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

H. T. STEARNS AND G. A. MACDONALD

BULLETIN 11
HAWAII DIVISION OF HYDROGRAPHY
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* 1. GEOLOGY AND GROUND-WATER RESOURCES OF THE ISLAND OF OAHU, HAWAII. By Harold T. Stearns and Knute N. Vaksvik. 1935.

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

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

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

10. BIBLIOGRAPHY OF THE GEOLOGY AND GROUND-WATER RESOURCES OF THE ISLAND OF HAWAII. Annotated and indexed. By Gordon A. Macdonald. 1947.

11. GEOLOGY AND GROUND-WATER RESOURCES OF THE ISLAND OF MOLOKAI, HAWAII. By Harold T. Stearns and Gordon A. Macdonald. 1947.

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

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* Out of print.

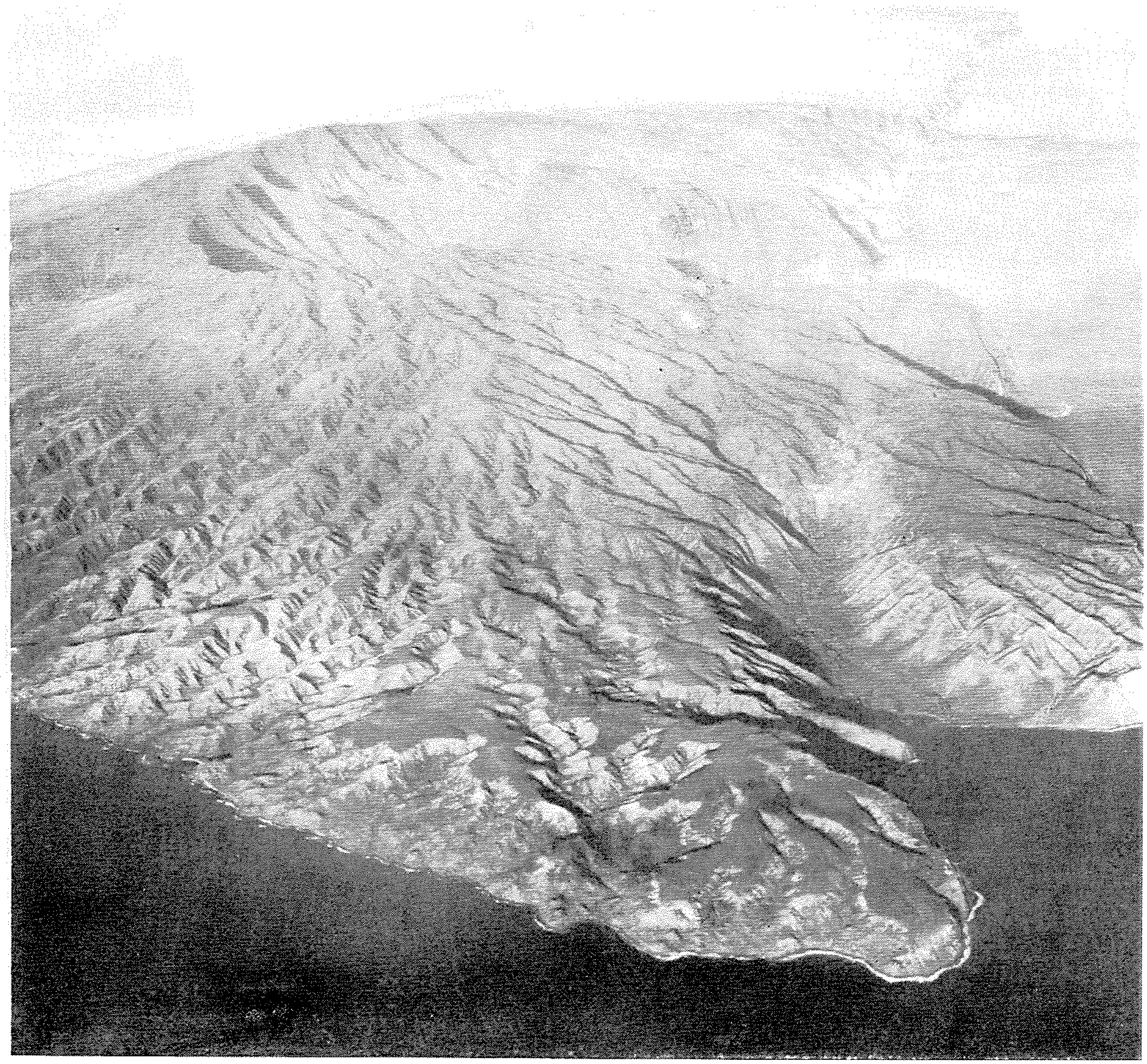

Plate 3. Aerial view of Molokai from the east, showing the great northern cliff on the right with Kalaupapa Peninsula at its foot, in the right foreground the amphitheater-headed Halawa Valley, and in the middle distance the great valleys of Wailau and Pelekunu, the heads of which mark the position of the ancient caldera. Photo by U. S. Army Air Force.

TERRITORY OF HAWAII
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GEOLOGY AND GROUND-WATER RESOURCES OF THE ISLAND OF MOLOKAI, HAWAII

BY

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**Prepared in cooperation with the Geological Survey,
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GEOLOGY AND GROUND-WATER RESOURCES OF THE ISLAND OF MOLOKAI, HAWAII

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ABSTRACT

The island of Molokai is the fifth largest of the Hawaiian Islands, with an area of 260 square miles. It lies 25 miles southeast of Oahu, and 8.5 miles northwest of Maui. It consists of two principal parts, each a major volcanic mountain. East Molokai rises to 4,970 feet altitude. It is built largely of basaltic lavas, with a thin cap of andesites and a little trachyte. The volcanic rocks of East Molokai are named the East Molokai volcanic series, the basaltic part being separated as the lower member of the series, and the andesites and trachytes as the upper member. Large cinder cones and bulbous domes are associated with the lavas of the upper member. Thin beds of ash are present locally in both members. The lavas of the lower member are cut by innumerable dikes lying in two major rift zones trending eastward and northwestward. A large caldera, more than 4 miles long, and a smaller pit 0.8 mile across existed near the summit of the volcano. The rocks formed in and under the caldera are separated on plate 1 as the caldera complex. Stream erosion has cut large amphitheater-headed valleys into the northern coast of East Molokai, exposing the dikes and the caldera complex.

West Molokai is lower than East Molokai, rising to 1,380 feet altitude. It was built by basaltic lavas erupted along rift zones trending southwestward and northwestward. Many of the flows were unusually fluid. The volcanic rocks of West Molokai Volcano are named the West Molokai volcanic series. Along its eastern side, the mountain is broken by a series of faults along which its eastern edge has been dropped downward. West Molokai Volcano became extinct earlier than East Molokai Volcano, and its flank is partly buried beneath lavas of East Molokai.

Both volcanic mountains were built upward from the sea floor probably during Tertiary time. Following the close of volcanic activity stream erosion cut large canyons on East Molokai, but accomplished much less on drier West Molokai. Marine erosion attacked both parts of the island, producing high sea-cliffs on the windward coast. In late Tertiary or early Pleistocene time the island was submerged to a level at least 560 feet above the present shore line, then reemerged. Later shifts of sea level, probably partly resulting from Pleistocene glaciation and deglaciation, ranged from 300 feet below to 100 feet or more above present sea level. Marine deposits on the southern slope extend to an altitude of at least 200 feet. Eruption of the Kalaupapa basalt built a small lava cone at the foot of the northern cliff, forming Kalaupapa peninsula; and a small submarine eruption off the eastern end of Molokai built the Mokuhooniki tuff cone, the fragments of which now form Hooniki and Kanaha

Islands. Deposition of marine and fluviatile sediments has built a series of narrow flats close to sea-level along the southern coast.

Nearly the entire island is underlain, close to sea level, by ground water of the basal zone of saturation. Beneath West Molokai, the Hoolehua Plain between West and East Molokai, and the southern coastal area of East Molokai, the basal water is brackish. Beneath much of East Molokai, fresh basal water is obtainable. Small amounts of fresh water are perched at high levels in East Molokai by thin poorly permeable ash beds. Fresh water is confined at high levels in permeable compartments between poorly permeable dikes in the rift zones of East Molokai, and can be developed by tunnels. Projects to bring the abundant surface and ground water of the large windward valleys to the Hoolehua Plain are described. Future developments are suggested. All wells and water-development tunnels are described in tables.

In the section on Petrography the volcanic rocks are described, and chemical analyses are listed.

PART 1. GEOLOGY OF MOLOKAI

by H. T. Stearns

INTRODUCTION

Location and area.—The island of Molokai, County of Maui, is separated from Oahu by Kaiwi Channel, 25 miles wide, from Maui by Pailolo Channel, 8.5 miles wide, and from Lanai by Kalohi Channel, 9 miles wide. (See insert map, plate 1.) Its form is shown by the topographic contours in plate 1, its appearance as seen from the east in the frontispiece, and its relief by plate 2. It is 38 miles long, 10 miles wide, and has an area of 260 square miles. The highest point is Kamakou Peak on East Molokai Volcano, altitude 4,970 feet. The distribution of the area on Molokai with respect to elevation follows:

Distribution of area of Molokai with respect to elevation[1]

Altitude in feet	Area in square miles	Percent
0–500	97.0	37.3
500–1000	66.0	25.4
1000–2000	50.6	19.5
2000–3000	30.1	11.6
3000–4000	13.8	5.3
4000–4970	2.5	.9
	260.0	100.0

Historical sketch[2].—Captain Cook sighted Molokai on November 26, 1778, but did not land. He called the island Morotai. The Rev. R. H. Hitchcock and wife were the first resident missionaries. They settled at Kaluaaha on November 7, 1832. R. W. Meyer, who arrived from Germany in the early forties, settled at Kalae and started the cattle industry with longhorns. He also raised sugar and operated a small horse-motivated sugar mill. Between 1870 and 1900 sugar mills were operated at Moanui and Kamalo. By 1900 all sugar production ceased.

Kamehameha V bought large tracts of land on Molokai for a country estate. Charles R. Bishop inherited these lands through his wife Bernice Pauahi Bishop. In 1897 the Bishop Estate sold the central and western holdings of about 70,000 acres to A. W. Carter,

[1] Wentworth, C. K., Physical geography and geology: in Hawaii Terr. Planning Board First Progress Rept., p. 15, 1939.

[2] The entire sketch is abstracted from Judd, G. P. IV, Puleoo, the story of Molokai: 28 pp., Honolulu, 1936.

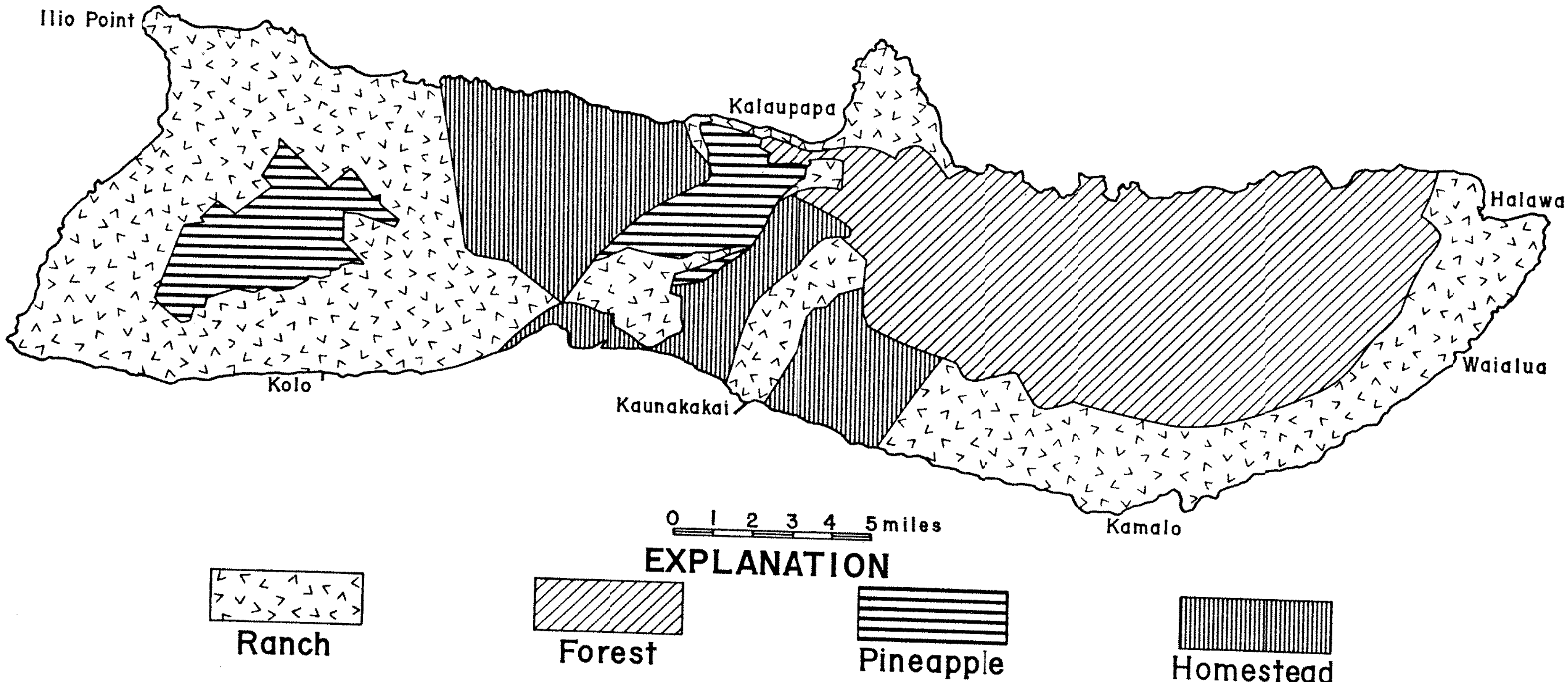

Figure 1. Map of Molokai showing land utilization in 1937.
(After pl. 36, Hawaii Terr. Plan. Bd., 1st Progress Rept., 1939.)

A. S. Hartwell, W. R. Castle, and J. B. Castle for $150,000. They formed the Molokai Ranch and promoted the American Sugar Co.

The American Sugar Co. leased 30,000 additional acres of land, and began operations in 1898. A mole half a mile long was constructed at Kaunakakai, a railroad from the mole to the Hoolehua Plain was built and put in operation, 500 acres of cane were planted, 8 miles of irrigation ditches dug, wells were drilled near Kaunakakai and steam-driven pumping equipment with a capacity of 10,000,000 gallons of water daily was installed. By 1900 the thin layer of fresh water had been pumped out and the wells were yielding only salt water which soon killed the cane. The whole plantation failed dismally before the mill had been erected. The population fell from about 6,000 in 1834 to 1,006 in 1910.

About 1918 it was discovered that pineapple could be raised on Molokai and a great boom developed in this product. The population climbed to 5,677 by 1935 and shifted from the wet windward areas and eastern end to the dry western part of the island. California Packing Corporation and Libby, McNeill, & Libby soon took over most of the pineapple industry either leasing the land or paying a fixed amount per ton for pineapples raised. In 1935 these two plantations occupied 11,000 acres with a capital investment of about $2,500,000. A wharf was built at Kolo for shipment of pineapples from the Mauna Loa section.

The Hawaiian Homes Commission, soon after they were formed in 1920, opened the Hoolehua homesteads for entry.

Population and industries.—Molokai had a population of 5,341 in 1940. Kaunakakai is the principal town and port. The island is reached by interisland steamers and planes. The main airport is on the Hoolehua Plain, an isthmus of land connecting East and West Molokai. The Territorial leper colony, population 447 in 1940, occupies only 4.2 square miles of the island on Kalaupapa Peninsula, a low peninsula separated from the major part of the island by a high cliff (pl. 4).

The chief industries are the production of pineapple and livestock. Formerly 200 to 300 tons of algaroba honey were produced annually by the Molokai Ranch, Ltd., but about 1935 it became uneconomical to produce honey. About 13,253 acres of land were used for the growing of pineapples in 1945, distributed as follows: Libby, McNeill, & Libby 8,453 acres and California Packing Corporation 4,800 acres. The pineapples are canned in Honolulu. About 76,200 acres are used for grazing. The two largest ranches are Molokai Ranch on the western end of the island, with 53,372 acres; and Puuohoku Ranch on the eastern end, with 13,891 acres.

About 6,150 acres of the Hoolehua Plain have been settled by Hawaiian homesteaders. Part of this land is used for truck gardening, but the chief crop is pineapples, grown under contract to Libby, McNeill, & Libby and California Packing Corporation. The Hoolehua Plain contains about 28,000 acres of land covered with deep soil. The climate is semi-arid and in many years is too dry for truck gardening. The U. S. Bureau of Reclamation has surveyed a project to irrigate 12,000 acres of this land with water conducted through a series of tunnels 18.3 miles long from the windward wet valleys of East Molokai.[3]

The development of the island has been greatly retarded by the lack of water in the inhabitated areas. The Molokai project, if constructed, would greatly change the economy of the island.

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, U. S. Department of the Interior, in cooperation with the Division of Hydrography, Territory of Hawaii. The study was started by H. T. Stearns in 1935 to furnish the basic geologic and hydrologic data for the investigation started subsequently by the Bureau of Reclamation as the Molokai irrigation project. During this period, camps were established in the difficultly accessible windward valleys with the aid of the Civilian Conservation Corps, and every tributary of Wailau, Pelekunu and Haupu streams was mapped. Part of West Molokai, Waikolu Valley, and the Kalaupapa Peninsula were mapped also at this time. The field work lasted from June 1 to September 13, 1935. D. John Cederstrom traversed the leeward valleys of East Molokai during this same period and made a collection of rock specimens for microscopic study.

In 1938 and 1939 Stearns investigated water supplies for Kaunakakai and adjacent areas at the request of the Board of Supervisors, Maui County. In 1939 a Maui-type well was started, at an altitude of 301 feet, in Kaunakakai Gulch by the Works Progress Administration, but was stopped at a depth of 30 feet because of the lack of excavating equipment. In August, 1939, a test hole was drilled in this shaft at the expense of the County of Maui. It demonstrated clearly the presence of potable water at this site. Another test hole was drilled by the Geological Survey near the Hoolehua airfield in 1938. G. R. MacCarthy, of the Geological Survey, made a resistivity survey of the isthmus area in 1939. G. A. Macdonald

[3] Howell, Hugh, Final report on water-supply studies, Hawaii FP. No. 45, Island of Molokai (abridged), 61 pp., Honolulu, 1938.

spent from September 12 to October 18, 1945, completing the geologic mapping and ground-water investigations on the leeward slopes of East Molokai and the eastern part of West Molokai. (See key map, pl. 1.)

ACKNOWLEDGMENTS.—The Geological Survey is greatly indebted to the Molokai Ranch, Ltd., especially to Mr. George P. Cooke, manager, for splendid cooperation throughout the work. Libby, McNeill, & Libby likewise cooperated generously in the resistivity survey of West Molokai. Messrs. Herbert Wilson, Mitchell Pauole and Solomon Hanakeawe have rendered valuable assistance by measuring certain observation wells monthly. Mr. Julian Yates, executive officer of the Hawaiian Homes Commission, supplied helpful information.

The Department of Agriculture of the Territory of Hawaii cooperated by furnishing boat transportation and guides for the work in the windward canyons. Numerous local residents assisted in various ways, especially Messrs. Charles Morris, George Apana, Raymond Duvauchelle, F. N. Tollefson, Charles Kamali, Daniel Naki, Basilio Agcaoili, and George Davis. The Hawaiian Sugar Planters Association generously permitted the use of a house at their Mapulehu experiment station, and Mr. George Otsuka supplied information regarding the wells and tunnel at Mapulehu.

Mr. W. F. Feldwisch, of the U. S. Weather Bureau, furnished data on rainfall. Mr. M. H. Carson, of the U. S. Geological Survey, furnished data on stream and spring discharge. Messrs. Howard Leak and H. W. Beardin aided in measuring the dug wells.

Mrs. Ethel U. McAfee edited the report and Mr. J. Y. Nitta prepared the illustrations.

PREVIOUS INVESTIGATIONS.—Dana[4] recognized the fact that Molokai had been built by two volcanoes and suggested that the great windward cliff might be a fault scarp. Lindgren[5] made the first field study of the island. He recognized that West Molokai Volcano became extinct earlier than East Molokai Volcano. He described the cliffs on the eastern side of West Molokai and the great windward cliff of East Molokai as due to faulting. He thought, erroneously, that Kalaupapa Peninsula was a part of a sunken block still above sea level. He reported boulders of a coarse-grained intrusive in Wailau Valley. He described in detail the water resources, and recognized that the basal water is floating on salt water, and suggested the construction of tunnels to bring water from the wind-

[4] Dana, J. D., Characteristics of volcanoes: p. 290, New York, 1890.

[5] Lindgren, Waldemar, The water resources of Molokai, Hawaiian Islands: U. S. Geological Survey, Water-Supply Paper 77, 62 pp., 1903.

ward valleys to the dry leeward slopes. Powers[6] noted the presence of trachyte on East Molokai and that Kalaupapa is a young cone of olivine basalt. Bigelow and Stewart[7] reported on the water supply and development of power at Kalaupapa. Wentworth[8] described in detail the sand dunes on West Molokai and noted three different ages of dunes. Hinds[9] recognized Penguin Bank as a possible volcanic vent. He reviewed what was known about the physiography of Molokai in a subsequent paper, and concluded that the main vent of East Molokai had probably been downfaulted beneath the sea.[10] The presence of a large eroded caldera in East Molokai has been reported by Stearns.[11] The fossil mollusca from the emerged reefs of East Molokai have been described by Ostergaard[12] as late Pleistocene. Swartz[13] noted briefly the results of G. R. MacCarthy's ground-water resistivity survey that was subsequently summarized in 1942 in Department of the Interior Press Release 160579. Howell's[14] report gave a description of the plan and cost of transporting water from the streams of windward Molokai to the Hoolehua Plain for irrigation. In it was published a preliminary report on ground water in Wailau, Pelekunu, and Waikolu valleys by H. T. Stearns.

Numerous unpublished reports relating to water development exist. Among them are: M. M. O'Shaughnessay's report in 1899 to the American Sugar Co. on developing water power; W. Lindgren's report in 1900 to the American Sugar Co., essentially the same as his report published in 1903 by the Geological Survey; Frederick Ohrt's report in 1919 on water supply and power at Kalaupapa; H. A. R. Austin's report in 1919 to the Commissioner of Public Lands regarding a proposed domestic water supply for Halawa, his report in 1929 on water supply and power at Kalaupapa, and his reports in 1944 on projects to bring the water of the large

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[6] Powers, Sidney, Notes on Hawaiian Petrology: Amer. Jour. Sci., vol. 50, pp. 259-260, 1920.

[7] Bigelow, L. H., and Stewart, J. E., Report on the water supply and development of power at Kalaupapa, Molokai, by the Supt. of Public Works and the Chief Hydrographer & Engineer to the 1921 legislature: 55 pp., 1921.

[8] Wentworth, C. K., The desert strip of West Molokai: Iowa Univ. Studies, new ser., no. 89, vol. 11, pp. 41-56, 1925.

[9] Hinds, N. E. A., Maui and the Maui Group, Hawaii: Geogr. Soc. Phila., Bull., vol. 23, p. 150, 1925.

[10] Hinds, N. E. A., The relative ages of the Hawaiian landscapes: Univ. Calif. Pub., Dept. Geol. Sci. Bull., vol. 20, no. 6, pp. 179-182, 189-190, 1931.

[11] Stearns, H. T., Large caldera on the island of Molokai, Hawaii (Abst.): Geol. Soc. America Proc. for 1937, p. 116, 1938.

[12] Ostergaard, J. M., Reports on fossil mollusca of Molokai and Maui: B. P. Bishop Museum Occ. Papers, vol. 15, pp. 67-77, 1939.

[13] Swartz, J. H., Geophysical investigations in the Hawaiian Islands: American Geophy. Union Trans. of 1939, pp. 294-295, 1939.

[14] Howell, Hugh, op. cit.

windward valleys, and of Waikolu Valley alone, to the Hoolehua Plain; J. Jorgensen's report in 1922 on a domestic water supply for homesteaders at Kalamaula and his report in 1923 on the possibility of irrigating the Hoolehua homesteads with water from the streams on the windward coast of East Molokai; H. S. Palmer's report in 1928 on a proposed deep well in Palaau; M. H. Carson's report in 1931 to the Governor of Hawaii summarizing the reports available regarding the water resources of Molokai; H. T. Stearns' report in 1938 to the Chairman of the Board of Supervisors of Maui County regarding water supplies for Kaunakakai, and another in 1939 regarding Ahaino Spring and water supplies for Waialua; J. Matson's report in 1939 to Maui County estimating the costs of the various possible water supplies for Kaunakakai; and C. K. Wentworth's report to the County of Maui in 1945, on exploration for and development of water supplies for Kaunakakai.

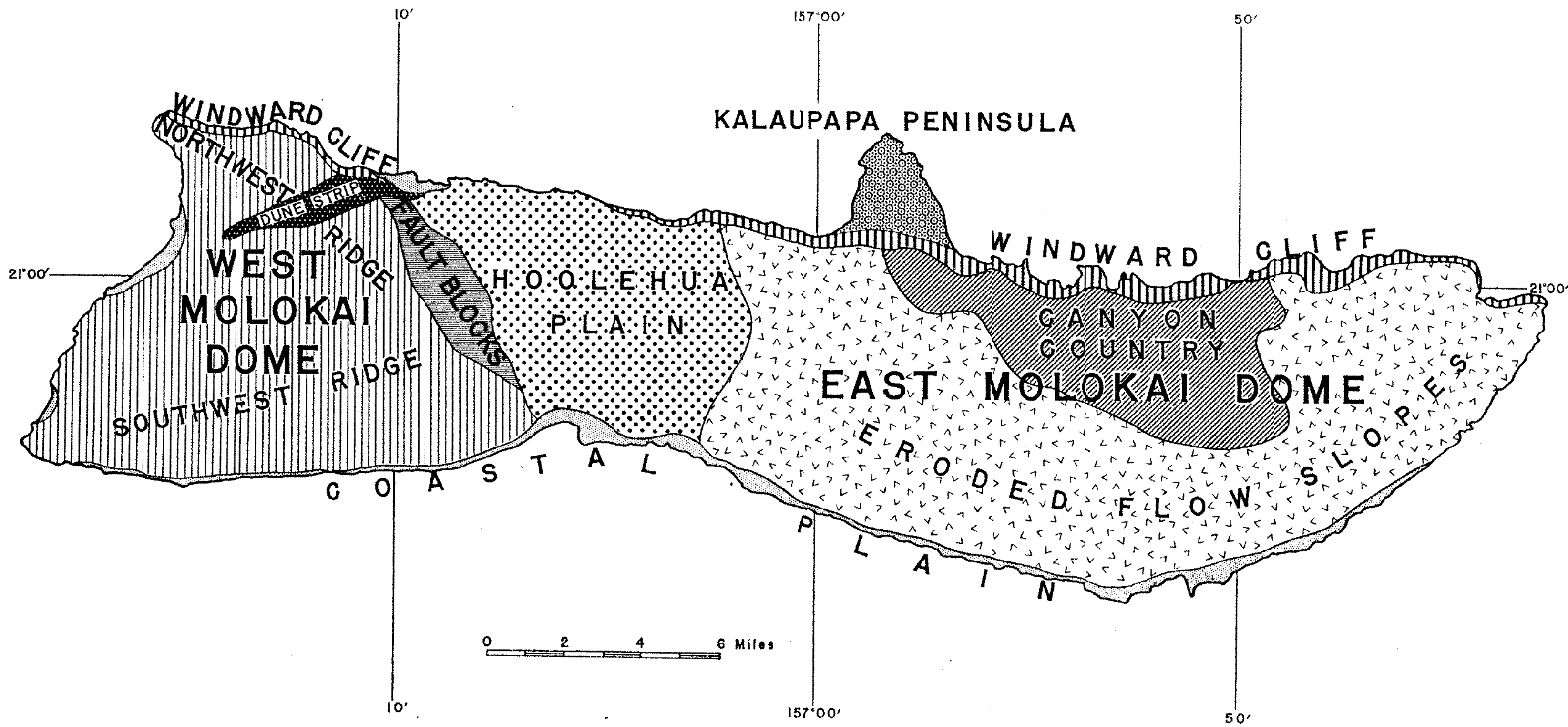

Figure 2. Map of Molokai, showing the major geomorphic areas on the island.

GEOMORPHOLOGY

Molokai consists of two major geomorphic areas: the East Molokai dome and the West Molokai dome. The East Molokai dome is subdivided into 6 subareas: eroded flow slopes, canyon country, windward cliff, Kalaupapa Peninsula, coastal plain, and the Hoolehua Plain (fig. 2). West Molokai has 6 subareas: fault blocks, dune strip, windward cliff, northwest ridge, southwest ridge, and coastal plains. The northwest and southwest ridges are built over rift zones having those trends.

ORIGINAL FORM OF EAST MOLOKAI.—East Molokai Mountain, prior to erosion, was a typical elongated basaltic shield-shaped dome, built over northwest- and east-trending rifts, with a steep slope on the north side where the lava flows plunged into deep water, and a gentle slope on the west side where the lava flows banked against the West Molokai dome.

