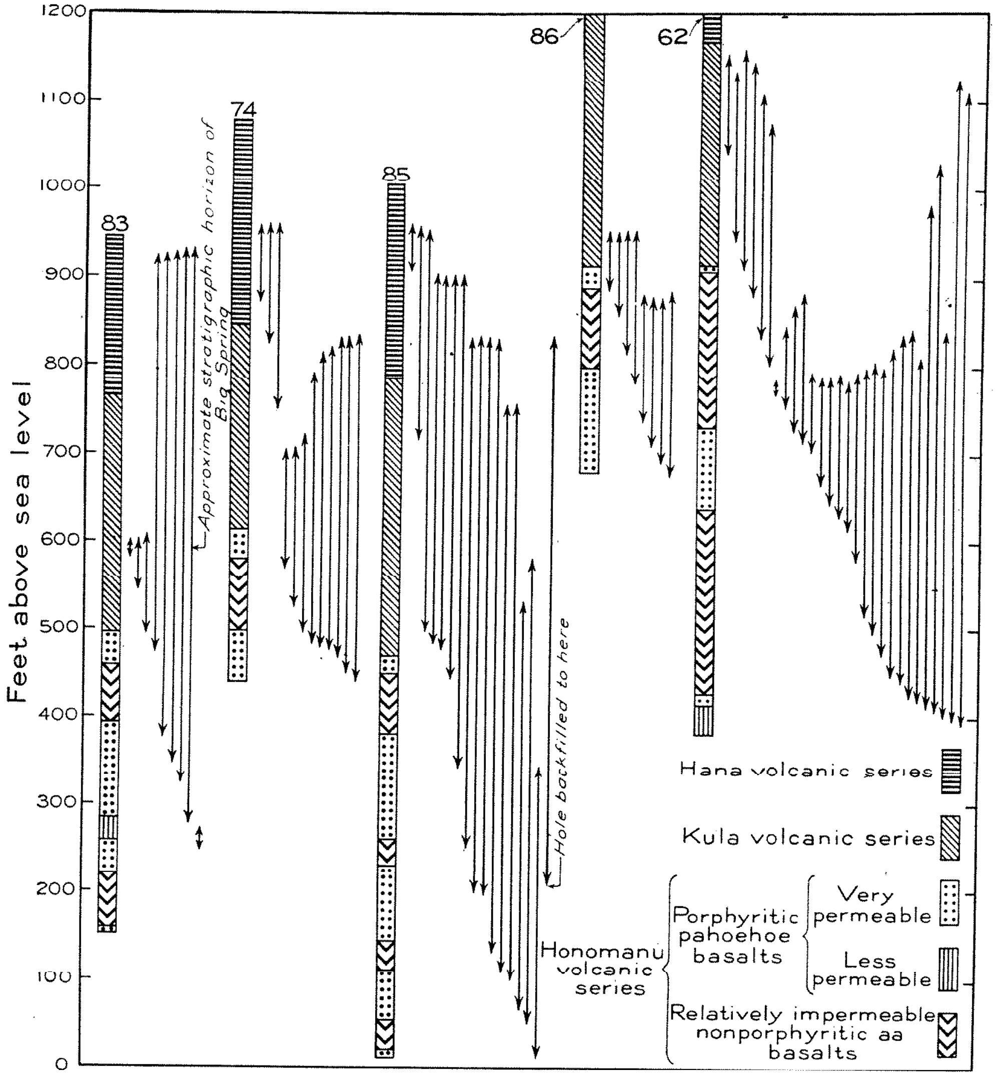

Figure 39. Diagram showing the water levels at various depths during the drilling of holes 62, 74, 83, 85, and 86. The lower end of each double-headed arrow indicates the depth of the hole, and the upper end the contemporaneous water level.

layer in the Honomanu lavas and entered the second layer of permeable pahoehoe, the water level suddenly rose showing that water was entering the hole in large volume and under sufficient hydrostatic pressure to force it high above the previous water levels. The progressive changes in water level during drilling are shown in figure 39, in which the upper end of each double-headed arrow represents the water level at the time the bottom of the hole was at the height of the lower end of the arrow. The graphic logs show the types of rocks.

Current-meter tests confirm the presence of artesian water. They indicate water rising in the holes while the bottom of the hole is within the aquifer.

The upper part of the Honomanu basalts at Nahiku consists of alternate beds of porphyritic pahoehoe and essentially nonporphyritic aa. The pahoehoe is generally very permeable, although some parts of it are relatively dense. The aa is dense and relatively impermeable, although ordinarily not so impermeable as to constitute an effective barrier to the downward movement of water to the basal zone of saturation. In part of the Nahiku area, however, the evidence from test holes demonstrates that these rocks are sufficiently impermeable to serve as confining members in an artesian system. As shown in figure 39, the holes encountered water under artesian pressure when they penetrated the uppermost layer of dense aa and entered the underlying pahoehoe. When 83 and 85 were continued through the second dense aa, the water level dropped, indicating that the second aa is the lower confining member of the artesian structure. When 83 entered the third layer of pahoehoe, the water level dropped beyond the reach of the measuring device, which was nearly on bottom, proving that the third layer of pahoehoe does not carry artesian water.

The water level in hole 85 did not rise when the drill entered the second pahoehoe, but remained at a high level. Current-meter tests indicated, however, that water encountered by this hole in the second pahoehoe was actually rising in the hole and therefore is under artesian pressure. When the hole entered the second aa the water level dropped slightly, but the level remained relatively high through the third pahoehoe and the third aa. This does not necessarily mean that the third pahoehoe also contains artesian water under considerable head, but may merely show that the rapidity with which water can descend through the hole and escape through the third pahoehoe is less than that with which water can enter the hole from the second pahoehoe. When the hole was deepened into the fourth pahoehoe the water level fell about 75 feet but still remained high. Again, this may or may not indicate the presence of water under considerable artesian pressure in the fourth pahoehoe. When the hole entered the fifth pahoehoe, the water level fell to a position within the artesian aquifer of the second pahoehoe, indicating that water could leave through the lower beds as rapidly as it entered from the second pahoehoe. The hole was backfilled with impervious material to the upper part of the third pahoehoe, and immediately the water level returned to its former high position.

Hole 62 lies farther east than the others in which artesian water has been found. Artesian water was not encountered in it until the third pahoehoe was reached. This aquifer is much deeper in the Honomanu lavas than the second pahoehoe which is the principal aquifer in holes 74, 83, and 85, and the head is much greater than in 86, which is located at a comparable altitude. It is therefore believed that the artesian system at 62 is not the same one as that at 74, 83, and 85.

In hole 86 current-meter tests revealed no upward movement of water. When the hole was completed its bottom was in the second pahoehoe, but the water level stood only 80 feet above the top of that bed, which is the artesian aquifer in holes 83 and 74. The current-meter shows downward movement of the water to an altitude of 745 feet, within the second pahoehoe, but this does not mean that artesian head is lacking. Water added to the hole in excess of the static level of the artesian water would move down and escape through the aquifer. Moreover, it is unlikely that the artesian head is much lower than the position of the water level in hole 86, because if it were the piezometric surface would reverse its slope and decline southward instead of rising as it should (fig. 40). In hole 86 the artesian water therefore appears to have a head of about 80 feet. The low head shows that the hole penetrated the aquifer near the effective inland edge of the upper confining member. Hole 12 has also been deepened to the level of the artesian structure, but encountered no artesian water.

The evidence shows the existence of a perched artesian structure underlying the area near Hanawi Gulch. For convenience, it will be called the Hanawi artesian structure. The aquifer is permeable porphyritic pahoehoe basalt; the confining members are dense nonporphyritic aa basalts. The structure must be perched, because when the holes penetrate the supporting member the water level drops, indicating that the water is escaping through the underlying lavas. Figure 40 indicates the position of the aquifer and the confining

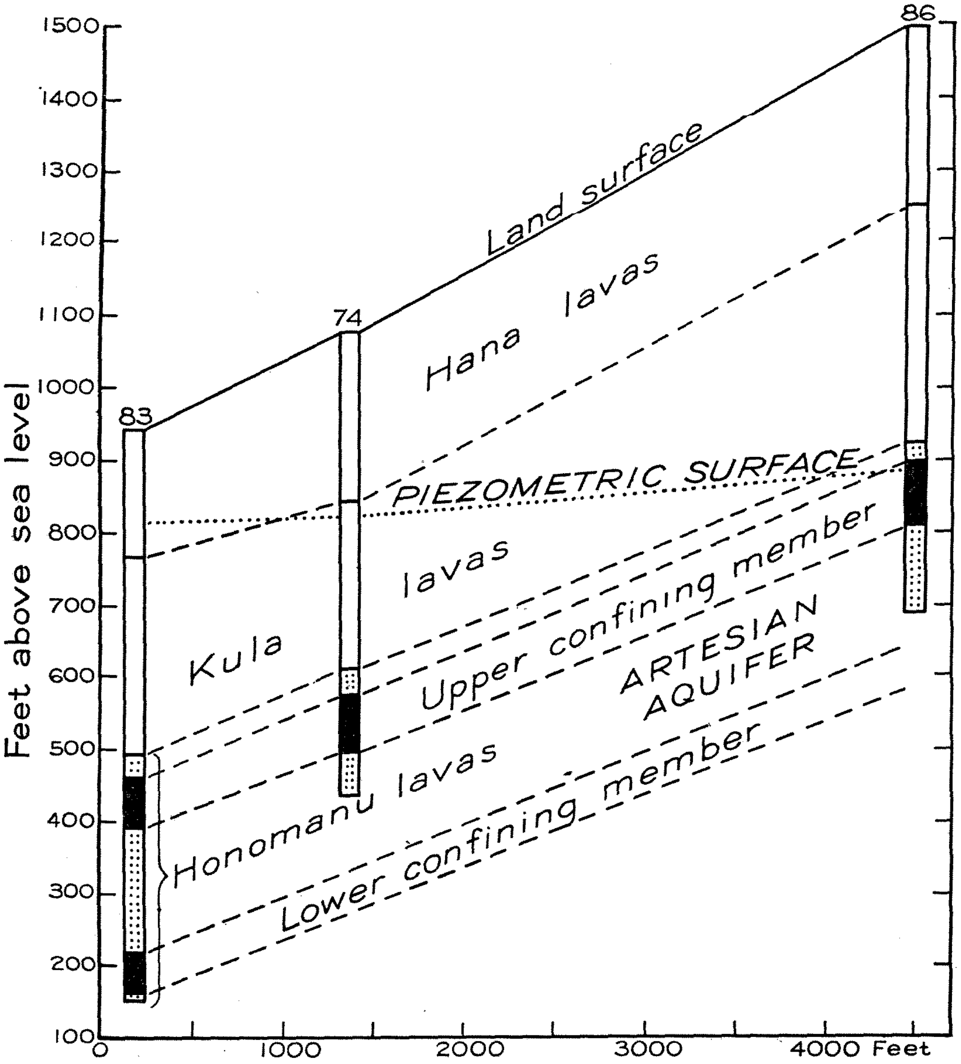

Figure 40. Graphic logs showing the position of the aquifer supplying the artesian water, and the piezometric surface in test-holes 83, 74, and 86. Stippled — permeable porphyritic pahoehoe basalts, solid black — relatively impermeable nonporphyritic aa basalts, in Honomanu volcanic series.

beds in holes along a line east of Hanawi Gulch. The extent of the artesian structure is not entirely known. Hole 86 appears to be close to its southern edge. The artesian water in hole 62 appears to come from a lower artesian structure, and consequently it is probable that the eastern edge of the Hanawi artesian structure lies somewhere between hole 85 and Makapipi Stream. Hole 12 did not find artesian water, and is probably west of the western edge of the Hanawi artesian structure, which therefore appears to be restricted to a narrow belt in the vicinity of Hanawi Stream.

The existence of an artesian structure in this area was entirely unforseen. The nonporphyritic lavas do not appear sufficiently impermeable to act as efficient confining members, and indeed probably would not do so over more than a small area. Even within the small area underlain by the Hanawi artesian structure there must be innumerable leaks through them. The existence of artesian conditions must be attributed to the enormous recharge on the very rainy mountain-slope to the south, so that the water entering the structure exceeds the amount which can escape through the leaks in the confining members. Some sort of barrier is also required to retard the movement of water down slope through the aquifer. Such a ground-water dam might be (1) one or more dikes, (2) faulting which brings impermeable lavas against the aquifer, or (3) termination of the aquifer. Dikes with a suitable trend or significant faulting have not been found, and both are regarded as improbable. It is more likely that the aquifer pinches out, and the confining members converge around its end, as shown in figure 13.

The static level of the artesian water in the holes indicates that little hope exists of developing flowing artesian water from the Hanawi artesian basin at levels above the Koolau ditch. However, although the artesian basin terminates near hole 86, the perching member which feeds the artesian structure, and which becomes its lower confining member, must continue southward up the mountainside for a considerable distance. A tunnel reaching the saturated rock overlying this supporting member would recover the same water which farther north enters the artesian structure. Tunnel 46 could be extended until it encountered this water-bearing structure. Assuming the same dip for the lavas as between test holes 74 and 86, the length of additional tunnel needed to reach the saturated zone would be about 1 mile. It might then be necessary to drive lateral infiltration galleries along the strike of the upper surface of the supporting member to recover the water. The quantity recoverable by such a tunnel would probably be at least several million gallons a day and might reach 10 million gallons a day or more.

BIG SPRING

The second order[17] spring known as Big Spring, at an altitude of 540 feet in Hanawi Gulch, is by far the largest in the area. Its flow of approximately 10 million gallons a day (see table, p. 257) issues from the basal clinker of the second Kula lava near the base of a

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[17] Meinzer, O. E., Outline of ground-water hydrology: U. S. Geol. Survey Water-Supply Paper 494, p. 53, 1923.

high waterfall, and below water level in the plunge-pool (pl. 41A). A 42-foot tunnel has been driven at the spring, and at the tunnel heading the water issues from clinker. A layer of soil 3 or 4 inches thick is present locally beneath the clinker, but is very discontinuous. The soil and the dense underlying lava perch the water locally, but appear inadequate to explain the occurrence of the spring.

It was formerly thought that Big Spring might be supplied by leakage through Kula clinker from the Big Falls lavas.[18] Subsequent diamond drilling has failed, however, to reveal any notable flow of water through the Big Falls lavas, and has demonstrated that the buried Big Falls valley decreases greatly in size within 6,000 feet of the coast (fig. 37). The temperature of Big Spring averages 14.9° C., which is lower than that of any other spring or tunnel in the area. It indicates that the recharge area lies at an altitude of about 4,000 feet. The temperature of the spring discharging from Big Falls lavas near Big Falls was found by Powers to be 16.3° C. at noon on January 13, 1933. On January 12 and 14, at 12:50 p. m. and 6:50 a. m. respectively, the temperature of Big Spring was 14.9° C.[19] The average temperature of West Makapipi Spring, which probably is supplied by Big Falls lavas, is 15.8° C. The temperature of Big Spring is thus decidedly lower than that of springs from the Big Falls lavas, and it no longer appears likely that the water is derived from the Big Falls basalts.

Plotting of the average monthly discharge of Big Spring from April 1933 to December 1937 against 3-month moving averages of the monthly rainfall at Kuhiwa camp shows that the discharge of Big Spring varies with the rainfall, but generally with a lag of 4 to 5 months. Comparison of the spring discharge with the rainfall at Nahiku camp, by D. S. Summers, shows about the same lag. In contrast, discharge curves for the other springs and the water tunnels at Nahiku show a lag in response to rainfall of only 3 to 10 days, and usually less than 6 days. In general, the lag shown by springs fed from deep-seated aquifers is greater than that at springs which issue from near-surface lavas.

The discharge of Big Spring is considerably larger than that of most perched springs in the Hawaiian Islands, which suggests that it probably owes its existence to an unusual set of geologic conditions. Careful geologic mapping yielded no explanation of the spring, which in turn shows that it is caused by structures not exposed at the surface. The most likely explanation of Big Spring is

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[18] Powers, H. A., Manuscript rept., 1934.

[19] Idem.

that it is supplied by the underlying recently discovered Hanawi artesian structure, which is nowhere exposed on the surface. However, the water has not been definitely traced from the artesian structure to the spring, and the evidence consists largely of the fact that artesian water underlies the area and has a head sufficient to force it about 280 feet above the level of the spring.

Fluorscene dye tests are suggestive but not conclusive. Dye introduced into hole 83 at altitudes of 488 to 500 feet, opposite the upper porphyritic pahoehoe in the Honomanu series, reappeared in Big Spring. This suggests that the spring may be supplied by water from the Honomanu lavas, but the dye was introduced at a level 95 feet above the aquifer and at a time when the water level was about 595 feet, close to a large leak in the wall of the hole which is approximately at the horizon of the clinker bed from which Big Spring emerges. Thus it is possible that the dye may have moved up the hole and out the leak to reach the spring.

Nevertheless, it appears probable that the water of Big Spring is derived from the artesian structure in the Honomanu lavas. Fractures through the upper confining member of the Hanawi artesian structure and the overlying lavas probably permit the water to rise until it reaches the basal clinker of the second Kula lava, at an unknown distance south of the spring. The point of emergence of the spring is determined by the intersection of the clinker bed with Hanawi Canyon.

At present Big Spring is entirely wasted. If the water supply for Nahiku Village should ever prove insufficient, it would be feasible to pipe Big Spring water to Nahiku. Also, the 300-foot drop over Big Falls could be used to generate electricity, which in turn could be used for pumping water to the Koolau ditch, a plan under consideration by the East Maui Irrigation Co. Also, it has been suggested by J. M. Heizer that a well might be drilled to the artesian aquifer at a point near Big Spring, a short distance east of Hanawi Gulch, and a tunnel driven from the gulch to intersect the well. Artesian well-water escaping through the tunnel would greatly increase the flow of Hanawi Stream available for power generation at Big Falls.

WATER-DEVELOPMENT TUNNELS

Twenty-two tunnels have been driven in the Nahiku area by the East Maui Irrigation Co. Four were for the purpose of gaining geological information, and were not intended to recover water. Most of the other tunnels encountered perched water, although a few are completely or nearly dry. The total length of tunnel, excluding the transportation tunnels along the Koolau ditch, is 20,646 feet, and the total yield of the tunnels during average periods is about 5.83 million gallons a day, an average yield per foot of tunnel of 282 gallons a day. A careful study by D. S. Summers[20] of the records of the Nahiku weir on the Koolau ditch just east of Waiaaka Gulch indicates that additional water made available by the tunnels east of the weir has been 6 million gallons a day or more, for 50 percent of the time, and 3.8 million gallons a day or more, for 90 percent of the time. These amounts represent both tunnel flow and the elimination of seepage loss in the Koolau ditch.

All of the later tunnels have been driven on the advice of W. O. Clark, geologist for the East Maui Irrigation Co. Many of them illustrate well the principle of the movement of perched ground water along buried valley systems (fig. 27), a principle clearly recognized and used with marked success by Clark.

The tunnels are briefly described in the table on page 267, and their location is shown on insert B, plate 1. Two of the tunnels are especially instructive and are described in detail on the following pages. The following table shows the yield of the principal tunnels over periods of several years. The increase in yield of most of the tunnels is attributable largely to progress in tunneling, and only in small part to variation in the amount of available ground water or changes in rainfall. The name and number of the tunnel in parenthesis is that used by the East Maui Irrigation Co.

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[20] Letter from D. S. Summers, dated Nov. 26, 1940.

Average discharge of water-development tunnels, Nahiku area, Maui, in millions of gallons a day

(Data supplied by East Maui Irrigation Co.)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Avg.[h]
No. 35 (Paakea no. 3 tunnel)													
1932					.10	.07	.09	.07	.08	.07	[a].06	.07	.08
1933	.09	[a].08	[a].09	.08	.08	.08	.08	.08	.15	.13	.14	.13	.10
1934	.17	.15	.16	.22	.26	.28	.21	.17	.19	.18	.32	.22	.21
1935	.24	.22	[a].14	.28	.18	.18	.20	.19	.16	.15	.28	.15	.20
1936	.21	.17	.27	.30	.31	.22	.26	.25	.26	[a].18	.21	.27	.24
No. 36 (Paakea no. 1 tunnel)													
1932					.42	.39	.41	.39	.40	.35	.35	.41	.39
1933	.44	[a].43	[a].41	.37	.37	.35	.38	.36	.33	.29	.29	.29	.36
1934	.33	.32	.30	.40	.48	.46	.42	.35	.38	.34	.45	.36	.38
1935	.38	.35	[a].27	.36	.28	.25	.27	.25	.28	.23	.29	.20	.28
1936	.23	.17	.32	.38	.51	.33	.41	.44	.48	[a].31	.37	.44	.36
No. 39 (Waiaaka tunnel)													
1932					.40	.34	.37	.32	.33	.32	[a].29	.36	.34
1933	.37	[a].34	[a].36	.34	.34	.33	.36	.33	.32	.30	.32	.34	.34
1934	.41	.37	.30	.43	.56	.59	.60	.58	.57	.56	.76	.75	.54
1935	.80	.78	[a].75	.81	.79	.78	.80	.82	.80	.80	.77	.71	.78
1936	.66	.61	.72	.81	.90	.81	.82	.89	.81	[a].78	.78	.85	.79
1938[b]											[a].88	.86	.87
1939	.94	.94	.96	.89	.92	.89	.89	.88	.88	.82	.88	.92	.89
1940	.79	.73	.71	.75	.80	.75	.79	.89	.94	.80	.84	.76	.80
No. 40 (Kapaula no. 3 tunnel)													
1933											[a].03	.06	.04
1934	.07	.08	.11	.15	.26	.25	.23	.21	.21	.25	.40	.33	.21
1935	.35	.36	[a].35	.42	.42	.45	.48	.47	.47	.43	.51	.39	.42
1936	.39	.36	.46	.59	.60	.53	.53	.57	.61	[a].50	.50	.55	.52
No. 41 (Kapaula no. 4 tunnel)													
1934		[a].02	.04	.10	.12	.13	.12	.09	.05	.04	(c)	.04	.07+
1935	.03	.02	[a].02	.03	.03	.02	.02						.03
No. 42 (Kapaula no. 2 tunnel)													
1931										.48	.57	.46	.53
1932	.51	.99	.40	.63	.63	.31	.54	.35	.33	.21	[a].14	.23	.44
1933	.53	[a].44	[a].25	.29	.30	.20	.34	.23	.10	.04	.09	.08	.24
1934	.20	.20	.10	.41	.49	.49	.40	.19	.20	.14	.60	.32	.31
1935	.33	.33	[a].27	.67	.23	.21	.23	.21	.15	.10	.14	.05	.24
1936	[a].12	.02	.35	.42	.66	.22	.43	.41	.48	[a].27	.36	.77	.38
No. 43 (Kapaula no. 1 tunnel)													
1931										.29	.29	.28	.29
1932	.30	.31	.27	.30	.29	.27	.29	.26	.26	.24	[a].24	.28	.28
1933	.31	[a].30	[a].26	.27	.27	.25	.28	.26	.24	.23	.23	.22	.26
1934	.22	.22	.23	(c)	(c)	.28	.28	.29	.28	.27	.28	.28	.26+
1935	.28	.28	[a].28	.28	.28	.28	.28	.28	.28	.28	[a].32	.28	.28
1936	[d].26+	.21	(c)	(c)	(c)	[d].28+	(c)	(c)	[d].28+	[d].26+	[d].27+	(c)	.26+
No. 45 (Hanawi no. 2 tunnel)													
1931										.10	.12	.10	.11
1932	.10	.16	.09	.13	.11	.07	.11	.08	.07	.05	[a].05	.07	.09
1933	.10	[a].08	[a].06	.07	.07	.05	.08	.06	.04	.04	.04	.06	.06
1934	.05	.05	.04	.11	.10	.09	.09	.06	.04	.04	.07	.05	.07
1935	.06	.04	[a].05	.08	.04	.06	.05	.06	.07	.03	.06	.05	.05
1936	.06	.01	.11	.17	.28	.04	.09	.09	.08	[a].03	.05	.09	.09
No. 46 (Hanawi no. 3 tunnel)													
1931										.62	.69	.96	.75
1932	.96	1.25	1.18	1.42	1.35	1.20	1.35	1.23	1.21	1.10	1.13	1.31	1.22
1933	1.48	[a]1.47	[a]1.26	1.30	1.30	1.17	1.28	1.18	1.12	1.05	1.12	1.15	1.24
1934	1.19	1.19	1.05	1.63	2.02	1.74	1.48	1.27	1.21	1.17	1.78	1.39	1.43
1935	1.54	1.32	[a]1.10	1.73	1.30	1.23	1.31	1.27	1.23	1.05	1.08	.91	1.26
1936	[e].94	.91	1.49	1.57	1.97	[d]1.32+	1.66	[d]1.79+	[d]1.57+	[a]1.28	1.38	[d]1.54+	1.45+
No. 54 (West Makapipi no. 2 tunnel)[f]													
1932										.08	.06	.06	.07
1933	.07	[a].08	[a].08	.07	.07	.06	.07	.08	.06	.05	.07	.06	.07
1934	.05	.06	.04	.07	.08	.07	.04	.04	.05	.05	.07	.06	.06
1935	.08	.05	[a].07	.07	.06	.07	.07	.07	.07	.06	.11	.08	.07
1936	.07	.01	.20	.38	.39	.11	.26	.18	.07	.03	.03	.07	.15
No. 55 (East Makapipi no. 1 tunnel)													
1931										.83	.83	.78	.81
1932	.83	1.17	1.10	1.27	1.44	1.40	2.04	1.18	1.21	.46	.44	1.31	1.15
1933	1.96	[a]1.66	[a]1.17	1.29	1.34	.83	1.31	1.02	.44	.41	.45	1.24	1.09
1934	1.20	1.58	.96	2.21	3.77	3.33	2.98	2.26	1.54	1.86	3.76	2.44	2.32
1935	3.18	1.72	[a]1.92	3.40	2.21	1.78	1.81	2.47	2.36	1.14	1.47	1.47	2.08
1936	1.04	.63	[d]2.59+	[d]3.51+	[d]3.80+	2.34	[d]3.10+	[d]3.72+	[d]3.50+	[a]2.38+	[d]3.15+	[d]3.27+	2.75
No. 56 (Pogue's tunnel)[g]													
1935							[a]2.82	1.35	1.20	.61	1.08	.52	1.26
1936	.85	.33	2.68	3.00	3.68	1.62	2.65	3.08	2.57	[a]1.61	1.62	2.68	2.20

[a] Record incomplete. [b] No record for 1937. [c] No record; weir overflowing. [d] Weir overflowing part of time. [e] Weir leaking. [f] Water supply for Nahiku Village comes from this tunnel. [g] Flow largely derived from former spring and surface flow of Makaino Stream. [h] Increase in average annual discharge is largely caused by continuation of tunneling and development of additional water.

Tunnels in the Nahiku area, Maui
(Owned by East Maui Irrigation Co.)

No. (insert B, plate 1)	Name	Location	Average yield (m.g.d.)[a]	Length, including laterals (ft.)[a]	Yield per foot (g.d.)	Average temperature of water (in °C.)	Geologic setting and source of water
35	Paakea No. 3 (Ogino)	Koolau ditch, 550 ft. west of Paakea Stream.	0.17	618	275	17.3	Driven along contact of Paakea lava with underlying Waiaaka lava and clinker, the contact dipping west and northwest, in most places between 50° and 60°; a rock-to-rock contact is general, but a few inches of soil are present at the contact in a few places. Water emerges from base of the Paakea lava.
36	Paakea No. 1	Koolau ditch, 300 ft. southwest of Paakea Stream.	0.31	2,927	106	17.2	Driven along contact of Paakea lava with underlying Waiaaka lava and clinker. Water issues from basal part of Paakea lava.
37	Paakea No. 2	East bank of Paakea Stream 125 ft. south of Koolau ditch.	0.0	332	0		Driven along contact of Paakea lava with underlying Waiaaka lava and clinker; a few inches of baked red soil is present locally at the contact. A few small seeps emerge from the lower part of the Paakea lava.
38	Paakea No. 4	Southwest bank of Paakea Stream 900 ft. south of junction of Paakea Stream with Koolau ditch.	0.01	248	41		Driven into Waiaaka lava; cuts layers of lava and clinker. A small flow of water emerges from fractures in the lava 225± feet from the portal.
39	Waiaaka	East bank of Waiaaka Stream 100 ft. south of Koolau ditch.	0.85	2,200	386	17.3	Driven for most of its extent in Makapipi lava, but in several places it encounters the basal part of the overlying Waiaaka lava. Nearly all the water emerges from the basal part of the Waiaaka lava.
40	Kapaula No. 3	West fork of West Branch of Kapaula Stream 200 ft. south of Koolau ditch.	0.45	2,011	224	17.4	First part of tunnel driven approximately along contact of Waiaaka lava with the underlying Makapipi member, largely decomposed clinker; at about 600 feet a cross-cut to the west cuts into the Waiaaka lava, from which issue several flows of water. At about 725 feet the tunnel cuts the western wall of an ancient valley filled with Kapaula lava and follows approximately along this contact to the axis of the buried valley, and along the eastern wall of the valley. The Kapaula lava is underlain by stream gravel. Several flows of water emerge from the Kapaula lava but only a very little issues from the gravel.
41	Kapaula No. 4	Koolau ditch at east fork of West Branch of Kapaula Stream.	0.01	571	17	17.5	Starts in Kapaula lava, cuts across base of Kapaula lava 20 feet from the portal and from there on follows approximately the contact of the Waiaaka lava on underlying Makapipi lava and clinker. Water issues from the basal part of the Waiaaka lava.
42	Kapaula No. 2	East fork of West Branch of Kapaula Stream 1,100 ft. southwest of point where it crosses Koolau ditch.	0.25	708	367	17.4	Cuts back through Kapaula lava to its contact with the underlying Makapipi lava and clinker, and then follows approximately along this contact. Some water issues from the clinkery base of the Kapaula flow, but most of it emerges from fractures in the Kapaula lava about 200 feet from the portal.

See footnotes at end of table.