The high cliff truncating the northern slope of Molokai is cut in weak basalts, and may be solely the result of marine erosion. Faults along the coast show downthrow to the south. If the windward cliff was due primarily to faulting, unless the faults along which the northern part of the mountain collapsed were considerably seaward of the present coast, one would expect the faults along the coast to show downthrow to the north, but no such faults have been found. Soundings along the northern side of Molokai are too few to delineate accurately the submarine topography. There are, however, enough of them to indicate the general nature of the submarine slope. The submarine portions of the sections in figure 3 are based on projections of the few nearby soundings. The dashed lines in the sections indicate the original average slopes which would connect the lower portions of the profiles with the parts above sea level, assuming the absence of faulting. They are steeper than the slopes farther inland, as would be expected if the observed faults along the coast mark the northern edge of the caldera depression (page 30). None of the projected profiles are as steep as the actual southern slope of East Molokai above sea level. It is possible that the great northern sea cliff is a fault scarp battered back by erosion, as Dana, Lindgren, and others have hypothecated, but no faulting is necessary to explain the origin of the cliff, and it is equally or even more likely that no faulting was involved.

The valleys of Wailau and Pelekunu (pl. 5A) owe their great

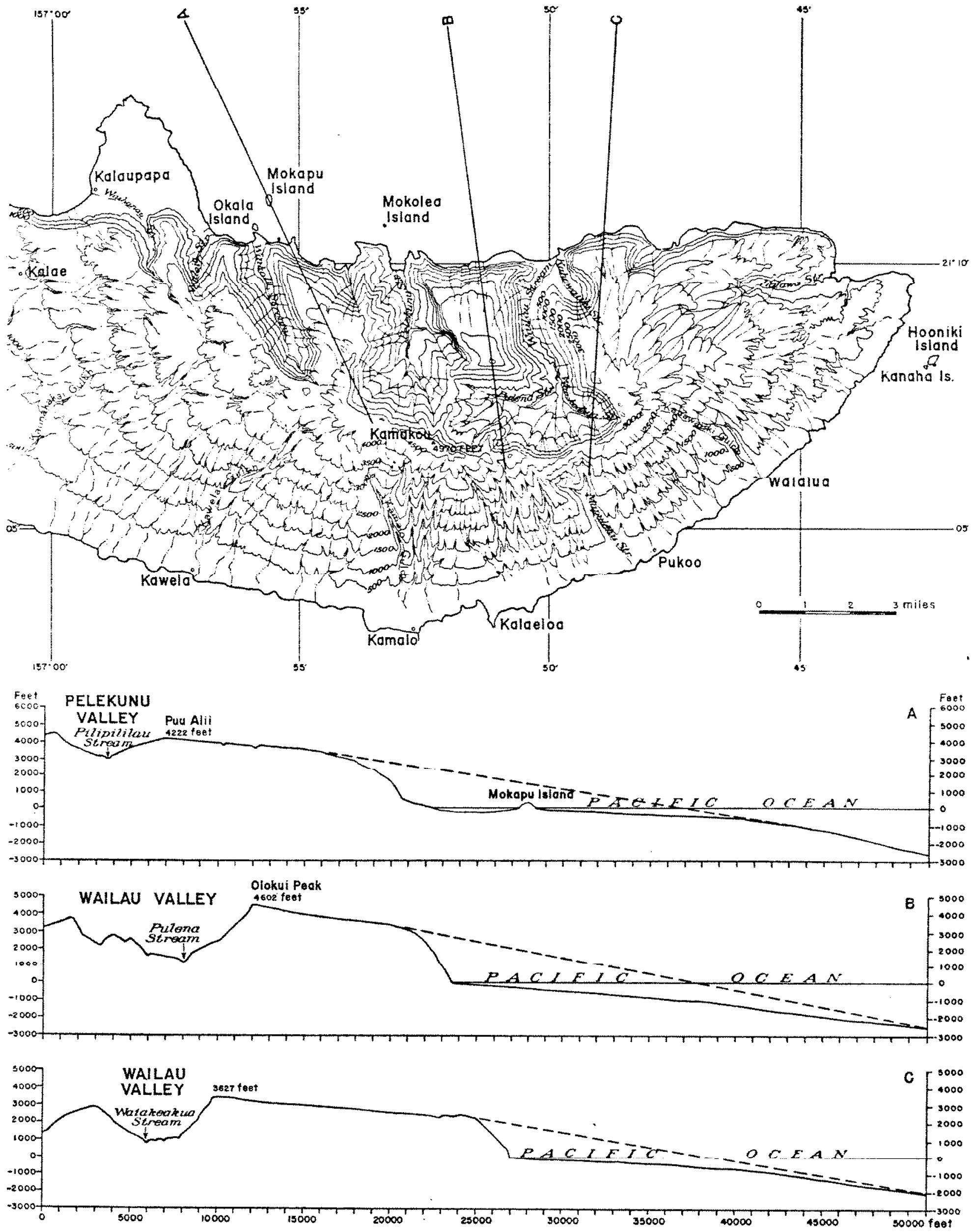

Figure 3. Profiles across the northern slope of East Molokai Volcano. The dashed lines show the projection of the submarine slope. Positions of the profiles are shown on the map.

depth essentially to stream erosion, but their outlines were determined by an ancient caldera 4½ miles long and 2 miles wide.[15] The depth of this caldera at the close of volcanism is unknown, but it seems probable from the great amount of andesite extruded in the post-caldera stage that it may have been nearly filled, resembling

[15] Stearns, H. T., Large caldera on the island of Molokai, Hawaii (Abst.) : Geol. Soc. of America Proc. for 1937, p. 116, 1938.

the summit area of Kohala Mountain, Hawaii.[16]

Erosion is rapid in these valleys now with a rainfall of about 100 inches annually. Prior to the great submergence of the Hawaiian archipelago the rainfall may have averaged about 500 inches annually in the summit area. Under such conditions, erosion would have been much faster than now.

ORIGIN OF THE HOOLEHUA PLAIN.—The Hoolehua Plain or isthmus of Molokai is composed of lava flows from the East Molokai Volcano banked against the older West Molokai Volcano. The lava beds dip 6° to 10° on the crest of East Molokai and only 1° to 3° on the Hoolehua Plain. Most of the plain is covered with 10 to 30 feet of lateritic soil. Overgrazing since white men introduced livestock and the cultivation of the land have accelerated erosion, and large flats of red soil washed from the plain are now forming along the south shore. Ancient Hawaiian fishponds are being filled with mud and mangrove swamps are developing.

EMERGED AND SUBMERGED SHORE LINES.—The following shore lines, with the youngest at the top, have been determined to date in the Hawaiian Islands. Some are well preserved on Molokai.

Pleistocene[1] shore lines in the Hawaiian Islands

Approximate altitude (feet)	Name	Evidence on Molokai	Type locality (island)
0	....	Present shore line.	....
+5	Kapapa	Wave-cut bench at this level, and abandoned beach and dune deposits.	Oahu
+25	Waimanalo	Terraces and marine deposits on East Molokai.	do.
—60±	Waipio	Partly drowned dunes on West Molokai.	do.
+45	....	Not identified on Molokai.	
+70	Laie	Wave-cut platforms.	do.
+100	Kaena	Wave-cut platforms and marine fossiliferous conglomerate.	do.
—300	Kahipa	Not identified on Molokai.	do.
+250±	Olowalu	Fossiliferous marine conglomerate at this level, stripping of soil, and wave-cut benches.	Maui
+325±	....	Not identified on Molokai.	Lanai
+375±	....	Do.	do.
+560	Manele	Stripping of soil and wave-rounded boulders.	do.
+1200±	Mahana	Do. (only doubtfully identified on Molokai).	do.
—1200 to —1800	Lualualei	Deeply drowned valley mouths indicating a large but unknown amount of submergence.	Oahu

[1] The shore lines older than the 250-foot level may be late Pliocene, although fossils from them have been classified as Pleistocene.

[16] Stearns, H. T., and Macdonald, G. A., Geology and ground-water resources of the Island of Hawaii: Hawaii Div. of Hydrography, Bull. 9, p. 181, 1946.

Couthouy[17] makes the following statement, "At Molokai, an island a few miles northwest of Maui, Mr. B. Munn, teacher for the mission assured me that he had seen masses of coral apparently in their original position, embedded in calcareous rocks, one hundred and even one hundred and fifty feet above sea level." Coral fragments are imbedded in limestone conglomerate 189 feet by level line above mean sea level in the gulch east of Puu Maniniholo.[18] They are also present in the unnamed gulch a mile west of Kaunakakai Gulch to an altitude of 280 feet (barometer). Emerged reefs crop out east of the town of Kaunakakai at altitudes of 25 and 100 feet. Beach sand of the 5-foot sea covers a considerable area near Kaunakakai. Fossiliferous marine limestone veneers intermittently many of the small gulches in this same area to levels up to 280 feet. The large gulches heading at the crest do not contain limestone probably because streams have removed it.

The 560-foot shore line is traceable on the south slope of West Molokai by the upward termination of black gypsiferous muds and a heavy cover of lag boulders. Spheroidally weathered boulders that lagged behind as the ocean swept away the soil from between them characterize the slopes up to more than 900 feet and possibly to the level of the Mahana shore line inland of Kaunakakai (pl. 5B). On West Molokai lag gravel left behind by wind erosion forms armored deserts below the level of the Manele 560-foot shoreline (pl. 6B).

Penguin Bank, averaging 180 feet below sea level just west of Molokai, is an extensive submarine platform indicative of a halt of the sea at this level probably during the Pleistocene. It is a common level throughout Pacific Islands but its position in the sequence of shore lines is unknown. Penguin Bank may be capped by a drowned coral reef.

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[17] Couthouy, Joseph P., Remarks upon coral formations in the Pacific with suggestions as to the causes of their absence in the same parallels of latitude on the coast of South America: Boston Jour. of Natural Hist., vol. 4, p. 150, 1843-44.

[18] Stearns, H. T., Pleistocene shore lines on the islands of Oahu and Maui, Hawaii: Geol. Soc. America Bull., vol. 46, p. 1953, 1935.

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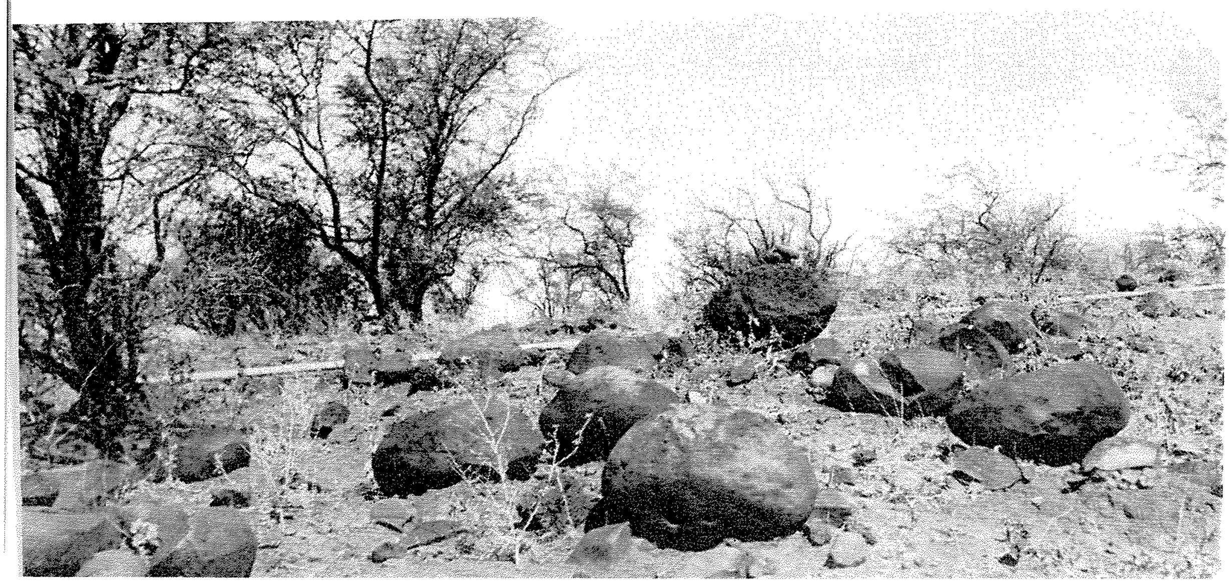
Opposite page: Plate 4. The great cliff on the northern side of East Molokai. Kalaupapa Peninsula, in the foreground, is a younger basalt cone built against the cliff. The crater of the young cone (Kauhako Crater) is clearly visible. Dikes project as walls along the face of the cliff in the right foreground. Photo by U. S. Navy.

Plate 5A. Pelekunu Valley, East Molokai. The head of this huge valley is excavated in the ancient caldera complex of East Molokai Volcano. The floor is alluviated owing to recent drowning. Terraces near the valley floor were graded to former high stands of the sea. Photo by U. S. Army Air Force.

Plate 5B. Spheroidal boulders on the ridge west of Kaunakakai Gulch, at 940 feet altitude, rounded by wave action during an ancient high stand of the sea. Photo by H. T. Stearns.



LIVING REEF.—A living fringing reef extends along much of the south coast (pl. 6A). It ranges from 1/4 to 3 miles wide. Red mud carried into the sea as a result of overgrazing in the last 150 years has buried much of the shoreward part of the reef. The shallow south shore was ideal for building fish ponds and the ancient Hawaiians built 53 ponds there, some as large as 500 acres, for raising mullet. Most of the ponds have been partly filled with mud in historic time.

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

The West Molokai Volcano built a shield-shaped dome of primitive basalts from a northwest rift and a southwest rift. Apparently, no caldera indented the summit. The basalts were laid down in a highly fluid condition, as indicated by the thinness and high vesicularity of most of the flows. Most of the vents were spatter cones but a few cinder cones were built near the close of activity. Vitric tuff deposits are scarce. After the dome was built about 1,400 feet above sea level, faulting dropped much of the northeast slope. Weathering and stream erosion set to work to destroy the dome, but erosion was not very effective because the growing East Molokai Volcano intercepted much of the moisture in the prevailing trade winds. Weathering continued, however, until deep soils formed over much of the surface. Then the dome was deeply submerged beneath sea level and later was partly emerged. These changes occurred so rapidly that the sea did little more than strip away soil along the leeward slope. Wave action, however, cut a high cliff along the windward side. Numerous smaller emergences and submergences subsequently occurred that seem to be correlative with Pleistocene changes in sea level. For this reason extinction of the West Molokai dome is placed in the Pliocene.

How long before that epoch the volcano started building from the ocean floor is unknown, and will probably forever remain so. The rocks of this volcano have been named the West Molokai volcanic series.

The East Molokai Volcano built a long narrow basaltic dome around a northwest rift, an east rift, and a central caldera. The last flows poured from vents on East Molokai were andesites and trachytes. The lavas of East Molokai Volcano overlapped the basalts of West Molokai after the latter had decomposed to a soil 6 feet deep. However, the overlap is made by late flows of the East Molokai Volcano and it is believed that the major parts of both volcanoes were built concurrently, but that West Molokai became extinct first. The same high emerged shore lines are found on East Molokai as on West Molokai; hence, it is believed that the East Molokai Volcano also became extinct in Pliocene time. The rocks erupted by this volcano are called the East Molokai volcanic series.

The Quaternary was chiefly a period of erosion and deposition. Relatively small quantities of limestone, calcareous dunes, and alluvium were deposited. During the late Pleistocene two eruptions occurred on the East Molokai dome, one of which formed the Kalaupapa Peninsula and the other the islet, Mokuhooniki.

All the volcanic rocks are very permeable except the dikes, which confine water at high altitudes on East Molokai, and a few thin tuff beds which give rise to small perched springs. The West Molokai volcanic series carries only brackish water because of the low rainfall on its outcrops.

The stratigraphic rock units on Molokai and their water-bearing properties are summarized in the accompanying table.

TERTIARY VOLCANIC ROCKS

EAST MOLOKAI VOLCANIC SERIES

The East Molokai volcanic series comprises all the volcanic rocks making up the East Molokai dome, except those in Kalaupapa Peninsula. Its rocks crop out over an area 26 miles long by 8 miles wide. They are 4,970 feet thick above sea level and probably extend downward 12,000 feet more to the ocean floor. They have been subdivided into upper and lower members. A caldera complex forms part of the lower member.

LOWER MEMBER

LAVA FLOWS.—The type locality of the lavas in the lower member of the East Molokai volcanic series is the 1,800-foot cliff that separates Kalaupapa Peninsula from the rest of the island (p. 93). It is composed of thin-bedded vesicular pahoehoe and aa. The beds range from a few feet to 75 feet in thickness. Nonporphyritic and porphyritic olivine basalts dominate, but olivine-augite porphyries are common among the latest flows. Overlying the basalts, and separated from them by a layer of ashy soil 3 to 12 inches thick, are several flows of andesite belonging to the upper member of the series. The lower member is exposed wherever the upper member was not laid down, as between Wailau and Pelekunu Valleys, or where the upper member has been removed by erosion. All major gulches expose the lavas of the lower member.

Stratigraphic rock units on the island of Molokai

Major geologic unit	East Molokai Mountain: Rock assemblage	Member	Thickness (feet)	Symbol on map (pl. 1)	General character	Water-bearing properties	West Molokai Mountain: Rock assemblage	Thickness (feet)	Symbol on map (pl. 1)	General character	Water-bearing properties
Recent sedimentary rocks	Beach sand		5±	Rs	Loose sand chiefly basaltic	Highly permeable but carries brackish water in most places	Beach sand	10±	Rs	Loose sand chiefly calcareous	Permeable but carries brackish water
	Dunes		10±	Too small to show	Mixed basaltic and calcareous sand	Highly permeable but carry no water	Dunes	50±	Rd	Loose calcareous sand	Highly permeable. They carry brackish water near the coast but no water inland
	Unconsolidated earthy deposits (Not differentiated on plate 1 from the consolidated earthy deposits)		20±	Qa	Silty gravel and boulder deposits chiefly stream-laid. Also blocky talus	Poorly permeable. They carry fresh water in small quantities at sea level in eastern Molokai and brackish water in central Molokai	Unconsolidated earthy deposits	10 ±	Qa	Silt, gravel, and poorly assorted bouldery alluvium	Poorly permeable. They carry small quantities of brackish water
Local erosional unconformity											
Pleistocene sedimentary rocks	Consolidated earthy deposits		200±	Qa	Consolidated and partly consolidated deposits consisting of older alluvium, ancient talus, landslide deposits, and marine noncalcareous sediments	They carry potable water in wet areas but usually in small quantities. In dry areas they yield brackish water	Consolidated earthy deposits	100±	Qa	Friable deposits of reddish brown silt and bouldery alluvium with minor amounts of talus	Poorly permeable. They carry small quantities of brackish water near the coast
	Consolidated marine deposits		5±	Pm	Patches of reef limestone and breccias containing basaltic fragments of lava. Includes some patches of poorly consolidated beach deposits	Permeable but carry only brackish water in a few places	Consolidated dunes	20±	Pd	Consolidated and partly consolidated cross-bedded calcareous dunes. The compact dunes are cream-colored limestone	Fairly permeable but carry salt water along the coast and none inland
Local erosional unconformity											
Quaternary volcanic rocks	Kalaupapa basalt		450+	Pb	Olivine basalt pahoehoe forming Kalaupapa Peninsula	Extremely permeable but carries only brackish water					
	Tuff cone of Mokuhooniki		250+	Pt	Palagonitic vitric-lithic basaltic tuff forming Hooniki Island and Kanaha Island	Nearly impermeable and carries only salt water					
Great erosional unconformity											
Tertiary volcanic rocks	East Molokai volcanic series	Upper member	20–500	Ta	Lava flows composed chiefly of dense and clinkery andesite and trachyte usually nonporphyritic. They form the upper member of the series	The dense beds have low permeability but the clinker beds are very permeable. They carry small quantities of perched water locally	West Molokai volcanic series	1381+	Twb	Basaltic lava flows composed of thin-bedded highly vesicular pahoehoe and aa	Highly permeable but carry water too brackish for humans
		Upper member	25–300	Tac	Cones consisting of compact red to black bedded cinders built at the vents by lava fountains	Highly permeable but carry no water. Red ashy soil layers correlative with these cones locally perch small quantities of water		25–110	Twc	Cones consisting of cinder, spatter, and thin layers of lava at vents	Highly permeable but carry salt water at the coast only
		Upper member	50–200	Tad	Bulbous domes of massive andesite and trachyte at vents	Nearly impermeable and carry no water		½–10	Red lines	Dikes composed of dense and vesicular basalt	Possibly confine brackish water somewhat above sea level in the middle of the dome
		Lower member	4970+	Tb	Lava flows composed of generally thin-bedded moderately to highly vesicular basaltic pahoehoe and aa	Highly permeable and freely yield water to wells and tunnels. They carry only brackish water along the coast of central Molokai					
		Lower member	20–150	Tbc	Cones consisting of compact red cinders and thin scoriaceous flows at vents	Highly permeable but carry no water. The correlative tuff beds perch water in wet areas					
		Lower member	½–15	Red lines	Dikes composed chiefly of dense cross-jointed basalt but a few are vesicular and platy. A few belonging to the upper member are not differentiated on plate 1	Confine water as much as 2,000 feet above sea level in the dike complexes. Most perennial water is supplied by dike structures					
		Lower member	1000±	Tc	Caldera complex of vent breccias, lava flows, plugs, stocks, talus, and pyroclastic rocks that accumulated in and under the summit caldera. The vesicles are commonly filled with pneumatolitic secondary minerals	Not very permeable as a whole but yields perennial springs at high levels					

The basalts weather to dark-gray, red, red-violet, and brown and stand in sharp contrast to the upper member which weathers to light-gray and white. Dark-red and reddish brown soils characterize the decomposed surface of the lower member. The lavas are decomposed for a depth of 50 feet or more in flat areas where the soil has not been eroded away. The beds accumulated rapidly as shown by the absence of interbedded residual soils and alluvial deposits.

The beds dip 3° to 15° away from the axis of the dome, except on the north coast between Waikolu and Wailau Valleys, where they dip southward 8° to 25° as a result of faulting.

The basalts are highly permeable and are the principal aquifer of Molokai. They carry brackish water in the western end and potable water in the middle and eastern end of East Molokai.

Cones and vitric tuff deposits.—Five cinder and spatter cones that erupted basalts lie on the western slope of East Molokai. Many others must be buried by the upper member. Several cones interbedded with lavas of the lower member are exposed in Waikolu and Kaunakakai Canyons.

Thin lenses of weakly consolidated vitric tuff are common in the gulch walls in the south central and eastern part of East Molokai. Apparently the prevailing northeast trade winds carried Pele's hair and pumice from the lava fountains and from adjacent cones in the caldera to these areas. The beds are too discontinuous to show on plate 1 and they rarely exceed 3 feet in thickness.

Three prominent thin vitric tuff beds crop out in the east wall of Pelekunu Valley where they perch high-level springs yielding about 1,000,000 gallons of water per day. Elsewhere they rarely carry perennial water.

Intrusives.—The intrusives of the lower member of the East Molokai volcanic series comprise a dozen or more stocks and plugs, hundreds of dikes, and a few short sills. All the stocks lie in the caldera complex. The texture of the stocks ranges from coarse-grained basalt through porphyries to coarse gabbros (See Petrography). The stocks occur chiefly in Wailau Valley. None of them exceed half a mile in diameter. A few lenses of dense rock, probably crater-fills, are exposed in the walls of Waikolu Valley and some of the other deep gulches.

Two great systems of dikes spread from the ancient caldera in Pelekunu and Wailau Valleys, one to the east and the other to the northwest. A few divergent dikes also crop out. The dikes range from a few inches to 15 feet in width and average about 2 feet. Multiple dikes are common. Some of the wide dikes are andesite and fed the flows in the upper member of the East Molokai volcanic series. They have not been differentiated from basalt dikes on plate 1. Many are cross-jointed but some are platy and vesicular. Most are bordered by glassy selvages ⅛ to ½ inch wide. The dikes range from fine-grained basalts to porphyries containing augite, olivine, and feldspar phenocrysts. A few are andesites. Only a few in Wailau and Pelekunu Valleys are plotted on plate 1 because they are too close together to be shown. The strikes of 265 dikes were recorded in Wailau Valley and many other dikes were noted for which no measurement was made. Thirty-eight dikes are exposed in Waikolu Valley and several hundred in Pelekunu Valley.

An unusual dike is exposed in the east side of Pelekunu Bay. It trends due north and is 2 feet wide. It has joints 3 to 4 inches apart parallel to the walls with the middle part of the dike made up

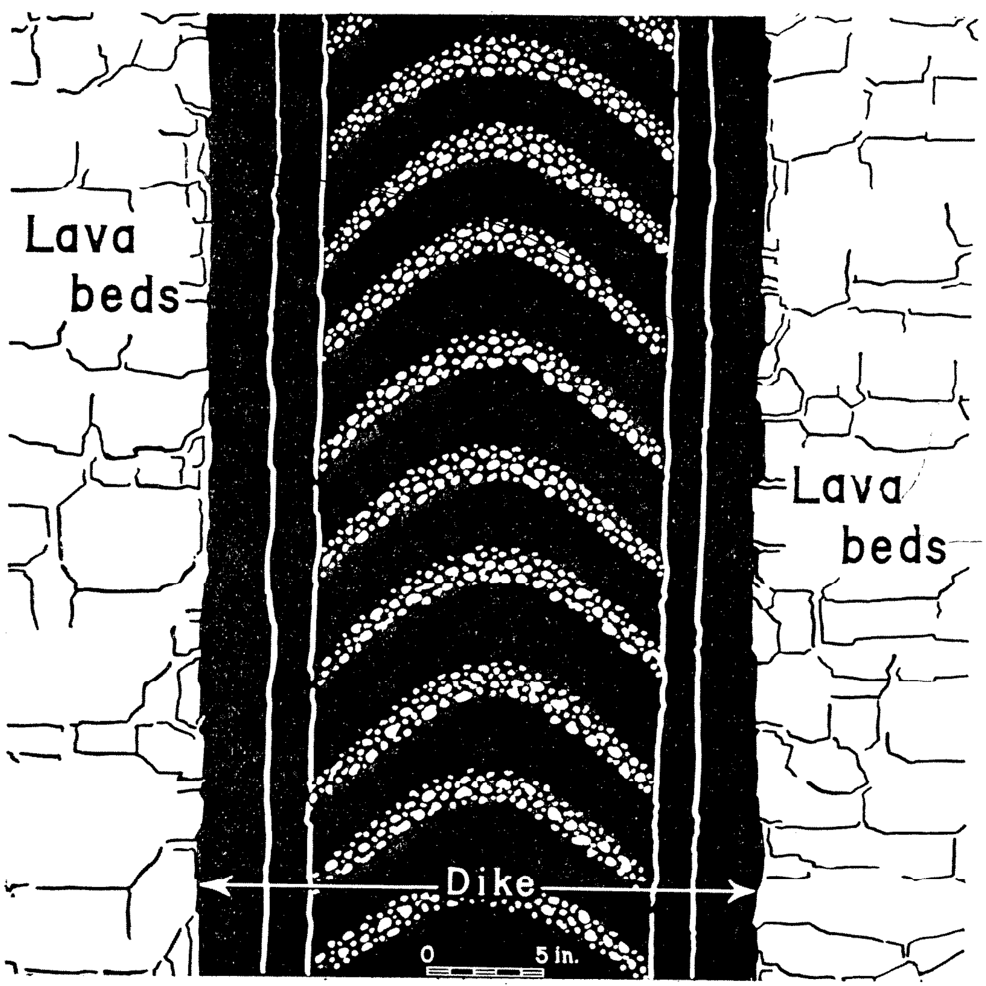


Figure 4. Diagram of a dike on the eastern shore of Pelekunu Bay, showing arched bands of vesicles.

of arcuate lines of vesicles a few inches apart. Weathering along the vesicles has brought the intervening dense rock into relief, giving the dike the appearance of a series of curved parallel ribs (fig. 4).

The dike swarms and dike complexes are the great water-bearers of East Molokai Mountain. The water is stored in the intervening permeable basalts. Dikes crop out at the head of every major valley and supply nearly all perennial streams, and provide a total low flow of about 9 million gallons daily. The water issues from dike swarms between 1,200 and 1,800 feet above sea level in Wailau and Pelekunu Valleys, between 300 and 900 feet in Waiohookalo Valley, and between 250 and 1,400 feet in Waikolu Valley. The proposed East Molokai project would depend for its low-water flow from tunnels penetrating the dike complexes.

The plugs and other large intrusive bodies of rock are so dense and the joints so tight that they are poor water-bearers.

Caldera complex.—The caldera complex of East Molokai Volcano lies in Pelekunu and Wailau Valleys, and forms a part of the lower member of the East Molokai volcanic series. The larger mass is 4½ miles long and 1½ miles wide. A smaller mass about 1 mile in diameter borders the southeast side of Haupu Bay (pl. 1). The complex is composed of stocks, plugs, crater fills, ponded lavas, and talus and fault breccias cut by dike swarms. The rocks accumulated in and under a caldera about 4½ miles long and 2 miles wide. Much of the area of these rocks shown on plate 1 is covered with older alluvium. The complex crops out chiefly in stream beds where the older alluvium has been cut away. Detailed traverses were made on foot up each tributary of Wailau and Pelekunu streams, but the results could not be plotted on the topographic base map (pl. 1) because the stream pattern shown on the map is seriously in error. For this reason outcrops had to be generalized to fit the base.

The rocks making up the complex are readily distinguished, in the field, from those formed outside the caldera by the presence of calcite, quartz and secondary minerals deposited by hydrothermal action in preexisting cavities, by a great variety of breccias, massive lava flows, stocks of gabbro and coarse textured basalt, and by fewer dikes than in the lavas adjacent to the complex. Some of the dikes must have intruded masses of hot rock, as they lack typical glassy selvages and in places merge with the rock they intruded. The coarse-grained gabbro in the southwesternmost tributary of Wailau Valley is unusual in Hawaii.