Tunnels in the Nahiku area, Maui—*Continued*

No. (insert B, plate 1)	Name	Location	Average yield (m.g.d.)[a]	Length, including laterals (ft.)[a]	Yield per foot (g.d.)	Average temperature of water (in °C.)	Geologic setting and source of water
43	Kapaula No. 1	100 ft. south of Koolau ditch and 220 ft. southeast of crossing of Koolau ditch and the East Branch of Kapaula Stream.	[b]0.15	838	179	17.4	The eastern section of the tunnel contours the base of the valley-filling Paakea flow, which rests on Waiaaka lava and locally on stream gravel. Water issues from the basal part of the Paakea lava. The western section of the tunnel is at a higher level and follows the base of the Kapaula lava, which here rests on Waiaaka lava and clinker with locally a little soil or stream gravel at the contact; this section of the tunnel is nearly dry. About 200 feet from the east portal, the tunnel taps Kapaula Stream.
44	Hanawi No. 1	West bank of Hanawi Stream 340 ft. southwest of Koolau ditch.	0.05	809	62		Driven along contact of Waiaaka lava with underlying decomposed Makapipi clinker. Small flows of water issue from the clinkery base of the Waiaaka lava, and from the platy basal part of the lava, and at the heading a small flow of water issues from nearly vertical columnar joints in the Waiaaka lava.
45	Hanawi No. 2	East bank of Hanawi Stream at Koolau ditch.	0.10	400	250	18.1	Starts in Hanawi lava, crossing lateral contact of Hanawi lava 25± feet from the portal; the rest of the tunnel follows the contact of the Waiaaka lava on Makapipi clinker, with locally 2 to 4 inches of soil at the contact. The water issues as numerous small flows and seeps from the platy-jointed basal part of the Waiaaka lava.
46	Hanawi No. 3	West bank of East Branch of Hanawi Stream 150 ft. southwest of Koolau ditch.	1.0	2,437	410	16.8	For most of its length follows the lateral contact of the Makaino lava. (See detailed description, p. 270, and map, fig. 41.) Water is derived largely from the Makaino lava, but smaller amounts issue from gravel and talus breccia beneath the Makaino flow, and a little seeps out of the Waiaaka lava.
47	Hanawi Sky-light[d]	East bank of East Branch of Hanawi Stream at Koolau ditch.	0.0	34	0		Exposes clinkery phase of the Makaino lava resting on decomposed Makapipi clinker with several inches of red baked soil at the contact.
48	Shishido Tunnel	Koolau ditch about 330 ft. southeast of Makaino Stream.	0.0	188	0		Starts in Mossman lava; 36 feet from the portal it crosses the basal contact of the Mossman lava and for the rest of its length it is in Waiaaka lava. The tunnel is nearly dry.
49	Big Spring[d]	Hanawi Gulch at Big Spring.		42		14.9	Driven into the clinker phase of the second Kula lava flow, from which issues Big Spring. The tunnel probably did not increase the flow of the spring.
50	Unnamed[d]	East wall of Hanawi Gulch 450 ft. northeast of Big Spring.	0.0	15	0		Driven on contact of Big Falls lavas with underlying Kula lavas; the contact is undulating, but in general dips eastward about 10°; it is marked by 0 to 10 inches of red soil grading down into partly decomposed Nahiku clinker. The tunnel is dry.

51	West Makapipi No. 2	West bank of West Branch of Makapipi Stream 40 ft. east of transportation tunnel of Koolau ditch.	[c]0.05	942	53	17.7	Tunnel follows contact of Waiaaka lava on decomposed Makapipi clinker; the contact is marked in many places by 1 to 6 inches of soil, and locally by pockets of fine stream gravel. The basal part of the Waiaaka lava is characterized by prominent platy jointing. The water issues as numerous small flows and seeps from the basal part of the Waiaaka lava.
52	West Makapipi No. 1	East bank of West Branch of Makapipi Stream, 75 ft. northeast of transportation tunnel of Koolau ditch.	0.02	206	98		Follows the lateral contact of Kuhiwa lava with Waiaaka lava. From 1 to 6 inches of red baked soil are locally present at the contact. The water issues as small fows and seeps from the Kuhiwa lava.
53	West Makapipi No. 3[d]	East bank of West Branch of Makapipi Stream, 320 ft. northeast of transportation tunnel of Koolau ditch.	[e]0.1	139	[f]719	15.8	Driven into the clinkery basal part of the Kuhiwa lava. At the heading it intersects a talus breccia of the pre-Kuhiwa valley wall. Water issues from Kuhiwa lava along the floor of the tunnel at several places for a distance of about 70 feet from the portal. This tunnel is at too low an altitude to be run into the Koolau ditch.
54	East Makapipi No. 2	West bank of Middle Branch of Makapipi Stream, 90 ft. east of transportation tunnel of Koolau ditch.	0.02	679	29		Driven along contact of Waiaaka lava with Makapipi lava; 20 feet from the heading the two are separated by 1 to 2 feet of poorly sorted stream gravel. Water issues from the basal part of the Waiaaka lava.
55	East Makapipi No. 1	East bank of Middle Branch of Makapipi Stream at Koolau ditch.	2.0	3,431	583	17.3	Follows basal contact of the Kuhiwa lava. (See detailed description, p. 272, and map, fig. 43.) Most of the water is derived from the Kuhiwa lava, although some is derived from Big Falls lava.
56	Pogue	West bank of West Branch of Makapipi Stream, 1,900 ft. southwest of point where the stream crosses the Koolau ditch.	[g]0.3	871	385		Starts in Makapipi clinker at base of Waiaaka lava; 15 feet from the portal the contact dips below map level and the tunnel continues through Waiaaka lava for 440 feet, to a point where the contact again rises to map level. For much of the next 200 feet the contact is exposed in the tunnel, and is locally marked by up to 6 inches of red soil and up to 3 feet of stream gravel. The tunnel passes into Mossman lava 700 feet from the portal. An estimated flow of 0.3 m.g.d. is derived from the Waiaaka lava or from Makapipi clinker exposed in the roof with Waiaaka lava only a short distance above. Additional water (about 0.2 m.g.d. on Jan. 18, 1940) was derived by draining a spring which formerly issued from Mossman lava at the western end of the tunnel.

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[a] Data supplied by East Maui Irrigation Co.; tunnel flows during Sept. 1938.

[b] Estimated flow Jan. 1940; total measured flow includes that of Kapaula Stream.

[c] Estimated flow, Jan. 1940; water supply for Nahiku village comes from this tunnel.

[d] Driven for geological information only.

[e] Estimated flow, Nov. 1939.

[f] The tunnel occupies the site of a former spring; the yield is probably not much greater than was that of the spring.

[g] Estimated flow, Jan. 1940; does not include the water from the former spring at the western end of the tunnel.

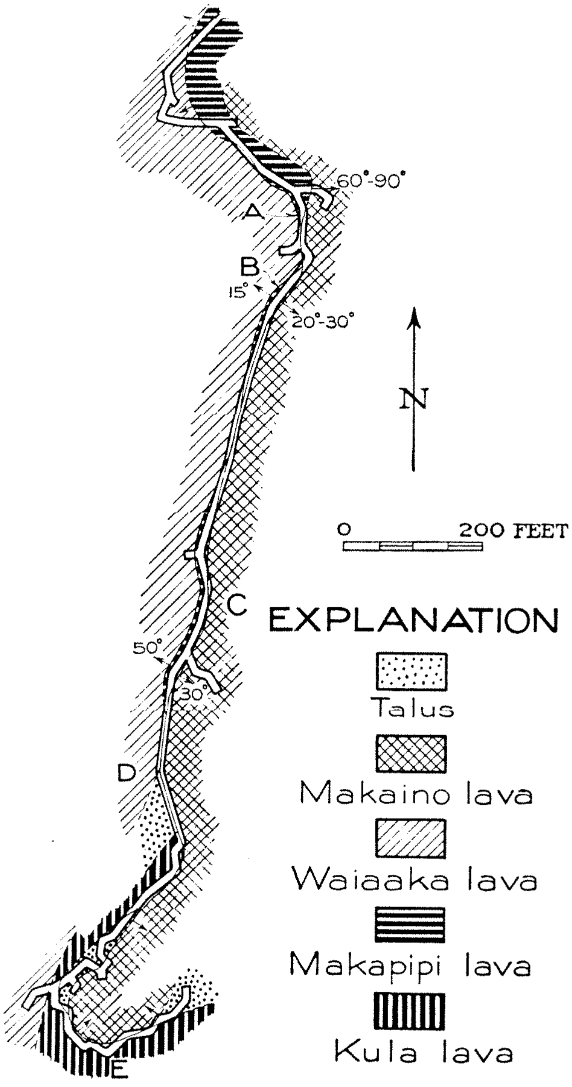

FIGURE 41. GEOLOGIC MAP OF TUNNEL 46.

TUNNEL 46 (HANAWI NO. 3).—The second longest water-development tunnel in the district is tunnel 46 on East Hanawi Stream. It is 2,280 feet long, and recovers 1 million gallons a day, an average recovery of 443 gallons a day per foot of tunnel. It follows the side of a valley-filling lava to the bottom of the buried valley (fig. 41).

The tunnel starts in partly decomposed Makapipi clinker, and passes into Waiaaka lava 35 feet from the portal. A few seeps issue from vertical joints in the Waiaaka lava about 200 feet from the portal. The tunnel passes into Makapipi clinker at 250 feet, and from 330 to 480 feet follows the base of the Waiaaka lava. A cross-cut to the east at 290 feet intersects the wall of the valley filled with the Makaino lava. Another cross-cut to the east at 440 feet exposes the same contact dipping eastward at an angle ranging from 60° to 90°, and 45 feet beyond (A, fig. 41) the contact in the main tunnel dips eastward at about 35°. At the latter locality the Makaino lava is underlain by poorly sorted coarse stream gravel. In a cross-cut at 520 feet this gravel rests on impermeable partly decomposed Makapipi clinker, apparently occupying a small lateral swale. A small amount of water issues from it here and for a short distance beyond. The base of the Makaino lava, dipping 20° to 30° eastward, is exposed in the roof and east wall of the tunnel 590 feet from the portal (B, fig. 41), and the base of the Waiaaka lava dipping 15° westward is exposed at waist level in the west wall (fig. 42). At C, figure 41, Makaino lava rests on coarse talus breccia composed largely of fragments of platy Waiaaka lava, some of them as much as 4 feet across. Abundant water issues from the scoriaceous base of the Makaino lava and from fractures in it, and a smaller amount of water issues from the underlying talus. For the next 275 feet, water issues freely from the base of the same lava. At D, figure 41, Waiaaka lava rests on stream gravel which contains many sharply angular blocks probably representing talus incorporated in the gravel. From this point on, Waiaaka lava is not exposed in the main tunnel, but clinker probably belonging to the base of this lava is exposed in a cross-cut to the west, 1,815 feet from the portal. The rock underlying the Makaino lava in the last part of the tunnel is massive, dense, columnar jointed, and similar in petrographic character to the Kula lavas. The pre-Makaino valley appears to have been cut through the Waiaaka and Makapipi lavas and into the Kula lavas. Where it crosses the bottom of the buried valley (E, fig. 41), the tunnel has uncovered an ancient buried waterfall, down which cascades the largest single flow of water recovered in the entire tunnel. The water apparently migrates through scoria and joint fractures in the basal part of the Makaino lava, and is perched by the relatively impermeable underlying Kula lava. At the foot of the waterfall is a deposit of talus breccia, which thickens in each direction along the tunnel, and for the last 40 feet the tunnel is located entirely within this breccia.

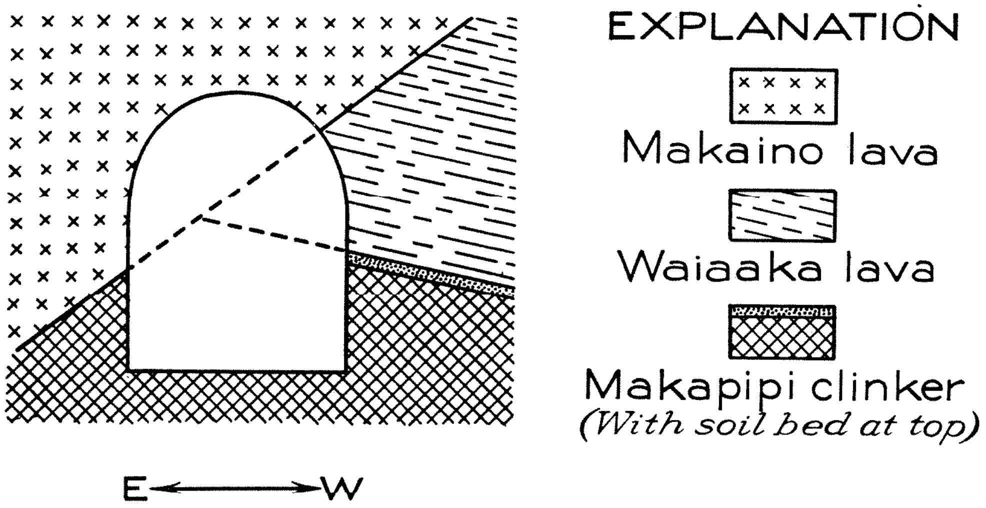

FIGURE 42. CROSS SECTION OF TUNNEL 46 (HANAWI NO. 3 TUNNEL), AT B, FIG. 41.

Tunnel 55 (East Makapipi no. 1).—This tunnel with its laterals is 2,850 feet long, and is the longest water-development tunnel in the district. It also has the largest yield, averaging close to 2 million gallons a day. Whereas tunnel 46 develops water from a single large lava-filled gulch, tunnel 55 crosses three small gulches, each filled with Kuhiwa lava. Laterals extend to the bottom of each of the buried gulches. The geology of the tunnel is shown in figure 43, and its location on insert B, plate 1.

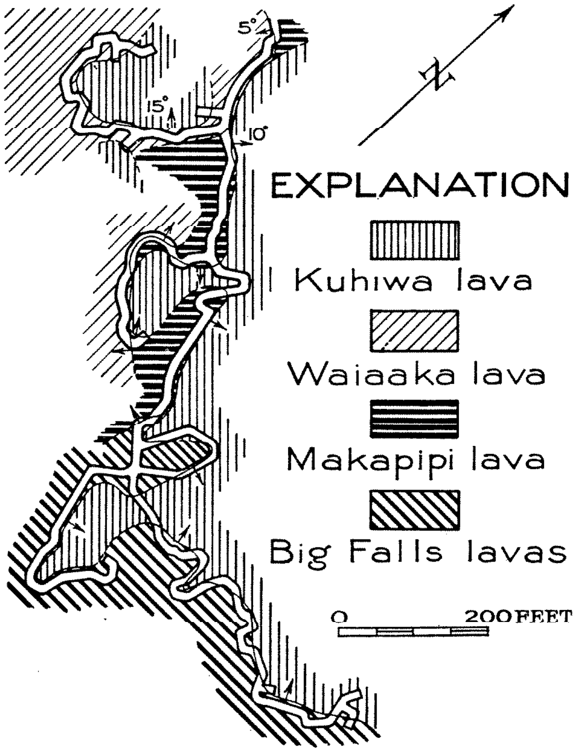

FIG. 43 GEOLOGIC MAP OF TUNNEL 55 (EAST MAKAPIPI NO. 1 TUNNEL).

Near the portal the tunnel follows the contact of the Waiaaka lava and the underlying Makapipi clinker, which dips gently southwestward, and is marked by two inches of red soil. Forty feet from the portal the tunnel encounters the edge of the Kuhiwa lava, and follows this contact with only local departures throughout the rest of its extent. A short cross-cut 145 feet southwest of the portal discloses the edge of a shallow gulch filled with Kuhiwa lava and develops water estimated at 40,000 gallons a day. This buried gulch is exposed also in the small waterfall on the Middle Branch of Makapipi Stream near the portal. Its course is approximately north and south. A long cross-cut 155 feet from the portal follows the lateral and basal contact of the Kuhiwa lava filling this small gulch, and recovers about 100,000 gallons of water a day from the base of the lava, which here shows prominent platy jointing, and rests on poorly sorted stream gravel.

The northwest side of the second small gulch filled with Kuhiwa lava is reached 330 feet from the portal and is explored by a long cross-cut to the southwest. The lava rests for the most part on Makapipi clinker, but to a less extent on Waiaaka lava. Several small flows of water emerge from its lower part. The same cross-cut exposes the basal contact of the Waiaaka lava, which rests on soil and gravel at the top of the Makapipi clinker.

The main tunnel crosses the second valley-fill of Kuhiwa lava and continues approximately along the contact of this lava with Makapipi clinker and lava. Soil, locally as much as 14 inches thick, is present at the contact. Several small streams issue from the basal part of the Kuhiwa lava. About 630 feet from the portal Makapipi lavas rest on the upper lava of the Big Falls member, and at the third long cross-cut, 725 feet from the portal, the upper Big Falls lava rests on a layer of red baked soil as much as 24 inches thick, at the top of the lower Big Falls lava. About 50,000 gallons a day issues from the lower Big Falls lava in the cross-cut just northeast of the main tunnel. Thirty feet beyond the cross-cut, the main tunnel crosses the third lava-filled gulch, and the cross-cut follows the west wall of the gulch to its bottom, and then turns northeastward along the east wall. The Kuhiwa lava here rests on a poorly sorted gravel which overlies the upper Big Falls lava. Trickles of water issue from the base of the Kuhiwa lava and a few seeps come from the Big Falls lava.

From the eastern wall of the third buried gulch to its heading, the main tunnel follows the contact of the Kuhiwa lava with the Big Falls lava. The latter is here lithologically more like the lower Big Falls lava exposed at the third cross-cut than like the upper one. The upper lava is only about 5 feet thick at the third cross-cut, and was probably removed by erosion beyond. About 200 feet from the heading, a tree mold 10 inches in diameter and 4 feet in length is exposed in the Kuhiwa lava in the roof of the tunnel. About 400 feet from the heading, the Kuhiwa lava overlies a gravel similar to that exposed in the third long cross-cut. Between the east wall of the third buried gulch and the heading, many seeps and small streams issue from the basal part of the Kuhiwa lava, and about 100 feet from the heading a large stream issues at the same horizon.

POSSIBILITY OF ADDITIONAL GROUND-WATER DEVELOPMENT

The most important possible future ground-water development is the recovery of the water of the Big Spring, already discussed (p. 262). Further tunneling at the base of the Waiaaka lava would probably recover additional small amounts of water, but large yields are not to be expected at this horizon. Additional tunneling at the base of the Kuhiwa lava east of tunnel 55 would probably discover water. The surface buried by the Kuhiwa lava is apparently cut by many small gulches, and it is probable that such a tunnel would encounter more buried gulches like those which yield water in tunnel 55.

The region west of Paakea Stream, as far as the West Branch of Kopiliula Stream, is similar geologically to the area mapped, except that lavas of Hana age are absent. Tunnels driven on the same principle as those in the Nahiku district might yield water there. This is true also of the region east of Kuhiwa Stream, although there a large valley which existed in the headwaters of the present Kuhiwa Gulch may have directed so many lava flows into the area that there was less opportunity for erosion and valley-cutting between successive eruptions. This might result in the water being less effectively perched, and distributed in many small streams.

PART 3

PETROGRAPHY OF MAUI

By Gordon A. Macdonald

PETROGRAPHY OF MAUI

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ABSTRACT

The lavas of East Maui are described according to stratigraphic groups. The oldest or Honomanu lavas are olivine basalts like the primitive lavas in other Hawaiian volcanoes. The later or Kula and Hana lavas include basalts, basaltic andesites, andesites, and picritic basalts. The normative nepheline of analyzed East Maui lavas has not been identified in the mode. The degree of differentiation is inversely proportional to the frequency of eruptions.

The lavas of West Maui volcano are divided into the Wailuku volcanic series, consisting largely of olivine basalts with less abundant olivine-poor basalts, hypersthene basalts, and picritic basalts; the Honolua volcanic series, consisting of oligoclase andesites and soda trachytes; and the Lahaina volcanic series, consisting of nepheline basanite and picritic basalts. Coarse-grained gabbros intrude the Wailuku lavas. Differentiation was undoubtedly partly by crystal settling, but the alkali curves of the variation diagram suggest that volatile transfer was of some importance.

PETROGRAPHY OF EAST MAUI

INTRODUCTION

The petrography of East Maui has been studied by the writer in connection with the investigation of the geology and ground-water resources of the volcano by H. T. Stearns. A knowledge of the types of rocks and their distribution is essential to a complete understanding of the hydrologic conditions. Moreover, the petrographic studies have served as a check on certain theories fundamental to the geologic history. The lessening of the frequency of eruptions in Kula time, permitting streams to gouge great canyons into the mountains, is paralleled by increased differentiation of the lavas, and the increase in frequency of eruptions in Hana time, which resulted in the partial burial of the great valleys, is reflected in the greater abundance of undifferentiated lavas.

One hundred and sixty-nine specimens from East Maui, collected by H. T. Stearns, H. A. Powers, and the writer, and one from Molokini, collected by Prof. H. A. Palmer of the University of Hawaii, have been studied under the microscope.

In the following pages statements of the size of optic axial angles are estimates based on the appearance of optic axis and acute bisectrix interference figures. They are of course only approximate, but for the most part are probably accurate to within about 5°. Statements of feldspar composition are based partly on various extinction angle methods and partly on refractive index. Refractive indices have been determined by immersion methods with ordinary white light and have a probable error of ±.003.

The writer is indebted to H. A. Powers for courtesies extended during collecting trips in the summit region. He is also greatly indebted to H. T. Stearns and C. S. Ross for discussion and criticism of the manuscript of this report.

PREVIOUS INVESTIGATIONS

E. S. Dana, in 1889, described eight specimens from East Maui volcano. Three were picritic basalts, called by Dana chrysophyric basalts, one from the rim of the summit depression and two from its floor. Two others, one from the top of the mountain and the other from within the summit depression, were of andesitic aspect, one containing a dark-brown mineral, probably biotite, and the other aggregates of finely granular magnetite marking the place of resorbed grains of biotite or hornblende. Two samples from Paia, on the northwest slope, were said to bear the same resemblance to andesite.[21] The rock containing the pseudomorphs of granular magnetite replacing hornblende was probably from the hornblende-bearing flow underlying the lava of White Hill, described on a later page. It is thus clear that Dana already recognized both the andesitic and ultrabasic affinities of some of the later lavas of East Maui volcano. Cohen had already described, in 1880, augite andesites and rocks transitional between andesite and basalt on the island of Hawaii.[22]

Möhle described a single specimen of basalt from the summit of East Maui. The lava from Wailuku, assigned by him to East Maui, probably belongs to the West Maui volcano.[23]

Cross has described a number of rocks from East Maui, including picritic basalts and lavas of andesitic affinities, three of which were analyzed.[24] All were from the relatively late lavas of the volcano, and it was pointed out that they were probably not representative of the great bulk of the underlying mountain.[25]

Sidney Powers stated that the lavas of East Maui range from basalt to trachyandesite, and compared them to the flows of Mauna Kea, on Hawaii,[26] but gave no detailed descriptions.

Washington and Keyes studied several East Maui lavas collected by others, and made seven analyses. All came from the lavas termed in the present report the Kula and Hana volcanic series. The rocks were found to range from picritic basalts through basalts to oligoclase andesite. All of the analyzed rocks contained normative nepheline, but the groundmass was said to be so fine that in most the modal nepheline was difficult or impossible to detect. The characteristic trachytic texture of these rocks was described.[27] The present writer has been unable to confirm the identification of modal nepheline in the lavas. The groundmass is generally fine, but careful microscopic search and staining of the slides has failed to reveal its presence. In a few slides there are found small interstitial grains which might be nepheline, but appear more probably to be feldspar.

GENERAL FEATURES

Distribution of rock types.—The lavas of East Maui have been

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[21] Dana, E. S., Contributions to the petrography of the Sandwich Islands: Am. Jour. Sci., 3rd ser., vol. 37, pp. 463-464, 1889.

[22] Cohen, E., Ueber laven von Hawaii und einigen anderen Inseln des Grossen Oceans nebst einigen Bemerkungen über glasige Gesteine im allgemeinen: Neues Jahrb., 1880, Bd. 2, pp. 46-47, 51-55.

[23] Möhle, F., Beitrag zur Petrographie der Sandwich- und Samoa-Inseln: Neues Jahrb., Beil. Bd. 15, pp. 67-68, 1902.

[24] Cross, W., Lavas of Hawaii and their relations: U. S. Geol. Survey Prof. Paper 88, pp. 28-32, 1915.

[25] Idem, pp. 28, 92-93.

[26] Powers, S., Notes on Hawaiian petrology: Am. Jour. Sci., 4th ser., vol. 50, pp. 263-265, 1920.

[27] Washington, H. S., and Keyes, M. G., Petrology of the Hawaiian Islands; VI. Maui: Am. Jour. Sci., 5th ser., vol. 15, pp. 209-215, 1928.

divided by Stearns into the Honomanu, Kula and Hana volcanic series. (See Part 1.) These have been subdivided according to their sources into lavas erupted in the summit area and summit depression, along the east and southwest rift zones, and on the west and northwest slopes. Within each series, lavas of the summit region and those erupted lower on the rift zones are for the most part closely similar.

The Honomanu lavas are all olivine basalts. They resemble the early lavas of the other Hawaiian volcanoes in all respects except the greater abundance of plagioclase phenocrysts. The Kula lavas also include olivine basalts, but the most abundant rocks are basaltic andesites. Some true andesites and many flows of picritic basalt also are found in the Kula series. The Hana lavas comprise much the same rock types as the Kula lavas, but basalts are relatively more abundant. The last lava flow from East Maui volcano was a picritic basalt erupted about 1750 low on the southwest rift zone (pl. 1).

INTERSTITIAL FELDSPAR.—Many of the lavas contain small amounts of an interstitial feldspar having the refractive index of andesine or oligoclase, but a positive optic sign and small optic axial angle. The same feldspar is found in lavas from the Waianae Range on Oahu,[28] Kahoolawe,[29] and West Maui. It has been recognized by Stark and Howland in basalts from Borabora,[30] and by Tomita in basalts from eastern Asia.[31] Barth found it in many Hawaiian lavas, and concluded that it was anemousite, a feldspar containing nepheline or carnegieite in solid solution.[32] Recent studies by the writer have shown, however, that the mineral occurs in rocks which contain normative quartz, and it is therefore believed that nepheline is not an essential part of the mineral. It has been shown that the quantity of the feldspar increases with the increase of normative orthoclase in the rock, and also that the feldspar with small optic angle in the lavas apparently bears a reciprocal relationship to antiperthite in gabbroic rocks, and it therefore appears probable that the mineral is a soda-lime feldspar holding in solid solution a variable proportion of potash feldspar.[33]

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[28] Macdonald, G A., Petrography of the Waianae Range: Hawaii Div. of Hydrography, Bull. 5, pp. 67-68, 1940.

[29] Macdonald, G. A., Petrography of Kahoolawe: Hawaii Div. of Hydrography, Bull. 6, pp. 151-153, 1940.

[30] Stark, J. T., and Howland, A. L., Geology of Borabora, Society Islands: B. P. Bishop Mus., Bull. 169, p. 34, 1941.

[31] Tomita, T., Olivine-trachyandesitic basalt from Hsueh-hua-shan Hill, Ching-hsing District, North China: Shanghai Sci. Inst. Jour., sec. 2, vol. 1, pp. 1-10, 1933.

[32] Barth, T. F. W., Mineralogical petrography of Pacific lavas: Am. Jour. Sci., 5th ser., vol. 21, pp. 401-402, 1931.

[33] Macdonald, G. A., Potash-andesine in Hawaiian lavas: Am. Mineralogist, in press.

Classification of the lavas.—Throughout this work, the lavas are named according to their modal composition. The basis for the division into basalts and andesites is the composition of the feldspar, as determined in thin section. The rocks designated as basalts are those in which the average feldspar is labradorite. The andesites are those in which the average feldspar is andesine or oligoclase. These basic divisons are modified by the addition of prefixes. Thus the basalts which contain more than 65 percent ferromagnesian minerals, approaching picrites in composition, are named picritic basalts. The andesites which resemble basalts in the abundance of mafic minerals and in habit are termed basaltic andesites. Those consisting largely of oligoclase are termed oligoclase andesites, in order to emphasize the sodic nature of the feldspar in comparison to the more ordinary andesites in which the feldspar is andesine. Rocks in which the dominant feldspar is alkali feldspar, and in which important amounts of neither quartz nor feldspathoids are recognized, are termed trachytes. The latter are unknown on East Maui but are fairly widespread on West Maui, where their content of sodic amphiboles and pyroxenes and the predominance of sodic over potassic feldspars is indicated by the appelation soda trachyte.

Many writers would classify as basalts, on the basis of the abundance of ferromagnesian minerals or of the presence of olivine, the more mafic of the rocks herein termed andesites. However, the abundance of ferromagnesian constituents may range widely even within a single hand specimen, and the average character of the feldspar appears a more fundamental characteristic. Separation of the basalts from the andesites at the line of division between labradorite and andesine, as advocated by many recent writers,[34] is, of course, arbitrary, but appears most suited to emphasize the important features of distribution and petrogenesis of Hawaiian lavas.

HONOMANU LAVAS

Lavas at Honomanu Bay.—Olivine basalts of the Honomanu volcanic series exposed at the type locality near the mouth of Honomanu Stream are representative of the series as a whole. Similar lavas are exposed along the northeast coast of East Maui both east and west of the type locality, and in the lower parts of the walls of Keanae Valley (pl. 1). Most of the rocks are porphyritic, with phenocrysts of olivine and feldspar attaining maximum dimensions of 1 to 3 mm. Some contain olivine phenocrysts alone, and a few contain only feldspar phenocrysts. A few are nonporphyritic. The flows

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[34] Holmes, A., The nomenclature of petrology, 2nd ed., p. 42, London, 1928.
Johannsen, A., A descriptive petrography of the igneous rocks, vol. 1, pp. 156-157, Chicago, 1931.
Rittmann, A., Vulkane und ihre Tätigkeit, p. 65, Stuttgart, 1936.

are typically thin, and both aa and pahoehoe are present in nearly equal abundance. (See p. 69.)

The texture is typically intergranular, and less frequently diabasic. The average grain size of the groundmass ranges from 0.04 mm to 0.2 mm, but in most is between 0.05 and 0.1 mm. Diabasic texture is generally local, and is often confined to part of a single thin section. Intersertal texture is rare except in glassy crusts. One specimen shows a peculiar tangential arrangement of small grains of augite around the vesicles, resembling ocellar or clathrate texture[35] except that no central mineral grain is present.