Numerous types of breccias can be distinguished in the caldera complex. The commonest is talus breccia, composed usually of exotic fragments, some of which are 6 to 10 feet across. Talus breccia is abundant along the margins of the complex and locally within the complex where pit craters have perforated the mass. The marginal breccias contain more vesicular rock than the pit crater breccias, because the pit craters usually had walls of massive ponded lava that yielded dense fragments. All the breccias are usually well cemented with silica and iron, except high in the section near the former floor of the caldera. There they are poorly cemented. These poorly cemented breccias would be distinguished with difficulty from talus breccia in the older alluvium if it were not for dikes cutting them.

Some lenses of massive lava carry numerous vesicular fragments near their bottom. The fragments are usually rounded by resorption but some are angular. The fragments are similar in composition to the matrix. These breccias are believed to have been formed by vesicular crusts sinking in a lava lake, a feature commonly observed at Kilauea Volcano, Hawaii, during its lake phase. Small patches of talus breccia were noted among the crusts in a few places. These patches are former slides from crater walls into lava lakes.

Where slight collapse of a solidified basaltic mass has occurred the breccias consist of fragments of one rock type only cemented in a matrix of the same rock. One breccia of this type was noted in which the matrix was apparently fluid at the time of the collapse. Breccias of this type probably result from the subsidence of a partly solidified lava lake.

Fault breccias and crack fills are identified by their longitudinal outcrops. The former usually show well-developed slickensides bordered by a few inches of gouge. The friction breccias along faults usually are crushed into small, sharp fragments. The fragments of some shattered blocks have been only slightly displaced, a feature rarely found in other types of breccias.

Some stocks carry fragments of fine-grained basalt in a coarse-grained matrix and are typical intrusive breccias. One intrusive, in Wailau Valley, is composed of angular fragments, reaching a foot across, of coarse-textured dense basalt in a matrix of feldspar and augite crystals averaging a third of an inch across. Some gabbros carry partly resorbed blocks of gabbro. Some of the intrusive breccias in this valley may be the result of the collapse of the solidified roofs of plugs.

In a few places talus breccia underlying solidified lava lakes has been fused. The welding usually extends downward only a few feet.

The most difficult breccias to interpret are those formed by former

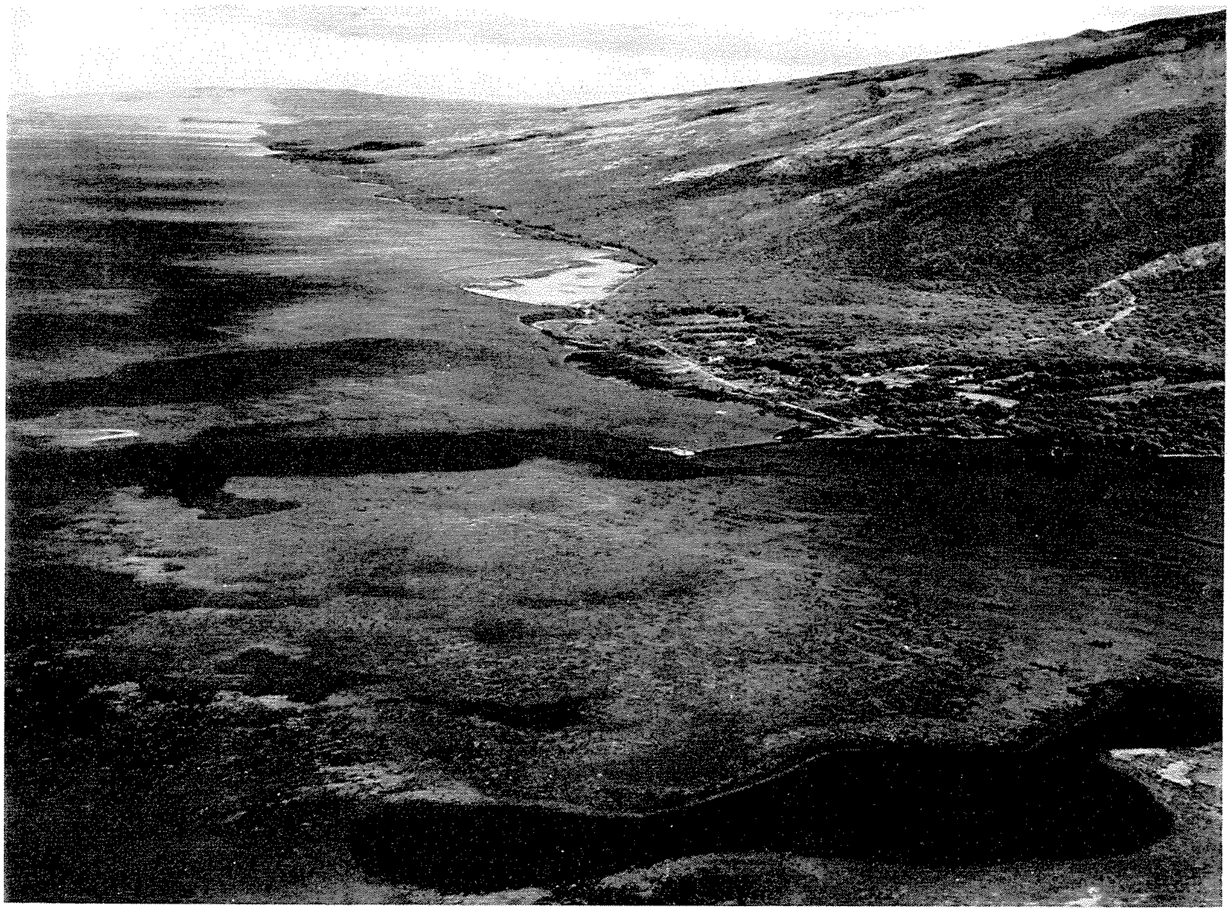
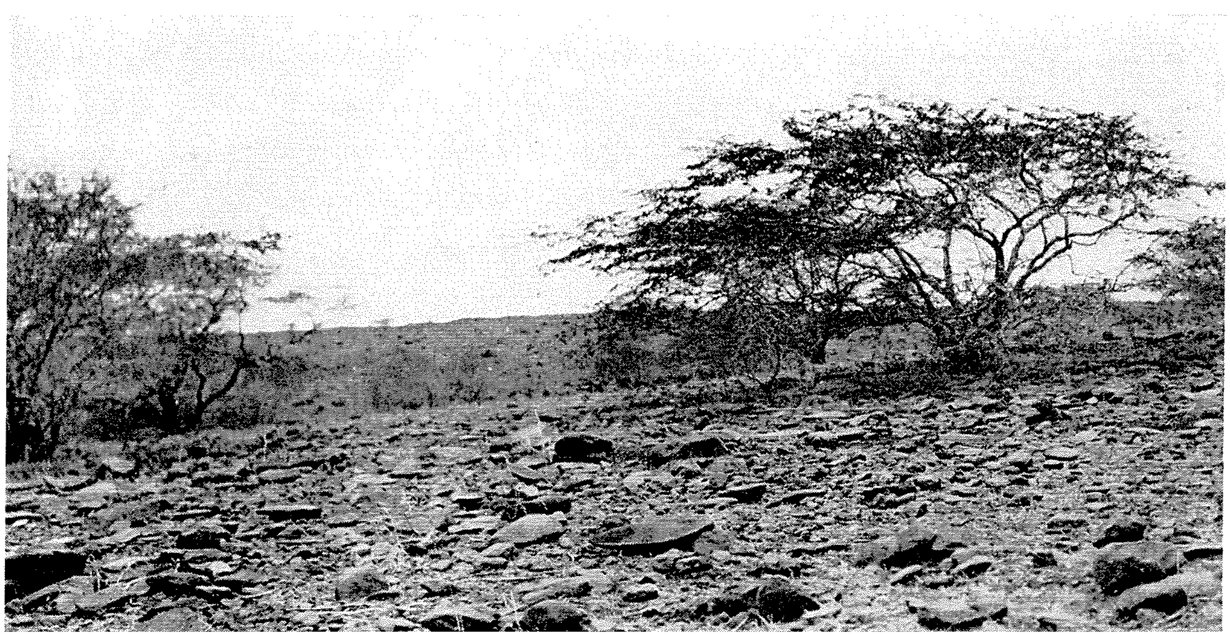


Plate 6A. Southern slope of East Molokai, showing the fringing coral reef and the alluvial flats along the coast. Kamalo wharf is in the foreground. Much of the visible slope is veneered with andesite. Lunate fishponds along the coast are partly filled with Recent sediment. In the background the domical shield of West Molokai is clearly visible. Photo by U. S. Navy.

Plate 6B. Armored desert on the southern slope of West Molokai. The lag gravel was left behind by wind erosion, but the soil was largely stripped away and the cobbles were rounded by wave action during the high stand of the sea which left the Manele (560-foot) shoreline. Photo by H. T. Stearns.



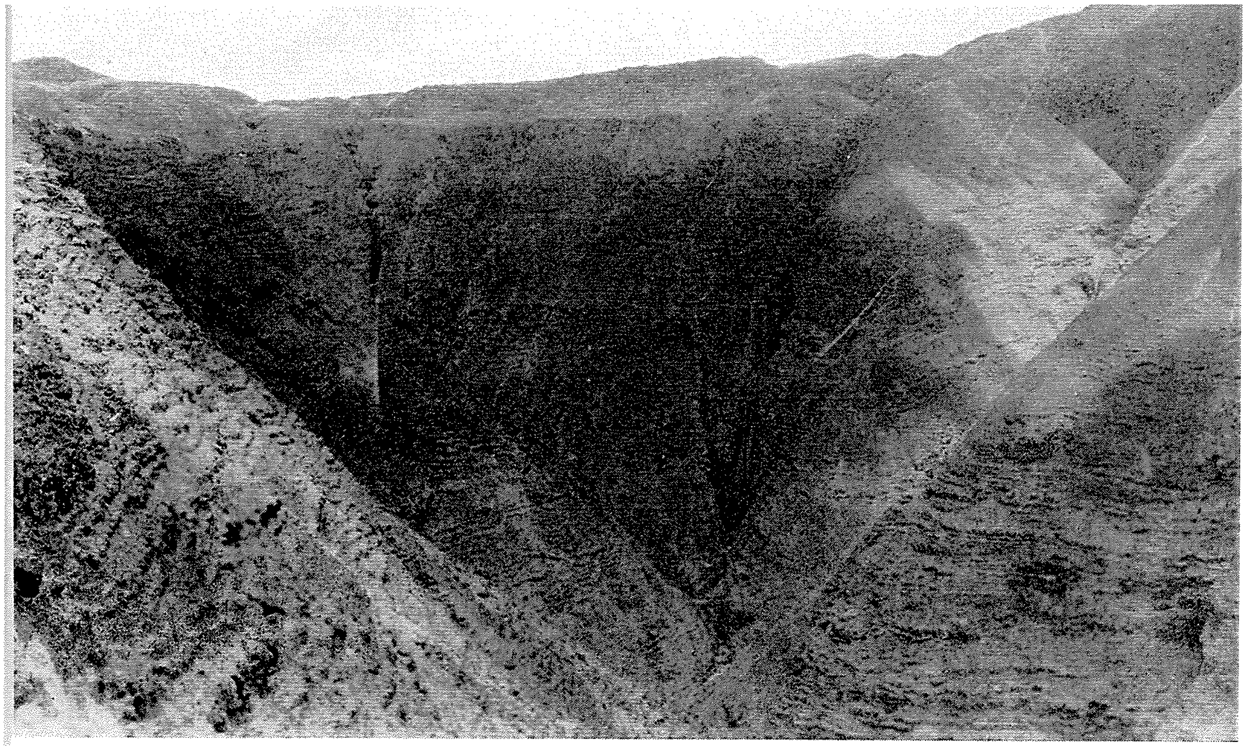


Plate 7A. Head of Kamalo Gulch, East Molokai, showing the characteristic thin bedding of the basalts of the lower member of the East Molokai volcanic series, and the prominent lighter-colored andesite cap. The height of the amphitheater head-wall is about 1,600 feet. Photo by G. A. Macdonald.

Plate 7B. The sea cliff on the northern coast of West Molokai, looking eastward to Mokio Point from near Kaeo cone. The cliff, which is about 500 feet high, exposes many dikes in the northwest rift zone of West Molokai. Kaa cone lies on the skyline. Photo by G. A. Macdonald.

"floating" islands that crashed to the bottom of a lava lake during rapid subsidence. They are clinkery and vesicular masses of very irregular form, commonly of large size, and chiefly of one rock type in a matrix of cemented reddish rock flour.

Near the amphitheater head of Wailau Valley, a few of the tributaries have cut to the contact of the complex with the extra-caldera lavas. The streams cascade alternately on ancient talus breccia, deposited along the caldera wall, and on thin-bedded pre-caldera lavas cut by dike swarms. The lack of faulting gouge and other evidence of movement at the contact indicate that this particular talus breccia accumulated at the foot of a cliff. The south edge of the caldera complex in the head of Pulena tributary of Wailau Stream is bounded by a well exposed fault trace.

An excellent exposure of the ancient caldera wall lies in the west fork of Pilipililau Stream at an altitude of about 1,200 feet. The wall dips 60° to 80° to the east. In the wall, typical massive caldera-filling lavas dipping slightly to the east rest unconformably against thin-bedded pahoehoe. Breccia composed only of the rocks in the wall underlies the massive basalts.

Single flow units in the ponded lavas in the caldera complex are commonly 50 feet thick and a few are 75 to 100 feet thick. The extra-caldera basalt flows rarely have flow units more than 15 feet thick.

The Haupu Bay mass is interpreted as a pit probably not connected to the caldera, similar to the relation of Lua Hou to Mokuaweoweo Caldera on Mauna Loa Volcano, Hawaii. The rocks are chiefly breccia capped by massive crater-filling lavas. The contact of the breccia and the crater wall is well exposed in the sea cliff on the eastern side of the bay. There 100 feet of breccia is exposed striking N. 10° E. and dipping 28° NE. under massive flows striking N. 70° W. and dipping 15° S. The crater wall strikes N. 15° W. and dips 60° NW. The inland boundary of the crater as shown on plate 1 is hypothetical, as the contact could not be traced in the field. There is some evidence suggesting that this crater was buried by lavas from the main caldera long before the completion of the East Molokai dome.

The caldera complex yields little water, even though it receives heavy rainfall. This small yield is due to the low permeability of the major part of the rocks and to the discontinuity of structures. However, there are many small springs in the area, the aggregate of which comprises a goodly share of the flow of Pelekunu and Wailau streams. Many of the springs discharge from the alluvium overlying the caldera complex although the water is largely derived from the underlying complex. Many of the tributaries were traced back to the canyon heads where the springs were found issuing from the dike swarms in the extra-caldera basalts. Thus the proposed tunnels to develop water for the Molokai project (p. 82) will probably obtain their largest yields after they leave the caldera complex and penetrate the extra-caldera basalts.

UPPER MEMBER

Lava flows.—The upper member of the East Molokai volcanic series consists chiefly of oligoclase andesite with lesser quantities of andesine andesite and trachyte. These rocks once formed a veneer over most of East Molokai. The upper member averages about 500 feet in thickness along the crest where it is composed of numerous flows, and thins to 50 feet or less on the lower slopes. The thinning is largely due to the flows having been so viscous that few reached the periphery of the dome. In many places erosion has removed one or two flows.

The flows range from 20 to 100 feet thick and form conspicuous rimrocks to the gulch walls (pls. 7A, 14A). All the lavas are aa and many carry heavy clinker beds. The dense parts of the flows are columnar jointed and usually platy, especially near their base. The lavas are generally non-porphyritic but a few carry feldspar phenocrysts (See Petrography).

The upper member serves as a protective armor over the easily eroded lower member; hence, most streams have falls or cascades where they cut through into the weaker basalts. Where these thick lava flows spread out fanwise as they moved down the slopes they caused streams to diverge from their normal course radial to the dome and follow the edge of the lava flow diagonally across the slope. Thus some streams, such as Kamalo, have received more than their share of the drainage and have cut abnormally deep amphitheater-headed canyons. The heavy andesite armor is responsible for swamps such as the one east of Wailau Valley remaining undrained while deep gorges were being cut in the weak basalts near by.

No erosional unconformities were found between the andesite flows, but interbedded ashy soil beds are fairly common. The upper and lower members are usually separated by a few inches to a foot of red soil, indicating that only a short time elapsed between the laying down of the basalts and the andesites.

The type locality of the upper member is along the trail down the windward cliff to the Leper Settlement (p. 93). There three or more flows of andesite, aggregating 200 feet in thickness, overlie the basalt with ¼ to 1 foot of intervening soil.

The dense beds of the upper member have low permeability, but the clinker beds are very permeable. Most of the perched water in the eastern part of the island of Molokai issues from the top of outcrops of interbedded ashy soils in the upper member.

Cones and bulbous domes.—Eruptions of andesite and trachyte were usually accompanied by lava fountains that built bulky cinder cones, of which 25 are shown on plate 1. Some of the hills in the swamp east of Wailau are probably cinder cones also but no exposures are available. Some of the lavas were extruded in so viscous a state that they made bulbous domes. These usually formed after the gas had been discharged during the lava fountain stage. Ten such domes are mapped on plate 1. Some of the peaks along the crest may be the margins of bulbous domes also, the northern part having been cut away by Wailau and Pelekunu streams. Puu Kaeo and Hanalilolilo hill, near the head of Waikolu Valley, are bulbous domes. The nearby Kaulahuki hill is a large andesite cinder cone, partly eroded to expose a bulbous dome and plug in the crater. A bulbous dome is shown at the head of the andesite flow forming the eastern rim of Kamalo Gulch, although positive evidence of the extrusion was not found. The cones and domes are not water-bearers. Dikes belonging to the upper member were not mapped separately on plate 1. Most of them are wider than the basalt dikes.

EROSIONAL UNCONFORMITY

The unconformity between the East and West Molokai volcanic series is well exposed in the east bank of Waiahewahewa Gulch at an altitude of 250 feet, 2 miles from the mouth. The section consists of 30 feet of lateritic soil resting on a flow of basaltic pahoehoe, containing phenocrysts of augite, olivine, and feldspar, from the East Molokai Volcano. Beneath this there is 3 feet of blocky baked laterite grading downward into 6 feet of spheroidally weathered highly vesicular nonporphyritic basaltic pahoehoe from the West Molokai Volcano. The contact strikes N. 50° W. and dips 10° NE. The deep soil between the two lavas indicates that this slope of West Molokai had long been extinct when the lava flows from East Molokai finally buried its eastern slope. Waiahewahewa Stream has been turned from its normal eastward course to a southerly course by the lavas from East Molokai.

WEST MOLOKAI VOLCANIC SERIES

Distribution.—The West Molokai volcanic series is named from West Molokai Mountain, which is composed of volcanic rocks erupted from a shield-shaped dome (pl. 6A) rising 1,381 feet above sea level locally known as Mauna Loa. However, the name Mauna Loa is avoided herein because of the confusion which might arise with the well-known Mauna Loa on the island of Hawaii. The rocks crop out over an area 12 miles long and 10 miles wide (p. 1). The lavas have weathered into such deep soils that over large areas little original structure can be discerned.

CHARACTER AND STRUCTURE.—The lavas of the West Molokai volcanic series are all basaltic and mostly exceptionally thin-bedded and non-porphyritic. Olivine basalts, basalts, and primitive-type picrite-basalts occur (page 105). The flow units average about 2 feet in thickness. The beds dip from 2° to 10° away from the southwest and northwest rifts and the dips are steepest along the south slope. Many of the beds converge toward the summit where the two rift zones intersect. Both aa and pahoehoe exist. The beds in the fault block area on the eastern side, especially ½ mile southeast of the summit, are considerably bleached and mineralized by hydrothermal action, presumably by gases that rose along the faults and dikes. Fragments of chalcedony and calcite several inches across are common in the stream beds draining this area. Fragments of secondary spongy brown iron ore as much as 6 inches across lie in this area also. Elsewhere the vesicles are not filled, except locally with a soft cream-colored deposit probably allied to montmorillonite deposited by percolating ground water.

A few of the latest flows, notably the one from Waiele cone, are underlain with ½ to 4 feet of red ashy soil. These are shown in figure 18.

A bed of breccia carrying blocks up to 2 feet across lies in the south wall of Waiahewahewa Gulch half a mile south of the summit.

The lavas in West Molokai carry brackish water suitable for stock along parts of the coast but none that is potable for humans. The test well drilled by Libby, McNeill, & Libby 3 miles northwest of the summit has demonstrated that these lavas do not carry potable water even 2 miles from shore, due to the low recharge and the large amount of salt carried to the water table from salt spray blown inland by the wind. This well is slightly thermal and alkaline, probably indicating rising volcanic gases admixed with ground water.

CONES AND VITRIC TUFF DEPOSITS.—Seventeen spatter and cinder cones were mapped on West Molokai. Many other small hills are probably cones but weathering is so deep that no rocks are exposed. Kanewai, Puu o Kaiaka, and Waiele are the largest cones, each covering about half a square mile. Kaiaka is 110 feet high and is chiefly composed of cinders. Kaeo cone and a few others contain dense beds of basalt that have been extensively quarried by the ancient Hawaiians for making stone adzes. The northern end of Kaa cone is a plug of dense basalt, exposed by erosion. Thin vitric tuff deposits lie interstratified with the lavas, especially in the windward cliff near Ilio Point, but are too small to show on plate 1. The lavas apparently accumulated rapidly, typical of the early phase of Hawaiian volcanoes.

DIKES.—Thirty-two dikes averaging about 2 feet thick are exposed in the sea cliff cutting the northwest rift (pl. 7B). They all strike northwest (pl. 1). About 20 dikes and numerous dikelets, striking chiefly southwest, are exposed in Waiahewahewa Gulch near the summit. The gulch has just begun to cut into the heart of the West Molokai Volcano. Many other dikes are probably covered with alluvium in this area. The widest dike is 10 feet across, but mostly they are ½ to 2 feet wide.

Two basalt dikes crop out in the southeast corner of West Molokai at the coast. Both strike N. 70° W. and range from 6 to 10 feet in width. The western one connects with a lava flow 10 feet thick.

The dikes probably confine water appreciably above sea level in the rift zones a mile or two from the coast, but because of the low rainfall and salt carried downward from spray, it is not potable.

QUATERNARY VOLCANIC ROCKS

KALAUPAPA BASALT

The Kalaupapa basalt is named from the leper settlement which is built on this lava. The basalt forms a peninsula 2½ miles long and 2½ miles wide projecting from the base of the great windward cliff of East Molokai Mountain (pls. 4, 8A). The lava is a porphyritic olivine basalt pahoehoe (See Petrography) that issued from a flat lava cone 405 feet high indented with a crater a quarter of a mile wide and more than 450 feet deep. A brackish pond lies in the crater. Two distinct rock benches in the crater indicate that the lava lake halted twice during the recession of the magma column. Most of the lava discharged northward through a large lava tube that is now collapsed. Several other tubes are exposed at the sea where they have been eroded to form natural bridges, blow holes, and other scenic forms. Most of the cone lies under the sea.

The lava flows forming the cones are essentially contemporaneous with each other and are only slightly decomposed. Long tumuli are common and thin flow units are characteristic.

Loose deposits of coral sand, shells, and boulders reach a height of 35 feet along the northeast coast of the peninsula. They indicate the 5-foot and possibly the 25-foot shore lines of late Pleistocene time. Conglomerate overlying the basalt forms a terrace 100 feet above sea level near the mouth of Waileia Stream. It is the remnant of an ancient alluvial fan graded to a stand of the sea at least 25 feet higher than the present. The Kalaupapa basalt is assigned on this evidence to the late Pleistocene.

The Kalaupapa basalt is highly permeable but carries only brackish water.

TUFF OF MOKUHOONIKI CONE

The remains of a large basaltic tuff cone lie 1 mile off the eastern end of Molokai. The cone has been cut in two by the waves. The northern part is called Mokuhooniki and the southern part Kanaha. Mokuhooniki is 203 feet high. The cone is typical of those formed by phreatomagmatic explosions and resembles Manana Island off Oahu. Lithic fragments and blocks of coralliferous limestone abound in a palagonitic matrix. During the closing phase of the eruption spatter was thrown out and lava flows cascaded down the leeward slope of the cone.

Several thin dikes cut these islands and a large vertical cave lies along one of them. One dike has controlled wave erosion in such a way that the bench on the windward side is 5 to 8 feet above sea level, whereas the one on the leeward side is 1 to 3 feet above mean sea level.[19] It is probable that these benches have been dressed down from those left by the 5-foot sea. The eruption is believed to have occurred in late Pleistocene time. The tuff of Mokuhooniki cone does not carry fresh water.

SEDIMENTARY ROCKS

Calcareous marine deposits.—The older calcareous marine sediments are breccias and poorly developed fringing reefs usually 1 to 8 feet thick. They lie chiefly in two ledges east of Kaunakakai (pl. 1) at about 25 and 100 feet above sea level (pl. 8B). Fossil nullipores and corals are abundant as well as foraminifera and molluscs. The latter have been identified as of Pleistocene age.[20] The marine deposits above 120 feet lie chiefly as thin intermittent veneers in the gully bottoms. They reach a height of about 280 feet above

[19] Stearns, H. T., Shore benches on the island of Oahu, Hawaii: Geol. Soc. America Bull., vol. 46, p. 1474 and pl. 132, 1935.

[20] Ostergaard, J. M., Reports on fossil mollusca of Molokai and Maui: B. P. Bishop Museum Occ. Papers, vol. 15, pp. 67-77, 1939.

Plate 8A. Kalaupapa Peninsula, at the base of the northern cliff of East Molokai, from the mouth of Waikolu Valley. The peninsula is a small basalt cone built against the cliff. The terrace in the middle distance is a gravel deposit graded to the Waimanalo (25-foot) stand of the sea. Photo by H. T. Stearns.

Plate 8B. Reef limestone of the Waimanalo (25-foot) stand of the sea, resting on partly decomposed gravel, in a roadcut 1.4 miles east of Kaunakakai. Photo by G. A. Macdonald.

Plate 9A. Lithified beach sandstone near Halena, on the southern shore of West Molokai. Photo by C. K. Wentworth.

Plate 9B. Gravel terrace at the mouth of Waileia Valley, resting on the Kalaupapa basalt. The terrace was graded to the Waimanalo (+25-foot) stand of the sea. A second terrace behind it may have been graded to the Laie (+70-foot) stand of the sea. Photo by H. T. Stearns.

sea level and many of the outcrops are too small to be shown on plate 1. It is likely that the soil-covered surfaces between the drowned bedrock gulches were unfavorable, because of shifting bottom, for nullipore and coral growth during the submergence; hence, the absence of calcareous deposits in most inter-stream areas. The scarcity of sediments indicates that the land was not long submerged.

Weakly consolidated beach deposits of calcareous sand lie about 25 feet above sea level near the south shore of East Molokai, from half a mile southeast of Puu Maniniholo to Kawela Gulch. The sand just west of the mouth of Kawela Gulch contains abundant basaltic debris.

Cream-colored beach rock is common on the sandy stretches of the West Molokai shore, especially at Halena. It lies in layers sloping seaward and is rarely more than 6 feet thick (pl. 9A). The rock is valuable for flagstones. The beach rock used for the construction of the Honolulu Academy of Arts building was quarried on Molokai. The rock is Recent in age. Its origin has been discussed elsewhere.[21]

The marine sediments are highly permeable but lie chiefly above the water-table; hence, they have little value as water-bearers.

Consolidated earthy deposits.—The consolidated earthy deposits consist chiefly of older alluvium and correlative talus. Part of the deposits may have been deposited beneath the sea. They floor the large canyons on East Molokai and form broad aprons at the foot of the fault scarps on the Hoolehua Plain. A nearby continuous narrow plain of alluvium borders the southern edge of East Molokai (pl. 6A). Near Panahahe Fishpond a thin capping of basaltic gravel contains shells of marine molluscs up to about 25 feet above sea level. The alluvial deposits are usually weakly consolidated and in wet areas are partly or completely decomposed. Much of the alluvium is composed of ochre to red-brown conglomerates, usually coarse and poorly sorted. Boulders 10 to 20 feet across are common in it in Wailau and Pelekunu Valleys. Some deposits resemble mud flows because they were laid down by torrential streams. They grade into coarse blocky talus near canyon walls. The older alluvium is several hundred feet thick in most of the windward valleys and at the mouths of the large gulches extends several hundred feet or more below sea level. In some places in Wailau and Pelekunu Valleys, the alluvium is sufficiently cemented to form cascades and waterfalls but in other places it is easily cut by a shovel. On the Hoolehua Plain it is chiefly silty and friable.

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[21] Stearns, H. T. and Vaksvik, K. N., Geology and ground-water resources of Oahu, Hawaii: Hawaii Div. of Hydrography Bull. 1, pp. 41-42, 1935.

The older alluvium in the major valleys forms two or more terraces, which indicates that it was laid down at different times. During high stands of the sea in Pleistocene time the valley floors were aggraded (pl. 9B) and during low stands the streams cut deeply into the alluvium. In places major streams have not yet cut down to their former bedrock floors even far inland.

Most of the alluvium has low permeability but in Wailau and Pelekunu Valleys many small springs and seeps discharge from its base. One such spring in the southwestern part of Wailau Valley yields about 100 gallons of water per minute. It comes from the base of a boulder deposit filling a narrow gorge cut in dense volcanic breccia. It apparently rises, however, from a dike swarm not far from where the spring issues, and represents an exhumed spring buried by the alluvium during a period of aggradation.

Valuable supplies of domestic water have been developed by dug wells in the older alluvium along the south shore.

CONSOLIDATED DUNES.—Stretching 2 miles southwestward from Moomomi Beach on West Molokai are consolidated dunes 5 to 25 feet high (pl. 10B). They migrated over a cliff 600 feet high before they became cemented. Another large outcrop lies at Ilio Point and smaller outcrops lie along the coast east of Moomomi Beach (pl. 1). The sand is chiefly comminuted coral, shells, and foraminifera with small amounts of basaltic sand. The dunes show several degrees of consolidation. The oldest sand is the hardest and is cemented into a firm rock called eolianite. Near Ilio Point this rock extends below sea level (pl. 10A). It is benched by the 5- and 25-foot stands of the sea. Fossil shells of land snails are abundant. These older dunes, in common with those elsewhere in the Hawaiian Islands, formed during the late Pleistocene when the sea level was about 60 feet lower than at present. Their relation to the sea cliff on West Molokai shows that most of the marine erosion which formed the cliff occurred before the minus-60-foot stand of the sea.

The dunes are permeable. They carry salt water along the coast and no water inland where they rise above the water table.

UNCONSOLIDATED DUNES.—Extending 5½ miles southwest from Moomomi Beach is a strip of unconsolidated dunes half a mile wide composed of cream-colored "coral" sand (pl. 1). Much of it has been blown from the older weakly consolidated Pleistocene dunes. The dunes reach a height of about 60 feet near Moomomi Beach. A few dunes, too small to show on plate 1, lie at Papohaku Beach. Most of the sand seems to have been derived from the former marginal ocean floor when it was bared during the Waipio low stand of the sea. The dunes carry brackish water near the coast but no water inland.

Beach deposits.—Cream-colored deposits of loose sand composed of comminuted corals, nullipores, molluscs, foraminifera, and other marine organisms form narrow beaches along much of the shore of West Molokai. The largest deposits are at Papohaku and Moomomi beaches. A few lie near Kaunakakai, and contain much comminuted basalt. Much of the leeward shore of West Molokai has red silt beaches formed by the waves reworking the torrential deposits brought by streams from the uplands. A black sand beach forms annually at the mouth of Wailau Valley during the summer months but is carried away by winter storms. Black sand beaches also occur near Waialua and between Kawela and Kaunakakai. Cobble beaches characterize the reentrants along the windward coast and a few stretches of eastern leeward coast.

The beach deposits carry potable water in some of the stretches in the wet eastern end, but only brackish water on western and central Molokai.

Unconsolidated earthy deposits.—The loose earthy deposits are chiefly poorly sorted, poorly rounded stream-laid brown silt, sand, gravel, and boulders lying in Recent stream channels. Many narrow bands along streams are too small to show on plate 1. They range from a few inches to 50 feet in thickness and form fans at the mouths of the gulches along the leeward coast. Extensive aprons of blocky landslide deposits lie between Halawa and Wailau valleys along the windward coast and at the foot of the cliff on Kalaupapa Peninsula.

GEOLOGIC STRUCTURE

East Molokai.—The East Molokai Mountain is an asymmetrical shield-shaped dome elongated eastward and westward and built about an ancient caldera in Wailau and Pelekunu valleys (pl. 1). The east-west elongation of the dome is due to the presence of northwest and east rift zones, from which lavas have been extruded. The beds have centrifugal dips of 2° to 15° away from the volcanic center except along the lower part of the great northern sea cliff, where the beds dip 8° to 25° S. The apex of the dome is missing due to collapse and erosion. No folding was seen. The caldera complex is bounded by normal faults, but the downthrown segment is not recognizable, possibly because it sank largely as thin peripheral slices which shattered to form breccia. The absence of explosion debris interbedded with the extra-caldera lavas is positive evidence that the caldera formed by subsidence rather than by explosions.

Faults are numerous near the mouth of Pelekunu Valley and in the cliffs bounding Haupu Bay. The main fault on the east shore of Pelekunu Bay strikes east-west and dips 57° S. The slickensides along the fault trace are well exposed as the gouge is more resistant to erosion than the adjacent rock so that the hanging wall has become an overhanging ledge 8 feet high. The gouge is 3 to 6 inches thick and is bordered by breccia with blocks reaching 2 feet across, many of which are slaggy pahoehoe. The pahoehoe on the south side has drag dips of 35° S. adjacent to the fault plane, but 10 feet away it dips only 18° S. The displacement could not be ascertained, but it may be large. Five faults are exposed nearby with displacements ranging from 3 inches to 6 feet. Two of the faults dip northward bounding small wedges. Some of the faults strike NW-SE and may belong to another set of faults well exposed in the east shore of Haupu Bay.

The main fault at Haupu Bay strikes N. 45° W. and dips 50° SW. Several fault traces with 6 feet or less displacement parallel the main fault. Near the point farther north, however, the faults strike N. 80° E. and dip 80° S.

The lava beds in Okala Island, off the mouth of Waikolu Valley, strike N. 60° W. and dip 15° SW. In the ridge between Haupu and Pelekunu bays they have a dip of 15° S. On the west side of the mouth of Wailau Valley they dip 13° S., yet near the top of the eastern wall of Pelekunu Canyon, 0.4 mile northwest of Pohakuulaula, the beds dip 6° N. It is concluded from these dips that during the accumulation of the lower member of the East Molokai volcanic series, a set of echelon faults threw down to the south a strip of land about 6 miles long and 2 miles wide along the north side of the dome (fig. 5, stage 3). Lavas pouring northward from the caldera ponded against these fault scarps and finally overtopped them. Eventually a northward slope must have been established or else the stream would not flow in that direction now. Kilauea Volcano, Hawaii, shows a similar history. Faults dipping toward the center of the mountain lie 3 miles south of the caldera, and lavas poured from the caldera have in places overtopped the fault scarps[22] and flowed seaward. Such a structure results in heavy-bedded lavas on the inland side of the fault scarps where the lavas are ponded and thin-bedded lavas seaward of the scarps where the lavas have unobstructed movement. This relation of thick and

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

thin-bedded lavas can be seen on Molokai, and for this reason it seems unlikely that the southward dipping lavas came from a volcano now beneath the sea north of the present coast.

The swarm of faults dipping southward parallel to the great sea cliff of Molokai suggests the possibility that this cliff is an obsequent fault-line scarp and wave erosion has been halted by the heavy ponded lavas in the downthrown blocks. A similar condition was noted in the great cliff of Kauai.[23]

West Molokai.—The West Molokai Mountain is made up of two broad fairly flat constructional arches, one extending southwestward and the other northwestward from the summit. These arches resulted from building along rift zones having those trends. The northeastern side of the dome is terminated in a set of echelon fault scarps, 100 to 500 feet high, facing northeastward (pl. 12A). The downthrown part of the dome lies under Hoolehua Plain and is buried by lavas from the East Molokai Volcano. The locations of the faults are shown on plate 1. The actual fault traces are not well exposed, but the fault-scarps are only slightly modified by weathering and erosion.

GEOLOGIC HISTORY

The amount of submergence of Molokai is unknown, but it must have been large as indicated by the deep drowning of the mouths of the large canyons. It is probable that the submergence is of the order of 1,200 feet, in common with the other islands of the group.

TERTIARY TIME

1. Building of a shield- or dome-shaped island of thin-bedded primitive basalts at the site of West Molokai Mountain.
2. Growth of the East Molokai Volcano above sea level with the eruption of the thin-bedded basalts in the lower member of the East Molokai volcanic series (fig. 5, stage 1).
3. Extinction of the West Molokai Volcano and downfaulting of its northeastern side. Weathering develops a soil cover and streams erode its slopes (fig. 5, stage 2).
4. Continued eruption of the East Molokai Volcano, accompanied by collapse of the summit to form a caldera 4½ miles long and 2 miles wide. Faulting may have dropped part of the north side of the cone during this or later stages. Lavas from East

[23] Stearns, H. T., Geology of the Hawaiian Islands: Hawaii Div. of Hydrography Bull. 8, p. 89, 1946.

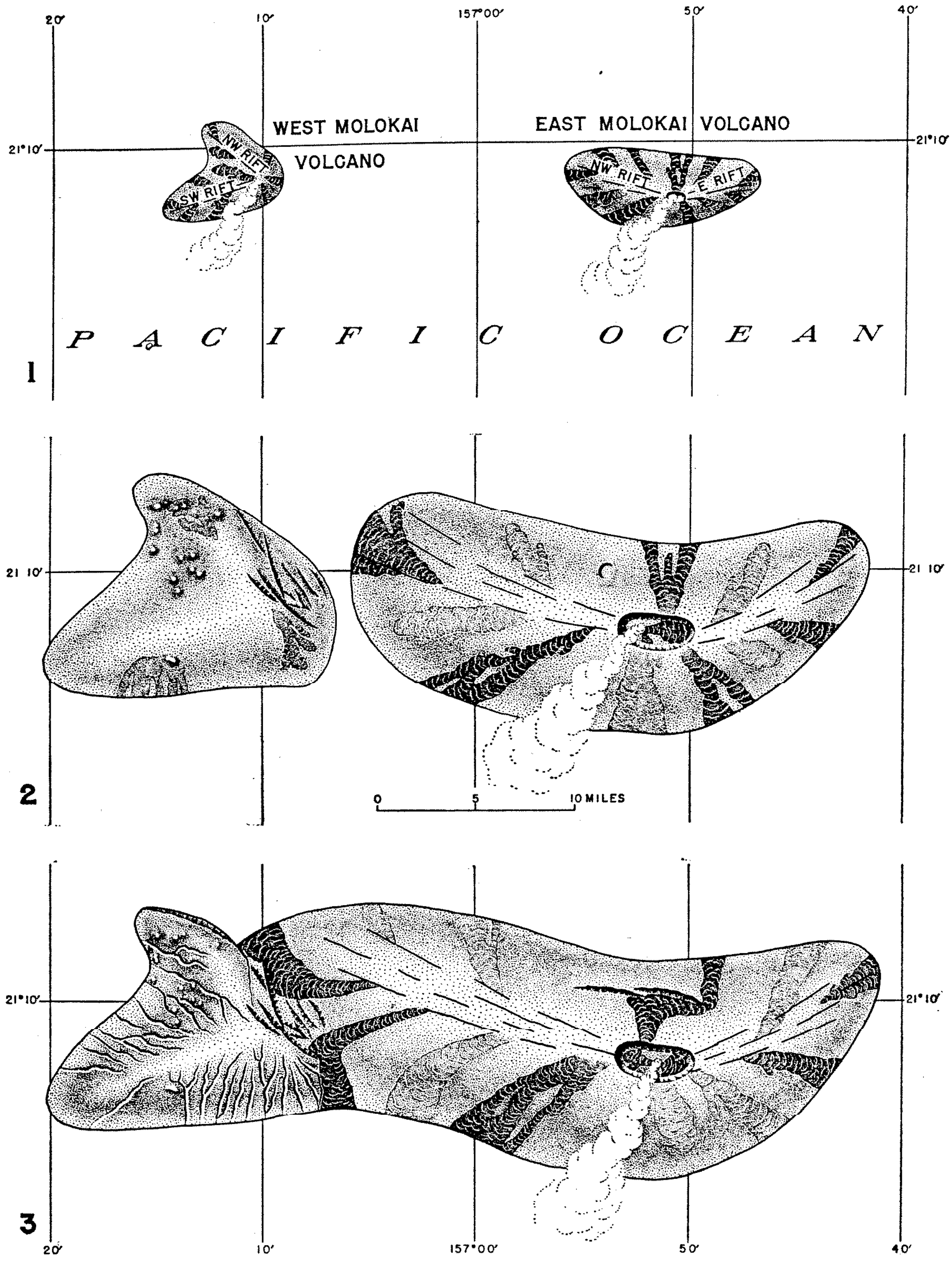
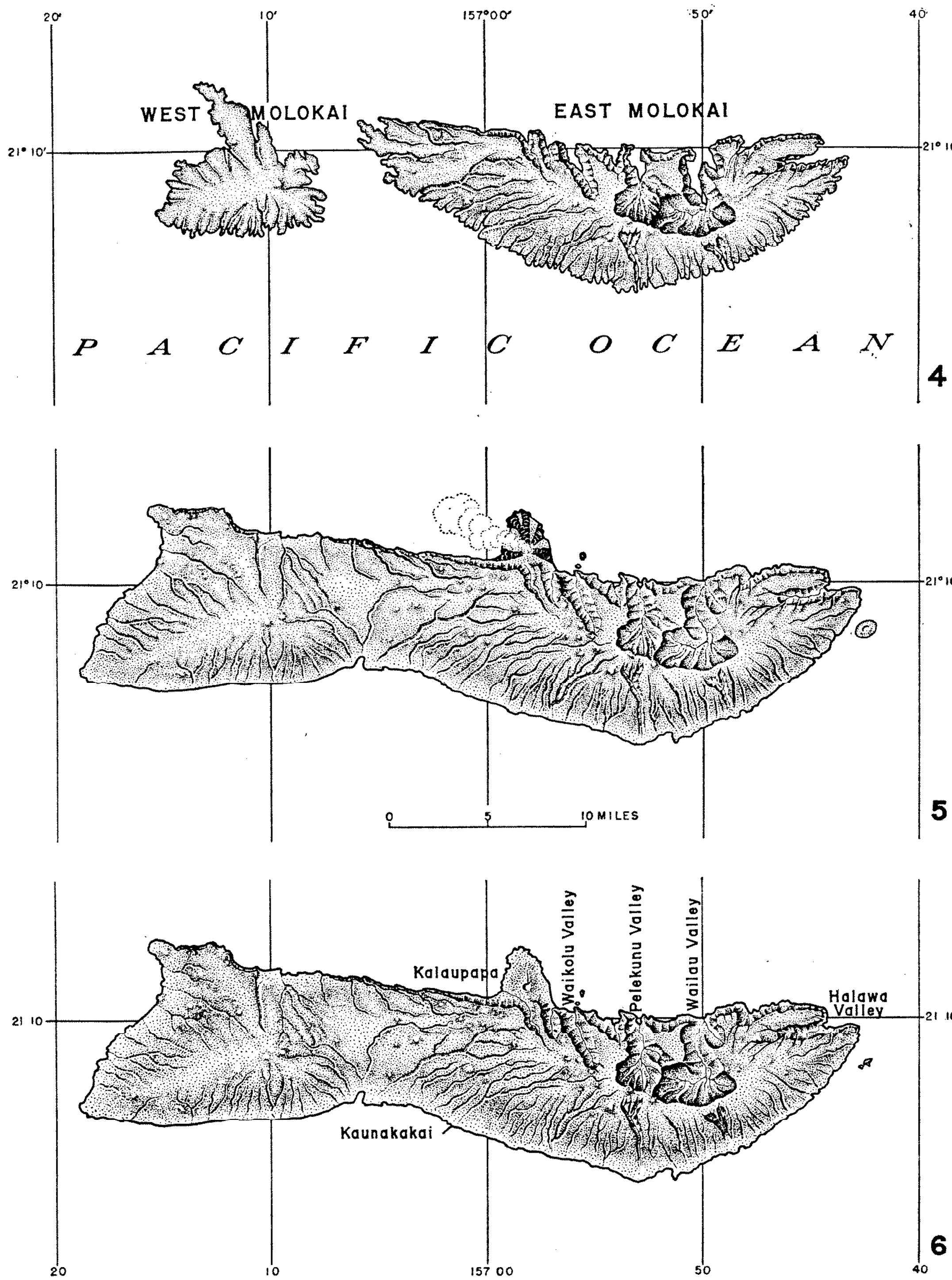


Figure 5. Drawings illustrating six stages in the development of the island of Molokai (see explanation in text). Stage 1 shows the appearance of two separate islands above sea level in Tertiary time. In stage 2 they are much enlarged, and a caldera has formed on East Molokai. In stage 3 the two islands have merged, and West Molokai Volcano has become extinct. Stage 4,



in late Pliocene or early Pleistocene time, shows a new separation into two islands by submergence. Stage 5, in late (?) Pleistocene time, shows a minor renewal of volcanism on East Molokai, and stage 6 shows the present condition of the island.

Molokai gradually fill the channel between East and West Molokai islands and the Hoolehua Plain is formed.

5. Nearly complete extinction of the East Molokai Volcano. Differentiation proceeds in its magma reservoir (fig. 5, stage 3).
6. Extrusion of the andesites of the upper member of the East Molokai volcanic series from bulky cinder cones and bulbous domes. The caldera was probably nearly filled with these lavas.
7. Gradual extinction of the East Molokai Volcano and beginning of erosion.

LATE PLIOCENE (?) AND EARLY PLEISTOCENE TIME

8. Long period of erosion during which deep canyons were formed on East Molokai and smaller ones on West Molokai. Marine erosion vigorously removed a large segment of the windward coast.
9. Gradual submergence of an unknown but large amount of the island, culminating in a shore line at least 560 feet above sea level (fig. 5, stage 4), and probably as much as 1,200 feet. East and West Molokai again became two islands and the sea flooded the Hoolehua Plain. The large canyons were filled with alluvium as the streams aggraded their beds in adjustment to the higher sea level.
10. Gradual emergence with a short halt at the 250-foot level. Small patches of coralliferous limestone accumulated at the mouths of gulches on the leeward side of East Molokai at this level. East and West Molokai joined to form one island again.

MIDDLE (?) PLEISTOCENE TIME

11. Fairly rapid emergence with the sea dropping to about 300 feet below present sea level. The streams cut deeply into their alluvial fills and the sea continued rapidly to cut away the windward side of the island.
12. Resubmergence of the island with the sea finally halting 100 feet above present sea level. A narrow fringing reef formed along part of the south shore of East Molokai.

LATE (?) PLEISTOCENE TIME

13. Reemergence of the island by about 160 feet exposing broad marine flats covered with "coral" sand. The wind drifted great quantities of this sand 2 miles inland up and over a 600-foot cliff on the northeast coast of West Molokai.
14. Renewed volcanic activity on East Molokai. Large volumes of basalt erupted at the foot of the great sea cliff to form

Kalaupapa Peninsula (fig. 5, stage 5). About this time, lava rising under the ocean just east of Molokai exploded in contact with sea water to form Mokuhooniki tuff cone.

15. Resubmergence of the island by about 85 feet. A narrow fringing reef formed 25 feet above present sea level. Most of the sand dunes formed during the preceding period became lithified. Some were drowned by this rise in sea level and others were cliffed.
16. Reemergence of about 20 feet with the formation of a fringing shore bench about 5 feet above the present strand.

RECENT TIME

17. Further emergence to the present strand (fig. 5, stage 6). Erosion, and deposition of terrigenous sediments along the southern coast.

HISTORIC TIME

18. Introduction of livestock and agricultural development causing great quantities of red soil to be eroded from the uplands, partly filling up the ancient Hawaiian fishponds along the south coast.

ROAD METAL

Most of the crushed rock used on Molokai comes from the County quarry, at an altitude of 400 feet in Manawainui Gulch (pl. 1). Several faces have been worked in dense andesite of the upper member of the East Molokai volcanic series. A small quarry in dense andesite 0.75 mile northwest of Kualapuu was operated during construction of the highway. A small quarry 0.4 mile southeast of Puu o Kahanui yielded basaltic aa clinker during construction of the private road between Umipaa and Manawainui Gulch. A large gravel pit has been opened in an alluvial fan at the mouth of a small gulch 2.5 miles west of Kamalo. Many of the cobbles and pebbles are of dense andesite, but some others are basaltic. Most of the cinder used comes from a large pit on the northern side of Puu Maniniholo, a basaltic cinder cone 0.75 mile east of Kaunakakai. Cinder was quarried near the top of Waiele cinder cone, on West Molokai, during construction of the road to the Kolo wharf, on the southern shore of West Molokai. Many other small quarries and borrow-pits have been operated temporarily along the roads during construction, or when repair materials were needed.

PART 2. GROUND-WATER RESOURCES OF THE ISLAND OF MOLOKAI

By Gordon A. Macdonald

CLIMATE

Temperature, wind, and humidity.—The climate of Molokai is semitropical. The island lies in the belt of northeasterly trade winds, which blow almost constantly throughout most of the year. In the fall and winter months the trade winds are interrupted by periods of kona (southerly) winds, which usually last only a few days at a time. The normal trade winds are forced upward when they encounter the island mass, and adiabatic cooling commonly results in the formation of a cloud-cap over the high portion of East Molokai, and less markedly over the top of lower West Molokai. The southern, or leeward, slopes are largely sheltered from the prevailing trade winds, and are markedly drier and sunnier than the windward slopes.

Records of wind velocity are not available, but at Haiku on the neighboring island of Maui wind velocities average 11.5 miles per hour, being highest in the afternoon. On the nearby island of Oahu, during 1944, the average wind velocity at Bellows Field on the windward side of the island, was 14.1 miles per hour, and at Honolulu on the leeward side, it was 9.6 miles per hour.

The average mean temperature decreases about 3° F. for a rise in altitude of 1,000 feet. August and September are the warmest months; January and February the coldest. The leeward slopes have the highest daytime temperatures, and the greatest change in temperature from day to night. Temperature records are available for only three stations. They are given in the table on page 38.

No humidity records are available, but on Oahu Island relative humidity is lowest in July and highest in December. During periods of light kona winds humidity reaches about 95 percent. Humidity is less on the leeward than on the windward side of the island.

Rainfall.—The mean monthly and annual precipitation at 40 stations on the island of Molokai is given in the table on page 42. The location of the stations and the areal distribution of the rainfall are shown in figure 6. Over much of the island the stations are

Mean monthly and annual temperatures at stations on Molokai, in Fahrenheit degrees, up to and including 1944

(Data furnished by U. S. Weather Bureau)

Stations																
No.[a]	Name	Altitude (feet)	Length of record (years)	January	February	March	April	May	June	July	August	September	October	November	December	Annual
10	Maunaloa	1100	19	68.6	68.6	69.3	69.4	71.4	73.7	74.2	75.2	74.6	73.7	71.2	70.3	71.7
24	Kualapuu	878	38	68.4	68.3	68.4	69.7	72.7	73.7	75.2	76.0	75.8	74.6	72.1	70.1	72.1
27	Kalaupapa	50	12	71.2	71.2	70.6	71.6	73.7	75.9	77.3	77.7	77.9	76.6	74.1	72.5	74.2

[a] Numbers are the same as those of rain gages (fig. 6).

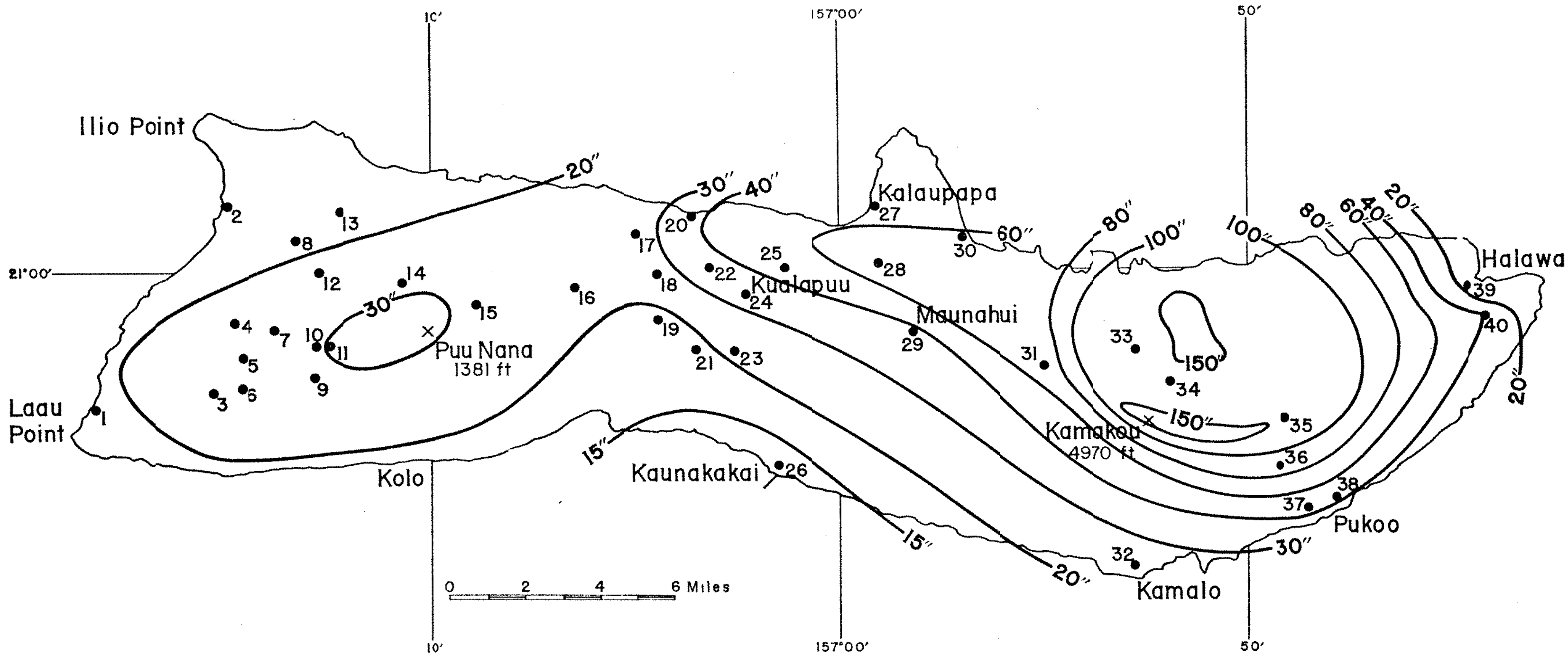


Figure 6. Map of Molokai, showing distribution of average annual rainfall and locations of rain gages.

so few and the records so short that the isohyets are only approximate. The table on page 43 gives the annual rainfall at the same stations for each year the station was in existence, since 1892.

The rainfall is highest on the crest and windward slopes of East Molokai, decreasing rapidly toward the leeward coast. The crest region is enveloped in clouds much of the time, and receives nearly constant mists and light rains. The highest recorded rainfall is at the Puu Lua station, at the summit of the trail from Wailau Valley to Mapulehu, where the average annual precipitation is nearly 150 inches, but it is probably equally high and possibly even higher on the difficultly accessible peak of Olokui, between Wailau and Pelekunu Valleys. The lowest recorded average annual rainfall is 11.7 inches, at Kaunakakai. At the summit of West Molokai the average annual rainfall probably reaches 30 inches or a little more, but records are inadequate in that area. The driest months over the entire island are June, July, and August. The wettest months are less consistent, but in general are in the midwinter, from December to March. On the leeward coast, more rain may fall in a single kona storm than during all the rest of the year. During short periods when neither trade nor kona winds blow, monsoon type of circulation caused by local heating and updraft over the land may result in local showers moving inland from the south coast. Figure 7 shows the average monthly distribution of rainfall at eight stations on Molokai.

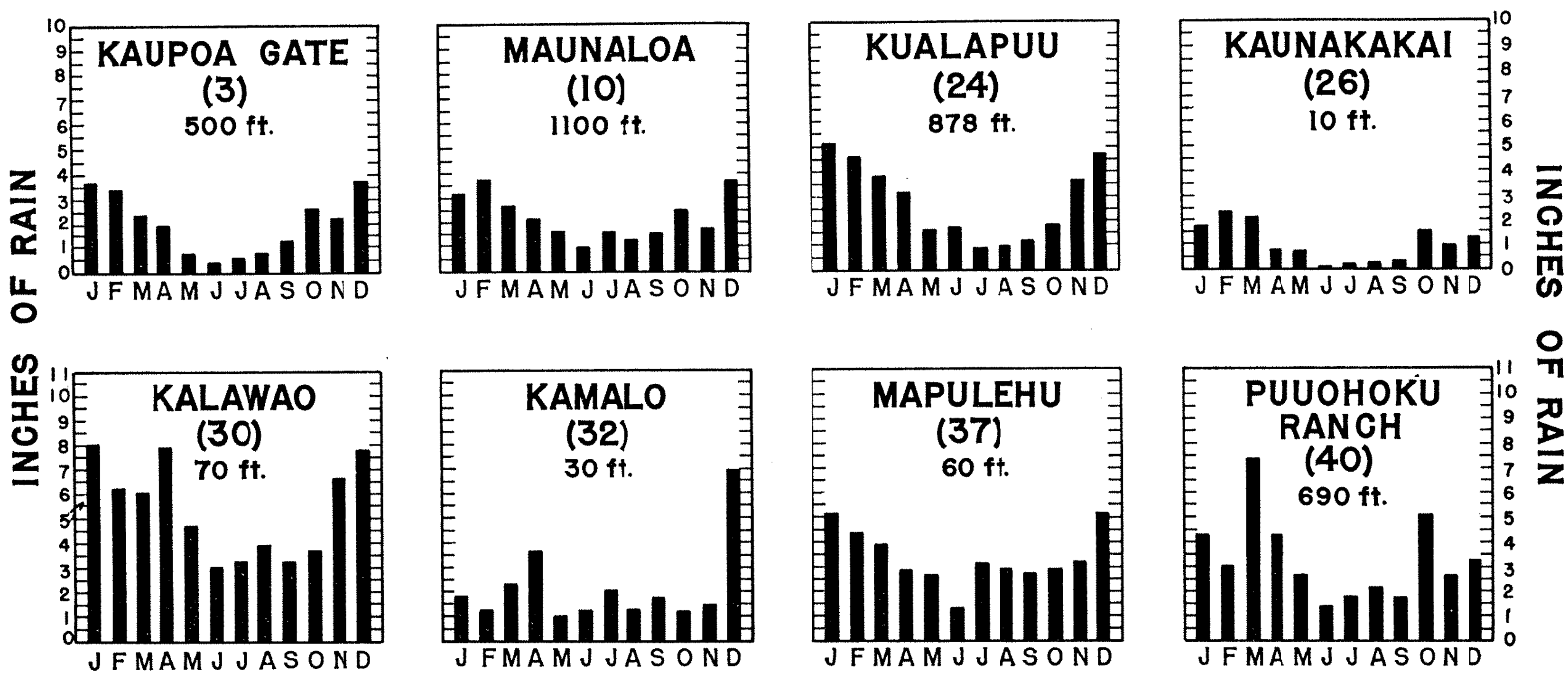


Figure 7. Diagrams illustrating the average monthly distribution of rainfall at eight stations on Molokai. The figures in parentheses are the numbers of the rain gages. The location of each is shown in figure 6.