The feldspar phenocrysts are in general tabular, and show Carlsbad and albite twinning. Pericline twinning is rare. The crystals show normal and oscillatory zoning, with a range in composition from sodic bytownite or labradorite-bytownite in the core to intermediate or sodic labradorite at the outside. One specimen contains feldspar phenocrysts with cores of intermediate bytownite. The groundmass feldspar has the same composition as the rims of the phenocrysts, and was probably crystallized at the same time.

Olivine forms both phenocrysts and grains in the groundmass. The optic angle is close to 90°. Zoning has not been detected. In many rocks the phenocrysts are rounded and embayed by magmatic resorption, and in most they are partly altered to iddingsite. The alteration to iddingsite is found occasionally in the groundmass olivine as well, but this is not common. Thin envelopes of fresh olivine surrounding cores of olivine partly altered to iddingsite have been observed in several slides. The deuteric origin of iddingsite was pointed out years ago by Ross and Shannon.[36] The rims of olivine surrounding iddingsite cores have been explained as resulting from alteration of the phenocrysts by gases before and during eruption, followed by renewed precipitation of fresh olivine following eruption, contemporaneously with the crystallization of the groundmass olivine.[37] Where iddingsite is present in the groundmass it must, however, have formed after eruption, possibly by volatiles liberated during crystallization acting on the newly crystallized groundmass olivine. It is also possible that some of this groundmass iddingsite was formed directly as such, and has not resulted from the alteration of olivine.

Monoclinic pyroxene is a prominent constituent of the groundmass. In a few specimens it forms microphenocrysts, but no true phenocrysts have been observed. It ranges from subhedral to euhedral, and from colorless to pale purplish-brown. In most lavas it is pigeonite. The size of the optic angle generally varies between 30° and 50°, but rare grains show figures which appear uniaxial. Less frequently the pyroxene is found to be augite, with an optic angle of 55° to 60°. Orthorhombic pyroxene has not been found.

Accessory minerals include both iron ores and apatite. The latter forms minute acicular crystals, length slow and with low birefringence, enclosed in larger grains of feldspar. The iron ore includes both nearly square grains of magnetite and rod-shaped grains of ilmenite. Typically, iron ore constitutes 10 to 15 percent of the rock, pyroxene 30 to 35 percent, olivine 10 to 15 percent, and feldspar 45 to 50 percent.

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[35] Washington, H. S., The Roman comagmatic region: Carnegie Inst. Washington Pub. 57, p. 109, 1906.

[36] Ross, C. S., and Shannon, E. V., The origin, occurrence, composition and physical properties of the mineral iddingsite: U. S. Nat. Mus. Proc., vol. 67, pp. 1-19, 1925.

[37] Edwards, A. B., The formation of iddingsite: Am. Mineralogist, vol. 23, pp. 277-281, 1938.
Macdonald, G. A., op. cit. (Bull. 6), pp. 155-156, 1940.

HONOMANU LAVAS IN THE NAHIKU AREA.—Only the uppermost part of the Honomanu volcanic series is exposed in the Nahiku area (insert B, pl. 1). It consists largely of basalts containing numerous phenocrysts of augite, olivine, and feldspar and approaching the picritic basalts in composition, interbedded with which are dense basalts, essentially nonporphyritic but with a few feldspar phenocrysts. In feldspar composition the latter rocks approach the basaltic andesites. Associated with these, and increasing in abundance downward, are olivine basalts resembling those at Honomanu Bay already described. The nonporphyritic basalts and the basalts approaching the picritic basalts in composition more closely resemble the lavas of the overlying Kula and Hana volcanic series than they do the typical Honomanu basalts. The upper part of the Honomanu volcanic series at Nahiku is thus, in the types of rocks comprising it, transitional to the Kula volcanic series. (See Part 2.)

The typical olivine basalts contain phenocrysts of olivine or feldspar or both, and resemble those in the Honomanu volcanic series elsewhere. They will not be further described. They are well exposed in the cliffs west of Moku Huki.

Some rocks lack ferromagnesian phenocrysts but contain a few phenocrysts of feldspar. They are typified by a dense layer of aa in the sea cliff 500 feet west of Hanawi Gulch. It is closely similar to rock encountered in the drill holes. The rock contains a few phenocrysts of feldspar up to 1.5 mm long in an intergranular groundmass with an average grain size of about 0.04 mm. The groundmass is composed of colorless subhedral grains of olivine (5%), some of which are partly altered to iddingsite; colorless subhedral to anhedral grains of monoclinic pyroxene (35%); subhedral to anhedral lath-shaped grains of plagioclase (40%), zoned from intermediate to sodic labradorite; interstitial oligoclase with an abnormally small positive optic angle (5%); and euhedral to anhedral grains of iron ore (15%), including both magnetite and ilmenite. In its feldspar composition this rock shows affinities to the basaltic andesites. A specimen from the sea cliff just west of Moku Huki is similar, but contains 15 percent of feldspar phenocrysts reaching a length of 1 cm, consisting of a core of intermediate bytownite surrounded by a narrow zoned rim in which the composition progresses to calcic andesine. Fine fibrous brownish-green chloritic or serpentinous material (5%) may represent an alteration of interstitial glass.

The predominant lavas in the upper part of the section are much like the normal Honomanu basalts except that they carry pyroxene phenocrysts. The addition of pyroxene phenocrysts to the normal olivine basalts results in rocks which approach the picritic basalts in composition. The pyroxene phenocrysts are augite, while the pyroxene of the groundmass is pigeonite. A rock collected from the sea cliff near water level 1,000 feet northeast of Kapaula Gulch is typical of the olivine-augite porphyries of the upper part of the Honomanu volcanic series. It consists of phenocrysts of olivine, augite, and plagioclase, reaching a length of about 8 mm, in an intergranular to intersertal groundmass with an average grain size of about 0.1 mm. The olivine phenocrysts (8%) are colorless in thin section, and are altered around the edges to reddish-brown iddingsite. The augite phenocrysts (10%) are pale-brown, euhedral to subhedral, with $+2V = 60°$, and $r > v$ weak. Plagioclase phenocrysts (17%) are zoned from intermediate bytownite in the core to sodic labradorite at the outside. The olivine (5%) of the groundmass is completely altered to iddingsite. The groundmass pyroxene (20%) is a pigeonite with

$+2V = 45°$, and weak dispersion; and the plagioclase (25%) shows normal zoning from intermediate to sodic labradorite. The iron ore (8%) is in euhedral to anhedral grains; both lath-shaped crystals of ilmenite and nearly square crystals of magnetite are present, but the latter are the more abundant. Minute acicular crystals of apatite are enclosed in the feldspar. Some of the interstices (2%) are filled with brownish-green serpentinous or chloritic material, which appears to represent an alteration product derived from interstitial glass. The uppermost Honomanu lava encountered in test hole 65 is very similar to that just described, except for the presence of unaltered interstitial glass and a few anhedral flakes of biotite, pleochroic with $X =$ pale straw-yellow, and Y and $Z =$ deep reddish-brown, $-2V =$ nearly uniaxial, and $r > v$ strong.

HONOMANU LAVAS IN THE SUMMIT DEPRESSION.—Olivine basalts assigned by Stearns to the Honomanu volcanic series crop out in the south wall of the summit depression near Kumuiliahi (pl. 1). They underlie unconformably typical Kula lavas (fig. 10). Two specimens have been studied microscopically. Both are pahoehoe lavas, with abundant phenocrysts of feldspar reaching a length of 2 mm in one and 3 mm in the other. In one the phenocrysts constitute 20 percent of the rock, and are zoned from sodic bytownite to intermediate labradorite. The groundmass is intergranular, with an average grain size of 0.15 mm, and is composed of olivine (5%), partly altered to iddingsite; pale-green augite (30%); labradorite (30%); and iron ore (15%), including both magnetite and ilmenite. Minute needles of apatite are included in the feldspar, and a few patches of pale-brown interstitial glass are present. In the other specimen the phenocrysts constitute 25 percent, and show normal and oscillatory zoning from calcic to sodic labradorite. They are enclosed in an unusually coarse intergranular groundmass with an average grain size of 0.2 mm. The groundmass is composed of sodic labradorite (30%), with $\beta = 1.559$, olivine (5%), augite (30%), and iron ore (10%). The latter appears to be largely or entirely ilmenite. The augite is pale purplish-brown, with $+2V = 55°$, and $r > v$ strong on one axis and weak on the other. The mineral is probably titaniferous.

Cobbles of olivine basalt resembling those in the Honomanu volcanic series were collected from Pahihi and Waoala Streams. Both streams head high on the southern slope of the volcano not far south of the exposures of Honomanu lavas in the summit depression. It is possible, therefore, that Honomanu lavas are exposed in the headwaters of these streams. The cobble from Waoala Stream contains phenocrysts of plagioclase up to 5 mm in length, and slightly smaller ones of olivine and augite, in a dense, partly glassy base. That from Pahihi Stream contains abundant tabular phenocrysts of labradorite as much as 8 mm long by 1 mm thick. A few phenocrysts of fresh olivine up to 0.8 mm across also are present. The groundmass consists of labradorite, monoclinic pyroxene, olivine, iron ore, and a little interstitial glass. It is extremely fine grained and heavily clouded with pulverulent iron ore.

Lavas similar to those on the south side of the summit depression are exposed in the ridge which projects southward from Hanakauhi Peak on the north side of the summit depression. The ridge is largely mantled with Hana volcanics, but small windows of the underlying rocks are found on its eastern side. Four specimens of these underlying rocks have been examined. All are olivine basalts containing phenocrysts of feldspar. Two of them contain also rare small phenocrysts of pyroxene, and a third carries microphenocrysts of the same mineral. Microscopic examination shows that the large pyroxenes are glomerocrysts, composed of several smaller crystals with various orientations. One contains microphenocrysts of olivine, but in the others olivine is confined to the groundmass. The pyroxene is pigeonite with a variable but small optic angle, purplish-brown color, and strong inclined dispersion, and is probably titaniferous.

Still another small patch of lavas mapped with the Honomanu volcanics is located 0.87 mile S. 76° W. of Hanakauhi Peak, on the east side of Koolau Gap. The two specimens studied are both olivine basalts. One contains plagioclase phenocrysts (25%), zoned from sodic bytownite to sodic labradorite, and olivine phenocrysts (2%). The olivine is entirely fresh. The intergranular groundmass consists of labradorite (30%); augite (30%), with $+2V = 55°$; olivine (3%); and iron ore (10%). Extremely fine grained brownish-green material in the interstices is probably derived by the alteration of glass. Some of the vesicles are filled with calcite.

HONOMANU LAVAS IN MANAWAINUI CANYON.—Honomanu lavas form the lower walls of the gorge of Manawainui Stream north of Kaupo. Petrographically, they resemble the lavas of the upper part of the Honomanu group at Nahiku. All three of the specimens examined are olivine basalts, although one shows a tendency toward the andesites in the composition of its feldspar. All carry phenocrysts of plagioclase and pyroxene, and two also contain phenocrysts of olivine. The rock which is transitional to the andesites was collected at about 1,120 feet altitude on the floor of the gorge. It shows phenocrysts of plagioclase (8%), some of them crowded with inclusions of groundmass, zoned from calcic labradorite to labradorite-andesine; and phenocrysts of augite (2%), pale-brown under the microscope, with $+2V = 55°$. The groundmass is intergranular, and consists of labradorite-andesine (40%), monoclinic pyroxene (28%), olivine (7%), and iron ore (15%). The latter is mostly magnetite. A few flakes of pale-brown biotite are present.

Another lava, at an altitude of 1,060 feet along Manawainui Stream, contains phenocrysts of feldspar (10%), olivine (7%), and pigeonite (8%), up to 1 cm across. Fresh euhedral phenocrysts of olivine show an optic angle close to 90°. The plagioclase phenocrysts are zoned from calcic to sodic labradorite. The pigeonite phenocrysts are much rounded and embayed by resorption. They show a $+2V$ ranging from 25° to 50°, and strong inclined dispersion, with $r > v$ strong on one axis and weak on the other. Zoning, in part of the hour-glass type, is detectable in many crystals, the size of the optic angle decreasing in the outer zones. The groundmass is composed of sodic labradorite (35%), olivine (3%), monoclinic pyroxene (25%), and iron ore (12%). Needlelike crystals of apatite are abundant in the feldspar. One microphenocryst of magnetite 0.9 mm across is present, and is crowded with vermicular inclusions of groundmass.

HONOMANU LAVAS IN KIPAHULU VALLEY.—Lavas mapped as Honomanu are exposed low on two spurs projecting southward into Kipahulu Valley (pl. 1). They are basalts that resemble in petrographic character those already described, but lack the prominent phenocrysts of feldspar. Four specimens collected by Stearns were studied by the writer. Two of these are pahoehoe, and two aa. Two of them, one pahoehoe and the other aa, contain phenocrysts of olivine and pyroxene; the other two contain only olivine phenocrysts. The phenocrysts attain maximum diameters of 1.5 to 2 mm. In three of the rocks the pyroxene is pigeonite, in the other it is augite. In all, the pyroxene is pale purplish-brown, with distinct dispersion, and is probably titaniferous. Two of the rocks are low in feldspar and are transitional to the picritic basalts. One of these contains scattered phenocrysts of olivine (10%) and pigeonite (5%), with +2V ranging from 25° to 50°, and inclined dispersion with $r > v$ strong on one axis and weak on the other; in an intergranular groundmass composed of olivine (5%), pigeonite (32%), labradorite (38%), and iron ore (10%). The other is much the same, except that pigeonite is not present as phenocrysts. These rocks are much like some in the uppermost part of the Honomanu volcanic series at Nahiku.

KULA LAVAS

LAVAS IN THE NAHIKU AREA.—The Kula lavas in the Nahiku area appear to be typical of the Kula lavas erupted from the east rift zone exposed at points around the east end of the island and in Kipahulu and Waihoi Valleys. For this reason, and also because their petrography has aided in the deciphering of the geologic history and structure of the Nahiku area, described in Part 2, the Kula lavas of the Nahiku area are described in some detail in the following pages.

The rocks are basaltic andesites, intergranular in texture, with more or less well developed fluidal arrangement of the feldspars. The composition of the latter averages about calcic andesine. A small amount of olivine is present in all specimens, but the principal ferromagnesian constituent is monoclinic pyroxene. Iron ore constitutes from 15 to 20 percent of the rock, and apatite is present as tiny acicular crystals enclosed in feldspar, particularly in the interstitial feldspar. The latter has refractive indices in the range of oligoclase or sodic andesine, but typically shows an abnormally small positive optic angle, and is therefore probably a potash-bearing variety. Many specimens contain a few small irregular flakes of biotite.

The basal Kula flow in Hanawi Gulch below the Big Falls is a dense, nonporphyritic aa with intergranular texture, poorly developed fluidal structure, and an average grain size of about 0.05 mm. It is composed of fresh euhedral to subhedral grains of colorless olivine (8%), with 2V close to 90°; subhedral to anhedral laths of andesine-labradorite (35%), with slight normal zoning; minute subhedral granules of colorless monoclinic pyroxene (30%); anhedral interstitial grains of oligoclase (10%) with a small positive 2V; and euhedral to anhedral nearly equant crystals of magnetite (17%). Minute needles of apatite are enclosed in the interstitial oligoclase, and a few small irregular flakes of purplish-brown biotite are scattered throughout the rock.

The second Kula lava, in the waterfall at Big Spring, is a nonporphyritic, sparingly vesicular aa, with intergranular texture, well developed fluidal structure, and an average grain size of about 0.1 mm. A small amount of glassy matrix is present in places, making the texture locally intersertal. Euhedral to subhedral grains of olivine (5%) are partly altered to iddingsite. Subhedral to anhedral grains of pale purplish-brown augite (30%) have a +2V of about 55°, and weak dispersion. The plagioclase (45%) forms subhedral to anhedral lath-shaped grains, oriented in nearly parallel position by flowage, with normal zoning from labradorite-andesine to intermediate andesine. Interstitial grains of oligoclase (3%) appear to have a small positive 2V. Accessory minerals are magnetite (15%), and minute prismatic crystals of apatite enclosed in feldspar. Pale-yellow to colorless glass (2%), with a refractive index less than 1.54, fills some of the interstices. A few small anhedral flakes of purplish-brown biotite are present, and in a specimen of the same flow from test hole 82, it forms about 2 percent of the rock.

The third Kula lava is a massive, dense, nonporphyritic aa. Its texture is intergranular, and its grain size averages about 0.05 mm. The rock is composed of colorless euhedral to subhedral grains of olivine (10%), largely altered to reddish-brown iddingsite; minute prismatic grains of colorless monoclinic pyroxene (38%); subhedral to anhedral lath-shaped grains of calcic andesine (30%); anhedral interstitial grains of oligoclase (15%), with an apparent positive 2V varying from nearly uniaxial to about 60°; anhedral flakes of brown biotite (2%), pleochroic from nearly colorless to yellowish-brown; magnetite (15%); and minute highly acicular crystals of apatite. The rock exposed near the end of tunnel 46 beneath the Makaino lava, along the upper surface of which moves the large flow of water intercepted by this part of the tunnel, is nearly identical in petrographic character with the rock just described. However, zoning is more pronounced in the plagioclase, which ranges from sodic labradorite to medium andesine, and the yellowish-brown biotite is not quite so abundant. It is almost certainly Kula lava, since biotite is found in no other rocks of the area except the Kuhiwa lava, and it is probably a part of the third Kula flow.

The uppermost Kula lava exposed in Hanawi Gulch is a sparingly vesicular to dense, nonporphyritic aa. The texture is intergranular, with moderately well developed fluidal structure, and an average grain size of about 0.03 mm. The rock is composed of subhedral grains of colorless olivine (5%), some of which are altered to iddingsite; subhedral to anhedral grains of colorless monoclinic pyroxene (25%); subhedral to anhedral lath-shaped grains of calcic andesine (30%); anhedral interstitial grains of calcic oligoclase (20%), showing a +2V ranging from about 10° to 50°, and refractive indices $\alpha = 1.545$, $\beta = 1.548$, and $\gamma = 1.550$ ($\pm .003$); euhedral to anhedral nearly square grains of magnetite (20%); and minute acicular crystals of apatite.

KULA LAVAS ON THE WEST AND NORTHWEST SLOPES.—The Kula lavas on the west and northwest slopes resemble closely those of the Nahiku area, except that some are even more silicic. The dominant types are basaltic andesites and basalts, but both picritic basalts and true andesites also are present. The lines of demarcation between the various rock types are purely arbitrary; it is possible to find every gradation in composition from one end of the series to the other. All the rocks contain olivine, although the amount is generally less in the andesites than in the basalts. Biotite is a common constituent of the andesites, and is found in a few basalts.

The olivine basalts include both aa and pahoehoe flows. Olivine phenocrysts are generally visible to the unaided eye, but are less abundant than in the Honomanu lavas, and feldspar phenocrysts are much less common. Pyroxene phenocrysts are rare. A specimen typical of these rocks was collected on the Olinda pipe-line road, 0.3 mile west of Waikamoi Stream. Phenocrysts of olivine up to 1.5 mm across lie in an intergranular groundmass with an average grain size of 0.04 mm. The phenocrysts show no evidence of resorption. Many are skeleton crystals, some of the swallow-tailed variety, and others containing a core of groundmass in the form of a negative crystal. The groundmass consists of sodic labradorite, colorless prismatic grains of monoclinic pyroxene, olivine, and iron ore. A lava 0.5 mile S. 40° E. of Puu Nianiau is similar, except that it contains a few phenocrysts of labradorite and microphenocrysts of magnetite.

Basalt along the road 0.4 mile southwest of Puu Nianiau is nonporphyritic except for rare small phenocrysts of pyroxene. The rock is intergranular, with prominent fluidal arrangement of the feldspars. It is composed of plagioclase (43%), zoned from calcic to sodic labradorite; interstitial andesine (7%), with a small positive 2V averaging around 40°; olivine (5%); purplish-brown grains of pigeonite (35%), with $+2V = 30°$ to 50°, and strong inclined dispersion; and magnetite (10%).

The lava flow from the northwest side of Puu Nianiau is transitional to the picritic basalts. It is a moderately vesicular pahoehoe with many phenocrysts of olivine and augite up to 1.5 mm across. Many of the vesicles are partly filled with calcite. The olivine phenocrysts have an optic angle close to 90°. The augite phenocrysts are purplish-brown in thin section, with $+2V = 60°$, and strong inclined dispersion with $r > v$ strong on one optic axis, and $r < v$ weak on the other. Hour-glass structure is common, and many phenocrysts are compound. The groundmass is intersertal, with labradorite, olivine, monoclinic pyroxene, and iron ore in a glassy base. The lava which flowed down Honopou Valley is megascopically nonporphyritic, but in thin section resembles that from Puu Nianiau. Microphenocrysts of olivine, augite, labradorite, and magnetite lie in an intersertal groundmass of the same minerals with a little interstitial glass.

Picritic basalts are least abundant. They resemble the picritic basalts of the Hana volcanic series, such as the Big Falls lavas in the Nahiku area. One specimen, collected in a sewer trench at Paia, is remarkable for its large augite phenocrysts, and its abundant dunite and less abundant gabbro inclusions (pl. 43B). The rock is a dark-gray, sparingly vesicular pahoehoe, with phenocrysts of black augite as much as 2 cm across, and green olivine up to 5 mm across abundant in its basal part but rare near the top. In thin section the olivine phenocrysts (10%) are colorless, rounded and embayed by magmatic resorption, and altered around the edges and along fractures to iddingsite. Many of the grains show an outer layer of fresh olivine, often reforming the euhedral outlines of the crystal. The augite phenocrysts (15%) are pale-brown, euhedral to subhedral, with $+2V = 55°$, inclined dispersion and strong optic axial dispersion, $r > v$. The color becomes slightly purplish near the edges of the grains, and the dispersion and birefringence increase slightly, probably indicating an increase in titanium in the outer parts of the crystals. The groundmass consists of fresh olivine (10%), augite (20%), labradorite (35%), and iron ore (10%), the latter including both magnetite and ilmenite. The gabbro inclusions are small, 1 to 3 cm across, and angular to subangular in outline. They consist very largely of augite and feldspar, an average composition being 65 percent plagioclase and 35 percent augite. The plagioclase is intermediate labradorite ($\beta = 1.564$); the augite has $+2V = 60°$, and distinct dispersion. The dunite inclusions are angular to rounded, and are formed largely of anhedral grains of olivine, with minute crystals of magnetite or chromite and a few grains of monoclinic pyroxene.

Basalts which approach the basaltic andesites in feldspar composition are common. They contain plagioclase of the composition of sodic labradorite, but in addition considerable amounts of interstitial andesine or potash-andesine. In other respects they are like the olivine basalts. One specimen, from a depth of 550 feet in test hole 102 on Waikamoi Stream, contains many small flakes of brown biotite.

The basaltic andesites are essentially the same in texture and mineral composition as the basalts, except that the average composition of the feldspar falls within the range of andesine. The flows are characteristically denser and thicker than those of basalt, but these properties are greatly influenced by the distance from the vent and the steepness of the slope over which the lava flowed. Many joint surfaces parallel to the base of the flow show a micaceous sheen resulting from the parallel arrangement of innumerable small plates of feldspar. Most specimens show intergranular texture, and the average grain size of the groundmass is generally between 0.02 and 0.04 mm. Phenocrysts are much less abundant than in the basalts. The rocks are typically nonporphyritic, but phenocrysts of feldspar, augite, and olivine are present, the feldspar phenocrysts being most common.

The basaltic andesites are composed of feldspar, monoclinic pyroxene, olivine, and iron ore. The latter is generally magnetite. Apatite can be detected in nearly all the slides examined, forming minute highly acicular crystals enclosed in the interstitial feldspars. The olivine is colorless in thin section, with an optic axial angle close to 90°. It is altered to iddingsite in a few specimens, and to serpentine in one, but in most it is fresh. The nature of the groundmass pyroxene is uncertain, owing to the smallness of the grains, but the pyroxene phenocrysts are augite, with $+2V = 55°$ to $60°$, and distinct dispersion. Feldspar phenocrysts are zoned from intermediate or sodic labradorite to calcic andesine. The groundmass contains lath-shaped subhedral grains of calcic andesine, lying in a matrix of anhedral feldspar having the refractive index of sodic andesine or oligoclase, which often shows a small positive optic angle. This matrix of anhedral feldspar varies in amount from mere traces to 10 or 15 percent of the rock. It is found in small amounts in a few of the basalts, but is especially characteristic of the basaltic andesites and andesites.

Biotite is a common constituent of the basaltic andesites. It comprises only 1 or 2 percent of the rocks, but is widely distributed through them as small irregular flakes occupying interstices between the other minerals or projecting into vesicles. It is pleochroic from pale straw-yellow to purplish- or reddish-brown, with $-2V = 0°$ to $15°$, and $r < v$ generally strong. The reddish- and purplish-brown colors suggest that the mineral is probably titaniferous.[38]

Hornblende was found in only one specimen, collected by H. A. Powers at the Koolau ditch intake on the first stream west of Waikamoi Stream. The rock is unusual in containing phenocrysts of augite (14%), olivine (10%), and plagioclase (6%). The hornblende is greenish-brown and weakly pleochroic. Biotite constitutes about 2 percent of the rock.

Only three specimens of true andesite have been found on the west or northwest slopes of the mountain. All occur in test hole 102 on Waikamoi Stream, at depths of 171, 260, and 463 feet. They resemble the andesite of White Hill, to be described later. Small phenocrysts of andesine are imbedded in a trachytic groundmass composed of andesine, interstitial oligoclase with an apparent small optic angle, monoclinic pyroxene, olivine, and magnetite.

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[38] Hall, A. J., The relation between colour and chemical composition in the biotites: Am. Mineralogist, vol. 26, pp. 29-33, 1941.

The specimen from a depth of 260 feet contains vesicles into which project euhedral crystals up to 0.25 mm long of andesine, slightly pleochroic purplish-brown augite, and brown biotite. The rock contains prominent acicular crystals of apatite, some as much as 0.3 mm long.

KULA LAVAS IN THE SUMMIT REGION.—The Kula lavas of the summit region of East Maui include all the rock types found on the volcano. They range from picritic basalts to feldspathic oligoclase andesites. Kula lavas are well exposed in the walls of the summit depression and Koolau and Kaupo Gaps.

Olivine basalts are widely distributed. They closely resemble those of the western slope, already described. A specimen of this sort was collected on the north rim of the summit depression 0.8 mile east of Hanakauhi Peak, another on the east wall of Koolau Gap 0.39 mile S. 78° W. of Hanakauhi Peak, another at Waikane Spring on the west side of Kaupo Gap, and still another on the old Halemauu trail a little over half way up the west side of Koolau Gap. The lava from Aniani cone, a late Kula vent half a mile south of the south rim of the summit depression, fills the ancient valley of Waiopae Stream at the coast 1.85 miles west of Nuu. It is an olivine basalt, but is noteworthy in containing numerous flakes of biotite, some of them as much as 0.15 mm across. The mineral is strongly pleochroic, from pale straw-yellow to deep reddish-brown. Biotite is a common constituent of the andesitic rocks, but is rare in the olivine basalts.

A specimen collected on the south wall of the summit depression 0.2 mile N. 66° E. of Kumuiliahi, immediately above the unconformity at the top of the Honomanu lavas, contains phenocrysts of olivine, augite, and plagioclase, the latter zoned from intermediate bytownite to intermediate labradorite, in an intersertal groundmass of the same minerals with lesser amounts of magnetite and interstitial glass. It is transitional to the picritic basalts. A similar lava exposed on the summit road just west of the Haleakala rest house contains about 5 percent each of augite and olivine phenocrysts, but none of feldspar. The groundmass contains olivine (10%), augite (25%), labradorite (35%), interstitial andesine with an apparent small positive optic angle (10%), and iron ore (10%).

Typical of the picritic basalts is the "big-augite flow" exposed along the summit road west of the trail to the Haleakala rest house. The augites from this flow have been described and analyzed by Washington and Merwin,[39] and the analysis is quoted in the table on page 309. The properties of the augite were stated to be as follows: 2V for red $= 61°–62°$, 2V for blue $= 58°–60°$, $Z \wedge c = 47°–48°$ for red, 49° for blue, $\alpha = 1.700$, $\beta = 1.706$, $\gamma = 1.724$. The density, determined by L. H. Adams, is 3.358. The rock is dark-gray and sparingly to moderately vesicular, with phenocrysts of brownish-green olivine (25%) and black augite (25%) commonly reaching 1 cm across and some as much as 2 cm. In thin section the olivine phenocrysts are colorless, and euhedral to subhedral in outline. Many are slightly rounded and embayed by resorption, and surrounded by a thin shell of iddingsite, but others are completely fresh and unresorbed. The augite phenocrysts are euhedral to subhedral, and slightly purplish-brown. The groundmass is intergranular, with an average grain size of about 0.03 mm. It is composed of fresh olivine (5%),

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[39] Washington, H. S., and Merwin, H. E., Augite of Haleakala, Maui, Hawaiian Islands: Am. Jour. Sci., 5th ser., vol. 3, pp. 117-122, 1922.
Washington, H. S., and Keyes, M. G., Petrology of the Hawaiian Islands; VI. Maui: Am. Jour. Sci., 5th ser., vol. 15, p. 213, 1928.

augite (15%), labradorite (20%), magnetite (10%), and apatite enclosed in a few small interstitial patches of oligoclase or sodic andesine.

A picritic basalt collected on the old Halemauu trail just below the rim of the west wall of Koolau Gap is very similar to that just described, but slightly less mafic. Phenocrysts of olivine (15%) and augite (20%) lie in an intergranular groundmass containing olivine (5%), augite (30%), labradorite (30%), magnetite (20%), and a few small interstitial grains of andesine with an apparent small +2V. Mineral relationships in the groundmass are partly obscured by the abundant finely granular iron ore.

The transition from basalts to andesites is accomplished through a series of rocks of intermediate composition, closely similar to those described from the western slope of the mountain. Andesitic basalts are found unconformably overlying the Honomanu lavas on the south side of the summit depression, 0.15 mile N. 46° E. of Kumuiliahi, and forming a heavy-bedded flow which overtops a cinder cone near Waikane Spring, on the west wall of Kaupo Gap. Basaltic andesites are found in both walls of Koolau Gap and at other localities in the walls of the summit depression.