Mean monthly and annual rainfall at stations on Molokai, through 1944
(Data from U. S. Weather Bureau, plantations, ranches, and Hawaiian Homes Commission)

Station																
No. (fig. 6)	Name	Altitude (feet)	No. Years Record	January	February	March	April	May	June	July	August	September	October	November	December	Annual
1	Kamakaipo	10	8	1.98	2.32	1.26	0.76	0.13	0.44	0.20	0.35	0.69	2.91	1.50	1.33	13.87
2	Kepuhi	40	10	2.75	0.48	1.90	1.21	0.41	0.10	0.31	0.11	0.41	2.94	1.34	1.28	13.24
3	Kaupoa Gate[a]	500	18	3.84	3.27	2.72	1.73	0.93	0.56	0.52	0.75	1.11	2.61	2.28	3.51	23.83
4	Goatskin Gate	450	21	3.25	2.46	2.51	1.67	0.96	0.70	0.89	1.02	1.19	2.66	2.01	3.48	22.80
5	Libby No. 20	580	13	2.76	3.28	2.47	2.14	1.09	0.60	0.63	1.19	1.36	2.46	2.24	4.07	24.29
6	Libby No. 21	645	13	2.74	3.37	2.73	2.67	1.52	1.21	1.33	1.61	2.00	3.29	2.82	4.36	29.65
7	Libby No. 2	680	17	2.94	3.23	2.85	2.26	1.26	0.77	1.09	1.32	1.45	2.53	2.33	4.73	26.76
8	Apalu	450	10	2.87	3.43	2.54	2.27	1.19	0.38	0.60	1.42	0.97	2.75	1.61	2.87	22.90
9	Libby No. 1	1060	17	2.76	3.36	2.63	2.40	1.39	0.58	1.04	0.91	1.51	2.18	2.15	4.48	25.39
10	Maunaloa	1100	20	3.16	3.74	2.69	2.17	1.60	0.97	1.60	1.27	1.54	2.55	1.73	3.73	26.75
11	Manager's House (Maunaloa)	1200	5	4.10	4.19	3.35	2.03	1.75	1.16	0.98	1.13	1.10	5.31	2.31	4.00	31.41
12	Papohaku Gate	545	17	2.53	2.88	2.17	2.18	1.01	0.40	0.80	1.05	0.82	2.14	2.35	3.77	22.10
13	Keonelele Gate	590	7	4.07	0.14	1.80	1.53	0.69	0.00	0.31	0.09	0.50	3.24	1.65	1.45	15.47
14	Libby No. 27	850	10	5.04	3.33	3.97	2.13	1.48	0.80	0.97	0.97	0.72	4.40	2.42	2.80	29.03
15	Mahana	680	10	2.65	2.98	4.04	1.61	0.48	0.54	0.50	0.82	0.58	4.34	1.76	1.80	22.10
16	Kakainapahao	450	4	1.20	3.62	2.94	0.53	0.50	0.27	0.04	0.14	0.51	0.94	1.15	3.18	15.02
17	Maneopapa	550	4	1.29	4.50	3.04	1.37	0.44	1.32	0.15	0.26	0.29	1.50	1.26	3.01	18.43
18	Kapeelua	650	4	1.46	5.09	3.42	1.40	0.83	1.03	0.18	0.13	0.53	0.91	1.72	3.60	20.30
19	Kanaio (C.P.C.)	600	16	2.40	2.64	3.42	1.39	0.90	0.29	0.20	0.38	0.47	2.00	2.00	2.20	18.29
20	Field 501 (C.P.C.)	775	13	3.82	3.87	5.85	4.11	3.15	1.44	1.24	1.56	1.45	3.74	3.17	4.56	37.96
21	Pekeo (C.P.C.)	480	15	2.57	3.43	4.01	1.92	1.14	0.28	0.32	0.59	0.70	2.36	2.49	2.39	22.20
22	Hoolehua	840	18	4.00	4.44	4.55	4.50	2.89	1.61	1.45	1.19	1.05	3.46	4.20	4.52	37.86
23	Hoolehua southeast	560	12	1.88	2.91	3.27	2.65	1.38	0.49	0.54	0.71	0.55	3.51	2.84	2.58	23.31
24	Kualapuu	878	45	5.13	4.67	3.84	3.17	1.59	1.71	0.92	0.94	1.19	1.80	3.63	4.71	32.52
25	Kipu	1250	15	3.52	5.43	5.82	5.70	3.83	1.65	1.59	2.12	1.71	4.65	4.17	5.10	45.29
26	Kaunakakai	10	14	1.71	2.30	2.08	0.69	0.64	0.01	0.13	0.21	0.24	1.54	0.93	1.22	11.70
27	Kalaupapa	50	12	5.78	5.39	8.11	7.40	4.74	2.33	2.23	2.75	2.03	6.11	4.67	6.36	57.90
28	Meyer Lake	2000	2	....	....	....	....	....	....	....	....	....	....	....	....	92.5
29	Poholua	2400	15	3.60	4.74	6.39	5.49	2.36	0.73	1.11	1.78	1.31	3.16	3.26	4.15	38.08
30	Kalawao	70	27	8.04	6.21	6.10	7.89	4.72	3.04	3.29	3.91	3.23	3.65	6.62	7.83	64.53
31	Waikolu	3700	15	6.36	7.58	10.37	5.78	4.33	1.77	2.29	3.30	2.47	4.74	5.73	7.34	62.02
32	Kamalo	30	5	1.80	1.26	2.35	3.67	1.01	1.21	2.06	1.32	1.73	1.24	1.46	6.95	26.06
33	Pelekunu	550	5	....	....	....	....	....	....	....	....	....	....	....	....	93.—[b]
34	Pohakaunoho Ridge	2800	1	....	....	....	....	....	....	....	....	....	....	....	....	90.=
35	Puu Lua	2900	12	....	....	....	....	....	....	....	....	....	....	....	....	148.7[c]
36	Mapulehu mauka	650	5	11.27	8.91	8.02	7.20	8.96	6.62	5.65	9.30	8.72	4.87	4.84	9.73	92.09
37	Mapulehu	60	35	5.17	4.43	3.94	2.87	2.66	1.39	3.11	2.94	2.73	2.89	3.18	5.16	41.47
38	Pukoo	90	6	6.41	4.89	4.05	2.97	3.25	2.58	2.46	4.63	4.08	2.44	2.57	5.91	46.24
39	Halawa	200	4	1.35	2.83	1.49	1.52	0.90	1.03	0.84	0.57	0.92	1.62	2.22	3.89	19.18
40	Puuohoku Ranch	690	10[d]	4.38	3.51	6.73	2.84	3.20	1.74	2.22	2.65	2.22	6.02	3.01	3.72	42.24

[a] Libby No. 22.
[b] Gage read irregularly; overflowed part of time.
[c] Gage read irregularly.
[d] Through June, 1943; record thereafter appears unreliable.

Annual rainfall at stations on Molokai

(Data furnished by U. S. Weather Bureau, plantations, ranches, and Hawaiian Homes Commission)

Station number (fig. 6)	1	2	3	4	5	6	7	8	9	10	11	12
Name	Kamakaipo	Kepuhi	Kaupoa Gate	Goatskin Gate	Libby No. 20	Libby No. 21	Libby No. 2	Apalu	Libby No. 1	Maunaloa	Maunaloa (manager's house)	Papohaku Gate
Altitude (feet)	10	40	500	450	580	645	680	450	1,060	1,100	1,200	545
Year												
1924	.....	.....	.....	21.47	.....	.....	22.29	.....	25.98	.....	.....	19.46
1925	.....	.....	.....	14.34	.....	.....	16.31	.....	15.14	19.46	.....	16.36
1926	.....	.....	.....	13.88	.....	.....	16.09	.....	14.70	17.77	.....	13.60
1927	.....	.....	31.49	32.88	35.55	28.64	35.06	.....	42.99	41.15	.....	36.39
1928	.....	.....	10.36	9.83	13.15	11.09	9.05	.....	12.38	12.63	.....	10.04
1929	.....	.....	30.84	32.82	34.02	30.95	34.49	.....	35.07	.....	.....	30.89
1930	.....	.....	24.89	22.43	26.32	24.20	26.49	21.81	29.86	.....	.....	21.81
1931	.....	.....	9.81	14.59	12.92	10.29	22.70	14.78	21.87	.....	.....	14.78
1932	.....	.....	16.65	23.72	19.98	14.45	25.15	17.78	21.04	23.92	.....	17.78
1933	.....	.....	27.51	16.22	21.56	17.65	25.74	19.54	24.70	22.92	23.00	19.53
1934	.....	13.22	26.66	23.06	23.30	19.76	29.81	16.55	27.76	.....	27.96	16.55
1935	.....	6.41	22.25	18.59	18.31	16.08	27.15	16.79	21.95	24.24	25.06	15.08
1936	17.12	12.51	32.66	25.05	22.82	20.13	35.11	22.68	26.78	32.25	39.65	22.72
1937	25.15	11.37	38.95	26.32	27.85	26.69	34.64	34.04	29.76	37.23	41.41	34.04
1938	9.60	8.45	26.64	27.05	24.60	22.13	36.48	27.31	23.73	30.30	.....	27.31
1939	21.65	21.15	28.57	25.97	25.40	38.24	32.19	35.32	32.44	33.21	.....	35.32
1940	12.20	12.78	21.29	22.68	.....	.....	.....	.....	.....	28.86	.....	.....
1941	2.75	6.16	5.22	10.48	.....	.....	.....	.....	.....	13.49	.....	.....
1942	17.28	24.20	25.64	32.81	.....	.....	.....	.....	.....	40.58	.....	.....
1943	5.20	16.50	20.25	21.91	.....	.....	.....	.....	.....	27.51	.....	.....
1944	.....	.....	22.04	23.18	.....	.....	.....	.....	.....	27.88	.....	.....

Annual rainfall at stations on Molokai (continued)

Sta. No. (fig. 6)	13	14	15	16	17	18	19	20	21	22	23
	Keonelele Gate	Libby No. 27	Mahana	(Howell No. 26)	(Howell No. 23)	Kapeelua	Kanaio	Field 501 (C.P.C.)	Pekeo	Hoolehua	Hoolehua southeast
(Alt. (feet)	590	850	680	450	550	650	600	775	480	840	560
Year											
1929	....	....	....	....	....	....	....	....	....	47.07	....
1930	....	....	....	....	....	....	....	....	26.69	....	....
1931	....	....	....	....	....	....	11.32	....	15.74	34.47	....
1932	....	....	....	15.70	22.82	23.06	....	....	18.65	31.18	....
1933	....	....	19.60	17.58	16.95	21.67	11.28	32.93	13.53	....	19.54
1934	....	....	15.66	14.27	14.70	19.93	14.48	31.76	17.58	33.94	16.26
1935	....	20.35	23.73	12.54	19.38	16.69	13.94	....	15.96	....	....
1936	....	28.71	31.40	....	....	....	16.03	47.70	20.69	48.75	16.59
1937	14.85	36.77	30.86	....	....	....	26.85	53.81	29.52	47.13	27.95
1938	9.98	28.94	20.79	....	....	....	18.83	55.62	27.33	....	14.89
1939	21.85	30.76	20.52	....	....	....	23.04	47.71	28.55	46.58	29.20
1940	13.62	28.34	20.76	....	....	....	25.37	51.88	30.73	40.51	34.63
1941	7.44	16.29	10.57	....	....	....	6.41	18.70	9.53	26.87	7.67
1942	27.29	37.67	26.07	....	....	....	22.45	44.55	29.35	54.05	....
1943	13.21	25.28	....	....	....	....	19.04	....	22.79	30.18	19.31
1944	....	24.16	19.60	....	....	....	17.58	....	20.29	34.46	19.09

Annual rainfall at stations on Molokai
(continued)

Sta. No. (fig. 6)	24	25	26	27	29	30	31	32	36	37	38	39	40
Name	Kualapuu	Kipu	Kaunakakai	Kalaupapa	Poholua	Kalawao	Waikolu	Kamalo	Mapulehu mauka	Mapulehu	Pukoo	Halawa	Puuohoku Ranch
Alt. (feet)	878	1,250	10	50	2,400	70	3,700	30	650	60	90	200	690
Year													
1892	.....	.....	.....	.....	.....	.....	.....	.....	.....	44.27	.....	.....	.....
1893	.....	.....	.....	.....	.....	.....	.....	.....	.....	43.88	.....	.....	.....
1894	.....	.....	.....	.....	.....	.....	.....	.....	.....	32.28	.....	.....	.....
1895	.....	.....	.....	.....	.....	.....	.....	.....	.....	37.92	.....	.....	.....
1896	.....	.....	.....	.....	.....	.....	.....	.....	.....	33.46	.....	.....	.....
1897	.....	.....	.....	.....	.....	.....	.....	.....	.....	33.92	.....	.....	.....
1898	.....	.....	.....	.....	.....	.....	.....	.....	.....	46.21	.....	.....	.....
1899	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
1900	34.31	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
1901	40.55	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
1902	40.41	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
1903	36.34	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
1904	56.96	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
1905	23.06	.....	.....	.....	.....	64.46	.....	.....	.....	.....	.....	.....	.....
1906	36.06	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
1907	44.45	.....	.....	.....	.....	79.69	.....	.....	100.39	.....	53.03	.....	.....
1908	15.44	.....	.....	.....	.....	33.56	.....	.....	72.99	.....	31.26	.....	.....
1909	30.12	.....	.....	.....	.....	57.24	.....	.....	.....	.....	.....	.....	.....
1910	27.75	.....	.....	.....	.....	59.20	.....	.....	92.70	.....	43.10	.....	.....
1911	28.04	.....	.....	.....	.....	61.59	.....	.....	.....	.....	.....	.....	.....
1912	16.30	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
1913	26.87	.....	.....	.....	.....	55.97	.....	.....	.....	.....	.....	.....	.....
1914	33.46	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
1915	26.00	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
1916	59.32	.....	.....	.....	.....	111.73	.....	.....	.....	.....	.....	.....	.....

Annual rainfall at stations on Molokai
(continued)

Sta. No. (Fig. 6)	24	25	26	27	29	30	31	32	36	37	38	39	40
Name	Kualapuu	Kipu	Kaunakakai	Kalaupapa	Poholua	Kalawao	Waikolu	Kamalo	Mapulehu mauka	Mapulehu	Pukoo	Halawa	Puuohoku Ranch
Alt. (feet)	878	1,250	10	50	2,400	70	3,700	30	650	60	90	200	690
1917	41.52	.....	.....	.....	.....	52.17	.....	.....	.....	.....	.....	.....	.....
1918	44.78	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
1919	19.55	.....	.....	.....	.....	48.77	.....	.....	.....	.....	.....	.....	.....
1920	21.22	.....	.....	.....	.....	43.77	.....	.....	.....	.....	.....	.....	.....
1921	33.49	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
1922	20.00	.....	.....	.....	.....	47.67	.....	.....	.....	.....	.....	.....	.....
1923	.....	.....	.....	.....	.....	93.08	.....	.....	.....	57.18	.....	.....	.....
1924	29.40	.....	.....	.....	.....	.....	.....	27.98	.....	.....	.....	.....	.....
1925	.....	.....	.....	.....	.....	44.92	.....	26.51	.....	.....	.....	.....	.....
1926	.....	.....	.....	.....	.....	35.83	.....	13.11	.....	18.96	.....	.....	.....
1927	.....	.....	.....	.....	.....	102.39	.....	.....	.....	61.29	.....	.....	.....
1928	18.66	.....	.....	.....	.....	46.64	.....	.....	.....	43.02	.....	.....	.....
1929	40.35	.....	.....	.....	.....	77.44	.....	.....	.....	.....	.....	.....	.....
1930	36.04	60.24	.....	.....	29.35	.....	66.41	.....	.....	39.46	.....	.....	.....
1931	26.75	49.46	6.90	.....	34.07	59.03	65.61	.....	.....	.....	.....	22.17	.....
1932	27.72	43.71	8.81	.....	23.70	.....	37.38	.....	.....	.....	.....	17.44	.....
1933	25.72	33.60	13.29	.....	19.02	.....	36.62	.....	.....	36.84	.....	17.75	.....
1934	27.99	46.76	6.38	60.10	18.00	.....	49.57	.....	.....	.....	.....	.....	33.13
1935	24.79	32.07	8.81	44.69	23.27	.....	44.92	.....	.....	.....	.....	.....	40.48
1936	32.62	48.67	11.56	67.75	28.95	.....	52.66	.....	.....	42.19	.....	.....	46.08
1937	40.02	47.41	23.50	74.65	50.44	.....	75.09	.....	.....	64.81	.....	.....	59.30
1938	37.71	74.88	7.26	84.00	60.05	.....	62.12	.....	.....	37.12	.....	.....	39.23
1939	39.00	65.62	20.18	61.04	53.65	.....	78.34	.....	.....	59.79	.....	.....	53.34
1940	39.70	58.56	20.91	56.00	68.79	.....	96.58	.....	.....	48.19	.....	.....	47.42
1941	20.37	46.65	3.31	33.82	34.36	.....	57.44	.....	.....	28.45	.....	.....	38.20
1942	41.14	52.37	13.72	51.58	32.86	.....	47.60	.....	.....	39.53	.....	.....	25.71
1943	31.24	42.06	7.99	29.71	46.95	.....	77.04	.....	.....	46.87	.....	.....	.....
1944	25.95	40.82	11.14	29.75	54.75	.....	85.36	.....	.....	32.62	.....	.....	.....

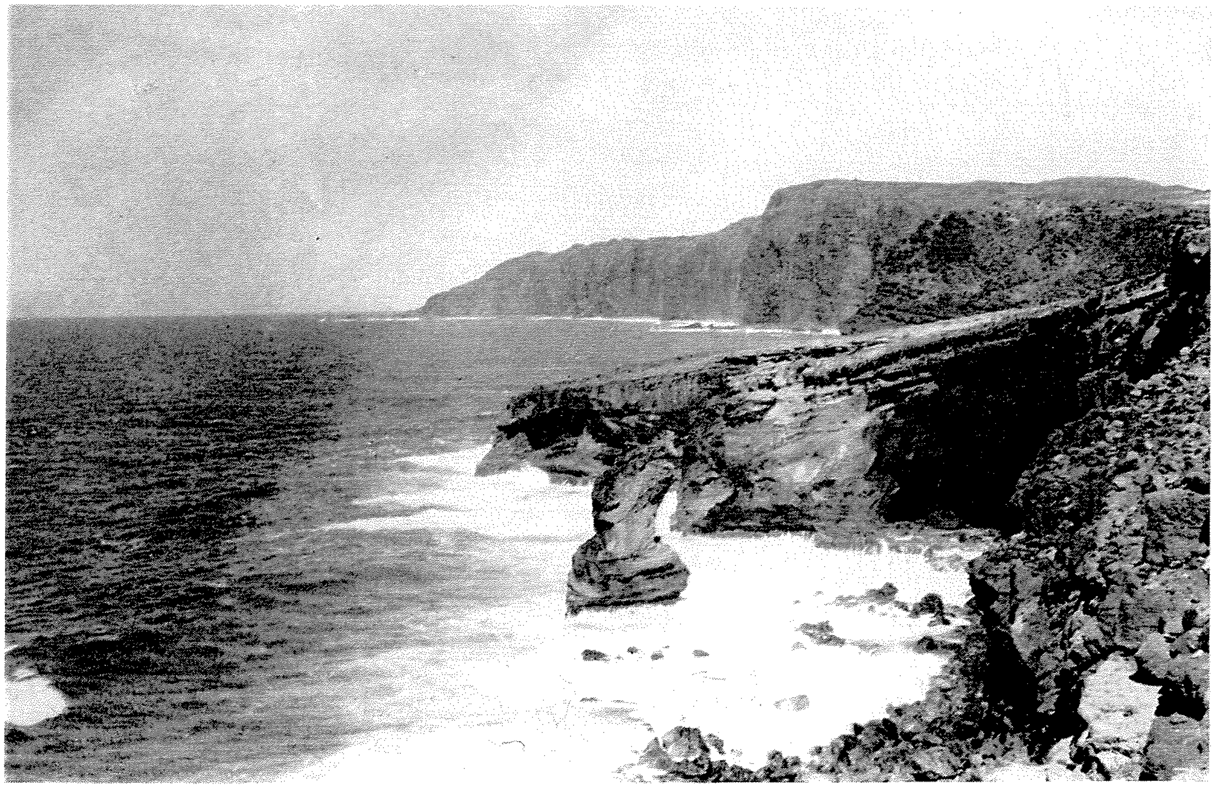
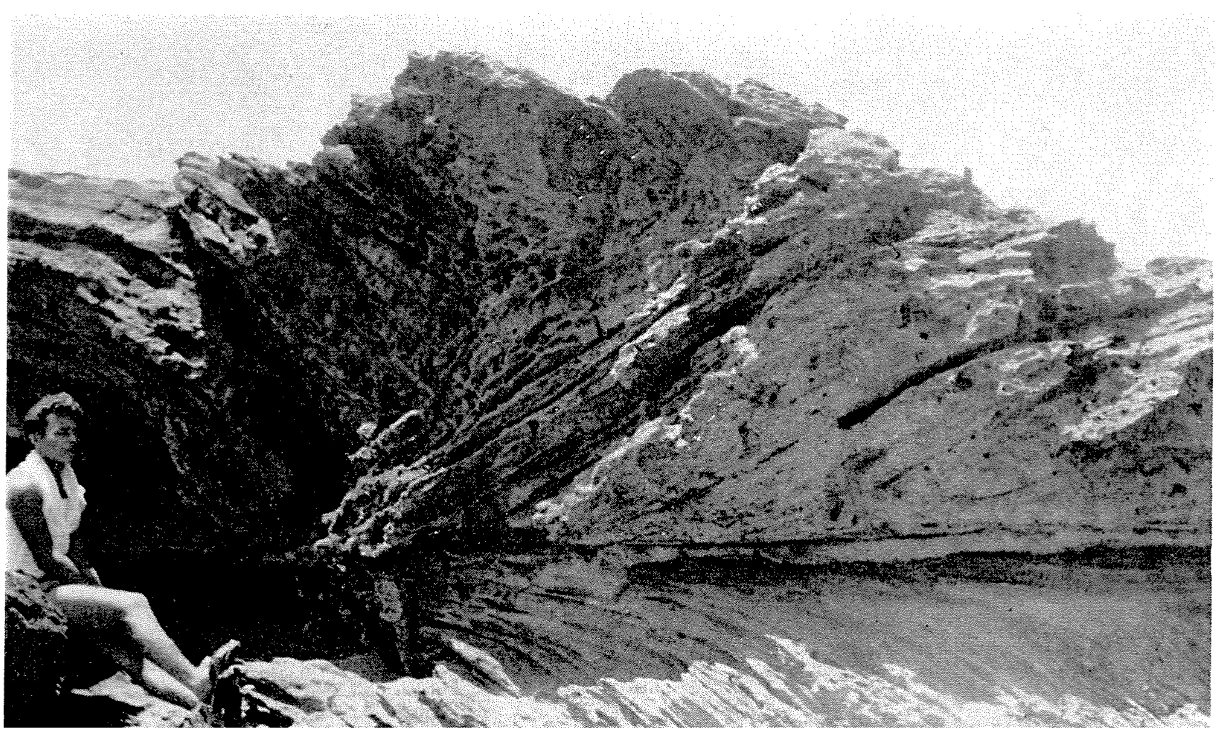


Plate 10A. Lithified sand dunes (foreground) extending below sea level near Ilio Point, West Molokai. The dunes were formed during the Waipio stand of the sea, when sea level was about 60 feet lower than at present. Photo by H. T. Stearns.

Plate 10B. Lithified calcareous sand dunes near Moomomi Beach, showing cross-bedding. Photo by David Rice.



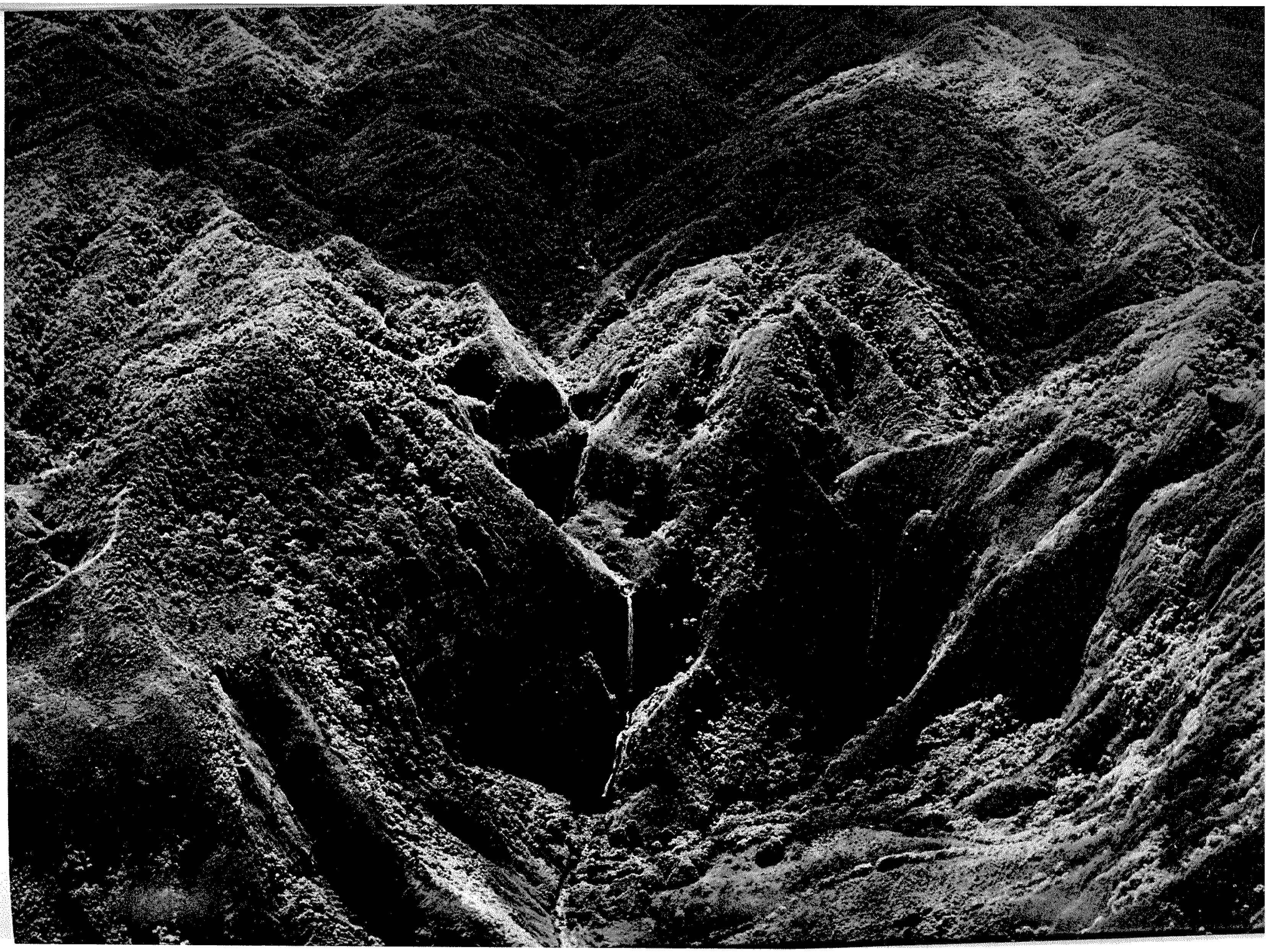


Plate 11. Halawa Valley, East Molokai, a typical amphitheater-headed valley. The amphitheater is carved in weak basalts of the lower member of the East Molokai volcanic series. Above the amphitheater the streams are flowing over the stronger andesites of the upper member of the series. Photo by U. S. Army Air Force.

SURFACE WATER

The only perennial streams which reach the sea are those of the large valleys on the windward side of East Molokai, from Halawa Stream (pl. 11) on the east to Waikolu Stream on the west, and Waialua, Honouliwai, and Honoulimaloo Streams on the southeastern slope. The permanence of the streams on the northern slope results largely from the numerous high-level springs which issue from the dike complex exposed by erosion in the big valleys. Papalaua (pl. 13A) and Halawa Streams, and the streams on the southeastern slope, are fed largely by seepage from the swamps. Other streams reach the sea only at times of exceptionally high water, during and immediately following heavy rains. All of the streams are flashy, because of the steepness and high permeability of the terrane, and the intermittent character of the heavy rainfall. No perennial streams exist on West Molokai.

Several streams on the southern slope of East Molokai are perennial in their upper courses, but during most of the time lose their water by seepage and evaporation long before reaching the coast. Such streams are the forks of Kawela and Kamalo Streams, which are fed by seepage from the swamp areas. Kawela Stream is now generally dry below an altitude of about 2,500 feet, the water reaching the alluvial flats at the mouth of the canyon only during heavy rains, although it is reported that Kawela Stream formerly reached the coastal area much more frequently. Between 2,500 feet altitude and the Molokai Ranch intakes, at about 3,600 feet, the tributaries of Kawela Stream lose heavily by seepage. Even during dry weather the tributaries of Kamalo Stream generally form small waterfalls pouring into the large amphitheater-head of Kamalo Canyon, but the water sinks in the amphitheater leaving the lower 3 miles of the streambed dry. The South Fork of Kaunakakai Stream is permanent as far as the high water fall at about 1,900 feet altitude, being fed in its upper course by seepage from the swamps and in its middle course by a series of small perched springs. On the northern slope, the upper courses of Waihanau and Waileia Streams flow most of the time, the water being supplied by seepage from the swamps, but during ordinary weather the streams sink before reaching the sea. The intermittence of all of these streams in their lower courses, contrasted with their permanence in their upper courses, is largely the result of the streams flowing in their lower courses over the much more permeable basalts of the lower member of the East Molokai volcanic series, after leaving the poorly permeable cap of andesite lava of the upper member.