The andesite of White Hill, on the rim of the summit depression 0.3 mile northeast of Red Hill, described by Cross and analyzed by Steiger,[40] is typical of the East Maui andesites. The analysis is shown in the table on page 309. The rock is dense, medium-gray, and nonporphyritic, with fairly prominent flow structure expressed in platy jointing. Under the microscope the texture is trachytic with an average grain size of about 0.1 mm. Thin sections cut normal to the flow planes show subhedral to anhedral, lath-shaped crystals of plagioclase, between which are euhedral to subhedral stubby grains of olivine, colorless prismatic grains of monoclinic pyroxene, nearly square grains of magnetite, and crystals of apatite. Rare interstitial grains of feldspar with low index of refraction were identified as orthoclase by Cross, who noted also a few flakes of biotite.[41] No biotite was observed in the slides examined by the writer, but it is a common constituent of other andesites of East Maui. In a section cut parallel to the flow planes the feldspar plates are largely anhedral, and contain many inclusions of the other minerals. The plates average 0.2 mm long, 0.15 mm wide, and 0.05 mm thick. Many of them show a small +2V, generally about 45° to 50°. Judging from the refractive indices and the normative composition, the feldspar is probably a calcic oligoclase containing a considerable amount of potash feldspar. A micrometric analysis of the section yields the following values:

Feldspar	62.3%	Olivine	7.5%
Pyroxene	19.8	Magnetite	10.4

The lava beneath the White Hill andesite is similar, except that it contains scattered phenocrysts of olivine, augite, and basaltic hornblende. Many of the olivine phenocrysts are surrounded by a narrow rim of granular pyroxene. The augite phenocrysts are colorless to pale-green in thin section, with $+2V = 60°$, and $r > v$ weak. The subhedral crystals of basaltic hornblende have been much resorbed, with attendant liberation of finely granular magnetite. Many grains have entirely disappeared, leaving only a dense cloud of dusty ore marking the outlines of the former crystal. The basaltic hornblende is pleochroic, with X = brownish-yellow, Y = medium reddish-brown,

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[40] Cross, W., Lavas of Hawaii and their relations: U. S. Geol. Survey Prof. Paper 88, pp. 30-31, 1915.

[41] Idem, p. 31.

and Z = dark reddish-brown. The negative $2V$ is large, $r < v$ strong, and extinction is parallel. Basaltic hornblende originally formed about 1 percent of the rock.

The andesite exposed beneath the Haleakala rest house, at the western brink of the summit depression, was analyzed by Washington and Keyes[42] (table, p. 309). The rock is dense, medium- to light-gray, and nonporphyritic, with platy jointing parallel to the flow planes. The texture is intergranular, with a few microphenocrysts of plagioclase. The groundmass consists of subhedral lath-shaped grains of plagioclase, zoned from calcic andesine to oligoclase-andesine (40%); oligoclase (15%), with $+2V = 30°$ to $50°$, in anhedral interstitial grains and mantling the andesine laths; olivine (10%); augite (60%); magnetite (10%); and minute needle-like grains of apatite enclosed in the interstitial feldspar.

The most silicic rock studied from East Maui, judging by microscopic appearance, is an oligoclase andesite collected by Stearns on the east wall of Koolau Gap, 0.63 mile S. 89° W. of Hanakauhi Peak. The rock is a light-gray slightly vesicular aa, with poorly developed fluidal texture. Phenocrysts of andesine (6%) up to 1.5 mm across, are enclosed in a thin shell of oligoclase. Rare microphenocrysts of olivine and somewhat more abundant microphenocrysts of augite (1%) and magnetite (3%), are present also. A few stubby prisms of apatite reach lengths as great as 0.2 mm. The groundmass consists largely of anhedral to subhedral plates of oligoclase (60%), minute prisms of monoclinic pyroxene (23%), and magnetite (7%). The oligoclase has $\beta = 1.539$. The size of the optic angle appears normal in some grains, but positive and abnormally small, in the vicinity of 50°, in others. Another slide shows an irregular nest about 0.75 mm across, nearly devoid of dark minerals, in which lath-shaped grains of oligoclase are imbedded in alkali feldspar. This rock resembles the oligoclase andesites of West Maui, but in the latter the oligoclase always appears to have a normal large optic angle.

The most silicic lava from East Maui which has thus far been analyzed was collected by Cross at about 1,000 feet altitude in the ravine west of the old Vieira Ranch (present Kaupo Ranch) house. A careful examination of this area shows that the lavas in place, which belong to the Hana series, are all basalts or picritic basalts. However, these lavas have largely buried an old alluvial fan, which contains large blocks of a very silicic andesite, and it is believed that the specimen analyzed by Cross came from one of these blocks. The source of the blocks is uncertain, but is probably one of the massive Kula lavas exposed in the walls of the Kaupo Gap. The analysis is quoted in the table on page 309. The rock is described by Cross as dark and aphanitic, with small phenocrysts of andesine and magnetite in a groundmass of oligoclase-andesine, augite and olivine. These minerals lie in a matrix composed of two colorless minerals, one with a refractive index distinctly lower than that of balsam, which was considered to be orthoclase or some alkali feldspar, and the other with an index about the same as that of balsam and occurring rarely in rectangular forms, which was regarded as nepheline.[43] The description of the latter suggests that it might be the oligoclase with abnormally small positive optic angle and low birefringence which is found in many of the andesites of East Maui.

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[42] Op. cit., p. 211, no. 3.

[43] Cross, W., op. cit., p. 31.

HANA LAVAS

LAVAS IN THE SUMMIT DEPRESSION

The Hana lavas in the summit depression and those that flowed down Keanae and Kaupo Valleys include rocks which range nearly as widely in composition as the Kula lavas. Picritic basalts and basaltic andesites are common, but olivine basalts are probably most numerous.

A late prehistoric flow of aa which broke out on the southwest side of Mauna Hina is composed of medium-gray olivine basalt with many small crystals of feldspar up to 0.3 mm across arranged in parallel position by flowage. The texture is intersertal. Lath-shaped grains of intermediate labradorite and granules of olivine lie in a matrix of labradorite, monoclinic pyroxene, and glass. The glass is pale-brown, with a refractive index slightly above that of balsam, but is rendered nearly opaque by abundant iron ore dust. An olivine basalt collected by Powers at a waterfall on Waiokamilo Stream at 600 feet altitude represents the Waiokamilo lava (see page 96), an eastern branch of the lavas which form the floor of Keanae Valley. The rock is a dark-gray aa, containing a few phenocrysts of labradorite up to 5 mm across. The intergranular groundmass consists of olivine (10%); pale-brown augite (40%) with $+2V = 60°$ and weak dispersion; labradorite (40%); magnetite (10%); and a few interstitial grains of andesine. A rock from 1,000 feet altitude in the gully west of the trail in Kaupo Valley is similar to that just described, except that phenocrysts are absent.

Picritic basalts occur at a number of localities within the summit depression. One was described by Cross.[44] Steiger's analysis is quoted in the table on page 309. The lava was collected at the northeast base of Puu Namanaokeakua,[45] also known as Mamani Hill, which is located half a mile N. 21° W. of Puu Maile. A specimen collected by the writer at the same locality has been studied under the microscope. The rock is dark-gray, and contains numerous phenocrysts of brownish-green olivine and black augite up to 5 mm across. Phenocrysts are less abundant than in Cross' specimen, in which they were nearly equal in amount to the groundmass. The olivine phenocrysts (12%) contain many small inclusions of magnetite. The augite phenocrysts (15%) are pale purplish-brown, with $+2V = 60°$, and $r > v$ distinct on one axis and weak on the other. The purplish tinge is more intense near the border of some grains. Inclusions of magnetite in the augite are common, and one crystal includes a grain of olivine. The groundmass is intergranular and locally intersertal with an average grain size of 0.04 mm. It consists of olivine (6%); augite (30%) with $+2V = 50°$ and strong dispersion; labradorite (27%); magnetite (10%); and a small amount of pale-brown interstitial glass. A few interstitial grains of andesine are present, and appear to have a small optic axial angle. The lava flow from Puu o Maui is similar to that just described, but a little less mafic. The augite phenocrysts reach 1 cm across. A few microphenocrysts of plagioclase are present, and consist of intermediate labradorite surrounded by a narrow strongly zoned shell in which the composition changes to calcic andesine at the outer edge. The vesicles are lined or completely filled with botryoidal masses of white calcite.

Several olivine basalts from Keanae Valley are transitional toward the andesites. One of these is the Ohia lava, a specimen of which was collected

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[44] Op. cit., pp. 28-29.

[45] The name of this hill was spelled by Cross *Namaunakeakua*.

by Powers at the coast, 0.35 mile west of the triangulation station at Pauwalu Point (see page 94). Another specimen, also collected by Powers, comes from a point 0.1 mile southwest of the same triangulation station, and represents the Pauwalu lava. The Ohia lava contains 3 percent of olivine phenocrysts, reaching 1 mm across, in an intergranular groundmass composed of olivine (7%), monoclinic pyroxene (40%), labradorite-andesine (40%), and magnetite (10%). A few small interstitial grains of andesine are present. The Pauwalu lava is similar in composition, but lacks the olivine phenocrysts and carries instead rare phenocrysts of labradorite. The groundmass is composed of olivine (5%), monoclinic pyroxene (25%), labradorite (45%), interstitial andesine (15%) with a small positive optic angle, magnetite (10%), and minute prismatic crystals of apatite enclosed in the feldspar. In average feldspar composition the rock is a basalt close to the andesite line, but in abundance of feldspar it is andesitic. Much like the Pauwalu lava is a rock collected at the waterfall on Waiokamilo Stream at 600 feet altitude, underlying the Waiokamilo lava. The rock contains a few small phenocrysts of olivine in a groundmass which differs from that of the Pauwalu lava only in the slightly smaller percentage of interstitial andesine.

No andesites were found among the specimens of Hana lavas collected in the summit depression and Keanae and Kaupo Valleys, but they are almost certainly present, although probably less abundant than in the Kula lavas. Basaltic andesites of Hana age are known at Nahiku, and elsewhere along the east rift zone.

HANA LAVAS IN THE NAHIKU AREA

The Nahiku area, which has been studied in detail (see Part 2), affords a typical example of the structural and petrographic complexities of the Hana lavas erupted along the east rift zone. The rocks include olivine basalt, picritic basalt, and basaltic andesite. Along the rest of the rift zone the lavas are similar in type to those near Nahiku, but basalts and picritic basalts predominate over basaltic andesites. No special study has been made of lavas from the east rift zone in general, but those of the Nahiku area were described in detail, and lavas from Waihoi and Kipahulu Valleys are described in later sections.

BIG FALLS PICRITIC BASALTS.—The Big Falls lavas are very similar to the picritic basalt from the north base of Namanaokeakua cone in Haleakala Crater, described by Cross.[46] The type is common among the later Haleakala lavas. A specimen of Big Falls lava collected near sea level at the beach is a moderately vesicular pahoehoe with phenocrysts of brownish-green olivine and black augite up to 5 mm long, but averaging about 3 mm. In thin section the olivine phenocrysts (5%) are colorless euhedral to subhedral crystals. The augite phenocrysts (5%) are pale brown, euhedral to subhedral, with $+2V = 55°$, and $Z \wedge c = 44°$. The groundmass is intergranular, with an average grain size of 0.05 mm. It is composed of subhedral to anhedral pale-brown grains of augite (40%), with optical properties much like those of the phenocrysts; subhedral to anhedral lath-shaped grains of plagioclase (35%), with cores of labradorite-bytownite, passing to calcic andesine in a narrow, strongly zoned rim; interstitial oligoclase (5%) with an apparent small

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[46] Op. cit., pp. 28-29.

+2V, enclosing tiny acicular crystals of apatite; and euhedral to anhedral nearly square grains of magnetite (10%).

The lava exposed in the plunge pool where Makaino Stream drops into Hanawi Gulch is a moderately vesicular pahoehoe, with phenocrysts of olivine and augite up to 5 mm across, but most of them only 1 or 2 mm. The olivine phenocrysts (17%) are colorless, euhedral to subhedral in outline, a few showing a small amount of corrosion by magmatic resorption, and all of them altered around the edges to a narrow rim of iddingsite. The augite phenocrysts (3%) are euhedral to subhedral, with a pale, slightly purplish-brown color, and +2V about 60°. The slight purplish tinge suggests that the mineral is probably titaniferous. The groundmass is intergranular, with an average grain size of 0.08 mm. It is formed of olivine (10%), largely or entirely altered to iddingsite; subhedral to anhedral pale purplish-brown augite (25%), with $+2V = 55°–60°$; subhedral to anhedral lath-shaped crystals of sodic bytownite (25%), the larger grains showing slight normal zoning; interstitial oligoclase or sodic andesine (5%), with a small apparent +2V; apatite (1%), especially abundant in the interstitial feldspar; and euhedral to anhedral grains of magnetite (14%). Lava from the plunge pool on the West Branch of Makapipi Stream is very similar to that just described, except that interstitial oligoclase is a little more abundant; and a small amount (1%) of pale brownish-yellow interstitial glass, with a refractive index slightly above that of balsam, is locally present. The olivine is largely altered to iddingsite, but a few cores of iddingsite are surrounded by subhedral shells of unaltered olivine.

The rock mapped as Big Falls lava on the west wall of Kapaula Gulch contains besides the usual phenocrysts of olivine and augite, others of plagioclase and magnetite. The olivine phenocrysts (4%) show evidence of minor resorption. The augite phenocrysts (6%) are pale brown in color, with $+2V = 55°$ and weak dispersion. The plagioclase phenocrysts (8%) are euhedral to subhedral in outline, with Carlsbad and albite twinning and normal zoning from calcic to sodic labradorite; some grains are crowded with irregular inclusions of glass and groundmass materials. Magnetite phenocrysts (2%) reach a maximum diameter of 1 mm; some of them contain near their margins peculiar lobate bays and inclusions of groundmass. The groundmass is intergranular to intersertal, and averages 0.05 mm in grain size. It comprises pale brown subhedral to anhedral crystals of augite (20%) like that of the phenocrysts; subhedral to anhedral lath-shaped grains of plagioclase (25%), zoned from intermediate labradorite to labradorite-andesine; anhedral interstitial grains of oligoclase or sodic andesine (5%), with an apparent small +2V; nearly equant crystals of magnetite (15%); and interstitial glass and fibrous brownish-green material, possibly celadonite (5%). The latter also lines a few small vesicles.

Makapipi basalts.—A specimen of Makapipi basalt collected 15 feet above water level in the plunge pool where Makaino Stream falls into Hanawi Gulch has an intergranular texture, with a few larger grains of olivine set in a matrix of small plagioclase crystals with still smaller grains of pyroxene, olivine, feldspar, and iron ore filling the interstices. The average grain size is about 0.04 mm. Fluidal structure is moderately well developed. The large grains of olivine, which reach a length of 0.07 mm, are colorless, subhedral in outline, and contain a few small inclusions of iron ore. They show a transition in size into the olivine of the matrix. The total olivine is about 20 percent of the rock. The plagioclase (34%) forms subhedral to anhedral, lath-shaped crystals, with normal zoning from intermediate labradorite to intermediate andesine. Interstitial grains of oligoclase (10%) show a small +2V. Augite (17%), in colorless prismatic grains, shows +2V = 60° and weak dispersion. Apatite (1%) forms minute needlelike crystals enclosed in the interstitial feldspar. Euhedral to anhedral nearly square grains of magnetite form about 18 percent of the rock. A specimen collected about 15 feet above the plunge pool under the big waterfall on Makapipi Stream 2,300 feet north of the highway, is closely similar microscopically to that just described, except that the pyroxene is a pigeonite, with +2V = 35°.

In a 4-foot waterfall on Makapipi Stream 1,300 feet north of the highway, Makapipi basalt is exposed beneath a thin capping of Mossman lava. The rock is a moderately to highly vesicular pahoehoe, with a few small phenocrysts of olivine reaching 1 mm across. Some of the vesicles contain hemispherical masses of calcite up to 3 mm across, known in Hawaii as Pele's pearls. The texture of the groundmass is intergranular, and locally diabasic; the grain size is unusually large, averaging 0.1 mm. The grains of olivine (15%) are colorless, euhedral to subhedral, with a few small inclusions of iron ore, and an optic axial angle close to 90°. The augite (35%) is probably titaniferous. It has a purplish-brown color, +2V = 55°, and strong dispersion of the bisectrices, with $r > v$ strong on one axis, and $r < v$ weak on the other. The plagioclase (30%) forms subhedral to anhedral lath-shaped grains, with normal zoning. The core of each zoned crystal is of calcic to intermediate labradorite, passing through a narrow strongly zoned rim into sodic andesine. Interstitial anhedral grains of oligoclase (7%) appear to have a small +2V. Minute acicular crystals of apatite (1%) are enclosed in the feldspar and are especially abundant in the interstitial oligoclase. Iron ore (12%) includes both lath-shaped grains of ilmenite and nearly square grains of magnetite, but the latter is the more abundant.

WAIAAKA BASALTIC ANDESITE.—The Waiaaka lava is typically dense and nonporphyritic, although some specimens contain a few small phenocrysts of plagioclase, and others contain scattered phenocrysts of brownish-green olivine reaching 1.5 mm across. The composition of the feldspar varies in different thin sections, but averages about calcic andesine in each of the slides examined. The rock is a basaltic andesite.

The Waiaaka lava at the first large waterfall on East Hanawi Stream north of the Koolau ditch is nonporphyritic, with intergranular texture, and 0.03 mm average grain size. Lath-shaped subhedral microlites of plagioclase (40%), zoned from intermediate labradorite to sodic andesine, lie in subparallel positions. Between them are colorless subhedral to anhedral grains of olivine (5%); pale-brown subhedral grains of augite (30%), with +2V = 60°, and distinct dispersion of the bisectrices; anhedral grains of oligoclase (15%), with an abnormally small positive apparent optic angle, and abundant inclusions of apatite; and euhedral to anhedral grains of magnetite (10%).

The basal part of the flow exposed in a road cut on the west side of Hanawi Gulch about 500 feet north of the bridge, is similar in many respects to that just described. The rock is sparingly vesicular and the vesicles are lined with a thin layer of brownish-green material, possibly celadonite. Many of them contain small hemispherical masses of calcite with radiating structure.

Abundant plates of feldspar, averaging about 0.3 mm across, and well oriented in the planes of flow, are imbedded in an intergranular matrix with an average grain size of 0.02 mm. The large plates of plagioclase (20%) are zoned from calcic labradorite in the center to calcic andesine on the outside. The rest of the rock consists of olivine (5%), pale purplish-brown augite (25%), calcic andesine (20%), interstitial oligoclase or sodic andesine (10%), apatite, and magnetite (20%).

KAPAULA BASALTIC ANDESITE.—The Kapaula lava in the highway cut near the western edge of the flow is moderately vesicular and nonporphyritic. The texture is intergranular and locally intersertal. Microphenocrysts of plagioclase and olivine reach a length of 0.5 mm, and lie in a groundmass with an average grain size of 0.02 mm, composed of feldspar, pyroxene, and iron ore. The olivine (10%) is colorless, and euhedral to subhedral in outline. The pyroxene (25%) forms colorless prismatic grains with inclined extinction. Euhedral to anhedral nearly square grains of magnetite are abundant (18%). Subhedral to anhedral lath-shaped crystals of plagioclase (45%) show normal zoning from sodic labradorite to intermediate andesine; and a few anhedral grains of oligoclase or sodic andesine, a small amount of colorless glass, and fibrous green chloritic material occupy the interstices. A rock from the east fork of Kapaula Stream about 300 feet north of the road, is similar to that just described, except that it contains a single phenocryst of augite 15 mm long. The augite is pale-brown, with $+2V = 55°$ and weak dispersion. Another rock, from the south side of the bridge across the east fork of Kapaula Stream, is much like the first two, but magnetite is a little less abundant and the plagioclase slightly more calcic, zoned from medium labradorite to medium andesine. Interstitial oligoclase (5%) shows a small positive 2V. The Kapaula lava is a basaltic andesite.

In many places the Kapaula lava contains numerous minute irregular vesicles into which project a few laths of feldspar. The texture resembles that described by Fuller, in which the escape of the residual liquid or gaseous portion leaves an open network of plagioclase laths and grains of olivine and pyroxene.[47]

MAKAINO BASALTIC ANDESITE.—The Makaino basaltic andesite at the highway bridge over the western distributary of Makaino Stream has well developed fluidal structure and very irregular vesicles generally less than 0.5 mm across, into some of which project thin plates of feldspar. The texture is intergranular to intersertal. Crystals of feldspar and olivine as much as 0.4 mm long are imbedded in a matrix of feldspar, pyroxene, iron ore, and glass, with an average grain size of 0.05 mm. The plagioclase (40%) has normal zoning, and ranges from sodic labradorite to calcic oligoclase; $X \wedge 001$ ranges from 26° to 4°. Anhedral interstitial grains of oligoclase (15%) have a positive optic angle ranging from about 20° to 50°, and contain abundant minute acicular inclusions of apatite. Monoclinic pyroxene (20%) forms subhedral to anhedral colorless grains. Olivine (10%) occurs in subhedral crystals, mostly colorless, but a few showing greenish-yellow stain owing to incipient alteration. Inclusions of iron ore are common in the olivine. Magnetite (15%)

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[47] Fuller, R. E., The geomorphology and volcanic sequence of Steens Mountain in southeastern Oregon: Washington Univ. (Seattle) Pub. in Geology, vol. 3, no. 1, p. 116, 1931; Gravitational accumulation of olivine during the advance of basaltic flows: Jour. Geology, vol. 47, p. 304, 1939. The name *dictytaxitic* was proposed for this texture.

forms nearly square grains, some of which reach a diameter of 0.1 mm. Another specimen, from the East Branch of Hanawi Stream at the Koolau ditch, is similar to that just described except that olivine is slightly more abundant, and fluidal structure is absent.

The Makaino lava at Hanawi Spring no. 2 is similar to that at the highway. Olivine forms about 10 percent, and monoclinic pyroxene about 20 percent. Plagioclase (40%) is zoned from intermediate labradorite to sodic andesine, and a few anhedral grains of oligoclase occupy interstices between the other minerals. Magnetite is abundant (20%), forming euhedral to anhedral grains, and much of the rock is so clouded with dusty iron ore that the nature of the minerals and their relationships are partly obscured. About 5 percent of colorless to pale yellow glass is present in the interstices.

MOSSMAN PICRITIC BASALT.—The Mossman lava 50 feet upstream from the highway in the western distributary of Makaino Stream is a moderately vesicular pahoehoe with abundant phenocrysts of augite up to 4 mm across, and less abundant phenocrysts of olivine, in a microcrystalline base. A few phenocrysts of magnetite, up to 0.5 mm across, are also present. The olivine phenocrysts (10%) are colorless, euhedral to subhedral in outline, and reach a maximum diameter of 2.5 mm. They contain many small inclusions of iron ore. Augite phenocrysts (15%) are euhedral to subhedral, some of them much embayed by magmatic resorption, and also contain many small inclusions of iron ore. They are pale purplish-brown, suggesting the presence of titanium, with $+2V = 55°$, moderate inclined dispersion of the bisectrices, and dispersion of the optic axes with $r > v$ strong on one axis, and weak on the other. Zoning, with $Z \wedge c$ about 44° in the center and 49° at the outside, suggests a progressive change in composition toward a more iron-rich member. The groundmass is intergranular, with an average grain size of 0.1 mm. It is composed of pale purplish-brown augite (20%), with $+2V = 55°$, and $Z \wedge c = 49°$; olivine (10%); subhedral to anhedral laths of calcic labradorite (25%); interstitial grains of oligoclase or sodic andesine (5%), with a small to moderate positive optic angle, and many minute acicular inclusions of apatite; and euhedral to anhedral nearly square grains of magnetite (15%).

Along the West Branch of Makapipi Stream 650 feet southwest of its confluence with the East Branch, the lava is similar to that just described, except that phenocrysts are even more abundant. Augite phenocrysts constitute about 20 percent of the rock, and olivine phenocrysts about 15 percent. The Mossman lava is much like the picritic basalt described by Cross from the base of Namanaokeakua cone in the summit depression of Haleakala.[48]

KUHIWA BASALTIC ANDESITE.—The Kuhiwa flow is the only one in the Nahiku area later than the Kula lavas, which has been found to contain biotite. A specimen collected on the east bank of Makapipi Stream 700 feet south of the road is typical. The texture is intergranular and trachytic, and averages 0.07 mm in grain size. The rock is composed of colorless subhedral grains of olivine (10%); subhedral to anhedral pale-brown to colorless grains of augite (30%), with $+2V = 50°$, and $r > v$ strong; subhedral to anhedral lath-shaped crystals of plagioclase (40%), with normal zoning from sodic labradorite to calcic andesine; interstitial oligoclase or sodic andesine (10%) with a $+2V$ ranging from nearly uniaxial to about 50°; euhedral to anhedral nearly equant grains

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[48] Cross, W., op. cit., p. 28.

of magnetite (10%); tiny prismatic crystals of apatite enclosed in feldspar; and a few pale purplish-brown flakes of biotite. Another specimen, taken in tunnel 18, is similar to that just described. A few small phenocrysts of olivine are present, and olivine is also found in the groundmass. The rock consists of olivine (8%); pale purplish-brown augite (25%); plagioclase (35%), zoned from sodic labradorite to intermediate andesine; interstitial oligoclase (15%), with irregular or undulatory extinction and a small positive optic angle; anhedral interstitial flakes of purplish-brown biotite (2%); magnetite (15%); and minute acicular crystals of apatite.

The lava exposed on the road to Nahiku Village 200 feet north of the highway is identical to those described above, except that biotite is absent and platy jointing and trachytic texture are much better developed. The Kuhiwa lava is a basaltic andesite.

PAAKEA BASALT.—The rock exposed near the highway bridge over Paakea Stream is fairly typical of the Paakea basalt. It is moderately vesicular, with scattered phenocrysts of olivine up to 2 mm across. Phenocrysts of olivine and microphenocrysts of feldspar and augite grade in size into the intergranular groundmass. The average grain size is 0.03 mm. Microphenocrysts of feldspar reach a maximum length of 0.5 mm, and augite 0.25 mm. Fluidal texture is present but weakly developed. The olivine crystals (10%) are colorless, euhedral to subhedral, with an optic angle near 90°. Augite microphenocrysts form subhedral pale brown grains with $+2V = 50°$, and $r > v$ strong. The grains of groundmass pyroxene are too small to yield optic figures. Total pyroxene forms about 30 percent of the rock. Lath-shaped crystals of labradorite (40%) show Carlsbad and albite twinning, and weak normal zoning. Anhedral interstitial grains of oligoclase or sodic andesine form about 5 percent of the rock. Nearly equant grains of magnetite constitute about 15 percent of the rock.

A specimen collected at the Koolau ditch 600 feet west of Paakea Stream is similar in every respect to that just described, except that feldspar phenocrysts are a little more numerous and a little larger, attaining a length of 0.75 mm. Also, the zoning in the feldspar phenocrysts is more pronounced, the composition ranging from calcic labradorite in the center to labradorite-andesine on the outside. A specimen from the lava occupying the lower end of Waiohue Gulch is much the same, except that olivine is slightly more abundant and microphenocrysts of augite and feldspar are smaller, being hardly separable from the groundmass. Throughout the Paakea flow it is probable that very few of the phenocrysts other than those of olivine represent intratelluric crystallization.

HANAWI BASALTIC ANDESITE.—The lava occupying the bed of Hanawi Stream 150 feet north of the highway bridge is nonporphyritic, with poorly developed platy jointing. The texture is intergranular to intersertal, and weakly fluidal. Lath-shaped microlites of plagioclase and microphenocrysts of olivine, up to 0.5 mm long, lie in a groundmass averaging 0.02 mm in grain size but which is locally so fine grained that it cannot be resolved under ordinary magnifications. The olivine (15%) is colorless, subhedral, and totally unaltered, with a few small inclusions of iron ore. It occurs both as microphenocrysts and in the groundmass. Some of the microphenocrysts have been partly corroded by magmatic resorption. Minute colorless subhedral prisms of monoclinic pyroxene (20%) are probably pigeonite; the positive optic angle appears to be less than 40°, and $Z \wedge c = 48°$. The plagioclase (30%) forms lath-shaped subhedral to anhedral crystals, the larger ones with a core of intermediate to sodic labradorite surrounded by a narrow outer rim of andesine. Interstitial anhedral grains of oligoclase or sodic andesine (15%) show a small positive 2V. Magnetite (20%) forms nearly square subhedral to anhedral grains, and tiny acicular crystals of apatite are enclosed in the feldspar.

Hanawi lava collected at the Koolau ditch contains several phenocrysts of olivine less than 1 mm across, and one about 5 mm in diameter. Platy jointing is only moderately well developed, but the joint surfaces show a distinct micaceous-appearing sheen owing to reflection from the cleavage faces of innumerable similarly oriented tabular crystals of feldspar. Microscopic examination shows microphenocrysts of augite lying in an intergranular groundmass consisting of lath-shaped plagioclase microlites in a matrix of finely granular pyroxene, feldspar, and iron ore. The olivine phenocrysts (18%) are euhedral to subhedral, colorless, with a few small inclusions of iron ore. Some contain irregular masses of finely crystalline groundmass material. The augite microphenocrysts (4%) are pale brown in color with $+2V = 55°$, strong dispersion of the bisectrices, and dispersion of the optic axes $r < v$ weak on one axis and $r > v$ strong on the other. A few grains of augite show hour-glass structure. The monoclinic pyroxene of the groundmass (22%) forms tiny subhedral colorless grains. Lath-shaped plagioclase microlites (25%) are zoned from intermediate labradorite to intermediate andesine. Minute interstitial grains of oligoclase or sodic andesine (10%) are too small to yield conoscopic figures. Subhedral to anhedral nearly square grains of iron ore, probably magnetite, form about 20 percent of the rock, and apatite (1%) occurs as minute prismatic crystals enclosed in the feldspars.

A sample collected near that just described, but higher in the flow, is nonporphyritic, and lacks the platy jointing. In thin section it resembles the other rock, except that augite microphenocrysts are absent, and the average composition of the plagioclase microlites is slightly more sodic, the zoning progressing from a core of intermediate labradorite to an outer shell of oligoclase-andesine.