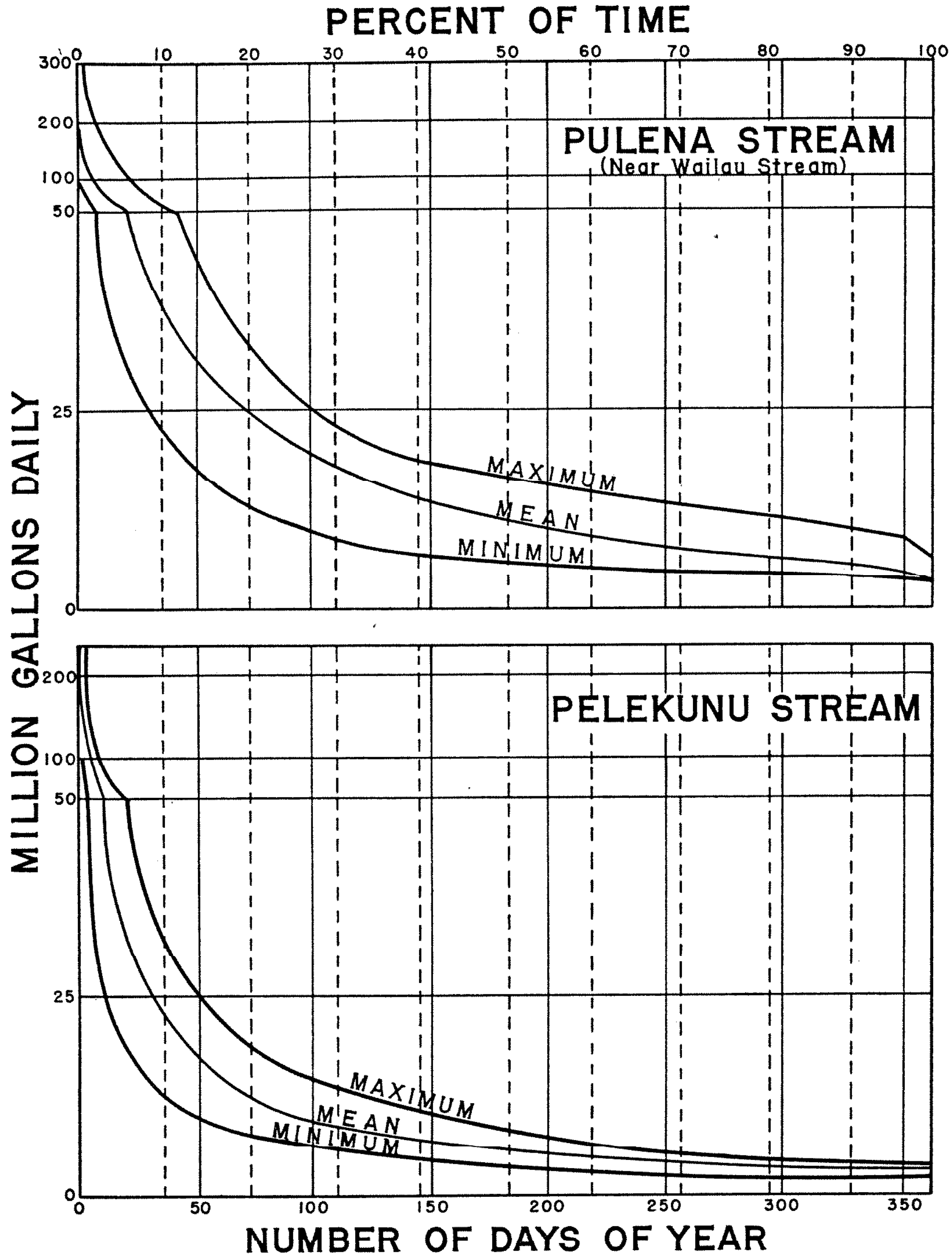


Figure 8. Duration-discharge curves for Pulena Stream near its junction with Wailau Stream, and for Pelekunu Stream, East Molokai. (After M. H. Carson, pl. 64, First Progress Rept., Territorial Plan. Bd., 1939.)

Daily discharges of streams on the island of Molokai are published in the annual Surface Water Supply Papers of the U. S. Geological Survey.[24] A summary of records of stream flow from

[24] U. S. Geol. Survey, Water Supply Papers 485, 515, 516, 535, 555, 575, 595, 615, 635, 655, 675, 695, 710, 725, 740, 755, 770, 795, 815, 835, 865, 885, 905, 935, 965, 985, 1919-1946; no. 795, p. 9, contains a list of the gaging stations and years each was in operation.

1917 to 1938, and a map showing the location of the gaging stations, are contained in a publication of the Territorial Planning Board.[25]

Figure 8 shows duration-discharge curves for Pulena Stream near its junction with Wailau Stream, and for Pelekunu Stream. Figure 9 shows an intensity-frequency curve for Halawa Stream.

MEYER LAKE.—Meyer Lake (pl. 12B) occupies a shallow depression on the andesite lavas of the upper member of the East Molokai volcanic series, at the southeastern foot of Puu Olelo cinder cone, at an altitude of approximately 2,000 feet. It is a perched pond, held at that level by the comparatively impermeable underlying andesite and the surficial soils and weathered rock. The capacity of the natural basin has been somewhat increased by construction of a dam about 6 feet high. The depth of the pond varies by several feet. On October 30, 1929, it was at no point more than 5 feet. The area also varies with the stage, from about 8.4 to 10.3 acres. The pond appears to be fed entirely by surface runoff from the surrounding drainage basin, which has an area of about 100 acres. It has been claimed that the pond is partly fed by submerged springs. Temperature measurements by M. H. Carson on October 30, 1929, at 36 stations over the pond, range from 20.29 to 20.52 degrees Centigrade, a range of only 0.23 degrees. If the pond were fed partly by submerged springs it would be expected that these springs would locally result in areas of colder water, but the measurements show no such cold areas, the range being much less than would be expected if springs existed. On the other hand, it is reported that even during prolonged droughts the pond falls only to a certain stage, and then remains approximately constant

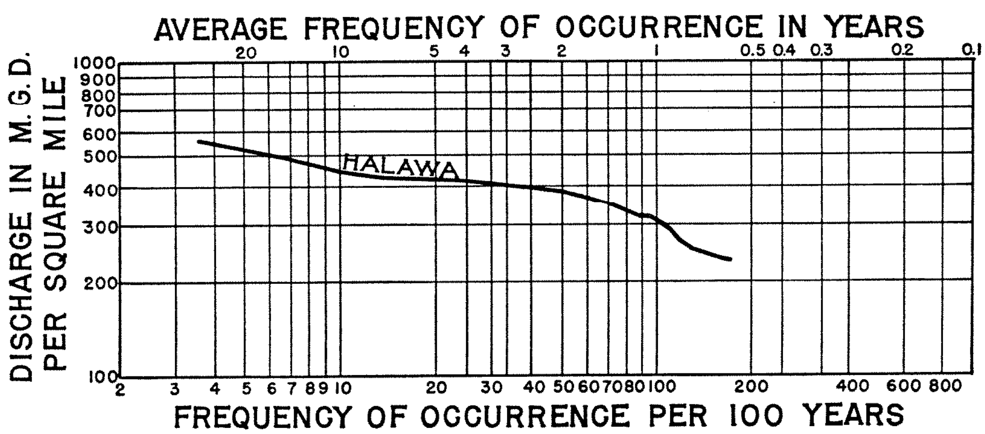


Figure 9. Intensity-frequency curve for Halawa Stream, East Molokai. (After M. H. Carson, pl. 68, First Progress Rept., Territorial Plan. Bd., 1939.)

[25] Surface water resources of the Territory of Hawaii, 1901-1938; First Progress Rept. Hawaii Terr. Plan. Bd., pp. 341-349, Honolulu, 1939.

in volume. This suggests that it is spring fed. It is concluded that Meyer Lake probably is partly fed by small submerged springs and seeps. The spring water probably is perched on beds of poorly permeable ash, as it is at the neighboring Waialala springs and tunnels (no. 4, 5a, 5b) and Waikalae tunnel (no. 6).

It was at one time proposed to increase the capacity of the basin by construction of a higher dam, and use Meyer Lake as a storage reservoir to augment the supply of water to the Hawaiian Homes Commission, or the County of Maui, during periods of low stream flow. The proposal was investigated during 1929, by a Committee appointed by the Territorial legislature, and reported upon unfavorably. Tests appear to indicate that the present pond loses somewhat by seepage into the underlying rocks, although the amount of loss has not been accurately determined. The walls of the basin above present water level would undoubtedly leak more than those below the present water level, and furthermore the increase in head would result in greater leakage below present water level. To be used effectually, the entire basin would have to be sealed with bentonite, or by some other method. A further obstacle to the domestic use of the water is its continuous turbidity, which would necessitate filtration. Turbidity could probably be decreased or even largely eliminated by fencing the drainage areas tributary to the pond to keep out cattle.

DOMESTIC WATER SUPPLIES ON MOLOKAI

Drinking water on the island of Molokai is supplied largely by distribution systems owned and operated by the County of Maui, the Hawaiian Homes Commission, and Molokai Ranch, Ltd. (fig. 10). On Kalaupapa Peninsula the communities of Kalaupapa and Kalawao are supplied by a system owned by the Territorial Board of Hospitals and Settlement. Puuohoku Ranch and the Meyer Estate have their own supply and distribution systems. The camps of California Packing Corporation, and Libby, McNeill, & Libby, are supplied from the Molokai Ranch system. Along parts of the southern coast not served by the County systems, water for domestic purposes is obtained from shallow dug wells.

A tunnel 3,000 feet long leads water for the Hawaiian Homes Commission system from Waihanau Stream, at 2,264 feet altitude, westward through the ridge to the slopes above Hoolehua Plain. The flow of Waihanau Stream for considerable periods exceeds 100,000 gallons daily, but at other times drops as low as 15,000 gallons daily. Present storage facilities of the Hawaiian Homes Commission are insufficient to provide for protracted drought periods.

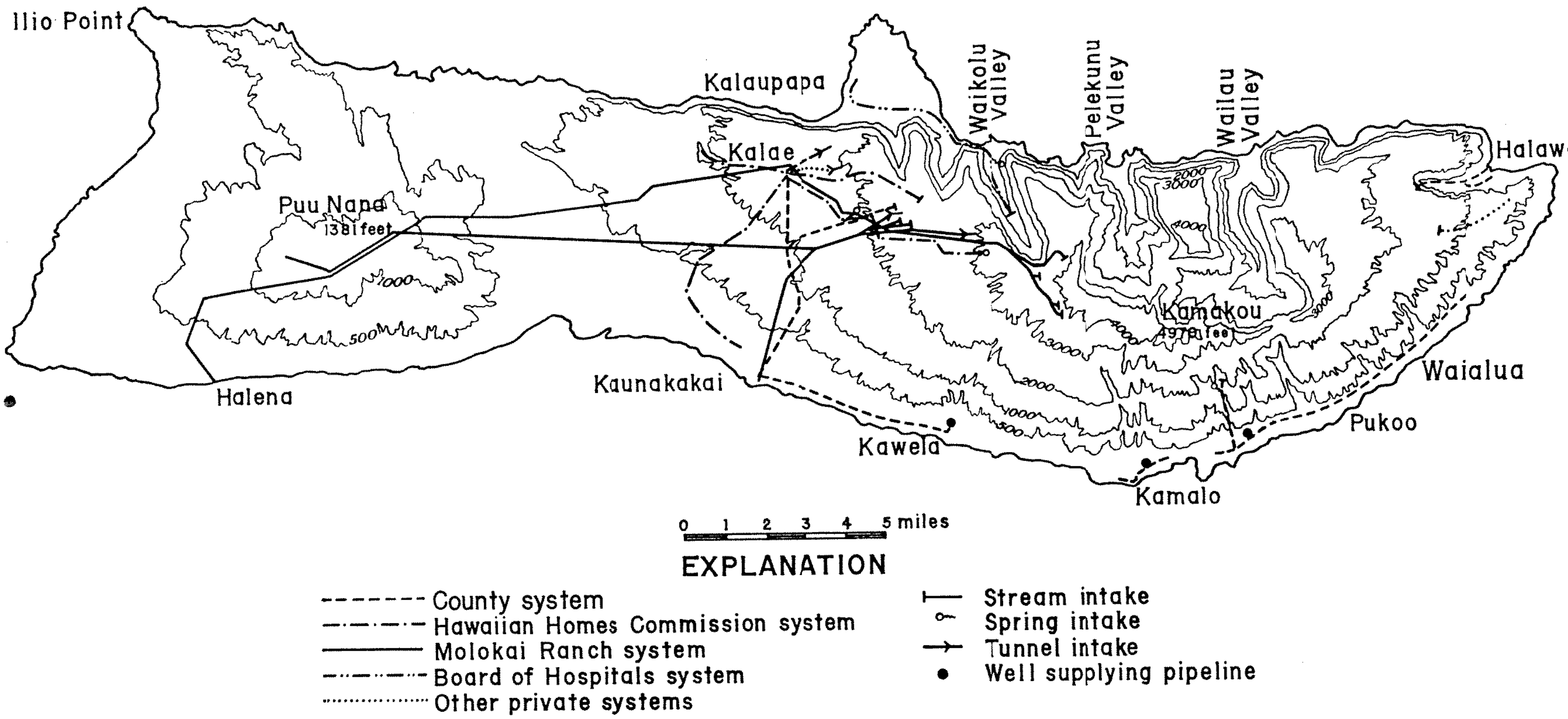


Figure 10. Map of Molokai, showing the main pipe lines supplying domestic water, and the character of the water sources.

The following table shows the principal domestic water systems on the island of Molokai, and the sources from which each derives its water.

Water supplies of towns and villages on Molokai

Community	Approximate population[a]	Approximate daily consumption (gallons)	Distribution system[b]	Source of supply
Maunaloa	979	....	M. R.	Molokai Ranch sources.[c]
Hoolehua	1,050	....	H. H. C.	Waihanau and Kamiloloa Streams, and spring near Kamiloloa intake (page 69).
Palaau	......	....	H. H. C.	
Kalamaula	......	....	H. H. C.	
Molokai airport	......	....	Do.	Do.
Kualapuu	641	....	M. R.	Molokai Ranch sources.[c]
Kaunakakai ...	722	25,000	County No. 1	Waialala Springs, Kapuna Spring, tunnels 4 and 5, and Mokomoko Stream; dug well 30.
			M. R.	Molokai Ranch sources.[c]
Kalae	......	....	County No. 1	Waialala Springs, tunnels 4 and 5.
			H. H. C.	Waihanau and Kamiloloa streams, spring near Kamiloloa intake.
			M. R.	Molokai Ranch sources.[c]
			M. E.	Tunnels 4, 5, and 6.
Kalaupapa .. / Kalawao	447	....	B. H. S.	Waikolu Stream; spring on east wall of Waikolu Valley.
Molokai lighthouse ..	2	....	Do.	Do.
Kawela to Kamalo	40	....	....	Dug wells.
Kamalo	90	4,000	County No. 2	Dug well 42.
Ualapue to Waialua	500	25,000	County No. 3	Maui-type well 6, Kahananui Stream, and spring at 1,230 feet altitude in Kahananui Gulch.[d]
Mapulehu Experiment Sta.	10	1,000	H. S. P. A.	Tunnel 11.
Puuohoku Ranch	......	....	P. R.	Waieli Stream.
Halawa	100	5,000	County No. 4	Halawa Stream.

[a] Figures supplied in part by Molokai Ranch, Ltd., California Packing Corp., Libby, McNeill, and Libby and Puuohoku Ranch; in part estimated from the number of service connections. Population of Kalaupapa and Kalawao from 1940 census.

[b] Abbreviations as follows: M. R.—Molokai Ranch, Ltd.; H. H. C.—Hawaiian Homes Commission; M. E.—Meyer Estate; B. H. S.—Board of Hospitals and Settlement; H. S. P. A.—Hawaiian Sugar Planters Assn.; P. R.—Puuohoku Ranch.

[c] Molokai Ranch sources include East and West Kawela, Kamoku, Ohialele, Luolohi, and Kalihi streams; tunnels 8, 9, and 10.

[d] Previous to June, 1938, part of the water for County system 4 was derived from Ahaino Spring. Earlier, part of the water supply for Waialua came from Waialua Stream.

BASAL GROUND WATER

General features.—Ground water moving downward through the rocks to sea level encounters sea water of greater density and floats upon it, forming a layer of fresh water, known as basal ground water.[26] The water table formed by the top of this body of fresh water rises gently inland, its slope depending on the permeability of the rocks and the amount of downward-percolating water supplied from above, but in general from 2 to 4 feet to the mile. The floating fresh water displaces salt water to an amount inversely proportional to the difference in their specific gravities, and therefore the rise of the water table inland is accompanied by a thickening of the layer of fresh water. This behavior of fresh water resting on the salt water in a permeable rock formation is known as the Ghyben-Herzberg principle.[27] It was first enunciated for the coast of the Netherlands and certain sand islands in the North Sea, but has been found widely applicable to volcanic islands, and has been discussed for the Hawaiian Islands by Lindgren,[28] W. D. and A. C. Alexander,[29] Andrews,[30] Meinzer,[31] Stearns and Vaksvik,[32] and Wentworth.[33] Figure 11 illustrates the manner in which fresh water floats on salt water under an oceanic island. If g is the specific

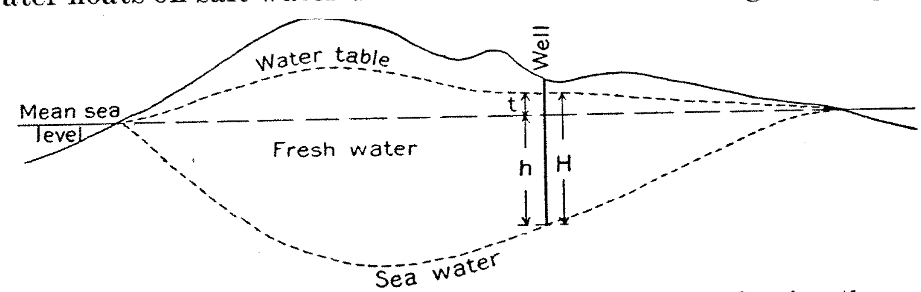


Figure 11. Section of the island of Norderney, Germany, showing the application of the Ghyben-Herzberg principle. (From Herzberg.)

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[26] Meinzer, O. E., Ground water in the Hawaiian Islands: U. S. Geol. Survey Water-Supply Paper 616, p. 10, 1930.

[27] 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, Baurat, Die Wasserversorgung einiger Nordseebader: Jour. Gasbeleuchtung und Wasserversorgung, Jahrg. 44, Munich, 1901.

[28] Lindgren, W., The water resources of Molokai: U. S. Geol. Survey Water-Supply Paper 77, p. 27, 1903.

[29] Alexander, W. D., article in Pacific Commercial Advertiser, Oct. 9, 1908.

[30] Andrews, Carl, The structure of the southeastern portion of Oahu, Hawaiian Islands: Master's thesis submitted to Rose Polytechnic Inst., Terre Haute, Ind., 1909.

[31] Meinzer, O. E., op. cit., pp. 13-41.

[32] 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. 235-239, 1935. Stearns, H. T., Geology and ground-water resources of the islands of Lanai and Kahoolawe, Hawaii: Hawaii Div. of Hydrography, Bull. 6, pp. 76-77, 1940.

[33] Wentworth, C. K., The specific gravity of sea water and the Ghyben-Herzberg ratio at Honolulu: Univ. Hawaii Bull., vol. 18, no. 8, 24 pp., 1939.

gravity of the salt water and the specific gravity of fresh water is 1, then $h = \frac{t}{g - 1}$, where t is the height of the free fresh water surface above sea level and h is the distance to which fresh water extends below sea level.[34] The average specific gravity of sea water off the island of Oahu is 1.0262 at 22° C.[35] Using this value, and assuming the specific gravity of fresh water at 22° C. to be 1, it is found that the length of column h is 38.5 t. Owing to the variability of temperature, the specific gravities of the salt and fresh water, and the increase of specific gravity of ocean water with depth, this value is only approximate, and is commonly expressed as $h = 40t$. That is, for every foot the water table stands above sea level, the base of the fresh water will be approximately 40 feet below sea level.

In actual practice, the thickness of this lens of potable water will be somewhat decreased by admixture of fresh and salt water, producing a zone of brackish water near its base. Where the supply of fresh water is large, and conditions have not been disturbed by pumping, this zone of admixture is probably thin. But where the amount of fresh water added from above is small, and the water is nearly stagnant, diffusion of the salt upward and the small amount of turbulence created by rise and fall of the tide may result in a thick zone of brackish water. Where the rate of recharge of fresh water is very low, the lens may be brackish throughout.

Basal ground water underlies the entire island, with the exception of the rift zones of East Molokai, and possibly those of West Molokai, where ground water is confined at high altitudes by dikes and is probably not in counterpoise with sea water. Beneath West Molokai, the Hoolehua Plain, and the southern shore of East Molokai in the vicinity of Kaunakakai, the rate of addition of fresh water to the basal lens is low, and the lens is entirely brackish. Drilled well 1 (pl. 1), nearly in the center of West Molokai, encountered water nearly as brackish as that produced by shallow wells along the southern coast. Test hole 1 (pl. 1), nearly in the middle of the Hoolehua Plain, encountered brackish water. Beneath most of the rest of the island, the basal water is of good quality.

Along the southern coast of East Molokai a thin capping of poorly permeable sedimentary rocks retards the rate of escape of basal ground water from the much more permeable volcanic rocks. As a result, the basal water table is a little higher than it would be

[34] Brown, J. S., A study of coastal ground water, with special reference to Connecticut: U. S. Geol. Survey Water-Supply Paper 537, pp. 16-17, 1925.
[35] Wentworth, C. K., op. cit., p. 12.

if the sediments were absent. Thus at dug well 30 and test hole 9 (pl. 1), only a quarter of a mile from the shore, the basal water table stands respectively 1.8 and 2.0 feet above sea level. At Mapulehu also, the water level in dug well 56 is reported to be 2 feet above sea level. Accurate measurements of head are lacking in other wells east of Kawela Gulch. In test borings 3 to 8, between Kawela Gulch and Kaunakakai, basal water appears to stand abnormally high, considering their nearness to the shore, presumably because of the confining effect of the fringe of sediments. The heads in these holes are shown in the following table. In spite of the fairly high head, the water in the area west of Kawela Gulch is brackish, because

Test borings on the island of Molokai
(Data from County of Maui and U.S.G.S. files)

No. (pl.1)	Land Division	Altitude (feet)	Depth (feet)	Diameter (inches)	Salinity NaCl (gr. gal.)	Salinity Cl (p.p. m.)	Head (feet above sea-level)	Drilled by
T1	Hoolehua	398	415	1.5	60.1	624[a]	3.9-6.2	U. S. Geological Survey
T2	Kaunakakai	314	324	1.5	2.8	29.1	7.7-8.9	County of Maui[b]
T3	Do.	51.5	55.5	6	12.0	255	2.50	Do.[c]
T4	Do.	15.3	19.3	6	28.0	290	2.35	do.
T5	Kamiloloa	12.2	13.4	6	89.0	925	1.19	do.
T6	Do.	13.8	18.8	6	74.0	770	1.13	do.
T7	Makakupaia	17.0	17.5	6	125.[d]	1,300	1.10	do.
T8	Kawela	6.4	7.4	6	40.0	420	1.22	do.
T9	Do.	10.5	14.0	6	14.0	144	1.96	do.

[a] Average for 1945; ranges from 114 on Sept. 12, 1938, to 652 on May 15, 1945.
[b] In bottom of uncompleted shaft. The high head and low chloride content are probably the result of perched water running down the hole. Small amounts of perched water were encountered at depths of 157 and 174 feet.
[c] Pumping at a rate of 54,000 gallons daily, drawdown was 6 inches.
[d] Pumping at a rate of 55,000 gallons daily, drawdown was unappreciable, and salinity was 113 grains per gallon.

of the low rate of recharge. In test boring 2, at the shaft started to supply water for Kaunakakai but abandoned, the measured head is certainly raised and the salinity lowered by a small amount of fresh perched water entering the small drill-hole at higher altitudes. The head and salinity at test boring 3 are more nearly representative of the basal water in the area just inland from Kaunakakai.

The basal water produced from many of the shallow wells in sedimentary rocks east of Kawela Gulch is brackish, because of the nearness of the wells to the ocean. In others, some of which are equally close to the shore, the water is of better quality, owing to freer connection with the fresh basal water farther inland, more difficult connection with the ocean water, or both. Also, wells dug farther below the water table tend to yield water more brackish than that from wells which penetrate less deeply below the water table.

Basal springs.—Large numbers of basal springs issue along the shores of East Molokai. Many of those along the south shore are shown on plate 1, but many others undoubtedly have escaped observation. All issue close to sea level, within a foot or so above it, or a few feet below it. Those which issue below sea level are difficult to locate, especially when they are small, but the presence of submarine springs is often apparent to swimmers because the escaping ground water has a lower temperature than the shallow near-shore sea water. The numerous fish ponds along the south shore of East Molokai are in themselves evidence of numerous basal springs, as brackish water is necessary to the growth of certain plants on which the mullet feed.

Basal springs undoubtedly are numerous along the north and east shores of East Molokai also, but the rough and precipitous nature of the coast makes them difficult to observe. Very brackish basal springs occur along the shores of West Molokai.

Discharge and salinity measurements are available for only a few of the basal springs. Loiloa Spring, at Pukoo, issues from alluvium near the base of a spur of basalt. The owner, Mr. E. K. Duvauchelle, reports measurements made about 1910 showed the discharge to be approximately 750,000 gallons daily. At low tide on September 22, 1945, the salt content was 18.7 grains per gallon (194 parts per million of chloride). The large pond just east of the mouth of Kawela Gulch is fed by basal springs which issue in the pond. At low tide, on October 15, 1945, the overflow of this pond was estimated to be about half a million gallons daily. The salt content of the water in the pond near one of the springs was 23.5 grains per gallon (244 parts per million of chloride). At Kokokahi, 2.8 miles northwest of Kaunakakai, a spring issues from emerged coral reef of the 5-foot stand of the sea. It issues largely beneath the water of a mangrove swamp, and the discharge is difficult to estimate, but is probably in excess of half a million gallons daily. The water has a salt content of 74.7 grains per gallon (775 parts per million of chloride). A spring discharging into a fishpond 0.7 miles N. 39° W. of Kalaeloa Point is stated to have a flow of 20,000 to 30,000 gallons daily. Its salt content at low tide on October 15, 1945, was 14.9 grains per gallon (115 parts per million of chloride). A spring 0.2 mile farther east, at the head of Keawanui fishpond, was discharging on the same day about 70,000 gallons daily at low tide, with a salt content of 7.9 grains per gallon (82 parts per million of chloride).

WELLS.—A great number of shallow wells have been dug along the southern coast of Molokai. All of these produce water from the basal zone of saturation. Most of them obtain their water from the sedimentary rocks, but some penetrate the sedimentary cap and produce from the underlying volcanic rocks. The table on page 58 lists 61 dug wells now in use, or abandoned wells on which information is available, with their depth and salinity. The locations of the wells are shown on plate 1. Many other dug wells have been abandoned, and no data on them is now extant. The position of a few of these is shown on plate 1.

Nine of the wells on Molokai are of the Maui type.[36] These consist of a shaft sunk to, or slightly below, the basal water table, and one or more infiltration tunnels extending outward from the shaft to skim fresh water from the top of the basal zone of saturation. Data on these Maui-type wells are given in the table on page 60. All of them have vertical shafts. In 1938 construction of a Maui-type well was started by the W. P. A. for the County of Maui, at an altitude of 314 feet in Kaunakakai Gulch, on the advice of H. T. Stearns, to supply water for Kaunakakai. However work was terminated when the shaft was only about 40 feet deep because W. P. A. lacked equipment to complete the work. It was entirely in coarse bouldery alluvium. The Kanoa, Conant-Kawela, and Breadfruit-tree wells were dug for the American Sugar Co., under the supervision of Mr. E. E. Conant, in 1920 and 1921. The Conant-Kawela well (Maui-type well No. 4, pl. 1), has two tunnels, the eastern one 37 feet long and the western one 192 feet long. It is reported that water was encountered which entered the tunnel at too high a rate for the pumps to handle, necessitating the abandonment of the excavating equipment in the tunnel. Pumping at a rate of 3 million gallons daily lowered the water level only one foot. The County of Maui is now cleaning out this well for use as part of the water supply for Kaunakakai.

[36] Stearns, H. T., and Vaksvik, K. N., Geology and ground-water resources of the island of Oahu, Hawaii: Hawaii Div. Hydrography, Bull. 1, p. 324, 1935.