HANA LAVAS IN WAIHOI VALLEY

Three specimens of the Hana lavas which fill the bottom of Waihoi Valley have been studied. Two of these are olivine basalts. One, collected by Powers near the center of the valley at an altitude of 1,800 feet, contains phenocrysts of olivine (5%) up to 2 mm across, slightly altered around the edges to iddingsite, in an intergranular groundmass composed of olivine (5%), pale purplish-brown augite (30%) with $+2V = 60°$ and weak dispersion, labradorite (40%), interstitial andesine with a small positive 2V (5%), and magnetite (15%). The other, collected by Stearns from the lava which follows Opaekui Stream (the north fork of Waiohonu Stream), 0.3 mile S. 62° E. of Puu Hoolewa, contains in addition to phenocrysts of olivine, microphenocrysts of augite and labradorite. The augite is pale purplish-brown, with $+2V = 55°$, and strong dispersion. Hour-glass structure is common, and a few cruciform twins were observed. The groundmass consists of sodic labradorite, olivine, pigeonite, and magnetite, the pigeonite showing a small variable optic angle and strong dispersion.

A specimen of picritic basalt was collected by Stearns at the north side of Waihoi Valley, 0.18 mile S. 60° E. of Puu Hoolewa. It contains phenocrysts of augite and brownish-green olivine, and resembles the Mossman lava at Nahiku and the lava from the northeastern base of Puu Namanaokeakua in the summit depression. The phenocrysts are smaller, however, not exceeding 1.5 mm. The olivine phenocrysts (8%) are rounded and embayed by resorption and surrounded by a thin shell of iddingsite. The augite phenocrysts (10%) are pale purplish-brown, with distinct zoning, some of it of the hour-glass variety. The core shows $+2\text{V} = 60^\circ$, $\text{Z} \wedge c = 47^\circ$, $r > v$ strong on one axis, and $r < v$ weak on the other. The outer zones show even stronger dispersion, and $\text{Z} \wedge c = 53^\circ$, but there is no obvious change in the size of the optic angle. The variations in the properties of the augite are like those described by Stark and Howland for zoned augites from Borabora,[49] and indicate a change of later crystallized pyroxenes toward types poorer in lime and richer in iron. The same change has been noted previously in Hawaiian lavas,[50] and agrees with the trend of pyroxene differentiation found by Barth[51] and by Wager and Deer.[52] The groundmass of the rock consists of olivine (5%), purplish augite (30%), labradorite (30%), and iron ore (17%).

EARLY HANA LAVAS IN KIPAHULU VALLEY

Kipahulu Valley has been subjected to two great cycles of valley filling in Hana time. (See Part 1.) Specimens of the early valley-filling lavas, known as the Kipahulu member of the Hana volcanic series, were collected by Stearns. They include both basalts and andesites. One specimen was collected near the center of the valley, 1.52 miles S. 24° E. of Wai Anapanapa, from a cliff over which cascaded lavas of the later valley fill. It is a brownish-gray, sparingly vesicular, nonporphyritic basaltic andesite, consisting of lath-shaped microlites of andesine arranged in a well-defined fluidal structure, between which are grains of olivine, monoclinic pyroxene, and magnetite. A few flakes of brown biotite are present. The ferromagnesian minerals have been partly altered and minute flakes of hematite are scattered through the rock, probably as a result of gas action during consolidation of the flow.[53]

A similar lava was collected 35 feet below the top of the cliff at the northeast edge of the early valley-filling lavas, 1.42 miles S. 80° W. of Kaumakani Peak. Phenocrysts of olivine up to 1 mm across, many of them partly altered to iddingsite, lie in a fine-grained partly glassy groundmass heavily clouded with iron ore dust. Flakes of biotite project into some of the vesicles. The biotite appears uniaxial, and is pleochroic from X = nearly colorless to Y and Z — pale-brown. A few grains of alkali feldspar, with refractive index less than that of balsam, also line the vesicles. The plagioclase microlites have the refractive index of calcic andesine. Many of the olivine phenocrysts are skeleton crystals, containing cores of the groundmass.

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[49] Stark, J. T., and Howland, A. L., Geology of Borabora, Society Islands: B. P. Bishop Mus. Bull. 169, pp. 32-33, 1941.

[50] Macdonald, G. A., Petrography of Kahoolawe: Hawaii Div. of Hydrography, Bull. 6, p. 157, 1940.

[51] Barth, T. F. W., Crystallization of pyroxenes from basalts: Am. Mineralogist, vol. 16, p. 199, fig. 1, 1931; The crystallization process of basalt: Am. Jour. Sci., 5th ser., vol. 31, pp. 325-328, 1936.

[52] Wager, L. R., and Deer, W. A., Geological investigations in East Greenland, III. The petrology of the Skaergaard intrusion, Kangerdlugssuaq, East Greenland: Med. om Grønland, Komm. for Videnskabelige undersøgelser i Grønland, Bd. 105, Nr. 4, pp. 240-261, 1939.

[53] Broderick, T. M., Differentiation in lavas of the Michigan Keweenawan: Geol. Soc. America Bull., vol. 46, p. 505, 1935.

A specimen collected at the same locality, 300 feet below the top of the cliff, is an olivine basalt, with a few phenocrysts of olivine and microphenocrysts of olivine, augite, and labradorite in a groundmass composed of monoclinic pyroxene, olivine, labradorite, magnetite, and a little interstitial glass. The olivine phenocrysts have an optic angle close to 90°. The augite phenocrysts are pale purplish-brown, with $+2V = 55°$, $r > v$ distinct on one optic axis and no detectable dispersion on the other.

LATE HANA LAVAS IN KIPAHULU VALLEY

The lavas of the later Kipahulu Valley fill are predominantly basalts, although a few andesitic rocks were found. There is nothing especially noteworthy about the olivine basalts. Most specimens contain small phenocrysts of olivine, and a few contain small phenocrysts of labradorite. Some contain pale purplish-brown augite, with +2V close to 60° and distinct dispersion, but in most the monoclinic pyroxene is colorless, and the grains too small to yield optic figures. Pale-brown interstitial glass with $n <$ balsam is common, and in one specimen it lines the vesicles. Two specimens, in which interstitial glass is absent, contain small amounts of interstitial andesine.

A sample collected by Stearns near the southwest edge of the later valley fill, 1.25 miles S. 82° W. of Kaumakani Peak, represents a transition to the andesites. Petrographically it resembles the Makapipi basalts at Nahiku. Microphenocrysts of intermediate labradorite (9%) and olivine (6%) lie in an intergranular groundmass composed of labradorite (30%), olivine (5%), monoclinic pyroxene (20%), magnetite (15%), and interstitial andesine (15%), the latter having a small positive 2V, some grains appearing nearly uniaxial.

A lava collected by Powers near the west side of Kipahulu Valley at the beach is similar to that just described. However, the olivine phenocrysts are larger, and plagioclase phenocrysts are absent. The groundmass pyroxene is diopsidic, colorless, with $+2V = 55°$ and no detectable dispersion. The plagioclase is zoned from intermediate labradorite to calcic andesine. The lava underlying this at the same locality is a dense nonporphyritic biotite andesite with poorly developed platy jointing. The rock is intergranular in texture, composed of olivine (8%); diopsidic pyroxene (25%), with $+2V = 60°$, and no detectable dispersion; purplish-brown biotite (2%); magnetite (10%); lath-shaped microlites of plagioclase (40%), zoned from calcic andesine to oligoclase-andesine; and interstitial oligoclase (15%), with refractive index close to that of balsam, low birefringence, irregular extinction, and +2V variable but small, generally close to 0°.

The western branch of the late Kipahulu lavas which descended the valley of Koukouai Stream has been sampled by Stearns at two places. Both samples are basaltic andesite. One, collected at an altitude of 940 feet in Koukouai Gulch contains lath-shaped microphenocrysts of plagioclase zoned from sodic labradorite to calcic andesine, and grains of olivine and magnetite, in a fine-grained matrix composed of calcic andesine, colorless monoclinic pyroxene, iron ore, and a few grains of andesine up to 0.3 mm across. The other specimen was collected at 3,900 feet altitude in the north fork of Koukouai Stream, in a jungle-covered area where the late Kipahulu and early Kipahulu lavas were not differentiated on the map. It is identical to the first in most respects, but is remarkable in containing a number of grains of riebeckite-like amphibole. The mineral is acicular, pale purplish-gray parallel to the *c* axis, and pale-yellow normal to it. X is nearly parallel to the *c* axis, and the birefringence is very low, about .004. The mineral is common in the Honolua andesites and trachytes of West Maui, but has been found in no other East Maui lava.

HANA LAVAS OF THE SOUTHWEST RIFT ZONE

The Hana lavas erupted along the southwest rift are too much like those of the summit depression and east rift zone to warrant their detailed description. They are mostly olivine basalts, but basaltic andesites are also present. One such lava is exposed along the highway near Makena, 2,500 feet east of Puu Mahoe. The flow crossed by the highway on the west side of Puu Mahoe is an olivine basalt, containing phenocrysts of olivine and microphenocrysts of labradorite and augite. The lava along the highway 1,500 feet east of Puu Mahoe, between the flow from Puu Pimoe and the 1750 (?) lava flow, contains phenocrysts of olivine and microphenocrysts of augite in a very fine grained, largely unresolvable, partly glassy base. The lava flow from Puu Pane is a nonporphyritic olivine basalt. The lava from Puu Pimoe is an olivine basalt containing phenocrysts of olivine (3%) and a few of augite in an intersertal groundmass composed of olivine (5%); augite (32%), with $+2V = 60°$ and distinct inclined dispersion; labradorite (35%); interstitial andesine (5%) with a small positive 2V; magnetite (15%); and pale-brown interstitial glass (5%). An older lava flow crossed by the coastal trail 1.2 miles southeast of Keoneoio, is similar to the Pimoe flow, but augite phenocrysts are more numerous, and interstitial andesine has not been recognized.

HISTORIC (1750?) LAVA FLOW

The lava flow near Makena, erupted about the year 1750, probably issued from two separate vents low on the southwest rift. One flow originated at Kaluaolapa, at an altitude of 575 feet, and the other from a fissure at an altitude of 1,200 feet a mile to the northeast (pl. 1). The two lavas are identical in composition in hand specimen and under the microscope. The rock is a picritic basalt of aa type, containing abundant phenocrysts of yellowish-green olivine up to 5 mm across and black augite as much as 8 mm across. The augite phenocrysts (18%) are pale purplish-brown, euhedral to subhedral in outline, with $+2V = 55°$, and distinct inclined dispersion with $r > v$ strong on one optic axis and very weak on the other. In places a number of small grains are grouped together to form glomerocrysts. The olivine phenocrysts (20%) are colorless in thin section, with a 2V close to 90°. The groundmass is intersertal, with an average grain size of 0.05 mm. It consists of olivine (5%); augite (25%) with $+2V = 55°$ and distinct inclined dispersion; labradorite (22%); interstitial andesine (2%); magnetite (10%); and pale-brown glass (3%), heavily charged with dusty iron ore.

The lava was briefly mentioned by Sidney Powers[54] and a specimen collected by him was described by Washington and analyzed by Keyes.[55] Powers states that the 1750 flow issued from Puu Pimoe, and Washington accepts this statement. Inasmuch as the 1750 flow and the flow from Puu Pimoe are entirely

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[54] Powers, S., Notes on Hawaiian petrology: Am. Jour. Sci., 4th ser., vol. 50, p. 265, 1920.

[55] Washington, H. S., and Keyes, M. G., Petrology of the Hawaiian Islands; VI. Maui: Am. Jour. Sci., 5th ser., vol. 15, pp. 213-215, 1928.

separate flows, probably of different age, there is some doubt as to which flow was analyzed by Miss Keyes. Washington's description, however, fits better the flow from Kaluaolapa, and on Powers' map the lava labeled "1750 flow" is the Kaluaolapa flow.[56] It is probable, therefore, that the analysis (see table, p. 309) is of the 1750 lava flow.

INCLUSIONS IN LAVAS

Inclusions in the lavas of East Maui volcano are of three sorts: fragments of intrusive gabbro, fragments of dunite, and fragments of one type of lava enclosed in lava of another type. The latter are most common and require no special comment. A typical example is the olivine basalt with abundant inclusions of lighter gray basaltic andesite which crops out 0.75 mile east of the Kolekole triangulation station on the south rim of the summit depression.

Gabbro inclusions have been found at three localities: in a basalt exposed in Pahihi Gulch a mile from the coast and 1.5 miles N. 59° W. of Nuu; in an olivine basalt which crops out in the east wall of Koolau Gap, 0.8 mile N. 72° W. of Hanakauhi Peak; and in the picritic basalt exposed in a sewer trench at Paia. All are of Kula age. The inclusions from the last two localities have been studied in thin section. Those from the second locality are angular, and coarse grained, reaching a maximum length of 5 cm. In some the dark minerals are equal to or slightly more abundant than the feldspar, but in others the feldspar greatly predominates, dark minerals constituting only about 20 percent of the rock. A thin section of one of the more typical mafic variety shows calcic labradorite (50%); olivine (20%) with $2V$ close to 90°, altered around the edges and along fractures to iddingsite; colorless diopsidic pyroxene (25%), with $+2V = 60^\circ$ and no detectable dispersion; and iron ore (5%). The texture is granitic. The gabbro inclusions in the picritic basalt from Paia have already been described.

Dunite inclusions from three localities have been studied. They are found at a number of other places, but are less abundant in the lavas of East Maui to subrounded fragments of dunite, from a few millimeters to 2.5 cm across than in those of some other Hawaiian volcanoes, such as Kauai.[57] Angular are present in a stream cobble of olivine basalt collected by Stearns in Pahihi Stream, and in boulders of basaltic andesite from the bed of Manawainui Stream. Both are probably of Kula age. Abundant dunite inclusions as much as 10 cm across, along with gabbro inclusions, were found in the picritic basalt exposed in a sewer trench in Paia (pl. 43B). The lava has already been described. The dunite inclusions vary from sharply angular to fairly well rounded. All are composed of over 90 percent olivine, with scattered small crystals of magnetite or chromite, and a few grains of monoclinic pyroxene. The lava solidified around boulders of dunite in the process of disintegrating into typical small inclusions. (See Part 1.) Lherzolitic nodules of the type described by Daly from Mauna Kea[58] have not been found.

PEGMATITOID SEGREGATIONS

The lava flow from Kalua o Umi, a fissure vent 0.1 mile southwest of Kalua Awa, on the north wall of the summit depression, is a picritic basalt much

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[56] Powers, S., op. cit., fig. 3, p. 264.

[57] Powers, S., op. cit., pp. 275-277.

[58] Daly, R. A., Magmatic differentiation in Hawaii: Jour. Geology, vol. 19, pp. 301-303, 1911.

like that from Puu o Maui already described, but a little less mafic. Feldspar phenocrysts are lacking, and olivine and augite phenocrysts are less abundant. The groundmass is normal in most respects, but contains irregular patches up to 2 mm across which are coarser grained and much lighter in color than the surrounding groundmass. They consist of subhedral grains of purplish-brown augite, acicular nearly colorless crystals of another monoclinic pyroxene, and euhedral grains of magnetite, in a matrix of colorless glass with index of refraction less than balsam. In places, particularly around the edges of the segregations, the colorless base has crystallized to anhedral grains of untwinned calcic andesine. The distinctly purplish color of the augite suggests that it is probably more titaniferous than that of the rest of the rock, and together with the coarser grain suggests that the patches may be segregations richer in mineralizers, similar to the pegmatitoid veins in the nepheline basalt at Moiliili Quarry, Honolulu.[59]

PYROCLASTIC ROCKS

Pyroclastic rocks are not abundant in the Honomanu series. A two-foot layer of lithic-vitric tuff occurs in its upper part in the sea cliff west of Hanawi Gulch. It is overlain by a nonporphyritic aa and underlain by a pahoehoe porphyry containing phenocrysts of olivine, augite, and feldspar. The tuff is crudely banded, and consists of angular fragments, some several inches across but most less than an inch, in a matrix of fine dust. The fragments are mostly of a fine-grained medium-gray lava with scattered phenocrysts of feldspar up to 1 mm in length. Some fragments are reddish-brown, and exceedingly fine grained, and probably represent altered devitrified glass; a few still retain a resinous luster. A few crystals and crystal fragments of olivine and augite are present. The material has not been identified in any of the test holes higher up the mountain. The deposit may be of local origin, formed by a lava flow exploding on entering the sea.

A somewhat similar tuff is interbedded with olivine basalts at the south end of Honomanu Bay. It consists of angular fragments of olivine basalt and crystals of feldspar, olivine largely altered to iddingsite, augite, and iron ore, in a powdery yellowish-brown matrix.

Pyroclastic rocks of Kula age are much more abundant than those of Honomanu age. The andesitic eruptions were in general more explosive than those of olivine basalt. Cinder cones are interstratified with Kula lavas in the walls of the summit depression, and numerous late Kula cinder cones are preserved on the flanks of the volcano. (See Part 1 and pl. 1.) Ejected blocks from Puu o Kali cinder cone, 2.75 miles northwest of Keokea, have been studied microscopically. The rock is a porphyritic olivine basalt, with phenocrysts of olivine and sodic labradorite less than 1 mm across in a matrix of pale-brown glass heavily charged with finely granular iron ore. The olivine is partly altered to iddingsite. The unusual abundance of glass indicates that the blocks are probably essential ejecta. The ejected blocks from Red Hill, on the rim of the summit depression, were analyzed and briefly described by Washington and Keyes.[60] The analysis is quoted in the table on page 309. The normative

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[59] Dunham, C. K., Crystal cavities in lavas from the Hawaiian Islands: Am. Mineralogist, vol. 18, pp. 371-377, 1933.
Stearns, H. T., and Vaksvik, K. N., Geology and ground-water resources of the island of Oahu, Hawaii: Hawaii Div. of Hydrography, Bull. 1, pp. 158-159, 1935.
[60] Op. cit., pp. 210-212.

feldspar is calcic andesine. In thin section, however, the rock is formed of lath-shaped grains of plagioclase (35%) composed predominantly of intermediate to sodic labradorite. A few grains have a narrow outer zone of andesine, and anhedral grains of andesine or calcic oligoclase (3%) occupy the interstices. The interstitial feldspar shows a variable but small positive optic angle, averaging about 40°. The rock contains small phenocrysts of olivine (3%) and augite (2%), and the groundmass consists, in addition to the feldspar, of olivine (10%), augite (30%), magnetite (12%), and pale-brown glass (5%). The rock is here classified on the basis of its modal feldspar as an olivine basalt.

Many Hana cinder cones are scattered along the rift zones and on the floor of the summit depression. They include the same rock types as the lava flows, and are microscopically much like the flows, except that the ejecta are in general more glassy. No special petrographic study of the pyroclastics has been made. Stearns collected blocks of basaltic andesite on the side of a small cone 1.9 miles S. 59° W. of the Kolekole triangulation station on the south side of the summit depression. He also collected a series of Strombolian-type bombs on the northwest side of Halalii Cone, in the summit depression (pl. 44C). The bombs from Halalii are composed of picritic basalt, typical except for the large amount (20%) of glass in the groundmass. The glass is pale-brown, with a refractive index of 1.56. Ribbon bombs of olivine basalt were noted by the writer along the ash-covered slope in the southwest corner of the summit depression, and Hawaiian-type, or "pancake" bombs of picritic basalt were found west of Ka Moa o Pele, on Puu Naue, on the flanks of the small hills 0.8 mile S. 70° W. of Puu Maile, and along the eastern margin of the flow from the Kalua Awa fissure. At the latter locality they apparently originated from splash from the lava river landing on the banks of older alluvium. Unipolar and bipolar Strombolian-type bombs were observed on the sides of Kalua Iki and on the slopes above it.

Loose crystals of olivine and augite are found on several cinder cones in the summit depression, including Puu Nole, Puu Naue, and Puu o Maui, and also on Puu Olai, 3 miles northwest of La Perouse Bay. The augites have been studied by Horace Winchell.[61] A few reach a length of 1 cm. They are stubby prismatic crystals, showing front and side pinacoid, prism, and pyramid faces. Arrow-head twins are common.

Molokini Island is a tuff cone lying in the channel between East Maui and Kahoolawe, and probably formed by eruption on the southwest rift of East Maui volcano. It has been described by Palmer.[62] A specimen of the Molokini ejecta collected by Palmer has been studied microscopically. In hand specimen it consists of fragments of black, glassy olivine basalt, with many plates of plagioclase up to 1 mm across, partly altered to soft yellowish-brown material in which the plates of feldspar are still visible. The fresh material consists largely of pale-brown glass, with $n = 1.588$, containing phenocrysts of calcic labradorite, olivine, and magnetite. The index of the glass corresponds to a silica content of about 49 percent.[63] In the soft yellowish-brown material the

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[61] Winchell, H., Mineralogy: augite crystals from the Koko region, from Puu Pa and from Haleakala: Hawaiian Acad. Sci., Proc. for 1939-40, B. P. Bishop Mus. Spec. Pub. 35, pp. 11-12, 1940.

[62] Palmer, H .S., Geology of Molokini; B. P. Bishop Mus. Occ. Papers, vol. 9, no. 1, pp. 3-14. 1930.

[63] George, W. O., The relation of the physical properties of natural glasses to their chemical composition: Jour. Geology, vol. 32, pp. 353-372, 1924.

glass is largely altered to palagonite, but the feldspar, olivine, and magnetite crystals are still fresh. The palagonite is partly isotropic and partly in minute doubly refracting fibers.

INTRUSIVE ROCKS

Many small intrusive masses are exposed in the walls of the summit depression. Most are dikes, but some are more nearly equant in horizontal section. They all appear to be of hypabyssal type; no coarse-grained gabbros, such as have been found in West Maui, Molokai,[64] Kauai,[65] and Oahu[66] are known. The dikes are identical in composition and texture to the Kula and Hana lava flows, for which they were the feeders.

A small intrusive body is enclosed in lavas of Honomanu age on the east side of the ridge which projects southward from Hanakauhi Peak into the summit depression. The rock is a dark-gray, dense olivine basalt with rare phenocrysts of feldspar up to 1.5 mm long. In thin section phenocrysts of feldspar, zoned from calcic to sodic labradorite, and microphenocrysts of olivine and magnetite, lie in a very fine grained partly glassy groundmass clouded with abundant finely granular iron ore. Irregular vesicles up to 0.4 mm long are lined with brownish-green chlorite, and many have cores of calcite.

A 6-foot dike just south of Holua Cave, on the west wall of the summit depression, is composed of oligoclase andesite, similar in many respects to the oligoclase andesites of Kohala[67] and West Maui. (See Petrography of West Maui.) The rock contains phenocrysts of plagioclase (5%) and a few of diopsidic augite and hornblende, in a trachytic groundmass. The plagioclase phenocrysts are albite-oligoclase, with Carlsbad twinning and some with faint albite twinning, and $\beta = 1.537$. The hornblende crystals are euhedral to subhedral, and pleochroic in shades of greenish-brown, with $-2V = 75°$. The pyroxene phenocrysts are acicular euhedral crystals, pale-green in color, with $+2V — 60°$. The groundmass consists of iddingsite pseudomorphs after olivine (5%), diopsidic augite (20%), albite-oligoclase (60%), magnetite (10%), and a few prismatic crystals of apatite. The apatite crystals attain a length of 0.25 mm, and show prominent basal fractures.

A small intrusive body in the west wall of the summit depression, 0.52 mile N. 84° E. of the Kilohana triangulation station, was used by the ancient Hawaiians as a source of rock for the manufacture of adzes. The rock is a dense fine-grained bluish-gray basalt consisting of microlites of labradorite, flakes of biotite, and crystals of magnetite up to 0.2 mm across, in a difficultly resolvable groundmass of labradorite, monoclinic pyroxene, olivine, and abundant iron ore. Little or no glass appears to be present. The biotite was mentioned by Powers.[68] It is pleochroic with X = nearly colorless, Y and Z = greenish-brown.

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[64] Lindgren, W., Water resources of Molokai, Hawaiian Islands: U. S. Geol. Survey Water-Supply Paper 77, pp. 14-15, 1903.

[65] Cross, W., Lavas of Hawaii and their relations: U. S. Geol. Survey Prof. Paper 88, pp. 14-16, 1915.

[66] Macdonald, G. A., Petrography of the Waianae Range, Oahu: Hawaii Div. of Hydrography, Bull. 5, p. 73, 1940.

[67] Washington, H. S., Petrology of the Hawaiian Islands; I. Kohala and Mauna Kea, Hawaii: Am. Jour. Sci., 5th ser., vol. 5, pp. 476-479, 1923.

[68] Powers, H. A., Hawaiian adze materials in the Haleakala section of Hawaii National Park: Hawaiian Acad. Sci. Proc. for 1938-39, B. P. Bishop Mus. Spec. Pub. 34, p. 24, 1939.

Boulders of coarse-grained diabase were found on the east wall of the summit depression 0.3 mile N. 40° W. of Kuiki Peak, but their source was not located.

CHEMICAL COMPOSITION OF EAST MAUI LAVAS

Ten analyses of East Maui lavas and one analysis of augite from a picritic basalt, made by earlier workers, are reproduced in the accompanying table. No new analyses have been made during the present investigation. The analyses cover the range of rock types in the Kula and Hana volcanic series, but no analyses of Honomanu lavas have been made. Analyses of Honomanu rocks are much needed, because they represent as near an approach to the primitive, undifferentiated magma of the East Maui center as it is possible to attain. The olivine basalts of later age may or may not correspond exactly in composition to the Honomanu lavas.

Considerable amounts of normative orthoclase and nepheline are present in the analyzed lavas. Alkali feldspar has been detected in the mode of only a few specimens, and nepheline has not been found at all, either by ordinary microscopic examination or by dye tests using phosphoric acid and methylene blue.[69] Small amounts of these minerals might escape detection, but such large amounts as are indicated by the norms would almost certainly be found. Both the orthoclase and nepheline must be to a large extent occult, held in solid solution by the plagioclase.

The variation diagram (fig. 44) expresses the degree of differentiation found in the Kula and Hana lavas. The transition from the basalts to the andesites involves a distinct rise in the alumina, soda, and potash lines, and a slight increase in phosphorus pentoxide. Magnesia and lime decrease greatly; ferrous iron, and titania somewhat less. Ferric iron shows little change. Provided the olivine basalts of the later flows are identical in composition with the Honomanu basalts, the diagram also represents the complete history of differentiation. It is probable that the correspondence in composition between the Honomanu and later olivine basalts is fairly close, because the latter resemble in composition the primitive lavas of other Hawaiian volcanoes. The diagram is therefore regarded as presenting a fair approximation to the trends followed by the curves for the various oxides throughout the change from the primitive basalt to the most highly differentiated lavas.

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[69] Shand, S. J., On the staining of feldspathoids, and on zonal structure in nepheline: Am. Mineralogist, vol. 24, pp. 508-510, 1939.

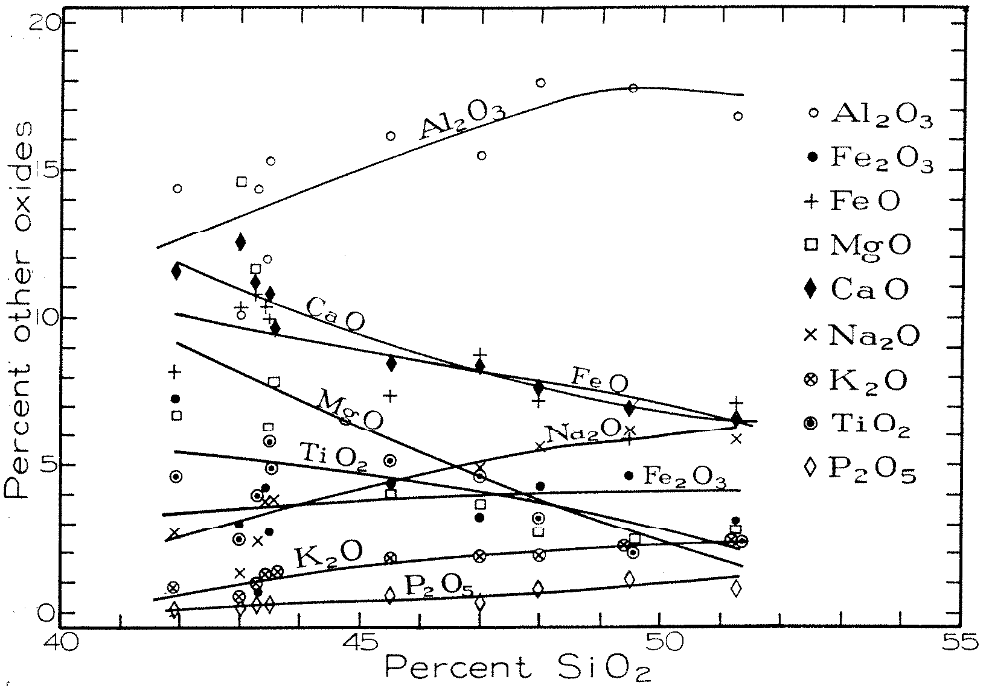

Figure 44. Variation diagram of East Maui lavas.

The andesites of East Maui are chemically most closely related to the mugearites and trachydolerites.[70] In silica content they are lower than typical andesites, and correspond more closely to the basalts, but in abundance and relative proportion of alkalies and lime they are more like the andesites. Cross has classified them as trachyandesites,[71] and although they are lower in silica than most rocks classed as trachyandesites by Rosenbusch,[72] this designation is probably as appropriate as any. It serves to emphasize their somewhat alkalic nature and their position in an alkaline suite intermediate between the parent basalt and alkali trachytes. Following the classification suggested by Peacock,[73] the alkali-lime index of the East Maui suite is 47.8, which places it in the alkalic group.

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[70] Rosenbusch, H., Elemente der Gesteinslehre, 4th Ed., revised by A. Osann, p. 460, Stuttgart, 1923.

[71] Cross, W., op. cit., pp. 30, 81.

[72] Op. cit., p. 416.

[73] Peacock, M. A., Classification of igneous rock series: Jour. Geology, vol. 39, pp. 54-67, 1931.

Chemical compositions and norms of volcanic rocks from East Maui

	1	2	3	4	5	6	7	8	9	10	11
SiO_2 . .	41.89	42.99	43.28	43.43	43.50	45.46	47.03	48.04	49.55	51.26	47.70
Al_2O_3 . .	14.41	10.21	14.43	12.01	15.27	16.18	15.57	17.95	17.78	16.74	6.82
Fe_2O_3 . .	7.32	3.01	0.70	4.23	2.74	4.40	3.22	4.28	4.65	2.92	3.36
FeO . .	8.26	10.28	10.92	10.38	9.91	7.38	8.68	7.21	5.89	7.11	4.43
MgO . .	6.73	14.61	11.68	6.37	7.85	4.07	4.29	2.79	2.49	2.80	13.34
CaO . .	11.69	12.54	11.22	10.84	9.71	8.56	8.67	7.52	7.01	6.61	21.35
Na_2O . .	2.68	1.40	2.49	3.78	3.80	6.06	4.88	5.55	6.12	5.86	0.65
K_2O . . .	0.94	0.52	0.83	1.36	1.39	1.82	1.84	1.91	2.29	2.25	0.03
H_2O+ .	0.47	1.10	0.05	0.72	0.31	0.06	0.67	0.14	0.34	0.42	0.15
H_2O- .	0.09	0.82	0.03	0.39	0.06	0.03	0.11	0.08	0.29	0.26	......
TiO_2 . .	4.68	2.52	4.12	5.81	4.84	5.10	4.60	3.27	2.09	2.57	1.89
ZrO_2 . .	n.d.	none	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.01	none	......
P_2O_5 . .	0.15	0.29	0.31	0.26	trace	0.51	0.42	0.88	1.10	0.81	......
Cr_2O_3 .	n.d.	0.06	0.10	n.d.	n.d.	n.d.	n.d.	n.d.	none	none	0.23
MnO . .	0.16	0.17	0.13	0.22	0.14	0.24	0.18	0.39	0.28	0.23	0.16
BaO . .	n.d.	none	0.05	n.d.	n.d.	n.d.	n.d.	n.d.	0.05	0.10	......
SrO . .	n.d.	none	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.08	0.09	......
	99.47	[a]100.58	[b]100.54	99.80	99.52	99.87	100.16	100.01	[c]100.06	100.03	100.11
Norms											
Orthoclase	2.78	5.00	5.56	8.34	8.34	10.56	11.12	11.12	13.34	12.79	
Albite	6.29	4.72	14.15	14.15	15.20	20.96	24.10	31.96	34.58	38.25	
Anorthite	20.02	36.70	24.19	11.68	25.02	11.68	15.01	18.35	15.01	12.79	
Nepheline	3.12	8.80	4.83	9.66	4.54	16.47	9.37	8.24	9.09	6.25	
Diopside	32.28	8.66	25.92	32.41	18.51	21.52	20.56	10.91	10.42	12.40	
Olivine	24.23	25.68	4.53	4.79	12.77	1.36	4.92	4.87	3.80	5.69	
Magnetite	4.41	0.93	10.44	6.03	6.03	6.50	4.64	6.26	6.73	4.18	
Ilmenite	4.71	7.75	8.97	11.10	9.12	9.73	8.82	6.23	3.95	4.86	
Apatite	0.67	0.67	0.34	0.67	.....	1.34	1.01	2.02	2.69	2.02	

[a] NiO=0.06 [b] SO_3=0.20 [c] FeS_2=0.03, V_2O_3=0.15

1. Basalt; Kula volcanic series. At Haleakala rest house, rim of summit depression; M. G. Keyes, analyst. Washington, H. S., and Keyes, M. G., Petrology of the Hawaiian Islands; VI. Maui: Am. Jour. Sci., 5th ser., vol. 15, pp. 211–212, 1928.
2. Picritic basalt; Hana volcanic series. Northwest base of Namanaokeakua Cone, summit depression; G. Steiger, analyst. Cross, W., Lavas of Hawaii and their relations; U. S. Geol. Survey Prof. Paper 88, p. 29, 1915.
3. Picritic basalt; Hana volcanic series. 1750(?) lava flow, near Makena; M. G. Keyes, analyst. Washington, H. S., and Keyes, M. G., op. cit., pp. 214–215.
4. Olivine basalt; Kula volcanic series. Ejected blocks from Red Hill, rim of summit depression; M. G. Keyes, analyst. Idem, pp. 211–212.
5. Olivine basalt, Kula volcanic series. Near Haleakala rest house, rim of summit depression; M. G. Keyes, analyst. Idem, pp. 211–212.
6. Basaltic andesite, Kula volcanic series. Three miles from Haleakala rest house, on Olinda trail, north slope of Haleakala; M. G. Keyes, analyst. Idem, pp. 211–212.
7. Basaltic andesite, Kula volcanic series. Two miles above Olinda, north slope of Haleakala: M. G. Keyes, analyst. Idem, pp. 211–212.
8. Andesite, Kula volcanic series. At Haleakala rest house, rim of summit depression; M. G. Keyes, analyst. Idem, pp. 211–212.
9. Andesite. Kula volcanic series. White Hill, rim of summit depression, 0.3 mile northeast of Red Hill; W. F. Hillebrand, analyst. Cross, W., op. cit., pp. 31–32.
10. Andesite, Hana volcanic series. 1,000 feet altitude in ravine west of Vieira ranch, south of Kaupo Gap, Haleakala; G. Steiger, analyst. Idem, pp. 31–32, 47.
11. Augite, from flow of picritic basalt, west rim of summit depression; H. S. Washington, analyst. Washington, H. S., and Merwin, H. E., Augite of Haleakala, Maui, Hawaiian Islands: Am. Jour. Sci., 5th ser., vol. 3, pp. 117–122, 1922.

MAGMATIC DIFFERENTIATION

The Honomanu lavas contain more feldspar phenocrysts than are typically present in the primitive basalts of other Hawaiian volcanoes. However, these lavas represent only the uppermost part of the great basaltic shield. In the Waianae Range on Oahu, where erosion has cut deeply into the mountain, feldspar phenocrysts are commoner in the Middle Waianae basalts than in those of the Lower

Waianae.[74] On this basis, it is probable that the older basalts of East Maui, which are not exposed to view, are poorer in feldspar phenocrysts than are the exposed Honomanu lavas, and that the primitive lavas are like those of the other Hawaiian volcanoes. The change probably represents a progressive decrease in temperature of the magmatic hearth. At first only olivine phenocrysts were formed, but later falling temperature resulted in the intratelluric crystallization of feldspar and augite as well. The presence of phenocrysts of these minerals probably has little effect on the bulk composition of the rocks. Throughout Honomanu time eruptions were frequent, and the vent remained essentially open. The frequent stirring of the magma column permitted little or no differentiation.

The evidence indicates that at the end of Honomanu time the frequency of eruptions greatly decreased. (See Part 1.) During Kula time the vent remained closed for much longer periods, and differentiation in the stagnant magma column was able to produce lavas of andesitic composition. Whatever the process by which the differentiation was accomplished, the andesitic magmas probably formed only relatively small bodies at the top of the magma reservoir. Assuming a reservoir with andesitic magma at the top and basaltic magma beneath, a fissure tapping the upper part of the reservoir would give vent to an andesitic flow, whereas one tapping it at a lower level would produce a basaltic flow (fig. 45). It is also possible that a series of frequent eruptions might completely remove the capping of andesite from the magma column, whereupon fissures tapping the upper part of the reservoir would yield basaltic flows. This hypothetical arrangement of andesitic and basaltic magmas in the same reservoir does not imply complete or even very limited immiscibility of the two magmas, but merely a difference in specific gravity of the liquids combined with comparative stagnation of the magma column. There will, of course, be a certain amount of intermingling near the boundary producing a transitional zone. The principle is illustrated by the well-known Ghyben-Hertzberg relationship of fresh water floating on salt water, separated by only a narrow zone of brackish water.[75]

The picritic basalts have been attributed by Bowen[76] and by Washington and Keyes[77] to the addition to basaltic magma, without remelting, of large crystals of olivine and augite which have settled out of the magma higher in the reservoir. The dunite inclusions

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[74] Macdonald, G. A., op. cit., p. 74.

[75] Stearns, H. T., and Vaksvik, K. N., op. cit., pp. 237–238.

[76] Bowen, N. L., The origin of ultrabasic and allied rocks: Am. Jour. Sci., 5th ser., vol. 14, p. 105, 1927.

[77] Op. cit., pp. 219-220.

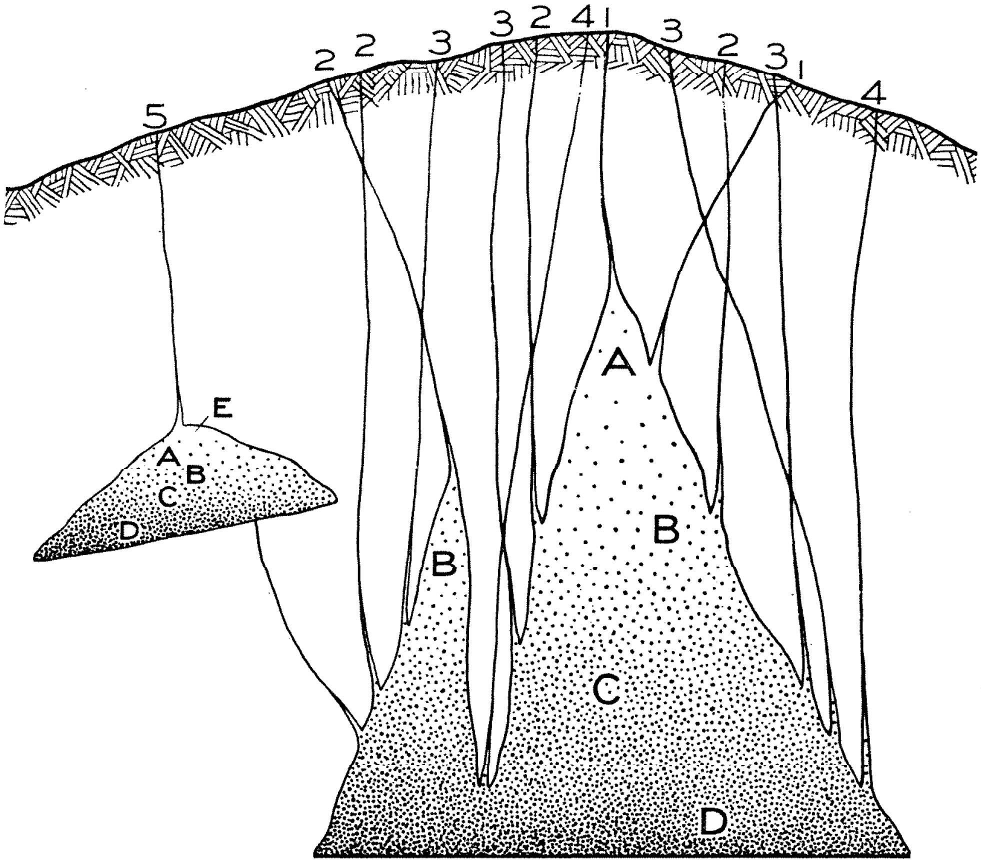

Figure 45. Diagram illustrating a manner in which lavas of differing composition might be erupted simultaneously from fissures tapping different parts of the magma reservoir. **A**, andesite; **B**, basaltic andesite; **C**, basalt; **D**, picritic basalt; **E**, trachyte; 1, dike erupting andesite; 2, dike erupting basaltic andesite; 3, dike erupting basalt; 4, dike erupting picritic basalt; 5, dike erupting trachyte (interbedded with basalt and andesite).

almost certainly represent gravitative accumulations of olivine crystals which have settled from overlying magma. The picritic basalts and dunite inclusions are to some extent complementary in composition to the andesites. It is significant that the picritic basalts are nearly absent in the primitive lavas, but are abundant in the part of the section in which andesitic rocks are also present. The removal of crystals of augite and olivine, and possibly also of plagioclase, from the magma in the upper part of the reservoir must play an important part in the differentiation, but it is uncertain whether or not it is the only important factor. The volatile transfer of certain substances, particularly the alkalies, to the upper part of the magma chamber may have aided in the production of the andesitic types.

PETROGRAPHY OF WEST MAUI

INTRODUCTION

Specimens collected at many points in the West Maui Mountains by H. T. Stearns and the writer have been studied in hand specimen, and 79 of them have been examined under the microscope. The feldspars have been determined by extinction angle methods or by refractive index. The size of optic axial angles has been estimated from acute bisectrix or optic axis interference figures. Refractive indices have been determined by immersion methods and are accurate to ±.003. Two new chemical analyses of West Maui rocks, by S. Iwashita of Honolulu, are given.

PREVIOUS INVESTIGATIONS

The first contribution to the petrography of West Maui was the description by E. S. Dana, in 1889, of specimens of trachyte and oligoclase andesite collected by Rev. S. E. Bishop from Paupau and Launiupoko Hills, near Lahaina.[78] Möhle described an andesite, several basalts, and a melilite nepheline basalt, all said to come from the vicinity of Lahaina.[79] No rock corresponding to the melilite nepheline basalt described by Möhle has been found during the present study. Cross redescribed the rock from Launiupoko Hill, classified it as a soda trachyte, and presented a chemical analysis of it by Steiger. He also briefly described olivine basalts and a diabase from stream boulders in Waihee and Iao Valleys.[80] Sidney Powers described oligoclase andesites or trachytes from Waiolai Gulch and Waihee Valley, and redescribed the oligoclase andesite from Paupau Hill.[81] Washington and Keyes gave descriptions and several new chemical analyses of West Maui rocks, including basalts, gabbro, and oligoclase andesite.[82] Finally, H. A. Powers mentions having found hypersthene in West Maui lavas.[83]

GENERAL FEATURES

Distribution of rock types.—The lavas of West Maui volcano are divided into three strongly contrasted groups. The oldest, the

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[78] Dana, E. S., Contributions to the petrography of the Sandwich Islands: Am. Jour. Sci., 3rd ser., vol. 37, pp. 463-466, 1889.

[79] Möhle, F., Beitrag zur Petrographie der Sandwich- und Samoa-Inseln: Neues Jahrb., Beil. Bd. 15, pp. 68-71, 1902.

[80] Cross, W., Lavas of Hawaii and their relations: U. S. Geol. Survey Prof. Paper 88, pp. 25-28, 1915.

[81] Powers, S., Notes on Hawaiian petrology: Am. Jour. Sci., 4th ser., vol. 50, p. 271, 1920.

[82] Washington, H. S., and Keyes, M. G., Petrology of the Hawaiian Islands; VI. Maui: Am. Jour. Sci. 5th ser., vol. 15, pp. 200-209, 1928.

[83] Powers, H A., Differentiation of Hawaiian lavas: Am. Jour. Sci., 5th ser., vol. 30, p. 64, 1935.

Plate 43A. Wailuku olivine basalt (1) containing a large inclusion of dunite (2) cut by a band of pyroxenite (3): Pohakea Gulch, West Maui. Natural size.

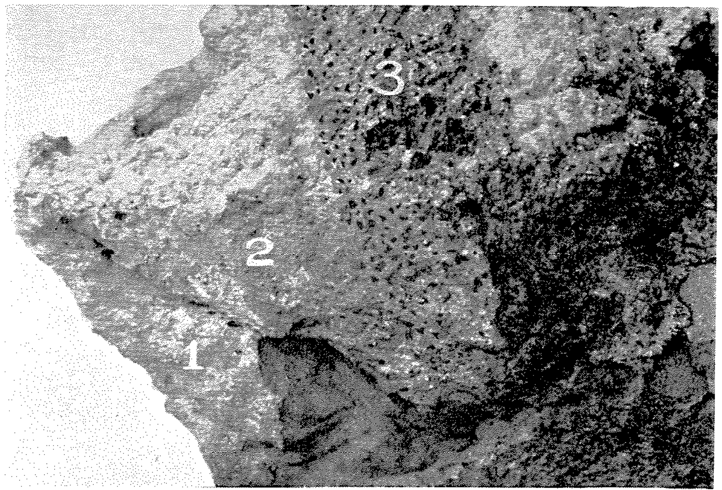
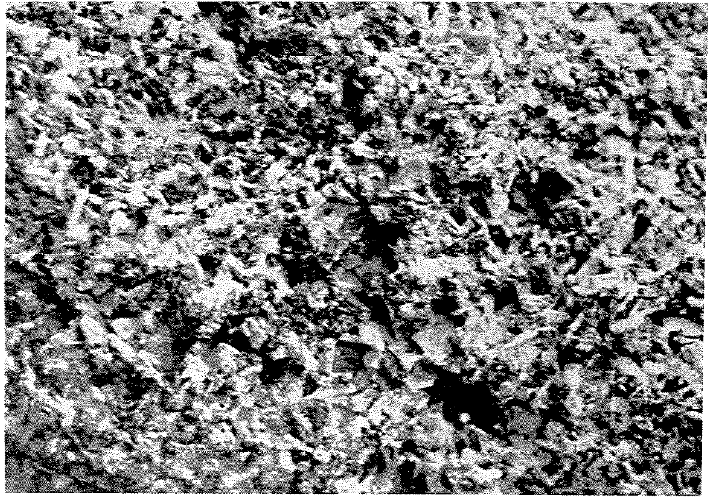
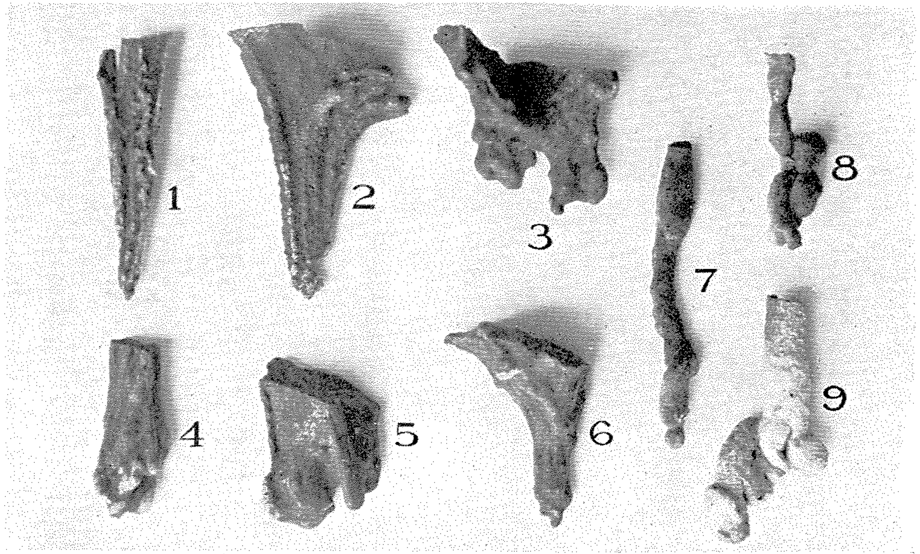


Plate 43B. Picritic basalt from sewer trench at Paia, East Maui, containing abundant large black augites (1) and inclusions of dunite (2). Three-quarters natural size.

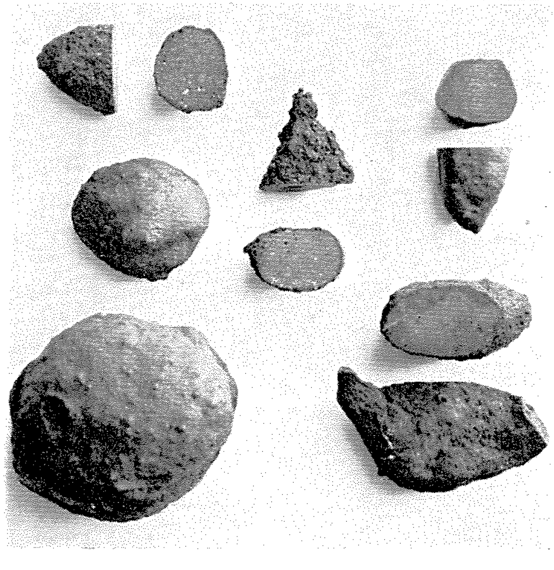
Plate 43C. Coarse-grained miarolytic gabbro from the stock in Kahakuloa Gulch, West Maui. Natural size.



Left: Plate 44A. Augite crystals from a nearly buried Wailuku cinder cone 1,000 feet west of Manawainui Gulch, West Maui. Natural size.



Center: Plate 44B. Andesitic stalactites (numbers 1–6) in comparison with basaltic stalactites (numbers 7–9). One half natural size.



Left: Plate 44C. Dense porphyritic basaltic bombs from Puu Halalii in the summit depression of Haleakala. One quarter natural size.

Wailuku volcanic series, comprises by far the greatest bulk of the visible part of the volcano and probably most of the part below sea level. The lavas are largely olivine basalts like the early lavas of the other Hawaiian volcanoes, and appear to represent the undifferentiated parent magma of the Hawaiian magmatic province. A few picritic basalts and basalts nearly free of olivine are interbedded with the normal olivine basalts. Sharply separated stratigraphically and in composition from the Wailuku basalts are the oligoclase andesites and soda trachytes of the Honolua volcanic series. In most Hawaiian volcanoes the change from basalts to andesites is transitional both in the presence of rock types of intermediate composition and in interbedding of andesites and basalts. In West Maui, however, there is no interbedding of andesites with basalts, and transitional rocks are lacking. Extinction and extensive erosion of the West Maui volcano was followed by a few small eruptions forming cinder cones and lava flows, termed the Lahaina volcanic series. They include picritic basalts and at least one flow of nepheline basanite. In their highly ferromagnesian nature and in the undersaturated alkaline character of the basanite the Lahaina lavas resemble the post-erosional nepheline basalts of Kauai and the Koolau Range on Oahu.

Composition of olivines.—As a possible indication of the trend of differentiation the β refractive index of olivine crystals in several rocks of each group has been determined by immersion. The indices, together with the approximate percentage of forsterite corresponding to each index based on curves published by Deer and Wager,[84] are shown in the accompanying table. The average of 82 percent forsterite for the phenocrysts of the Wailuku basalts corresponds well with the values determined by chemical analysis for olivine phenocrysts from olivine basalts and picritic basalts of Kilauea and Mauna Loa, in which the remainder of the mineral is composed largely of fayalite but with as much as 4.9 percent of other material, including TiO_2, Cr_2O_3, MnO, NiO, CaO, and Al_2O_3.[85] Whether or not the amounts of these other elements notably increase or decrease in the olivines containing less forsterite is not known, but it is possible that they may increase and may considerably affect the refractive index, so that the percentages of forsterite in the less magnesium-rich olivines shown in the table may be in considerable error. Despite such possible error, however, they certainly indicate

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[84] Deer, W. A., and Wager, L. R., Olivines from the Skaergaard intrusion, Kangerdlugssuaq, East Greenland: Am. Mineralogist, vol. 24, pp. 18-25, 1939.

[85] Aurousseau, M., and Merwin, H. E., Olivine: I. From the Hawaiian Islands; II. Pure forsterite: Am. Mineralogist, vol. 13, pp. 560-561, 1928.

a strong trend in the differentiation toward olivines containing less magnesium and more iron. The groundmass olivines in the basalts are richer in iron than the phenocrysts, and the olivines in the oligoclase andesites contain still more iron. Olivines progressively richer in iron crystallized from magmas which were in equilibrium with feldspars progressively richer in alkalies.

β refractive index and approximate percentage of forsterite in olivines of West Maui volcanic rocks

Specimen number	Wailuku olivine basalts and picritic basalts						Honolua oligoclase andesites (groundmass)		Lahaina picritic basalts and basanite (no. 313) (phenocrysts)	
	Dunite inclusions		Phenocrysts		Groundmass					
	β	% Fo	β	% Fo	β	% Fo	β	% Fo	β	% Fo
282	1.682	85	1.689	82	1.737	61				
295	1.683	85	1.691	81	1.728	65				
311			1.690	82	1.717	70				
312			1.693	80	1.735	62				
314			1.687	83						
319			1.693	80						
330			1.682	85						
296							1.755	52		
300							1.746	57		
304							1.767	46		
119									1.702	76
293									1.701	77
294									1.685	84
313									1.688	83
315									1.692	81
322									1.694	80
Average ...	1.682	85	1.689	82	1.729	64	1.756	52	1.694	80

282. Olivine basalt, with dunite inclusion cut by a veinlet of pyroxenite; float, near mouth of Pohakea Gulch.
295. Olivine basalt, with dunite inclusions; float, Manawainui Gulch.
311. Olivine basalt; on trail on west side of Honokohau Gulch about ¼ mile northwest of intake of Honolua ditch.
312. Olivine basalt; near portal of water-development tunnel on east side of Honokohau Gulch.
314. Picritic basalt; dike in water-transport tunnel between Amalu and Honokowai Streams.
319. Picritic basalt; on highway, on west side of first small gulch northwest of Kamaohi Gulch.
330. Crystal-vitric basaltic tuff; from cinder cone buried by Wailuku lavas; at 1,565 feet elevation about 1,000 feet west of Manawainui Gulch.
296. Oligoclase andesite; in highway cut at McGregor Point.
300. Oligoclase andesite; on highway about 0.2 mile north of Honolua.
304. Oligoclase andesite; Uau Peak, 3 miles N. 10° W. of Mount Eke.
119. Picritic basalt; southeast side of Puu Laina.
293. Picritic basalt; at beach, about 1 mile north of Mala.
294. Picritic basalt; Kekaa Cone, near loading dock.
313. Nepheline basanite; northwest side of Kilea Cone, ½ mile N. 30° E. of Olowalu.
315. Picritic basalt; on road, southwest side of Puu Laina, 1.1 miles northeast of Mala.
322. Picritic basalt; quarry on northwest side of Puu Laina.

WAILUKU VOLCANIC SERIES

The lavas of the Wailuku volcanic series are preponderantly olivine basalts, grading on the one hand into basalts poor in olivine, and on the other into picritic basalts poor in feldspar. A few contain hypersthene.

OLIVINE BASALTS.—These rocks are typically porphyritic, with phenocrysts of olivine, and less frequently phenocrysts of plagioclase and pyroxene. The olivine phenocrysts range in size up to 6 mm across, and in abundance from 1 to 15 percent. They are commonly altered around the edges and along fractures to iddingsite, but in some specimens are entirely fresh or show only a faint greenish stain resulting from incipient alteration. The fresh olivines frequently show all size gradations into the groundmass, indicating continuous crystallization, but in other instances the phenocrysts are rounded and embayed by resorption, and separated by a distinct difference in size from the groundmass olivines. In some rocks olivine phenocrysts, partly resorbed and altered around the edges to iddingsite, are surrounded by shells of fresh olivine which more or less restore the euhedral outlines of the crystals.

Pyroxene phenocrysts are much less common than those of olivine. In nearly all specimens they are augite, with +2V ranging from 55° to 60°, but in one a few microphenocrysts of pigeonite were found. The augite is pale-brown to colorless in thin section, and shows little or no dispersion. Phenocrysts of pyroxene are present in relatively few rocks, and numerous in only one, of which they form 10 percent. In most, they form only 1 or 2 percent. Hourglass zoning in the augite was noted in only one slide, and this augite also showed distinct dispersion. All the rocks except one which contain pyroxene phenocrysts also contain phenocrysts of plagioclase, which generally make up from 5 to 10 percent of the rock, although in one phenocrysts and microphenocrysts of plagioclase constitute 20 percent. All the plagioclase phenocrysts show normal zoning, and many also show oscillatory zoning. The core of the zoned crystal is generally calcic to intermediate labradorite, and the rim has the same composition as the groundmass plagioclase, generally sodic labradorite. One rock contains phenocrysts with cores of calcic bytownite surrounded by narrow zoned rims in which the composition changes to medium labradorite.

The groundmass generally is intergranular, but occasionally is intersertal. The average grain size ranges from 0.04 to 0.2 mm, but is generally near 0.1 mm. Olivine forms from 2 to 10 percent of the groundmass. It is absent in only one specimen, which contains unusually abundant phenocrysts of both olivine and augite. The phenocrystic and groundmass olivines together generally total between 10 and 15 percent of the rock. Groundmass pyroxene constitutes 30 to 45 percent. Grains of monoclinic pyroxene in many slides are too small to yield usable interference figures. Of those rocks in which the nature of the groundmass pyroxene could be determined, some contain augite and some pigeonite. The groundmass feldspar is intermediate to sodic labradorite, and constitutes 35 to 50 percent of the rock. Interstitial andesine with a small positive optic angle is present in several rocks, and in one reaches 3 percent. Minute acicular crystals of apatite are enclosed in the feldspar of most of the slides examined. A few contain a small amount of interstitial pale-brown glass with a refractive index below that of balsam. Ore minerals constitute from 5 to 15 percent, and include both magnetite and ilmenite. Many rocks contain both, with magnetite generally dominant over ilmenite, but some appear to carry only magnetite, and in one the ore appears to be all ilmenite. A few flakes of biotite, pleochroic from reddish-brown to nearly colorless, are present in three specimens, one collected at 1,800 feet altitude in Kahakuloa Gulch, another northeast of Olowalu, and the third from a block in throat breccia in Iao Valley, 0.85 mile S. 67° W. of The Needle. Chlorite lines vesicles in a rock collected 4.13 miles N. 35° W. of McGregor Point, and in a specimen from the throat breccia in Iao Valley irregular masses of chlorite probably were formed by alteration of interstitial glass.

An olivine basalt from Iao Valley has been described by Washington and analyzed by Keyes.[86] (See table, page 334.) A rock collected by the writer corresponds in most respects with Washington's description. It is a medium-gray sparingly vesicular aa, with phenocrysts of green olivine (10%) averaging 1 to 2 mm across but some reaching 5 mm, and a few phenocrysts of augite up to 3 mm, in a microcrystalline groundmass. Under the microscope the phenocrysts of diopsidic augite (1%) are colorless to pale-green, with $+2V = 60°$, and no detectable dispersion. The olivine phenocrysts are fresh, except for a little greenish-yellow staining. They show minor amounts of rounding and embayment by resorption, and rims of yellow stain follow the edges of the embayed crystals. Outside of this, and partly restoring the euhedral crystal outlines, are shells of fresh olivine averaging about 0.02 mm thick, which probably formed at the same time as the groundmass olivine. The groundmass has an average grain size of 0.07 mm. It is composed of labradorite (40%), colorless monoclinic pyroxene (35%), olivine (5%), iron ore (8%) including both magnetite and ilmenite, and pale-brown interstitial glass (1%). Minute acicular crystals of apatite are enclosed in the feldspar.