Dug wells on Molokai

No. (pl. 1)	Land Division	Approximate altitude (feet)	Depth (feet)	Salinity[a] NaCl (gr. gal.)	Salinity[a] Cl. (p.p.m.)	Use	Remarks
1	Kaluakoi	8	10	150	1,558	Abandoned	[b]
2	Do.	10	30	[c]	[c]	Do.	[b]
3	do.	35	40	403	4,187	do.	[b]
4	do.	8	11	182	1,890	Stock	Halena well
5	do.	29	31	466	4.840	Stock	Moomomi well
6	do.	7	9	212	2,200	Stock	Kolo well
7	do.	11	15	202	2,100	Stock	Waiakane well
8	do.	3	6	233	2,420	Stock	Kukuku well
9	do.	8	9	156	1,620	Stock	Punakou well
10	Iloli	1	6	95.6	993	Stock	Iloli well
11	Kaluakoi	23	25	770	799	Stock	Puu Pili well
12	Naiwa	6	7	58.8	610	Stock	Palaau well
13	Do.	2	4	89.8	932	Stock	Ooia well
14	do.	15	16	61.5	639	Stock	Oliwai well
15	Kalamaula	5	15	54.9	570	Unused	Kalamaula well
16	Kaunakakai	18	20±	74.0	769	Abandoned	[b]
17	Do.	8	11	115	1,190	Irrigation	Hotel well
18	Kapaakea	10	14	68.4	710	Unused	Head 1± foot
19	Do.	[d]2.1	3.56	93.0	970	Unused	Head 1.24 feet
20	do.	2	3	65.3	678	Stock	
21	Kamiloloa (Govt.)	2	4.5	58.8	610	Irrigation	
22	Do.	[d]18.0	18.7	60.0	620	Stock	Head 1.25 feet
23	do.	[d]8.2	8.4	73.0	760	Irrigation	Head 1.17 feet
24	Kamiloloa	[d]9±	9.8	106	1,100	Unused	
25	Do.	[d]10.3	11.0	94.0	980	Stock	Head 1.17 feet
26	do.	[d]13.5	13.9	279	2,900	Abandoned	Head 1.16 feet
27	Makakupaia	[d]11.8	12.6	116	1,210	Stock	Head 1.14 feet
28	Kawela	[d]13.9	14.6	22.0	230	Stock	Kaokini well; head 1.39 feet
29	do.	9	10	22.4	232	Stock	
30	do.	17.1	19.0	3.3	34	Domestic	Head 1.77 feet
31	do.	14	15	3.1	32	Domestic and irrigation	
32	Makolelau	8	10	51.5	535	Irrigation and stock	
33	do.	17	18	38.6	400	Stock	
34	do.	4	5	40.5	420	Stock	
35	Kapuokoolau	12	14	42.9	445	Irrigation	
36	Do.	11	15	29.8	310	Stock	
37	Kamalo	7	7	42.9	440	Stock	
38	Do.	19	20.5	7.9	82	Irrigation and stock	
39	do.	27	27	8.9	92	Stock	
40	do.	19	21	22.2	230	Irrigation	
41	do.	17	18	6.6	68	Irrigation	
42	Wawaia	41	41.5	7.5	78	Domestic	County Kamalo well[e]
43	Puaahala	16	19	58.8	610	Irrigation	
44	Do.	8	8	4.5	47	Domestic and irrigation	
45	Kaamola	6	6.5	7.9	82	Domestic and stock	

Dug wells on Molokai—(continued)

No. (pl. 1)	Land Division	Approximate altitude (feet)	Depth (feet)	Salinity[a] NaCl (gr. gal.)	Salinity[a] Cl. (p.p. m.)	Use	Remarks
46	Keawanui	19	20	5.0	52	Domestic and irrigation	
47	West Ohia	15	16	3.1	32	Irrigation	Goes dry on pumping
48	Manawai	23	27	6.7	70	Irrigation	
49	Ualapue	4	6	20.0	208	Irrigation	
50	Do.	8	11	18.8	195	Irrigation	
51	Kaluaaha	23	23.5	14.9	155	Do.	
52	Do.	20	22	14.3	148	do.	
53	do.	19	22	11.7	122	Irrigation	
54	do.	22	23	15.4	160	Do.	
55	Mapulehu	5	11.5	12.6	131	Irrigation	
56	Kainalu	20	20	4.2	44	Stock	
57	Waialua	7	8	29.8	310	Irrigation	
58A	Kapulei	14	16	2.4	25	Domestic	
58B	do.	15	17	2.1	22	do.	
59	do.	15	16	2.2	23	do.	
60	do.	12	16	3.3	34	Irrigation	

[a] Except where otherwise indicated, salt determinations are by S. Wong, Hawaii Div. of Hydrography.
[b] Reported by W. Lindgren, U. S. Geol. Survey, W. S. P. 77, pp. 37-47, 1903.
[c] Too salty to use.
[d] Data from County of Maui. Salt determinations by L. T. Bryson, Honolulu Board of Water Supply.
[e] For water levels, see figure 12.

Systematic water-level measurements have been made by Mr. Herbert Wilson, of the County of Maui, at Maui-type wells 1 (Conant-Kaunakakai) and 6 (Ualapue), and dug well 42 (County Kamalo well), since 1938. The records have been published in the annual water level reports of the U. S. Geological Survey.[37] Graphs of the water-table fluctuation in these three wells are shown in figures 12 and 13.

Several wells were drilled for the American Sugar Co., during the years 1900 to 1902. All were abandoned because of the high salinity of the water. The positions of the wells are shown on plate 1, and in figure 14. Information on the wells is listed in the table on page 64. The information on these long-abandoned wells is from the report by Lindgren.[38] A well is reported to have been drilled by

[37] U. S. Geol. Survey, Water Supply Papers 845, pp. 62-63, 1939; 886, p. 87, 1940; 911, p. 144, 1941; 941, p. 177, 1943; 991, pp. 194-195, 1945.
[38] Lindgren, W., The water resources of Molokai, Hawaiian Islands: U. S. Geol. Survey, Water Supply Paper 77, pp. 37-47, 1903.

Maui-type wells on the island of Molokai

No. (pl. 1)	Name	Land Division	Altitude of shaft collar (feet)	Depth of shaft (feet)	Number of tunnels	Length of tunnels (feet)	Salinity		Head (feet)	Owner	Use
							NaCl (gr. gal.)	Cl (p.p.m.)			
1	Conant-Kaunakakai	Kaunakakai	28±	27.3	1	50	50.0	520	1.25-2.00	Molokai Ranch	Unused
2	John Kupa	Do.	27.8	28.1	2	20	60.7	630	2.34	do.	Irrigation
3	Kanoa	Kawela	40±	41.0	2	....	12.7[a]	132	1.7	do.	Irrigation and domestic
4	Conant-Kawela	Do.	34.0	37.0	2	229	1.5	16	1.8	do.	Unused[b]
5	Breadfruit-tree	do.	30±	34.0	....	....	2.5	26	1.8	do.	Irrigation[c]
6	Ualapue	Ualapue	43±	41.5	2	214	6.2	64	4.08-4.67	County of Maui	Domestic
7	....	Mapulehu	50±	50.	2	90±	6.5	67	....	H.S.P.A.	Unused[d]
8	....	Do.	20±	22.5	2	35±	3.7	38	2.0	Do.	Irrigation
9	....	Punaula	30±	32.	2	100	2.0	21	....	do.	Do.

[a] Pumped for 4 weeks at a rate of 1.5 million gallons daily during 1920, with a drawdown of 18 inches. Salt content was stated to be 17 grains per gallon at the beginning of the test, increasing to 22 grains during the second day and remaining at that figure for the balance of the test. Data from unpublished diary of E. E. Conant.

[b] Reported by Mr. Conant (op. cit.) to have been pumped at a rate of 3 million gallons daily, with one foot drawdown. The tunnel running west from the shaft is 192 feet long, and yields most of the water. The eastern tunnel is 37 feet long. Mr. D. C. Derby, of Libby, McNeill, and Libby, reports that pumping at the rate of 1.5 million gallons daily for about a month, in December 1946 and January 1947, resulted in an increase of salt content to 29 grains per gallon.

[c] Stated by Mr. Conant (op. cit.) to have developed more than 650,000 gallons of water daily.

[d] Went dry on pumping.

McCandless Brothers near Kamalo, for the Hawaiian Government, in 1883.[39] Its location is no longer known. The water is said to have been salty, and the well was probably drilled too deep.

Drilled well 1, on the northwestern slope of West Molokai, was drilled for Libby, McNeill, & Libby during 1945. Basal water with a temperature of 93° F. was encountered 5.6 feet above sea level. With the bottom of the hole 12 feet below sea level, the salt content of the water was 196 grains per gallon (2,040 p.p.m. of chloride). Upon deepening the hole to 32 feet below sea level, the salt content increased to 279 grains per gallon (2,900 p.p.m. of chloride). A partial chemical analysis of the water is given in the table on page 78. The temperature of the water is much higher than the normal temperature (70°-85° F.) of ground water in the Hawaiian Islands. The high temperature is tentatively attributed to heating by hot volcanic emanations from greater depths.

Drilled well 15, at Kualapuu on the western slope of East Molokai, was drilled for the California Packing Corporation during February, 1946. Basal water was encountered 10.5 feet above sea level, with a salinity of 95 grains of NaCl per gallon (987 p.p.m. of Cl). The head is a little higher than would normally be expected at that distance (2.2 miles) from the sea. The lateral movement of the basal water is probably impeded by poorly permeable rock, possibly dikes, as the locality lies on the westerly projection of the dike complex exposed in Waikolu Valley. The rate of recharge is too low to keep the basal water fresh. The salinity undoubtedly results partly from diffusion upward from the salt water beneath, but probably also partly from carrying downward during rains of salt deposited by spray on the soil and vegetation. During October 1946 a pump was installed. Pumping at a rate of 200 gallons a minute, with a drawdown of five feet, resulted over three weeks time in a gradual lessening of the salt content to 36 grains per gallon. It is believed that removal of brackish water by pumping caused the inflow of fresher water from the regions of higher rainfall nearer the top of East Molokai Mountain.

Test boring 1 (T 1, pl. 1), 1.5 inches in diameter, was drilled with a diamond drill for the U. S. Geological Survey by J. M. Heizer, during 1938, on the Hoolehua Plain near Molokai airport. Data are given in the table on page 55. Systematic head and salinity measurements have been made at this hole since 1938, by Mitchell Pauole and Solomon Hanakeawe, of the Hawaiian Homes Commission, and

[39] McCandless, J. S., Development of artesian well water in the Hawaiian Islands, p. 68. Honolulu, 1936.

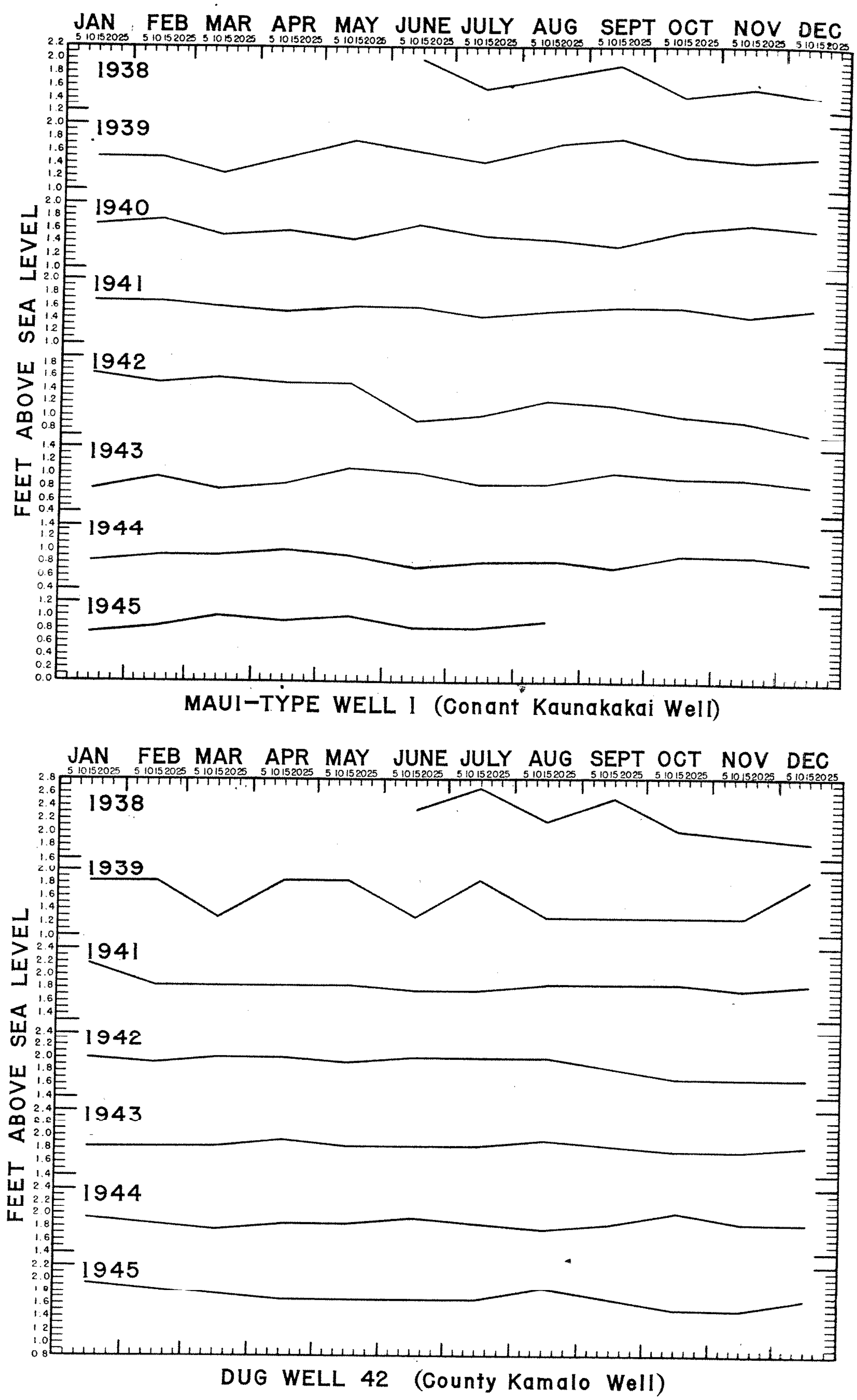
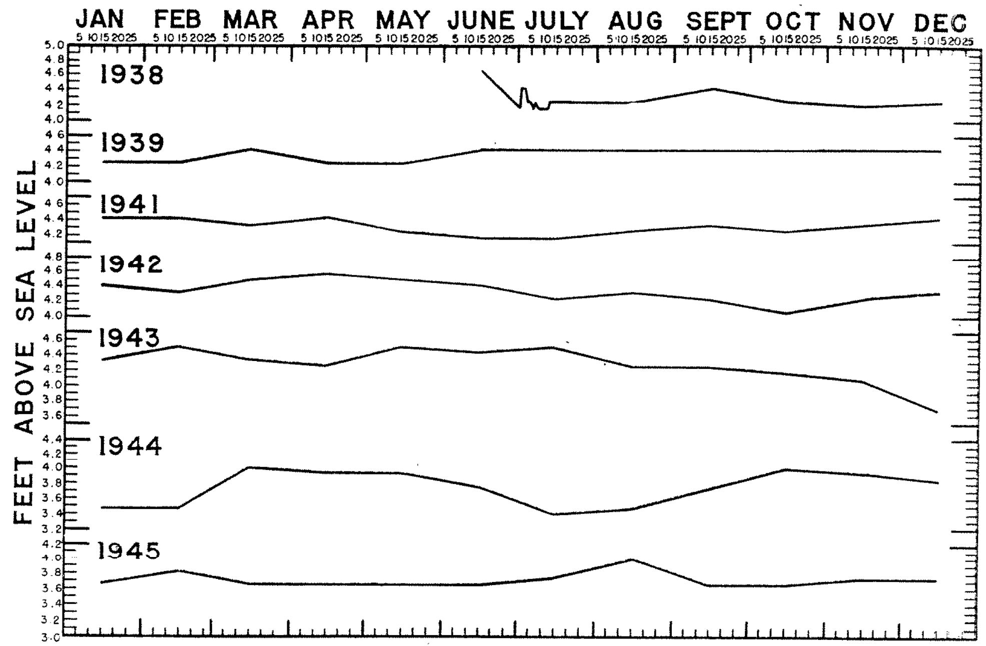
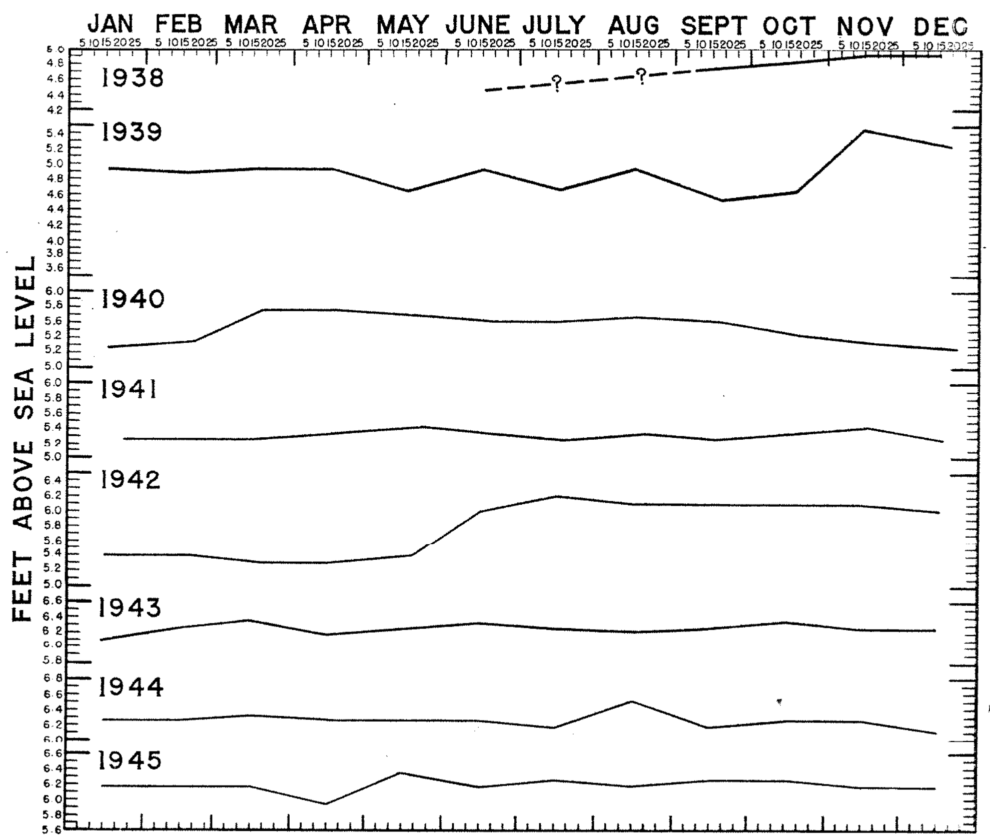


Figure 12. Graph showing the fluctuation of water level in Maui-type well 1 (Conant-Kaunakakai well) and dug well 42 (County Kamalo well), from 1938 to 1945.



MAUI-TYPE WELL 6 (County Ualapue Well)



TEST BORING I (Near Airport)

Figure 13. Graph showing the fluctuation of water level in Maui-type well 6 (County Ualapue well) and test boring 1, from 1938 to 1945.

Drilled wells on the island of Molokai[a]

No. (pl. 1)	Land Division	Altitude (feet)	Depth (feet)	Diameter (inches)	Salinity NaCl (gr. gal.)	Salinity Cl (p.p.m.)	Use	Remarks
1	Kaluakoi	503	540	6	279.[b]	2,900	?	Head 5.65 feet; water warm (93° F.)
2	Hoolehua	125	140	12	102.	1,060	Abandoned	
3	Naiwa	22	74	12	86.0	893	Do.	
4	Do.	23	73	12	86.0	893	do.	
5	do.	22	250	....	......[c]	......	do.	
6	do.	50	125	....	......[c]	......	do.	
7	do.	37	70	12	90.0	935	do.	
8	Kalamaula	20	60	12	102.0	1,060	do.	
9	Do.	27	343	12	......[c]	......	do.	
10A	Kaunakakai	22	60	12	86-96	893-997	do.	Canefield well.
10B	Do.	22	75	12	......[d]	......	do.	do.
10C	do.	25	60	12	50-86	520-893	do.	Settlement well.
10D-L	do.	31±	60	12	20-40	208-415	do.	
10M	do.	34±	75	12	11.5[e]	119	do.	Donkey Engine well.
10N	do.	35	500	12	......[c]	......	do.	Deep well.
11A	do.	50	60	12	74.0	769	do.	
11B	do.	60	60	12	74.0	769	do.	
11C	do.	63	63	12	74.0	769	do.	
12	Kapaakea	28	60	12	70.0	727	do.	Battery of 20 wells, 40 feet apart, in 3 rows. Head 1 foot above sea level.

13A	Kawela	12	46	14	15.0[f]	156	do.	Head 1¼ feet.
13B	do.	12	50	14	18.0[g]	187	do.	Head 2 feet.
13C	do.	11	56	14	19.0[h]	197	do.	Head 2¼ ft.
13D	do.	20	.....	14	25-35	260-364	do.	
14A	do.	17	58	14	......	......	do.	[j]
14B	do.	12	75	14	35.0	364	do.	Head 2½ feet.
14C	do.	18±	60	14	25.0[k]	260	do.	
14D	do.	...	59	14	......	......	do.	
14E	do.	...	58	14	......	......	do.	
15	Naiwa	888.5	963	18	36.0	374	Domestic	Head 10 feet.

[a] Data for wells 2 to 14 from Lindgren, W., U. S. Geol. Survey, Water Supply Paper 77, pp. 38-47, 1903.

[b] With the hole at a depth of 517 feet, salinity was 196 grains per gallon (2,040 parts per million of chloride).

[c] Reported to be close to sea water.

[d] Greater than 100 grains per gallon.

[e] On pumping 4 days, at a rate of 500,000 to 750,000 gallons daily, salinity increased to 83 grains per gallon.

[f] Increased to 25 grains per gallon after pumping 12 hours at a rate of 1 million gallons daily; and to 37 grains after pumping 3 weeks at a rate of 1¼ million gallons daily.

[g] Increased to 25 grains per gallon after pumping 12 hours at a rate of 1 million gallons daily.

[h] Increased to 64 grains per gallon after pumping 30 days at a rate of 2½ million gallons daily.

[j] A pit and two short tunnels were opened at this site, the bore hole being within the pit, and pumped at rates up to 4 million gallons daily. Water from the tunnels contained about 50 grains of salt per gallon, and that from the bore hole 200 to 400 grains. Water came about equally from the tunnels and bore hole. See Lindgren, op. cit., pp. 45-46.

[k] Increased to 31 grains per gallon, after pumping intermittently for 7 days at rates of 500,000 to 850,000 gallons daily.

published annually in water level reports of the U. S. Geological Survey.[40] Fluctuations of the water table are shown graphically in figure 13.

Test boring 2 (T 2, pl. 1), of the same diameter, was drilled at the uncompleted shaft in Kaunakakai Gulch for the County of Maui during 1939, by J. M. Heizer. Small amounts of perched water entered the hole at altitudes of 157 and 140 feet above sea level. The head of the basal water measured in the hole ranged from 7.7 to 8.9 feet above sea level, and the salt content was 2.8 grains (29.1 parts per million of chloride). The head is abnormally high and the salinity abnormally low for this area, undoubtedly because of the perched water entering the hole at higher altitudes, building up the head in the hole, and diluting the basal water.

Test Borings 3 to 9 (T3-T9, pl. 1) were drilled during 1945 for the County of Maui, by W. M. Mullin, as part of an investigation of

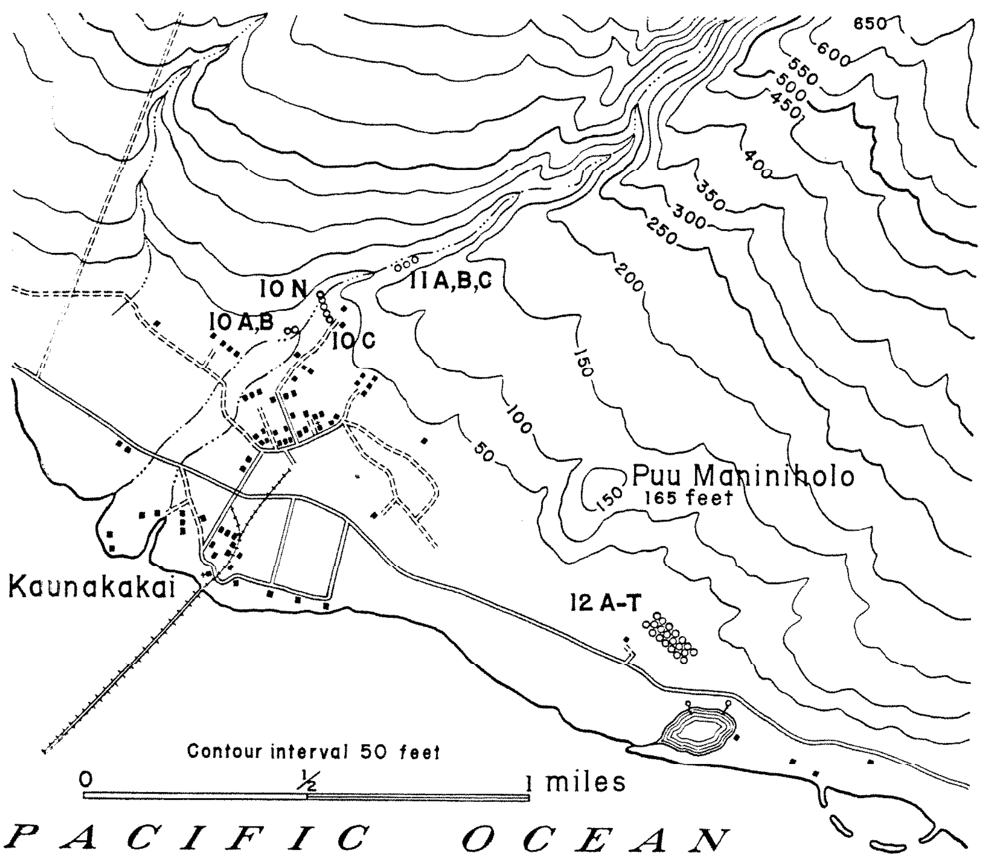


Figure 14. Map of Kaunakakai and vicinity, showing the positions of abandoned drilled wells. Twelve wells lie on the line between well 10C (Settlement Well) and well 10N (Deep Well), spaced too closely to be shown on the map. Wells 12A to T were the so-called Risdon Wells.

[40] U. S. Geol. Survey, Water Supply Papers, op. cit.

means for developing a new source of water for Kaunakakai.[41] Data on conditions at these holes are shown in the table on page 55. The head and salinity at test boring 3 are believed to be much more nearly representative of ground water conditions in the area just inland from Kaunakakai, than are those at test boring 2.

PERCHED GROUND WATER

GENERAL FEATURES.—Water percolating downward through the permeable lavas may encounter less permeable layers and be temporarily perched by them. These less permeable layers may be denser lava beds, decomposed aa clinker, or soil, but most are layers of palagonitized ash. Such ash layers, from several inches to 2 feet in thickness, are intercalated in the lavas of both the upper and lower members of the East Molokai volcanic series. The efficacy of these ash layers to perch water depends on their thickness, extent, grain size, and degree of decomposition. In dry areas, the ash layers are generally sufficiently permeable to allow the small amount of water reaching them to pass on through, and descend to the basal ground water body. In wet areas, permeability is insufficient to allow all of the larger amount of water reaching the ash beds to pass through and some of the water consequently runs off along the top of the bed, in the direction of steepest slope.

PERCHED SPRINGS.—Several perched springs issue from andesites of the upper member of the East Molokai volcanic series on the western slope of East Molokai. They are perched by poorly permeable ash beds. The two springs 0.4 mile southwest, and another 0.5 mile south of Puu Lua (pl. 1), flow only during wet weather. When they were visited during October 1945, all were entirely dry. Waiauni Spring, 1 mile S. 37° E. of Kalae, discharges about 1,000 gallons daily in wet weather, but was dry during October 1945. Two small springs, which lie nearly between tunnels 4 and 5, at Waialala, are reported never to dry up. The water from them is collected, together with the tunnel water, to supply part of the County water system.

Kapuna Spring, situated at 1,900 feet altitude in the bed of Kapuna Stream, is one of the sources of the County water system. The water issues from alluvium resting on a dense bed of andesite, but is probably supplied by leakage from the andesite beneath the alluvium in the lower walls of the valley. The perching structure in the andesite series is probably an ash bed, for although none is exposed at the spring, one is visible at about the same stratigraphic

[41] Wentworth, C. K., unpublished report to County of Maui, 1945.