Especially interesting is an olivine basalt which crops out near the southwest end of the spur 0.87 mile N. 15° E. of Olowalu. The rock is medium-gray and dense, with scattered phenocrysts of olivine reaching 1 mm in diameter and many irregular patches of feldspar up to 2 mm across. The phenocrysts of olivine (2%) are rounded and embayed by magmatic resorption, and are altered around the edges and along fractures to iddingsite. Around the iddingsite is an envelope of later olivine, crystallographically parallel to that of the core, which partly restores the euhedral outlines. The contact of the iddingsite with the olivine core is feathery and irregular, while that with the outer olivine is sharp, the relations being the same as those found by Edwards.[87] The outer olivine shows very slight alteration in the form of pale yellowish-green stain. Phenocrysts and glomerocrysts of plagioclase (10%) show normal zoning from labradorite-bytownite to sodic labradorite. The intergranular groundmass is composed of lath-shaped grains of sodic labradorite (40%), pale-brown subhedral crystals of pigeonite (25%), scattered grains of olivine (6%), and iron ore (10%), including both magnetite and ilmenite, the former being dominant. Interstitial grains of andesine (2%) show irregular extinction, and a $+2V$ ranging from about 25° to 50°. A few flakes of biotite, pleochroic from $X =$ colorless to Y and $Z =$ golden-brown, are scattered through the groundmass, and minute needles of apatite are enclosed in the feldspar. Many interstitial spaces are filled with calcite. Feldspars and pyroxenes in contact with this calcite or lying almost completely within it appear entirely fresh and unaltered. Irregular veinlets of calcite traverse the entire rock, in many places cutting the feldspar phenocrysts, but the feldspar, even where riddled with calcite veinlets, does not appear to be altered. Calcite constitutes about 5 percent of the rock. A very similar rock, even to the presence of a few flakes of biotite, was found by Howard Powers

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[86] Op. cit., pp. 203-204.

[87] Edwards, A. B., The formation of iddingsite: Am. Mineralogist, vol. 23, p. 279, 1938. Macdonald, G. A., Petrography of Kahoolawe: Hawaii Div. of Hydrography, Bull. 6, p. 153, 1940.

on the lower slopes of East Maui volcano near Paia.[88] The total lack of alteration of the associated minerals appears to indicate that the calcite was of primary, probably paulopost, origin rather than secondary.

An olivine basalt collected by Stearns on the north side of Iao Valley, 0.56 mile S. 76° E. of The Needle, contains minute reddish-brown, highly acicular crystals with high birefringence which may be rutile.

OLIVINE-POOR BASALTS.—There is a complete gradation from the olivine basalts which typically contain 10 to 15 percent olivine, to basalts containing less than 5 percent olivine. These olivine-poor basalts form only an insignificant part of the volcanic pile.

A rock collected at the west end of the highway bridge at Kahakuloa contains phenocrysts of plagioclase (7%) up to 6 mm long, with cores of calcic bytownite ($\beta = 1.574$) with abundant oscillatory zoning, surrounded by narrow rims of calcic labradorite. Microphenocrysts of olivine (1%) are largely altered to iddingsite. The intergranular groundmass consists of labradorite (38%), pale-brown monoclinic pyroxene (40%), magnetite (10%), and olivine (3%).

Another lava, exposed on the northwest side of Kahakuloa Gulch 1,500 feet south of Kahakuloa, is nonporphyritic. The texture is intergranular and distinctly fluidal. Between lath-shaped microlites of labradorite (40%) lie grains of pale-brown pigeonite (42%), with +2V variable but averaging about 45° and $r > v$ strong, olivine (3%), and magnetite (15%). Occupying interstices between the other minerals there is a small amount of feldspar with a refractive index in the range of andesine or calcic oligoclase and a small +2V. It frequently encloses minute needles of apatite. Basalts entirely free of olivine have been described by Washington and Keyes,[89] and their analysis of such a rock is quoted in the table on page 334, but all of the specimens examined by the writer contain at least a few grains of olivine.

HYPERSTHENE-BEARING BASALTS.—A number of lavas from West Maui contain small amounts of hypersthene, but hypersthene-bearing lavas are not nearly as numerous as they appear to be in the Koolau Volcano on Oahu.[90] Hypersthene is occasionally found among the lavas of other Hawaiian volcanoes,[91] but seldom forms more than 2 or 3 percent of the rock. Its presence in West Maui lavas was first recorded by Powers.[92] The hypersthene is of the bronzite variety, with a large negative optic angle. It is commonly colorless in thin section, but rarely is pleochroic from pale-pink to pale-green. In the West Maui lavas it generally forms microphenocrysts or small phenocrysts which are exceedingly irregular in outline and poikilitic, containing numerous inclusions of feldspar and iron ore. The lavas in which it is found are mostly olivine basalts, but one is a picritic basalt containing 25 percent olivine, 35 percent monoclinic pyroxene, and 3 percent hypersthene.

A lava cropping out in a road-cut 0.35 mile northeast of Papawai Point is remarkable for the unusual abundance of hypersthene. The rock is a medium-gray sparingly vesicular aa, with phenocrysts of olivine up to 4 mm across.

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[88] Powers, H. A., personal communication, Aug. 1940.
[89] Op. cit., pp. 203, 205.
[90] Cross, W., op. cit., pp. 19-20.
[91] Macdonald, G. A., op. cit., pp. 156-157. Contains also references to earlier descriptions of hypersthene from Oahu, and Kilauea and Mauna Loa.
[92] Powers, H. A., Differentiation of Hawaiian lavas: Am. Jour. Sci., 5th ser., vol. 30, pp. 64-65, 1935.

Three generations of olivine are present. Phenocrysts of fresh olivine (1%) are rounded and embayed by resorption, whereas microphenocrysts of olivine (7%), averaging 0.2 mm across, are sharply euhedral. Microphenocrysts of hypersthene (10%) reach a length of 0.8 mm, and are extremely irregular in outline with many variously oriented inclusions of feldspar and iron ore. The groundmass is intergranular, with an average grain size of 0.06 mm. It is composed of colorless monoclinic pyroxene (30%), olivine (2%), labradorite (40%), and iron ore (10%), the latter including magnetite and ilmenite in approximately equal proportions.

Picritic basalts.—These rocks may be divided into those containing phenocrysts of olivine alone, called chrysophyric basalts by J. D. Dana, and those containing phenocrysts of both olivine and augite. The latter are generally somewhat richer in total amount of ferromagnesian minerals than those which contain only olivine phenocrysts. All gradations are found between the normal olivine basalts and the picritic basalts. The typical picritic basalts contain large phenocrysts of both olivine and augite, as much as 1 cm or a little more across. The olivine phenocrysts are generally at least twice as abundant as those of augite, and in this respect they differ markedly from the picritic basalts of East Maui, in which the two minerals are generally about equally abundant. The picritic basalts appear to be restricted to the uppermost part of the Wailuku lavas, although transitional types are found deeper in the section.

One such transitional rock, collected at the junction of Honokowai and Amalu Streams, has been analyzed (no. 2 in table, p. 334). It is a medium-gray pahoehoe with phenocrysts of olivine (20%) in an intergranular, locally diabasic, groundmass. The phenocrysts are slightly rounded and embayed by resorption, and enclosed in a thin shell of iddingsite. The groundmass consists of labradorite (35%); augite (35%), with $+2V = 55°$ and weak dispersion; and ilmenite (10%). In many places finely granular iron ore is closely associated with the rims of iddingsite around the olivine phenocrysts. A lava exposed on the highway 4 miles southeast of Olowalu is much like the analyzed specimen, except that the iron ore is largely magnetite.

The picritic basalts containing phenocrysts of olivine alone are illustrated by a boulder collected in Iao Stream. The rock is dark-gray and dense, with crystals of olivine (40%) up to 7 mm across but averaging about 3 mm. In thin section a few phenocrysts show a small amount of rounding and embayment, but most show no signs of resorption. They are altered around the edges and along fractures to pale greenish-brown fibrous serpentine. The groundmass is composed of plagioclase (25%), zoned from calcic labradorite to labradorite-andesine; pale-brown augite (28%), with $+2V = 60°$ and no detectable dispersion; a few colorless subhedral grains of hypersthene (1%); ilmenite (5%); and irregular interstitial patches of a yellowish-green mineral (1%), length-slow, with a birefringence of about 0.015, probably celadonite.

The typical picritic basalts are illustrated by one from the top of Paupau Hill, near Lahaina. The rock is a medium-gray aa, with phenocrysts of olivine (30%) up to 5 mm across, and augite (10%) up to 1 cm across. The olivine phenocrysts are much rounded and embayed by resorption and are altered around the edges to iddingsite. The augite phenocrysts are also somewhat rounded by resorption. They are pale-green in thin section, with $+2V = 60°$, $r > v$ weak $Z \wedge c = 48°$, $\alpha = 1.692$, $\beta = 1.700$, $\gamma = 1.717$. The groundmass is intergranular, and is composed of olivine (5%), calcic labradorite (25%), monoclinic pyroxene (25%), and iron ore (5%), including both magnetite and ilmenite. A specimen collected by Stearns 3.05 miles N. 44° W. of McGregor Point is much like that from Paupau Hill. A lava exposed 1 mile S. 33° W. of Puu Koae, near Kahakuloa, contains phenocrysts of plagioclase (5%) in addition to those of olivine (20%) and augite (5%). The groundmass consists of plagioclase (23%), olivine (6%), augite (28%), iron ore (6%), and glass (5%). The plagioclase phenocrysts are calcic bytownite ($\beta = 1.575$), and the groundmass feldspar is labradorite-bytownite ($\beta = 1.568$). The plagioclase phenocrysts are transected by innumerable veinlets of a colorless isotropic substance with $n = 1.545$, probably halloysite.

PEGMATITOID VEINS.—A specimen of olivine basalt collected by Stearns in the east fork of Kahakuloa Stream, 0.6 mile S. 54° W. of Puu Olelo, contains a small segregation veinlet resembling in general appearance the pegmatitoid veins in the Sugar-loaf basalt at Moiliili quarry in Honolulu.[93] The rock is a medium-gray sparingly vesicular pahoehoe with moderately abundant phenocrysts of olivine up to 1.5 mm across. The veinlet is 10 cm long and a few millimeters wide, and appears to be a small fracture in the lava formed after the main body of the rock was essentially solidified. The walls of the fracture are lined with euhedral crystals of the same minerals found in the rest of the rock, including crystals of intermediate labradorite tabular parallel to the side pinacoid, acicular crystals of augite, crystals of olivine, and hexagonal plates of ilmenite.

DUNITE INCLUSIONS.—Fragments of dunite are found in Wailuku olivine basalts at a number of localities. They range from a few millimeters to several centimeters across, and in shape from sharply angular to well rounded. The dunite is composed entirely of olivine, except for scattered octahedral grains of a metallic spinel, probably magnetite or chromite. The rocks enclosing them are normal olivine basalts.

Dunite inclusions are common in boulders of basalt in Manawainui Stream. They are rounded in outline, and have been shattered and cut by stringers of the enclosing rock. The fragments were obviously undergoing rapid disintegration in the magma at the time of eruption. The dunite is composed of olivine and a few scattered grains of iron ore. The texture is anhedral, and the average grain size about 1.5 mm. Exsolution of finely granular iron ore has produced dark borders on most of the grains, and the oxidation of some of this liberated magnetite has resulted in abundant hematite staining. A band of iddingsite averaging about 0.2 mm thick follows the edge of the dunite inclusion. The olivine of the dunite has $\beta = 1.683$, the olivine phenocrysts in the enclosing lava have $\beta = 1.691$, and the groundmass olivine has $\beta = 1.728$, indicating a gradual increase in the amount of fayalite in the olivine, from 15 percent in the dunite to 36 percent in the groundmass olivine.

A unique dunite inclusion was collected near the mouth of Pohakea Gulch by Hisashi Kanno. The dunite fragment, which is enclosed in olivine basalt, is 8 cm across, and is cut by a band of pyroxenite 2.5 cm wide (pl. 43A). The contact between the dunite and pyroxenite at first glance appears sharp, but

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[93] Hitchcock, C. H., Geology of Oahu: Geol. Soc. America Bull., vol. 11, p. 47, 1900.
Dunham, K. C., Crystal cavities in lavas from the Hawaiian Islands: Am. Mineralogist, vol. 18, pp. 371-379, 1933.
Stearns, H. T., and Vaksvik, K. N., Geology and ground-water resources of the island of Oahu, Hawaii: Hawaii Div. of Hydrography, Bull. 1, pp. 158-159, 1935.

when examined in detail many grains are found to project across the general plane of the boundary. The texture of both dunite and pyroxenite is anhedral, with an average grain size of about 2 mm. The pyroxenite contains a few rounded vesicles from 1 to 3 mm across. The dunite is composed entirely of olivine, except for scattered grains of magnetite or chromite. The olivine of the dunite has $\beta = 1.682$, the olivine phenocrysts in the surrounding lava have $\beta = 1.689$, and the groundmass olivine has $\beta = 1.737$. The pyroxenite consists largely of augite, with scattered minute grains of iron ore and a few crystals of olivine. The augite has $+2V = 55°$, no detectable dispersion, $Z \wedge c = 43°$, $\alpha = 1.686$, $\beta = 1.692$, and $\gamma = 1.712$.

The exact mode of origin of the dunite inclusions is unknown, but as pointed out by Cross they are undoubtedly genetically related to the enclosing basalt.[94] They probably represent deep-seated accumulations of olivine crystals settled from the overlying magma. The origin of the augitite band in the dunite inclusion from Pohakea Gulch is less clear. It appears to be a small dike injected into the dunite, but if so it represents an instance of a nearly monomineralic ultrabasic rock which existed as a liquid. Moreover, the projection of crystals across the general plane of the contact suggests some mode of formation other than injection. It appears more probable that volatiles moving along a fracture in the dunite reacted with the olivine to form a band of augitite.

CRYSTAL-VITRIC TUFF NEAR MANAWAINUI GULCH.—Tuffs of firefountain origin are known at a number of localities in the Wailuku basalts, but only one has been studied under the microscope. This one locality is a cinder cone at an altitude of 1,565 feet, 1,000 feet west of Manawainui Gulch. The cone was breached and gave vent to a flow of olivine basalt, close to picritic basalt in composition. It was nearly or completely buried by later basaltic lavas, but has been re-excavated by erosion. The cone is formed of yellowish-brown friable tuff, consisting largely of partly altered pumiceous to dense cognate lava fragments, largely glassy, with abundant loose crystals of olivine and augite as much as 1.5 cm long. The olivine is fresh, with $\beta = 1.682$, corresponding to about 15 percent fayalite. The augite crystals are short and thick, showing the forms 110, 100, 010, and 111, with 110 predominating in the vertical zone (pl. 44A). Contact twins of arrow-head type are numerous. All of the augite crystals look as if they had been slightly fused on the outside; they are more or less rounded and have a glassy appearance. The surface of many is pock-marked as though bubbles had burst and the surface congealed before it could again become smooth. Despite this appearance, no glass can be detected under the microscope. The augite has $+2V = 60°$, no detectable dispersion, $Z \wedge c = 42°$, $\alpha = 1.687$, $\beta = 1.693$, and $\gamma = 1.713$.

HONOLUA VOLCANIC SERIES

The Honolua lavas include two types of the most silicic lavas of the Hawaiian Islands, oligoclase andesites and soda trachytes. The only Hawaiian rock thus far known to be more silicic than the West Maui trachytes is the trachyte of Mauna Kuwale, on Oahu.[95] In the other Hawaiian volcanoes where andesites have been studied, there

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[94] Cross, W., op. cit., pp. 34-35.

[95] Macdonald, G. A., Petrography of the Waianae Range, Oahu: Hawaii Div. of Hydrography, Bull. 5, pp. 81-84, 1940.

is a gradual transition in rock composition from the primitive basalts through basaltic andesites to true andesites, and basalts and andesites are to some extent interbedded. But in West Maui there is no transition in composition between the basalts and andesites, and there is no interbedding of the basalts with the andesites and trachytes. The change from basalts to oligoclase andesites is sudden and complete.

There is a continuous gradation in composition from the oligoclase andesites to the soda trachytes. The two types are closely similar petrographically. The feldspar is slightly more calcic in the andesites, but the greatest difference lies in the absence in most of the andesites of the sodic ferromagnesian minerals which characterize the trachytes. No effort has been made to map separately the andesites and trachytes. They are too similar in appearance to be readily separable in the field. In general, however, the trachytes appear to form viscous domes and short thick flows, and to be for the most part later than the thinner flows of andesite.

OLIGOCLASE ANDESITES.—These rocks were first described by E. S. Dana from Paupau Hill near Lahaina,[96] and later by Möhle.[97] Cross quoted Dana's description, but grouped the rock with the soda trachytes,[98] as also did Sidney Powers, who recorded a number of new localities on West Maui, and gave brief petrographic descriptions of specimens from Waiolai Gulch and Paupau Hill.[99] Washington and Keyes described and analyzed an oligoclase andesite from Iao Valley[1] and appear to have been the first to recognize it as a type distinct from the soda trachytes. Similar oligoclase andesites are known at Kohala Volcano on the island of Hawaii.[2] The West Maui oligoclase andesites are closely related in composition to the mugearites.

The oligoclase andesites are medium- to light-gray, and generally dense and nonporphyritic. In some a few phenocrysts of plagioclase, up to 3 mm long, are visible to the unaided eye, and rarely there are present a few phenocrysts of olivine. One specimen from Iao Valley contains a few phenocrysts of hornblende. Flow banding is generally prominent, and platy jointing parallel to the flow planes is present at many localities. In some places, as at Paupau Hill, the surfaces of the joint plates show a micaceous sheen owing to reflection from the surfaces of innumerable minute parallel-oriented tabular microlites of feldspar. Under the microscope the rocks are seen to be composed largely of subhedral to anhedral grains of sodic oligoclase arranged in a

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[96] Dana, E. S., Contributions to the petrography of the Sandwich Islands: Am. Jour. Sci., 3rd ser., vol. 37, pp. 465-466, 1889. The Mt. Ball of Dana's description is clearly Paupau Hill.

[97] Möhle, F., Beitrag zur Petrographie der Sandwich- und Samoa-Inseln: Neues Jahrb., Beil. Bd. 15, pp. 68-69, 1902.

[98] Cross, W., Lavas of Hawaii and their relations: U. S. Geol. Survey Prof. Paper 88, pp. 26-27, 1915.

[99] Powers, S., Notes on Hawaiian petrology: Am. Jour. Sci., 4th ser., vol. 50, pp. 270-271, 1920.

[1] Washington, H. S., and Keyes, M. G., Petrology of the Hawaiian Islands; VI. Maui: Am. Jour. Sci., 5th ser., vol. 15, pp. 203, 205-207, 1928

[2] 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. 424-425, 1896.
Washington, H. S., Petrology of the Hawaiian Islands; I. Kohala and Mauna Kea, Hawaii: Am. Jour. Sci., 5th ser., vol. 5, pp. 476-479, 1923.

trachytic texture. The feldspar phenocrysts are calcic to intermediate oligoclase, surrounded by a thin shell of sodic oligoclase. They show albite and Carlsbad twinning, the latter including both contact twins and the interpenetration twins described by Dana. Numerous highly acicular crystals of apatite are enclosed in the feldspar. Mafic minerals constitute 15 to 20 percent of the rock, and include olivine, colorless monoclinic pyroxene, and magnetite. Scattered flakes of biotite and grains of hornblende are present in many slides. In some the hornblende is pale-green, but in others it is pleochroic from X = pale brownish-yellow to Z = deep greenish-brown, with $-2V = 70°$, $r < v$ strong, and $Z \wedge c =$ about 20°. The index of the olivine ranges from 1.746 to 1.767, corresponding to a range in fayalite content from about 45 to 55 percent. A few lavas transitional to the trachytes contain scattered grains of pale grass-green pyroxene, probably aegirine-augite.

Another mineral recognized in the oligoclase andesites from several localities, as well as in many of the trachytes, is a riebeckite-like amphibole. It is acicular, with good prismatic cleavage, nearly parallel extinction, negative elongation, very low birefringence (.004±), a large positive optic angle, and strong dispersion with $r < v$. It is pale purplish-gray parallel to X and pale yellow parallel to Z. The mineral has also been noted in lavas from East Molokai and in one lava from Kipahulu Valley on East Maui. The properties are much like those of riebeckite, but the mineral is less strongly colored than is typical riebeckite.

Typical oligoclase andesites are exposed along the highway for several miles in the northwestern part of the mountain. A specimen collected 0.2 mile north of Honolua is a dense, medium-gray, nonporphyritic lava with faint flow banding and poorly developed platy jointing. It is composed largely of sodic oligoclase (80%) containing many inclusions of apatite, with olivine (4%), colorless monoclinic pyroxene (7%), iron ore (8%), anhedral flakes of biotite (1%) pleochroic from nearly colorless to pale reddish-brown, and a few crystals of the riebeckite-like amphibole. The olivine has $\beta = 1.746$, indicating a fayalite content of about 45 percent. A specimen collected on the highway 0.25 mile southwest of Honolua is similar to that just rescribed, but lacks the riebeckite-like amphibole and contains a few phenocrysts of feldspar. The phenocrysts are intermediate oligoclase ($\beta = 1.543$), the groundmass feldspar is sodic oligoclase ($\beta = 1.538$). A sample taken 0.35 mile northeast of Maunakini, near Kahakuloa, is much like those taken near Honolua, but contains a few microphenocrysts of olivine.

The andesite exposed in the highway cut at McGregor Point is light-gray, dense, and nonporphyritic, with prominent flow banding and poorly developed platy jointing parallel to the flow planes. The texture is trachytic, with an average grain size of about 0.15 mm. Feldspar forms about 80 percent of the rock. Most abundant are lath-shaped grains of oligoclase, with albite and Carlsbad twinning. Minute irregular grains of alkalic feldspar, with refractive index less than that of balsam, lie in the interstices. Scattered throughout the slide are subhedral grains of colorless olivine (10%), with $\beta = 1.755$, euhedral to anhedral grains of magnetite (8%), and small grains of colorless monoclinic pyroxene (2%). Rare small flakes of pale-brown biotite and a few crystals of the mineral resembling riebeckite are also present.

The andesite forming Uau Peak, 3 miles N. 8° W. of Mount Eke, resembles the above-described andesites, except that biotite and the riebeckite-like mineral are absent, and in their place are found flakes of pale-green chlorite and a few grains of green hornblende. The olivine has $\beta = 1.767$, indicating the unusually high fayalite content of 55 percent. The chlorite may have been derived from original biotite. A specimen collected 0.55 mile N. 30° E. of Kahana Camp, southwest of Honolua, contains a few crystals of pale-green hornblende together with scattered grains of biotite and the riebeckite-like amphibole. An oligoclase andesite exposed on the end of a spur north of Kope Canyon, 0.6 mile southwest of Waihee contains a single phenocryst of brown hornblende 1 mm long, pleochroic from X = pale-brown to Z = deep reddish-brown. It is much rounded by resorption and is surrounded by a mantle of finely granular exsolved iron ore. Similar hornblendes are found in the soda trachytes.

Boulders of oligoclase andesite in the bed of Iao Stream are almost certainly derived from the andesite which forms the north rim of Iao Valley near Puu Kukui. One of them was described by Washington and analyzed by Keyes.[3] Specimens collected by the writer are apparently not of the same lava, but from their description it appears certain that the rock analyzed by them is a typical oligoclase andesite similar to those described above. One boulder from Iao Valley is transitional to the soda trachytes. It is light-gray, with a few phenocrysts of oligoclase up to 3 mm long and of hornblende up to 1.5 mm. It has poorly developed platy jointing, but on the joint surfaces there is a distinct sheen owing to reflections from innumerable feldspar microlites oriented in parallel position. The rock is composed largely (85%) of subhedral to anhedral grains of oligoclase-albite ($\beta = 1.536$) averaging about 0.3 mm long by 0.1 mm wide, arranged in a trachytic manner. Scattered among these are grains of olivine (5%), colorless monoclinic pyroxene (3%) and magnetite (5%) averaging about 0.05 mm across. A few grains of pale grass-green monoclinic pyroxene are probably aegirine-augite. Minute highly acicular crystals of apatite are abundant in the feldspar. The hornblende phenocrysts are pleochroic from X = pale brownish-yellow to Z = deep greenish-brown, with $-2V = 70°$, and $r < v$ strong. They are much rounded by resorption and are surrounded by a rim of finely granular iron ore.

Soda trachytes.—The first printed mention of these rocks was by E. S. Dana, who described a specimen from Launiupoko Hill.[4] He did not, however, realize the true nature of the rock, and grouped it with the andesite from Mount Ball (Paupau Hill). The specimens were later re-examined by Cross, who recognized the sodic character of the Launiupoko trachyte, and compared it with similar trachytes from Sardinia.[5] A soda trachyte from Waihee Gulch containing aegerine-augite was described by Sidney Powers.[6] The Launiupoko rock was again studied by Washington and Keyes, whose description concurs with that of Cross in most respects except that they believe the dominant feldspar to be anorthoclase.[7] The writer has not been able to confirm this identification. The feldspars in the slides studied appear to have large optic angles, and have been classed as albite or oligoclase rather than anorthoclase. However, the trachyte of Launiupoko Hill contains 20 percent normative orthoclase (see table, p. 334) which has not been recognized in the mode, and consequently it is possible that some of the groundmass feldspar is anorthoclase.

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[3] Washington, H. S., and Keyes, M. G., op. cit., pp. 203, 205-206.
[4] Dana, E. S., op. cit., pp. 464-465.
[5] Cross, W., op. cit., pp. 26-27.
[6] Powers, S., op. cit., p. 271.
[7] Washington, H. S., and Keyes, M. G., op. cit., pp. 207-208.

The soda trachytes are light-gray, dense rocks, with moderately to well developed flow banding and platy jointing parallel to the flow planes. The joint surfaces show a micaceous sheen resulting from the parallel orientation of tabular feldspar microlites. All specimens contain phenocrysts of feldspar, from 2 to 7 mm across, with blocky outlines. One contains a few acicular phenocrysts of hornblende. The feldspar phenocrysts are calcic to intermediate oligoclase, and are surrounded by a narrow rim in which the composition changes rapidly to albite. Albite twinning is rare but Carlsbad twinning, of both contact and interpenetration varieties, is abundant. The groundmass is trachytic, with average grain sizes ranging from 0.1 to 0.25 mm. It is composed largely of subhedral to anhedral grains of albite, for the most part untwinned or with simple Carlsbad twinning. Ferromagnesian minerals generally constitute less than 15 percent of the rock. They include hornblende, aegirine-augite, biotite, magnetite, the riebeckite-like amphibole described above, and acmite.

The hornblende is of two varieties. One appears to be a normal hornblende, with X = pale yellowish-green, Y = yellowish-green, and Z = slightly brownish-green. The other has a pleochroism of X = greenish-brown, Y = yellowish-green, and Z = yellowish-green, $-2V = 70°$, $r < v$ very strong. $Z \wedge c = 24°$, $\alpha = 1.626$, $\beta = 1.636$, $\gamma = 1.644$, and $\gamma - \alpha = .018$. This latter hornblende is found in many Hawaiian rocks which also contain aegirine-augite or acmite, and is probably sodic. The two varieties of hornblende are occasionally present in the same rock.

The acmite forms small, pale-brown, stubby prismatic grains with nearly straight extinction, high birefringence, and $-2V = 60°$. It is frequently clouded with dusty iron ore, and is often closely associated with aegirine-augite. It is the mineral in the trachyte of Launiupoko Hill believed to be acmite by both Cross[8] and Washington and Keyes.[9]

The Launiupoko lava may be taken as typical of the soda trachytes. Launiupoko Hill is a steep-sided viscous trachyte dome, with flow banding and platy jointing dipping centripetally on all sides. On its west side the dome passes into a short thick flow which advanced westward about 2,000 feet. The banding and jointing in the flow dip to the west (fig. 4). The structures resemble those in the viscous dacite flows at Crater Lake.[10] About 3,000 feet northeast of Launiupoko Hill lies a second trachyte dome, and still others lie to the eastward and southeastward, from which flows of trachyte advanced southwestward to the coast. The Launiupoko trachyte is a light-gray dense rock, containing scattered phenocrysts of feldspar up to 7 mm long. The phenocrysts are intermediate oligoclase ($\beta = 1.544$), surrounded by a narrow zoned envelope in which the composition changes to albite. The phenocrysts grade into microphenocrysts, which average about 0.5 mm in length. They are blocky in outline, and albite twinning is rare. Carlsbad twinning, of both contact and interpenetration varieties, is very abundant. Together, phenocrysts and microphenocrysts form about 10 percent of the rock. The groundmass is weakly trachytic with an average grain size of 0.1 mm. It is composed of albite (75%), in anhedral to subhedral grains, untwinned or with simple Carlsbad twinning, and with $\beta = 1.531$. Hornblende (5%) forms anhedral to subhedral grains with $-2V = 75°$, $r < v$ strong, X = greenish-

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[8] Op. cit., p. 27.

[9] Op. cit., p. 208.

[10] Allen, J. E., Structures in the dacitic flows at Crater Lake, Oregon: Jour. Geology, vol. 44, pp. 737-744, 1936.

brown, Y and Z = yellowish-green. Aegirine-augite (3%) occurs in small subhedral to anhedral grains with weak pleochroism from grass-green to yellowish-green, a large extinction angle, and negative elongation. A small amount of pale-brown acmite is present in some slides. Magnetite (7%) ranges from anhedral to nearly euhedral. A few flakes of brown biotite, and prismatic crystals of apatite up to 0.2 mm long and 0.05 mm wide are scattered through the rock. In one place a former phenocryst of some acicular mineral, probably hornblende or the riebeckite-like amphibole, has been entirely altered to finely granular iron ore.

Trachyte from a quarry 1 mile S. 20° E. of the top of Launiupoko Hill is similar to the Launiupoko rock except that sodic ferromagnesian minerals are less prominent. Most abundant is a colorless monoclinic pyroxene. A few grains of aegirine-augite, acmite, and the riebeckite-like amphibole are present. The small hill of trachyte projecting through alluvium at the highway 0.65 mile S. 37° W. of the top of Launiupoko Hill is probably another local vent. The lava is much like those described above except that euhedral to anhedral grains of magnetite are abundant, forming about 15 percent of the rock, and attaining diameters as great as 1 mm. They are closely associated with red flakes of hematite. One large grain of magnetite contains several irregular inclusions of biotite, with $-2V = 15°$, $r > v$ strong, X = straw-yellow, Y and Z = reddish-brown.

The trachyte from the viscous dome of Puu Koae, near Kahakuloa, is much like that from Launiupoko Hill, but biotite is absent and acmite is more abundant. Phenocrysts of oligoclase (5%) lie in an unusually coarse-grained groundmass, with an average grain size of 0.25 mm, of which about 80 percent is albite ($\beta = 1.533$). Hornblende (5%) of both varieties is present, as are also aegirine-augite (3%), acmite (1%), and magnetite (6%). The acmite forms pale-brown stubby crystals with nearly straight extinction, high birefringence, and $-2V = 60°$.

Trachyte from Puu Olai, another viscous dome 1.5 miles southeast of Kahakuloa, lacks both acmite and aegirine-augite, but contains hornblende pleochroic from X = greenish-brown to Z = yellowish-green, which is probably sodic. The other femic minerals are colorless pigeonite, magnetite, and a few grains of olivine. A rock which crops out on the west end of the spur half a mile northwest of Waihee is much like the trachyte of Puu Olai, except for the presence of acicular phenocrysts of brown hornblende up to 1.5 mm long. These rocks are less sodic than the trachytes of Launiupoko Hill and Puu Koae, and approach in composition the oligoclase andesite of Iao Valley.

Mount Eke is another viscous dome. Specimens from Eke and the vicinity are much decomposed, owing to the extreme wetness of the climate, but clearly represent altered soda trachyte. In one from a shallow pool on top of Mount Eke the ferromagnesian minerals have been completely altered to chlorite, but the feldspar of both the phenocrysts and groundmass remains moderately fresh. The groundmass feldspar is albite. Another, collected half a mile northeast of Mount Eke, contains phenocrysts of oligoclase in a groundmass formed principally of albite, with scattered grains of hornblende, aegirine-augite, iron ore, and rare flakes of purplish-brown biotite. A specimen from the north fork of Waihee Stream is nearly identical in mineral components to that collected northeast of Mount Eke, except for the presence of small black phenocrysts of hornblende.

LAHAINA VOLCANIC SERIES

The post-erosional lavas of the Lahaina volcanic series include both picritic basalt and nepheline basanite. Four centers of eruption are known. Kekaa cinder cone, 3.5 miles north of Lahaina, and Puu Hele cinder cone, 1.5 miles north of Maalaea, have no known associated lava flows. Both are picritic basalt. The Kilea cinder cone, 0.5 mile northeast of Olowalu, produced a short lava flow which extends seaward about 500 feet. The rock is a nepheline basanite. Laina cinder cone near Lahaina erupted a flow of picritic basalt over a mile wide which extends westward to the sea (pl. 1).

Möhle found in the lavas of the Schauinsland collection a specimen of melilite-nepheline basalt said to come from the vicinity of Lahaina.[11] The rock was compared by him to a similar one from Oahu. It contained phenocrysts of olivine and a few of melilite, in a coarse-grained groundmass composed of melilite, nepheline, augite, magnetite, and a few needles of apatite. No rock corresponding to this description has been found during the present investigation, although a special search for it was made. In none of the Lahaina lavas is there any melilite, and all contain abundant feldspar. It appears probable that Möhle's specimen was wrongly labeled, and actually came from some other locality. It may have been carried to Lahaina from Oahu as ballast in some sailing ship.

The lava from Kilea cone has been studied both microscopically and chemically. (See table, page 334.) It is a dark-gray, sparingly vesicular aa, with scattered phenocrysts of brownish-green olivine up to 2 mm long, and microphenocrysts of augite. The olivine phenocrysts (20%) have $\beta = 1.688$, corresponding to a fayalite content of about 18 percent. They show no signs of resorption. The augite phenocrysts (10%) are pale slightly purplish brown, with $+2V = 60°$, distinct inclined dispersion and dispersion of the optic axes, $r > v$ strong on one axis and very weak on the other. Many grains show hour-glass zoning. The groundmass consists of subhedral to anhedral lath-shaped crystals of labradorite (30%), colorless subhedral crystals of monoclinic pyroxene (20%), and grains of magnetite (10%), in a colorless, low-birefringent base (10%) with a refractive index close to 1.54. Staining with methylene blue in the manner described by Shand[12] produces blue discoloration in some of the low-birefringent interstitial grains, and inasmuch as the specimen analyzed contains over 17 percent normative nepheline, the material showing blue discoloration is identified as nepheline. Because of the presence of abundant labradorite and olivine, the rock is classified as a nepheline basanite. The only other basanites thus far recorded from the Hawaiian Islands were two specimens from Diamond Head and Puu Kapolei, on Oahu, tenta-

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[11] Möhle, F., op. cit., pp. 67, 69-70.

[12] Shand, S. J., On the staining of feldspathoids, and on zonal structure in nepheline: Am. Mineralogist, vol. 24, pp. 508-510, 1939.

tively identified as nepheline basanite by Cross.[13] It has since been shown that the rock of Puu Kapolei probably does not contain nepheline.[14] However, several specimens of nepheline basanite have been found by the writer among lavas from the southern side of the island of Kauai.

The picritic basalt of Puu Hele contains phenocrysts of olivine (15%) up to 1 mm across, rounded and embayed by magmatic resorption, and microphenocrysts of augite (25%) in a dense, difficultly resolvable groundmass heavily charged with fine iron ore. The augite phenocrysts are pale purplish-brown, with $+2V = 60°$, and strong inclined dispersion. Many show hourglass structure. A few stellate groups of crystals are found, similar to some noted in the Koko fissure volcanics on Oahu. The groundmass consists of labradorite, augite, and magnetite, in a dense, partly glassy matrix. Staining with methylene blue reveals no nepheline.

Thin flows of picritic basalt are interbedded with the cinders of Kekaa cone. Phenocrysts of olivine and augite range in size from 2 to 0.1 mm. The augite is purplish-brown in thin section, with strong dispersion, and is probably titaniferous. Many grains have hour-glass zoning. The olivine phenocrysts are rounded and embayed by magmatic resorption and are altered to iddingsite around the edges. The β refractive index of the olivine is 1.685, corresponding to about 17 percent fayalite. The groundmass consists of microlites of labradorite, augite, and olivine in a dense, partly glassy matrix heavily charged with minute granules of iron ore. Some of the matrix material shows weak birefringence. Staining with methylene blue produces a small amount of discoloration in the matrix, but the color is largely restricted to the isotropic areas, and the birefringent patches are mostly unstained. It is therefore concluded that the birefringent material is mostly feldspar, although a small amount of nepheline may be present.

The lava from Laina cone is a picritic basalt much like those from Hele and Kekaa cones, but lacking phenocrysts of augite. At the beach 1 mile north of Mala the rock is a dark-gray pahoehoe with phenocrysts of brownish-green olivine (15%) up to 2 mm long, slightly rounded and embayed by resorption. The groundmass is intergranular, with an average grain size of 0.05 mm. It consists of labradorite (30%), pale-brown pigeonite (40%), olivine (5%), and magnetite (10%). The olivine phenocrysts have $\beta = 1.701$, indicating a fayalite content of about 24 percent. This determination corresponds closely with that of 1.702 for the olivine phenocrysts in a rock collected on the southeast side of Laina cone, but is higher than those of 1.692 and 1.694 for olivines in specimens respectively from the southwest and northwest sides of the cone. Treatment of the Laina lava with phosphoric acid and methylene blue results in staining of a few weakly birefringent interstitial grains, but many of these show the twinning or lath-shaped outlines of feldspar. It is possible that some of the rest are nepheline, but the identification is not positive.

INTRUSIVE ROCKS

DIKES.—The numerous dikes shown on plate 1 are for the most part identical in composition and texture to the Wailuku and Honolua flows. Andesite and trachyte dikes are less numerous and com-

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[13] Cross, W., op. cit., p. 23.

[14] Macdonald, G. A., op. cit., pp. 85-86.

monly thicker than those of basalt. Only a few of the dikes appear worthy of special mention here.

A dike of olivine basalt 25 feet thick, cut by a water-development tunnel on the south side of Honokowai Stream, contains unusually abundant subhedral phenocrysts and glomerocrysts of olivine in an intergranular, locally diabasic groundmass with an average grain size of 0.15 mm. The olivine phenocrysts (20%) contain many inclusions of magnetite. The groundmass consists of labradorite (40%), pigeonite (30%) with $+2V = 30°$ to $40°$ and weak dispersion, olivine (1%), and iron ore (8%). Most of the iron ore grains are anhedral, but of the subhedral grains most show the rod-like cross sections of ilmenite. Interstitial biotite (1%) is pleochroic from nearly colorless to deep greenish-brown.

A dike of picritic basalt in the water-transportation tunnel between Amalu and Honokowai Streams is sparingly vesicular, with phenocrysts of olivine (23%) up to 7 mm across, slightly rounded and embayed by resorption, in an intergranular groundmass composed of labradorite (30%), pale-brown pigeonite (38%), olivine (2%), and iron ore (7%). Most of the iron ore grains have the lath-shaped outlines of ilmenite. The pigeonite has a $+2V$ ranging from 30° to 50°. The olivine phenocrysts have $\beta = 1.687$.

A 15-foot dike of soda trachyte exposed at the ditch intake in Waihee Valley is identical to the rock of Launiupoko Hill, except that phenocrysts are absent. The rock is composed largely of albite, with subordinate colorless monoclinic pyroxene (5%), iron ore(5%), aegirine-augite (3%), hornblende (2%), abundant minute needles of apatite enclosed in the feldspar, and a few grains of biotite and the riebeckite-like amphibole. The hornblende is strongly pleochroic, with X = greenish-brown and Z = yellowish-green.

STOCKS.—Several stocks ranging from 0.1 to 0.55 mile in maximum diameter are shown on plate 1. The larger of these consist of moderately coarse-grained gabbro, with finer grained marginal facies, but the smaller ones are diabase or basalt porphyry. The coarser facies of the gabbros average between 1.5 and 2 mm. in grain size. Some of them are dense granitoid rocks, but others are characterized by an open, mesh-like texture (pl. 43C), with well-formed crystals of feldspar and augite projecting into miarolytic cavities. The rocks are typically composed of crystals of labradorite, surrounded by shells of andesine, pigeonite, olivine, and iron ore. Alkalic feldspar is present in several, and tridymite is found in two.

The first record of coarse-grained intrusive rock in West Maui was by Cross, who described a millimeter-grained olivine diabase from a boulder in Iao Valley.[15] Two gabbros from boulders in the bed of Iao Stream were described by Washington and Keyes, and one was chemically analyzed.[16] Similar rocks have been found at

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[15] Cross, W., op. cit., p. 26.
[16] Washington, H. S., and Keyes, M. G., op. cit., pp. 201-203.

other Hawaiian volcanoes, including Molokai,[17] Kauai,[18] Oahu,[19] and Kahoolawe,[20] as independent intrusive bodies or as inclusions in extrusive lavas.

A small intrusive mass of olivine basalt porphyry is exposed in Black Gorge, a tributary of Iao Valley (pl. 10A). The rock is medium-gray and dense, with phenocrysts of olivine (12%) up to 2.5 mm across in an intergranular to diabasic groundmass with an average grain size of 0.2 mm. The olivine phenocrysts are altered around the edges and along fractures to iddingsite. The groundmass consists of pigeonite (33%) with $+2V$ ranging from 25° to 55° and no detectable dispersion; olivine (3%) partly altered to iddingsite; iron ore, probably largely ilmenite (7%); plagioclase (45%) zoned from intermediate labradorite at the center to calcic andesine at the outside. A few interstitial grains of feldspar have the refractive index of calcic oligoclase, but a small positive optic angle.

A boulder of rock of unusual nature found in the bed of Iao Stream near the highway bridge is not definitely known to be of intrusive origin but is best discussed here because of its relatively coarse grain. In many respects the rock resembles one analyzed by Washington and Keyes.[21] It is best described as a picritic gabbro. The rock is dense, reddish-brown, equigranular, with an average grain size of 0.5 mm, and high specific gravity. It is composed of euhedral to subhedral crystals of olivine, surrounded by subhedral to anhedral grains of plagioclase, augite, and hypersthene. The olivine (40%) is heavily clouded by networks of minute granules of exsolved iron ore, and is extensively altered around the edges and along fractures to iddingsite. Hypersthene (20%) is colorless, with a large negative optic angle, and is frequently molded around the olivine. The augite (5%) is colorless, with $+2V = 60°$ and no detectable dispersion. The plagioclase (32%) is calcic labradorite. Irregular grains of iron ore (3%), in addition to that liberated from the olivine, are scattered throughout the rock, and some of the interstices are filled with concentrically banded, finely fibrous, colorless material, probably zeolite, associated with which in a few places is a little calcite. The presence of the calcite and the zeolite(?), together with the extensive alteration of the olivine to iddingsite, suggests that the rock may have been exposed to the action of volatiles. Except that much of the pyroxene is hypersthene rather than augite, the rock resembles in mineral composition the gabbro of the Uwekahuna laccolith at Kilauea.[22]

Another boulder from Iao Valley closely resembles in petrographic character a gabbro described and analyzed by Washington and Keyes.[23] (See table, p. 331.) The rock is dark brownish-gray and dense, with granitic texture and an average grain size of about 2 mm. It consists of lath-shaped crystals of plagioclase (55%), surrounded by anhedral grains of pale-brown pigeonite (25%), iron ore (3%), and interstitial aggregates of feldspar (18%). The pigeonite has an optic angle ranging from 15° to 50°. The plagioclase crystals

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[17] Lindgren, W., Water resources of Molokai, Hawaiian Islands: U. S. Geol. Survey Water-Supply Paper 77, pp. 14-15, 1903.

[18] Cross, W., op. cit., pp. 14-16.
Powers, S., op. cit., p. 278.

[19] Macdonald, G. A., op. cit., p. 73.

[20] Macdonald, G. A., Petrography of Kahoolawe: Hawaii Div. of Hydrography, Bull. 6, p. 163, 1940.

[21] Op. cit., p. 202.

[22] Daly, R. A., Magmatic differentiation in Hawaii: Jour. Geology, vol. 19, p. 293, 1911.

[23] Op. cit., p. 201-203.

contain cores of sodic labradorite, surrounded by strongly zoned relatively thin shells changing progressively in composition to oligoclase-andesine at the outside. The interstitial feldspar is about half orthoclase, which in many places is intergrown with oligoclase-andesine to form antiperthite. Crystals of apatite are enclosed in the orthoclase, some of them reaching 1 mm in length. A few grains of calcite are present. Another nearly identical specimen contains black lath-like crystals as much as 4 mm long. Microscopic examination reveals that they consist almost entirely of iron ore, with a little reddish-brown material resembling iddingsite. The interstitial perthite is even more abundant than in the other specimen, and a needle of apatite embedded in it is over 3 mm long, but only 0.02 mm thick. Small flakes of reddish-brown biotite are associated with the orthoclase.

The olivine gabbro of the stock at 1,600 feet altitude in Ukumehame Canyon is a dark-gray, dense granitic rock with an average grain size of 1.5 mm. The rock is composed of subhedral to anhedral crystals of plagioclase (55%); pale-brown, largely anhedral grains of pigeonite (30%); anhedral grains of olivine (5%); iron ore (4%); and interstitial alkalic feldspar (6%). The pigeonite has an optic angle of 15° to 45°. The plagioclase crystals contain cores of calcic to intermediate labradorite surrounded by strongly zoned shells in which the composition grades to andesine at the outside. Acicular crystals of apatite are enclosed in the interstitial feldspar, which consists of both albite ($+2V = 75°$) and sanidine ($-2V =$ small). The albite is considerably more abundant than the sanidine. Typically the sanidine and albite are intergrown as antiperthite. A few minute wedge-shaped grains resemble tridymite.

The coarse-grained facies of the olivine gabbro stock in Kahakuloa Gulch is similar in mineral composition to that in Ukumehame Canyon, but the rocks are quite different in texture. The gabbro in Kahakuloa Gulch is characterized by numerous irregular miarolytic cavities as much as 8 mm across into which project euhedral plates of feldspar (pl. 43C). The rock is medium-gray, with an average grain size of 2.5 mm. It is composed of plagioclase (50%), pigeonite (33%) with $+2V = 40°–55°$, olivine (5%), iron ore (5%), and interstitial feldspar (7%). A few small wedge-shaped twins of tridymite are present in the interstices. The plagioclase crystals show normal zoning from intermediate labradorite to sodic andesine. The interstitial feldspar is largely orthoclase, but some of it is oligoclase. In places the two feldspars form perthitic intergrowths, and many needles of apatite are enclosed in both, especially in the orthoclase. The size of the optic axial angle in the orthoclase is variable, ranging from near 0° to 70°. The olivine is tinged pale-green by incipient alteration, and in places has been largely changed to iddingsite. The border facies of the stock is similar in every respect to the rock just described, except for its finer crystallinity, the grain size averaging about 0.4 mm.

The gabbro exposed in Kahoma Gulch closely resembles that from Kahakuloa Gulch in texture and mineral composition, but lacks olivine. The coarse-grained facies of the Kahoma gabbro is a medium- to light-gray granitoid rock, with an average grain size of about 3 mm, and numerous irregular miarolytic cavities up to 7 mm across, into which project well-formed crystals of augite and feldspar. The rock is composed of plagioclase (55%), pigeonite (35%), iron ore (3%), interstitial alkalic feldspar (7%), and a few small wedge-shaped twins of tridymite. The pigeonite has an optic angle of 25° to 50°. The plagioclase is intermediate labradorite, surrounded by a narrow strongly zoned rim in which the composition changes progressively to sodic andesine.

The interstitial feldspar includes both orthoclase, with —2V ranging from 20° to 70°, and oligoclase. In many places the two are intergrown as antiperthite, which has the appearance of having been formed by unmixing. The fine-grained facies is identical except for the smaller average grain size, which approximates 0.5 mm.

CHEMICAL COMPOSITION OF WEST MAUI LAVAS

The chemical and normative compositions of seven rocks of the West Maui volcano are shown in the table on page 334. Two of the chemical analyses are new, and were made by Sadamoto Iwashita. The rest are quoted from papers by previous workers. Analysis 1 is of the nepheline basanite from Kilea Cone, the only Lahaina lava of which the chemical composition is known. Analyses 2, 3, and 4 are of Wailuku lavas, number 2 being close to the picritic basalts in modal composition. Analyses 6 and 7 are of Honolua lavas, representing respectively an oligoclase andesite and the soda trachyte of Launiupoko Hill. The soda trachyte is chemically much like that of Puu Anahulu on the island of Hawaii,[24] but is less silicic than the trachyte of Mauna Kuwale in the Waianae Range on Oahu.[25] A soda trachyte from James Island in the Galapagos group is very similar in both chemical and petrographic character to the West Maui soda trachyte,[26] but the trachytes of Tahiti are more phonolitic,[27] and those of Nukuhiva and Uahuka in the Marquesas Islands are more potassic.[28] Analyses of trachytes from Tahiti, the Galapagos Islands, and Puu Anahulu on Hawaii, are shown in the table for comparison with the West Maui trachyte.

The alkali-lime index of the West Maui suite is 53.3, which places the suite in the alkali-calcic group.[29] It is surprising to find this suite less alkaline than that of East Maui, but the result arises from the fact that although the end members of the suite, the soda trachytes, contain alkali pyroxenes and amphiboles, neither they nor the intermediate members are strongly alkaline.

MAGMATIC DIFFERENTIATION

Figure 46 is a variation diagram constructed from the analyses of West Maui rocks shown in the table. The lack of rocks with silica

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[24] Washington. H. S., Petrology of the Hawaiian Islands; II. Hualalai and Mauna Loa: Am. Jour. Sci., 5th ser., vol. 6, pp. 105-109, 1923.

[25] Macdonald, G. A., Petrography of the Waianae Range, Oahu: Hawaii Div. of Hydrography, Bull. 5, pp. 81-84, 1940.

[26] Richardson, Constance, Petrology of the Galapagos Islands: B. P. Bishop Mus. Bull. 110, pp. 46-47, 1933.

[27] Williams, Howel, Geology of Tahiti, Moorea, and Maiao: B. P. Bishop Mus. Bull. 105, p. 43, 1933.

[28] Chubb, L. J., Geology of the Marquesas Islands: B. P. Bishop Mus. Bull. 68, pp. 31-35, 1930.

[29] Peacock, M. A., Classification of igneous rock series: Jour. Geology, vol. 39, pp. 54-67, 1931.

contents between 49 and 59 percent renders this part of the diagram somewhat hypothetical, the shapes of the curves, particularly of the alumina curve, being based partly on the composition of analyzed rocks from other Hawaiian volcanoes. Between 47 and 62 percent silica the trend of the curves is normal, resembling that at many other volcanic centers. Between 47 and 45 percent silica, however, the curves for soda and potash show a rapid reversal in trend which is not generally found in variation diagrams. A similar trend of the alkali curves is found in a variation diagram for the Koolau Volcano on Oahu, if analyses of the nepheline basalts are included. The basanite represented by the diagram at 45 percent silica contains phenocrysts of olivine and augite, and as with the closely similar picritic basalts, its basic nature appears probably the result of the settling of crystals of these minerals from overlying magma. (See section on differentiation of East Maui lavas.) The trends of most of the curves of the variation diagram can be explained on the basis of such gravitative crystal differentiation, but the sharp rise of the curves for soda and potash between 47 and 45 percent silica do not appear to be explicable on this basis. It appears probable that to a magma already made slightly ultrabasic by the addition of crystals of olivine and augite there has been added several percent of alkalies

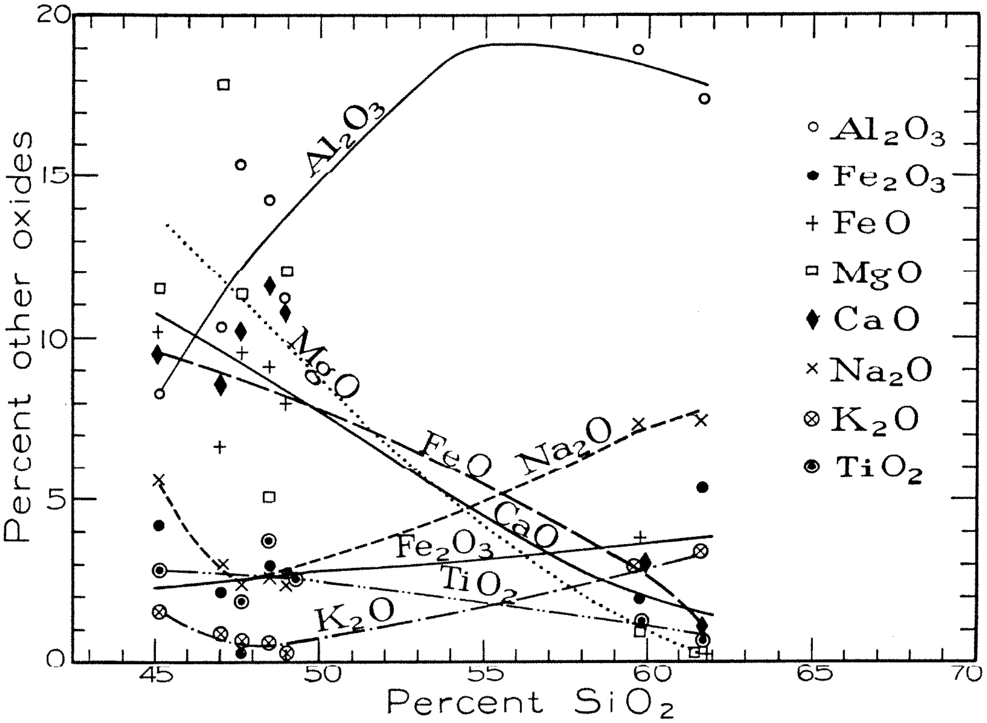

Figure 46. Variation diagram of West Maui lavas.

by some mechanism other than crystal settling. The most logical mechanism to have brought about this addition of alkalies is volatile transfer, the process suggested by Smyth for the generation of alkaline rocks in general.[30] Whenever the sum of the partial pressures of the components of a magma exceeds the external pressure, a gas phase will form and bubbles of gas will move upward through the liquid. The elements most abundant in the gas will include those forming compounds of low boiling point, and it is probable that soda and potash form such volatile compounds.[31] The transfer in the volatile phase of alkalies and other substances from the basal to the upper parts of thick lava flows has been demonstrated by Broderick,[32] and if such differentiation occurs within a single flow, it must occur to some extent in subterranean magma chambers in which physical conditions permit the separation of a gas phase.[33]

It is suggested that a magma containing phenocrysts of olivine and augite and having the bulk composition of picritic basalt was isolated in a small magma chamber, and that volatiles streaming upward enriched the uppermost part in alkalies, producing a small body of magma of basanitic composition.

The oligoclase andesites and trachytes have certainly been derived from olivine basalt magma partly by crystal differentiation, but it is probable that volatile transfer of certain elements was also a factor in their development. The importance of this factor is difficult to evaluate. Nearly all of the iron in the Launiupoko trachyte is in the ferric state, perhaps partly as a result of the oxidizing action of volatiles, but the total iron is considerably less than in the basalts. There was no concentration of iron by volatile transfer as in the rocks described by Broderick. The lack of data for the part of the variation diagram between 49 and 59 percent silica makes it impossible to tell whether the alkali curves progress smoothly or show changes in trend. However, even if the curves were found to progress smoothly in the normal manner, this would not disprove the possibility of volatile transfer having played a part in the differentiation.[34] The liberation and upward streaming of a gas phase is as normal a feature of the magmatic history as is the separation of the solid crystalline phase, and the effects of volatile

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[30] Smyth, C. H., The genesis of the alkaline rocks: Am. Philos. Soc. Proc., vol. 66, pp. 535-580, 1927.

[31] Bowen, N. L., The broader story of magmatic differentiation, briefly told: Ore deposits of the Western States, Am. Inst. Min. Met. Eng., Lindgren vol., p. 120, 1933.

[32] Broderick, T. M., Differentiation in lavas of the Michigan Keweenawan: Geol. Soc. America Bull., vol. 46, pp. 505-534, 1935.

[33] Volatile transfer appears to have been responsible for the differentiation of hornblende monzonite from diorite in the Stony Mountain stock in Colorado. See Dings, McClelland, Geology of the Stony Mountain stock, San Juan Mountains, Colorado: Geol. Soc. America Bull., vol. 52, p. 707, 1941.

[34] Broderick, T. M., op. cit., pp. 543-544.

transfer of certain elements may be represented in most normal variation diagrams. It is impossible at present to state the relative importance of crystal settling and volatile transfer in the development of the andesites and trachytes of West Maui.

Chemical compositions and norms of rocks from West Maui volcano

	1	2	3	4	5	6	7[a]	8	9	10
SiO_2 . .	45.20	47.06	47.72	48.53	48.95	59.74	61.69	62.02	61.90	61.73
Al_2O_3 . .	8.31	10.26	15.44	14.26	11.11	18.86	17.33	18.71	16.75	18.76
Fe_2O_3 . .	4.22	2.14	0.23	2.84	2.67	1.94	5.30	4.30	2.27	2.00
FeO . .	10.21	6.60	9.52	9.10	7.98	3.75	0.07	0.10	4.83	1.54
MgO . .	11.40	17.76	11.31	5.01	11.88	0.90	0.16	0.40	0.57	0.94
CaO . .	9.67	8.62	10.23	11.62	10.86	3.00	1.05	0.86	2.30	1.61
Na_2O . .	5.53	2.80	2.31	2.60	2.38	7.33	7.47	6.90	7.20	6.98
K_2O . .	1.53	0.84	0.63	0.66	0.27	2.89	3.47	4.93	3.25	5.40
H_2O+ . .	0.28	0.63	0.46	1.09	0.31	0.12	1.93	0.80	0.20	......
H_2O- . .	0.14	0.65	0.05	0.07	0.61	0.26	0.42	0.31	0.10	......
TiO_2 . .	2.80	2.62	1.81	3.72	2.44	1.02	0.67	0.31	0.25	0.87
ZrO_2 . .	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.16	0.06	n.d.	n.d.
P_2O_5 . .	0.62	0.50	0.15	trace	0.14	0.26	0.05	0.24	0.07	0.08
MnO . .	0.18	0.16	0.16	0.11	0.16	0.13	0.21	0.15	0.30	0.09
BaO . .	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.07	0.02	n.d.	n.d.
S . . .	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.02	n.d.	0.08	n.d.
	100.09	100.64	100.02	99.61	99.76	100.20	100.10	100.13	100.07	100.00

Norms

	1	2	3	4	5	6	7[a]	8	9	10
Quartz .	......	......	......	1.74	......	......	2.88	1.80	1.69	......
Orthoclase	8.90	5.00	3.89	3.89	1.67	17.24	20.57	28.91	19.24	31.69
Albite . .	2.10	20.96	19.39	22.01	20.44	58.16	62.88	58.16	58.94	52.40
Anorthite	......	13.07	29.75	25.30	18.63	10.01	3.61	2.22	4.14	4.17
Nepheline	17.32	1.42	......	......	......	1.99	......	......	......	3.41
Acmite .	11.09	......	......	......	......	......	......	......	......	......
Diopside .	35.72	20.59	16.19	26.31	27.74	2.57	0.43	......	5.93	3.03
Hypersthene	......	......	2.72	7.97	12.27	......	0.20	1.00	5.31	......
Olivine .	18.33	29.11	22.37	......	9.24	3.50	......	......	3.29	0.63
Magnetite	0.46	3.02	0.23	4.18	3.94	2.78	......	......	3.29	2.32
Pyrite . .	......	......	......	......	......	......	......	......	0.14	......
Ilmenite .	5.32	5.02	3.50	6.99	4.56	1.98	0.61	0.15	0.47	1.67
Hematite .	......	......	......	......	......	......	5.28	4.30	......	0.48
Apatite .	1.34	1.34	0.34	......	0.34	0.67	......	0.67	1.64	......
Rutile . .	......	......	......	......	......	......	......	0.24	......	......

[a] Includes S 0.02, SrO 0.03; normative Hematite 5.28, Titanite 0.98, and Zircon 0.24.

1. Nepheline basanite, Lahaina volcanic series. Flow on northwest side of Kilea Cone, near mouth of Olowalu Canyon; S. Iwashita, analyst.
2. Olivine basalt, transitional to picritic basalt, Wailuku volcanic series. Flow at junction of Amalu and Honokowai Streams; S. Iwashita, analyst.
3. Olivine basalt, Wailuku volcanic series. Stream boulder, Iao Valley; M. G. Keyes, analyst. Washington, H. S., and Keyes, M. G., Petrology of the Hawaiian Islands; VI. Maui: Am. Jour. Sci., 5th ser., vol. 15, p. 203, 1928.
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