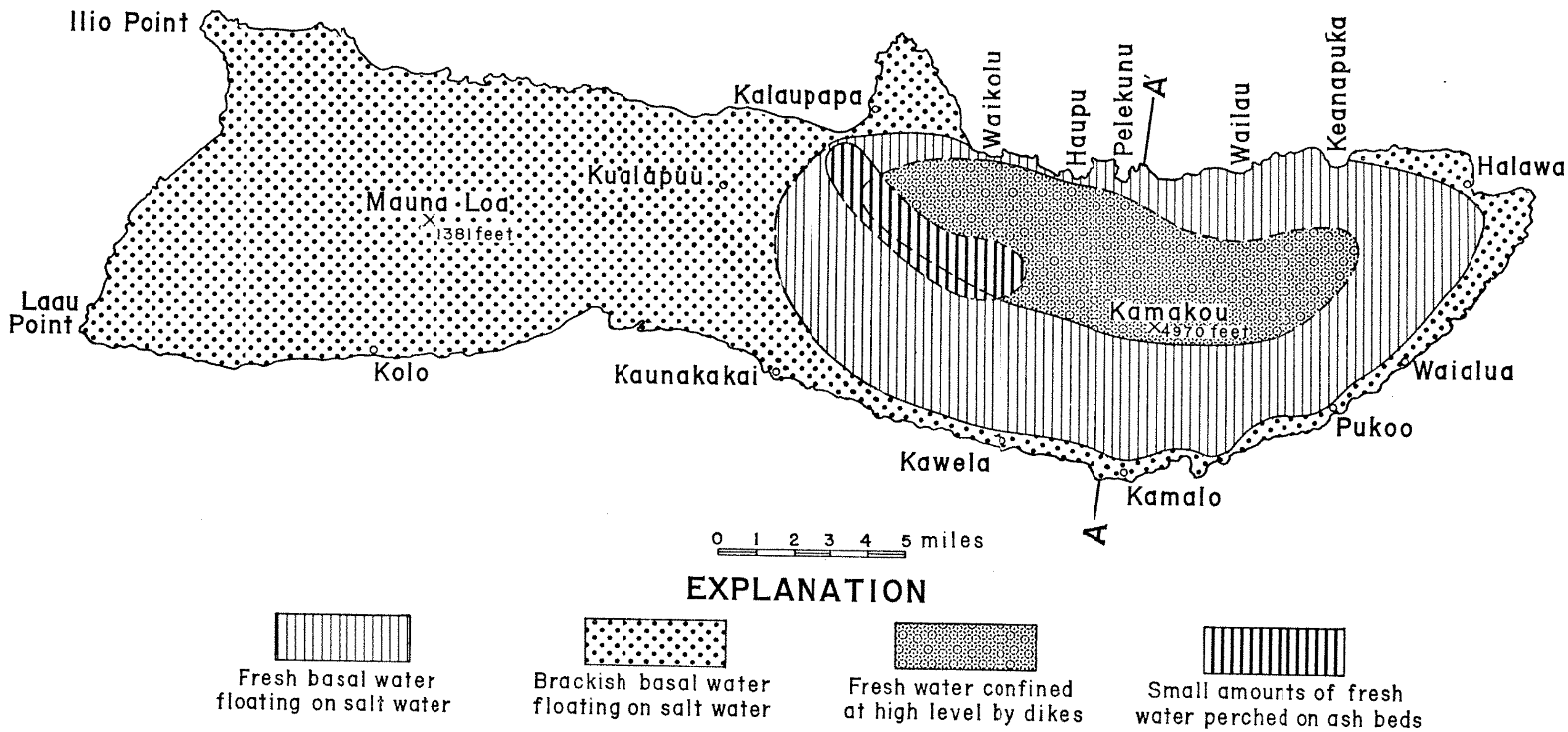


Figure 15. Map of Molokai, showing ground-water areas.

level farther down the canyon. A tunnel 70 feet long was dug previous to 1902 along the contact of the alluvium and the andesite, following nearly beneath the stream bed, but failed to increase the discharge. The inner 50 feet of the tunnel have caved in. It is possible that further tunneling, following the water back to its points of leakage from the volcanic rocks, would increase the discharge, but it appears doubtful whether the increase would be sufficient to warrant the expense of tunneling. Kapuna Spring never dries up, although at times the discharge becomes very small. The maximum, minimum, and mean daily discharges of Kapuna Stream for the years 1940 to 1945 are shown in the following table. The maximum

Daily discharge in gallons of Kapuna Stream[a]

	Maximum	Minimum	Mean
1940[b]	240,000	10,000	30,000
1941	100,000	10,000	30,000
1942	3.800,000	10,000	96,000
1943	130,000	10,000	31.000
1944	180,000	10,000	19,000
1945	420,000	3,000	15,000

[a] Data from U. S. Geol. Survey, Water Supply Papers 935, p. 71, 1943; 965, p. 66, 1945; and unpublished files. The low stage flow is entirely discharge of Kapuna Spring.
[b] July to December only.

discharges include a large proportion of surface runoff. The minimum discharges are entirely spring flow. The actual spring discharge probably ranges from 10,000 to about 25,000 gallons daily.

A small spring issues from andesite in the south wall of Luolohi Gulch, about 30 feet above the pipeline trail, 2,000 feet west of tunnel 9 (pl. 1). It appears to be perched by a thin bed of ash. On September 29, 1945, the discharge was about 300 gallons daily.

A spring issues from andesite, above a bed of red ash in the southeastern side of a plunge pool, 300 feet upstream from Kamiloloa intake of the Hawaiian Homes Commission. It is shown on plate 1, 0.4 mile northwest of Kaulahuki hill. During dry weather the entire stream flow at Kamiloloa intake, or about 40,000 gallons daily, is supplied by this spring.

Several small perched springs occur along the upper course of the South Fork of Kaunakakai Gulch, from about 2,450 to 3,150 feet (pl. 1). They issue in the lower part of the northern bank, at the base of the andesites, which here rest on 3 to 5 feet of red ashy soil. Near the westernmost spring the stream flow was estimated on October 9, 1945, during dry weather, to be about 75,000 gallons daily.

Above the easternmost spring, at the crossing of the abandoned Kawela pipeline, the stream carried about 40,000 gallons a day of water of pale brown color, derived by seepage from the swamps a short distance upstream. The spring discharge on that day was, therefore, about 35,000 gallons. On January 5, 1946, following a further period of three months of mostly very dry weather, the stream flow below the springs was measured by the waterman of Molokai Ranch as only 12,000 gallons daily, all of which probably came from the springs.

Haleloulu Spring is situated 0.9 mile southwest of Puu Kolekole, near the western boundary of the Makolelau land division (pl. 1). Three small springs issue close together, from clinkery andesite aa 0 to 10 feet above a bed of ashy soil 1 to 2 feet thick. The soil rests on a thick bed of clinker, decomposed at the top, forming part of the edge of a buried andesite cinder cone. On October 2, 1945, the total spring discharge was about 20,000 gallons daily, of which about half was recovered and led by pipeline to a cattle trough. During wetter weather, from June 3 to December 11, 1937, nine measurements by the Molokai Ranch showed the total spring discharge to range from 69,760 to 24,170 gallons daily.

On the west bank of Kahananui Stream, about 100 feet downstream from the County intake at 1,230 feet altitude, a small spring issues from basaltic aa clinker. An excavation about 5 feet deep and 6 feet high serves as an intake, and the water is led into the County's Ualapue pipeline. On February 25, 1939, the spring discharge was estimated by H. T. Stearns to be about 2,000 gallons daily. The water appears to be perched by a dense bed of lava.

Near the trail from Mapulehu to Wailau Valley, about a quarter of a mile south of the crest, a small spring issues from the andesite. The environment is swampy, and the water is swamp water, locally perched on the poorly permeable andesite. Many such springs and seeps issue in the swampy upland areas, feeding the perennial portions of the streams, but they are in general too poorly defined to show on plate 1, or to warrant individual description. The spring near the Wailau-Mapulehu trail is discussed only because it is habitually used as a source of drinking water by persons traveling the trail.

Ahaino Spring is situated at about 1,240 feet altitude, in land belonging to E. K. Duvauchelle in Ahaino 2 land division. The water issues from a clinker bed between two massive layers of andesite. It is probably perched by a thin layer of ashy soil, although no ash is visible at the spring. On February 24, 1939, H. T. Stearns estimated the spring discharge to be about 9,000 gallons daily. A short tunnel at this place would permit the development of all of the water underground, but the yield of the spring would probably not be materially increased. Ahaino Spring was formerly used as a source of water for the County's Ualapue system, but this use was discontinued in June 1938.

On the eastern wall of Pelekunu Valley, half a mile to a mile from the beach, a series of springs issues from basalt at the top of a bed of decomposed vitric tuff 4 to 8 inches thick. During September, 1935, the total discharge of these springs was estimated by H. T. Stearns to be about one million gallons daily.

Near Malahini Cave, in the eastern branch of Wailau Valley, a small spring issues from ancient alluvium. Although the water is locally perched in the alluvium, it is probably supplied by leakage from the dike complex.

TUNNELS DEVELOPING PERCHED GROUND WATER.—All but one of the tunnels yielding perched ground water were driven in andesites of the upper member of the East Molokai volcanic series. In most, the water is seen to be perched by thin beds of ash or ashy soil. The table on page 73 contains the principal data regarding the tunnels. A long tunnel from Waihanau Stream to the headwaters of the Manawainui drainage was constructed entirely for the purpose of transporting water from Waihanau Stream, and develops no perched ground water.

Tunnels 2a and 2b, 0.3 mile south of Puu Lua, yield a small amount of water during wet weather, but dry up completely during droughts. The tunnels are caved in and inaccessible. The portals are in alluvium, but the tunnels are probably mostly in andesite. A spring formerly existed at this locality, and it is reported that construction of the tunnels did not increase the discharge.[42]

Tunnel 11 was driven at the site of a former spring, at the toe of the ridge between the two major forks of Mapulehu Stream. Tunneling probably did not greatly increase the discharge. The water issues from basalt aa clinker, and is probably perched by the underlying dense bed of basalt. The source of the water is probably leakage from the adjacent dike complex (see pages 72–77), but some or all of it may be derived from seepage from the streams of the east and west forks, in the beds of both of which the clinker layer is exposed. Both streams are perennial near their heads, fed by seepage from the swamps, and both lose water rapidly in the half mile above the tunnel.

Tunnels 4, 5a, and 5b, and two nearby small springs, at Waialala, all yield water from andesite. No ash or soil bed is exposed in the

[42] Lindgren, W., op. cit., p. 29.

tunnels, but it is probable that such a bed, similar to those exposed in tunnels 3 and 6, is present and responsible for the perching of the water. The total discharge of the tunnels and springs is measured at a gaging station, and the records are published by the U. S. Geological Survey.[43] The maximum, minimum, and mean daily discharge for the years 1940 to 1945 are shown in the following table.

Daily discharge in gallons of Waialala springs and tunnels[a]

	Maximum	Minimum	Mean
1940[b]	35,000	18,000	25,000
1941	96,000	21,000	30,000
1942	275,000	21,000	43,000
1943	47,000	17,000	27,000
1944	64,000	12,000	20,000
1945	43,000	4,000	10,000

[a] Data from U. S. Geol. Survey, Water Supply Papers 935, p. 69, 1943; 965, p. 64, 1945; and unpublished files.
[b] September to December only.

WATER CONFINED AT HIGH LEVELS BY DIKES

Within the rift zones of East Molokai Volcano, the lavas are cut by very numerous dikes, representing the chilled fillings of fissures which fed lava flows, and other fissures which failed to reach the surface. Most of the dikes are essentially vertical, though some are inclined. A few pass into sills, which are essentially parallel to the bedding of the lavas; that is to say, nearly horizontal. In the eastern part of East Molokai Volcano most of the dikes trend roughly eastward. In the western part, most of them trend about N. 65° W. In Waikolu, Pelekunu, and to a less extent in the eastern part of Wailau Valleys, both these trends are represented, and it appears probable that the east-west trend extends as far as the Hoolehua Plain. In the area between the upper courses of Kamalo and Kawela Streams the trend is probably southeasterly. The dikes are most numerous in a band about two miles wide, known as the dike complex. At the edges of the dike complex the abundance of dikes decreases gradually, fewer and fewer dikes being encountered as one travels outward from the old rift zones of the volcano.

The dikes range in thickness from less than a foot to about 15 feet. The rock of the dikes is generally dense and nonvesicular, and although the dikes are generally cut by abundant joints roughly

[43] Carson, M. H., Surface water supply of Hawaii: U. S. Geol. Survey, Water Supply Papers 935, 965, 985.

Tunnels driven for perched ground water in Molokai

No. (pl. 1)	Name	Owner	Location	Altitude (feet)	Length (feet)	Yield (gallons per day)	Perching formation
1	Waiakane	Molokai Ranch Co.	S. fork of Kapale Gulch	1,000	40	500	Ash bed in upper member of East Molokai volcanic series.
2a	Puu Lua	Do.	0.3 mile south of Puu Lua	1,230	...[a]	0	....
2b	Do.	do.	Do.	1,230	...[a]	0	....
3	Waipunahonu	do.	0.4 mile east of Puu Lua	1,550	155	200	Ash bed in upper member of East Molokai volcanic series.
4	Waialala	Meyer Estate[b]	Waialala Gulch, 35 feet west of road to head of Kalaupapa trail	1,600	100[c]	25,000[d] (4, 5a, 5b together)	Ash bed (?), in upper member of East Molokai volcanic series.
5a	Do.	Do.[b]	Do., 100 feet east of the road	1,680	40		Do.
5b	Do.	Do.[b]	Do., just east of tunnel 5a	1,680	3		Do.
6	Waikalae	Do.	Waikalae Gulch, 0.65 mile S. 73° W. of Puu Olelo	1,780	327	20,000	Ash bed in upper member of East Molokai volcanic series.
7	Waihii	Molokai Ranch Co.	Waianui Gulch	1,650	100[c]	1,000[e]	Do.
8	Waiiole	Do.	Waiiole Gulch (north fork of Kahuanui Gulch)	2,200	60	20,000	Do.
9	Luolohi	Do.	Luolohi Gulch	2,780	800[f]	30,000	Do.
10	....	Do.	Do., 350 feet upstream from tunnel 9	2,800	50	300	Do.
11	Mapulehu	Hawaiian Sugar Planters Assn.	Mapulehu Gulch	650	60	35,000	Dense bed in lower member of East Molokai volcanic series.

[a] Caved in and inaccessible; reported as short by Lindgren, U. S. Geol. Survey Water Supply Paper 77, p. 29, 1903.

[b] Water sold to County of Maui.

[c] Partly caved in.

[d] Includes discharge of two adjacent small springs.

[e] Unused.

[f] Length reported by Lindgren, op. cit., p. 30; now caved 100 feet from portal, but nearly all the water was developed in the first 100 feet.

normal to the dike walls, they are on the average much less permeable than the vesicular and partly clinkery lava flows between them. Thus in the dike complex the intersection of numerous dikes of different trend gives rise to a condition somewhat resembling a honeycomb, in which roughly vertical prisms of moderately permeable lava rock are separated by relatively impermeable dike partitions. Rain water sinking into the rock at the tops of the permeable compartments tends to accumulate in the compartments, its lateral movement being prevented or retarded by the dikes. Within the permeable compartments the water accumulates to a level at which leakage through the confining dikes equals the recharge. The cumulative effect of the dikes results in the water level in the inner compartments of the rift zone being higher than that in the outer compartments, the rise of the water table being by steps, as shown in figure 16. Locally, the water in the inter-dike compartments may be resting on salt water, and in counterbalance with it according to the Ghyben-Herzberg principle (page 53). More commonly, however, the great increase downward in the abundance of intrusive rock results in the rock at depth being essentially impermeable, holding up the fresh water in the inter-dike compartments and shutting out the salt water. In most places, therefore, the high-level water in the dike complex is actually perched on poorly permeable intrusive rock.

In West Molokai Volcano, at altitudes above sea level, the dike complex appears to be much less well developed than in the East Molokai Volcano. Drilled well 1 (pl. 1) lies within, or close to the edge of, the northwest-trending rift zone, yet the water is brackish and stands at an altitude corresponding to the normal basal zone of saturation. Apparently at that location, at least, the concentration of dikes is insufficient to shut out the sea water, or to prevent the easy lateral escape of fresh water. Possibly in the vicinity of Puu Nana, where the northwest and southwest rift zones intersect, or for a short distance southwest of Puu Nana along the southwest rift zone, inter-dike compartments may confine fresh water. However, the rainfall, and consequently the recharge, is so low in this area that it is not likely the water is held very far above sea level. Some leakage through the dikes always occurs, and with low recharge not much leakage is required to allow the water to escape laterally instead of accumulating to high levels in the inter-dike compartments. For these reasons, no area of water confined at high levels by dikes is shown on West Molokai in figure 15.

Wailau, Pelekunu, and Waikolu Valleys are great notches cut into the dike complex of East Molokai Volcano. These notches serve to

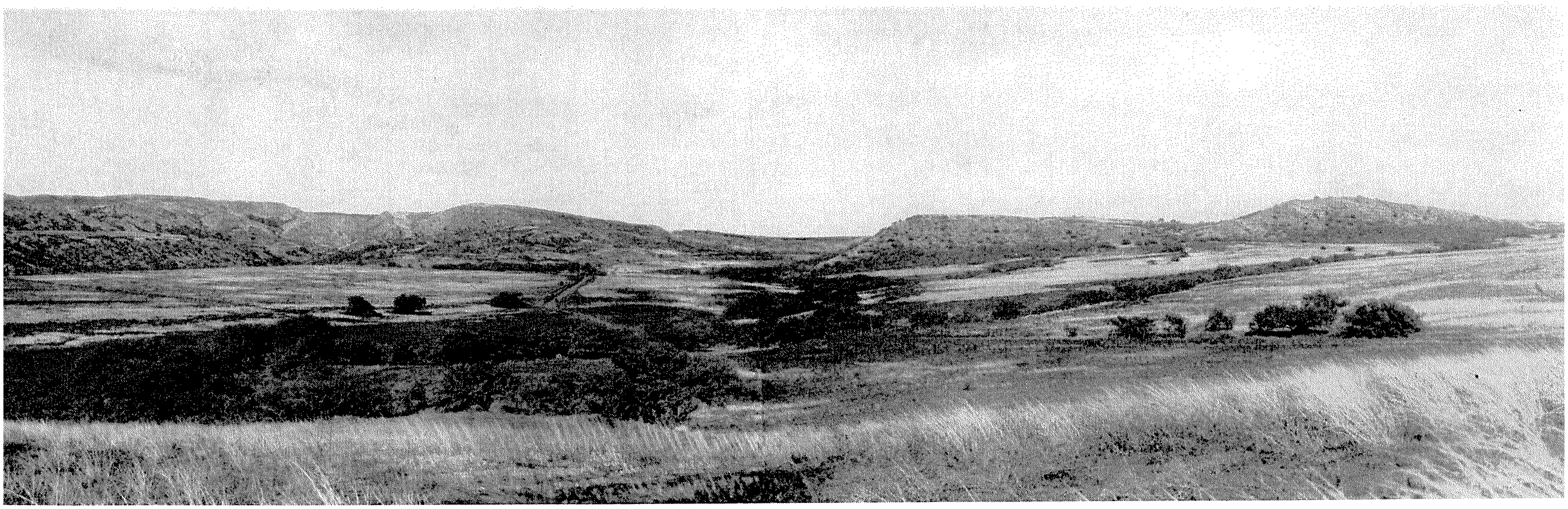
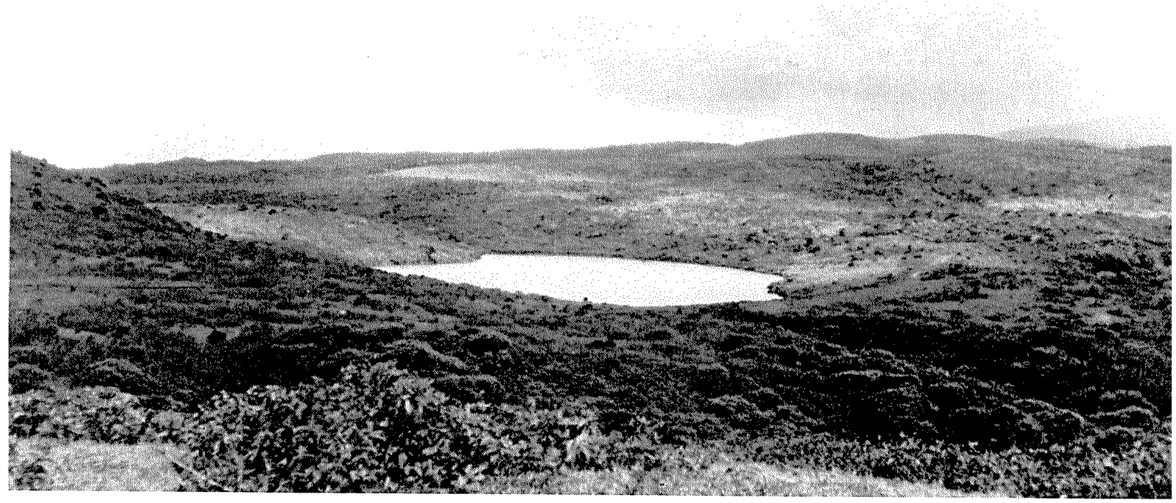
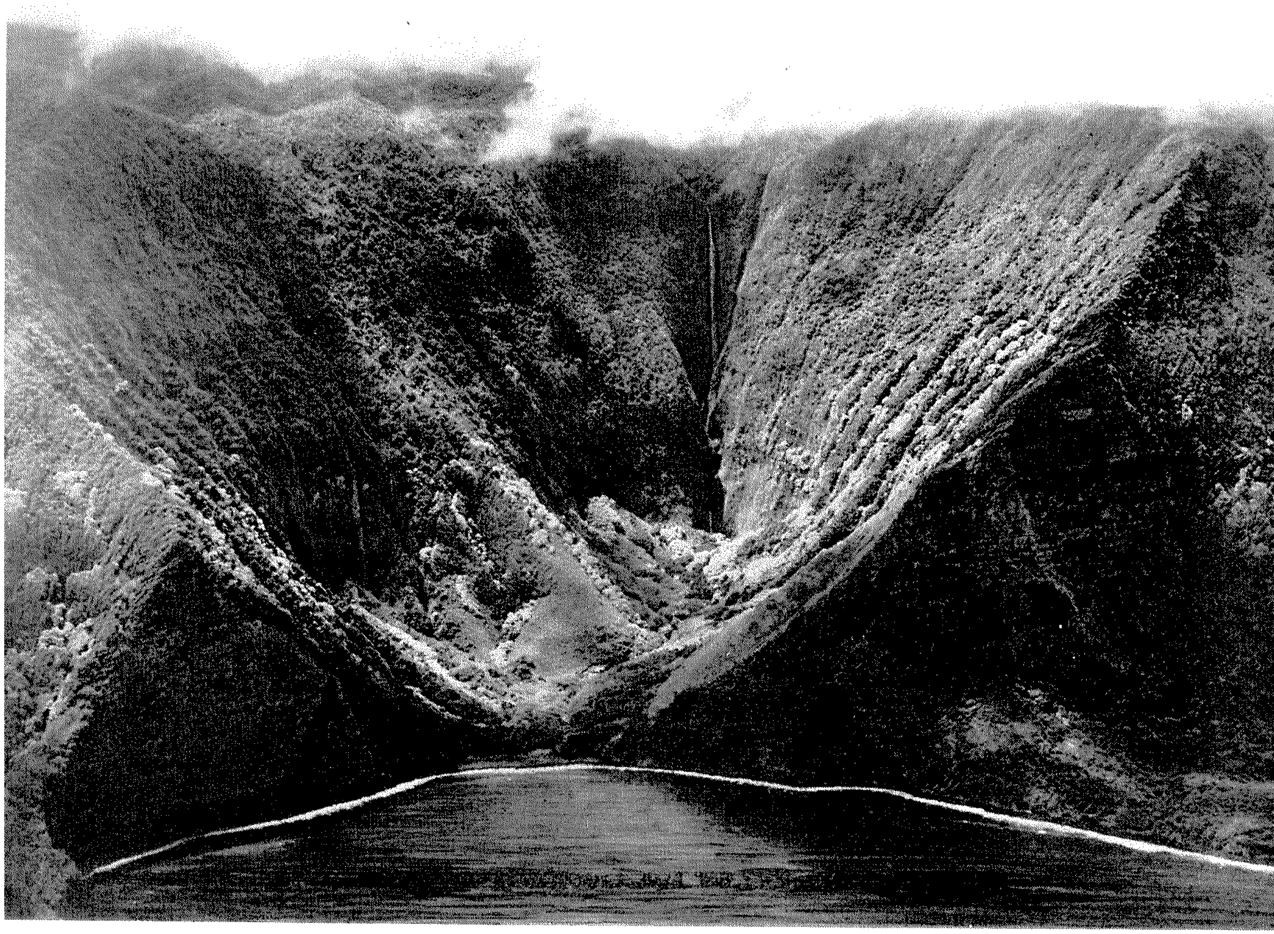


Plate 12A. View of the eastern slope of West Molokai from Puu o Pipika; showing step-fault scarps on the left, the Mahana graben in the center, and two small tilted fault blocks on the right. The right-hand block is Waihuna hill. Photo by G. A. Macdonald.

Plate 12B. Meyer Lake, occupying a small structural depression on the poorly permeable andesites of the upper member of the East Molokai volcanic series at the foot of Puu Olelo cinder cone. Photo by H. T. Stearns.





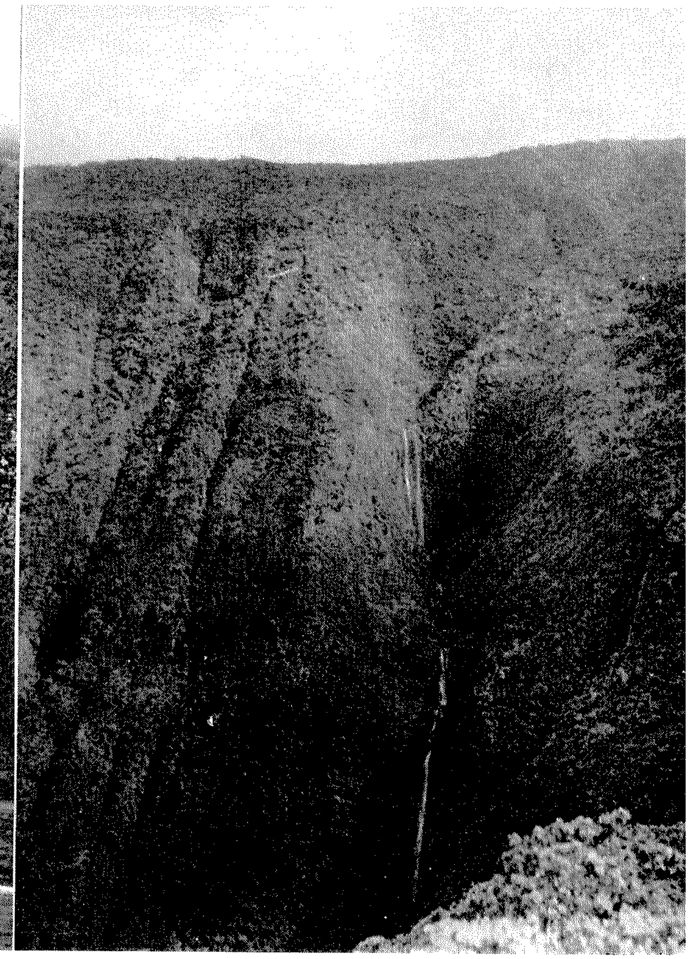


Plate 13A (left). Papalaua Valley, East Molokai, a short amphitheater-headed valley cut in basalts of the lower member of the East Molokai volcanic series. The rim of the valley is andesite of the upper member of the series. Photo by U. S. Army Air Force.

Plate 13B (right). Ohialele Stream, descending by a series of water falls and plunge-pools into the head of Waikolu Valley, East Molokai. Photo by R. J. Baker.

drain the adjacent inter-dike compartments. Many springs occur in these valleys, owing to the escape of water from behind dikes. It is to these springs that the streams largely owe their perennial character. In the heads of the valleys the level of escape and consequently of the water table in the adjacent inter-dike compartments is high. Near the coast it is low.

In the head of Waikolu Valley, springs occur at altitudes up to 1,500 feet, and in the inter-dike compartments farther south the water level is probably still higher. Other springs occur along Waikolu Stream and low on the walls of the canyon to an altitude of 500 feet (pl. 1). The total discharge of these springs, during dry weather, constitutes the entire flow of the stream at the gaging station, and averages approximately 4.7 million gallons a day (see table, page 77).

Half a mile south of the mouth of the stream a series of springs issues on the eastern wall of the canyon at 400 to 500 feet altitude. One of these serves as a source of water forKalaupapa and Kalawao. On June 11, 1935, its discharge was estimated by H. T. Stearns to be about 250,000 gallons daily. It is possible that this group of springs is perched by an ash bed. However, no ash bed could be found, and it is believed more probable that the water escapes from inter-dike compartments at and near the upper edge of the relatively impermeable alluvium banked against the valley side.

In the head of Pelekunu Stream springs issue at least as high as 2,000 feet altitude, and probably higher. Only a few of them are shown on plate 1. The low-stage flow of Pelekunu Stream is probably largely or entirely from these springs. The average minimum discharge of Pelekunu Stream and Lanipuni Stream (the large eastern tributary which joins Pelekunu Stream at about 340 feet altitude), is about 2.4 million gallons daily (see table, page 77). During the same period, the average minimum flow of Lanipuni Stream was also 2.4 million gallons daily, probably largely or entirely the discharge of springs from inter-dike compartments in the headwaters of that stream. Springs from inter-dike compartments in the upper part of Pilipililau Valley yield about 0.5 million gallons daily. Along the eastern shore of Pelekunu Bay springs issue from inter-dike compartments practically at sea level.

In the head of Wailau Valley springs issue from inter-dike compartments up to 2,100 feet altitude, and possibly higher. A small spring at that altitude on the trail to Mapulehu issues from alluvium, but undoubtedly derives its water from inter-dike compartments behind the thin alluvial cover. Most of the low-stage flow of both major branches of Wailau Valley is discharge from dike-com-

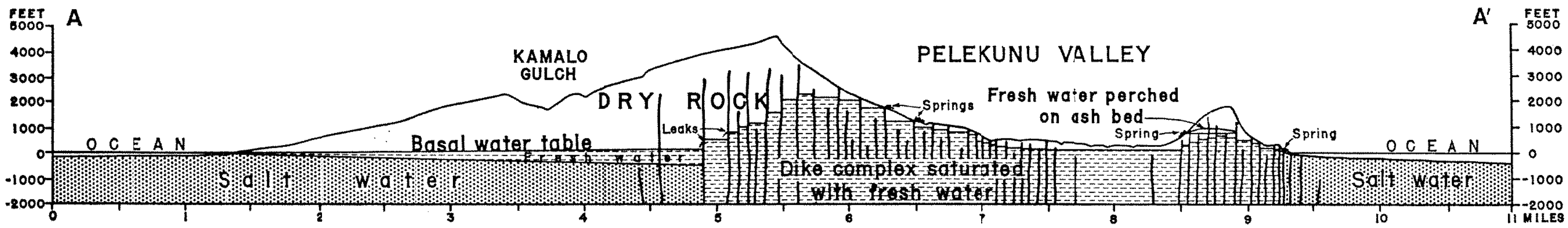


Figure 16. Section across East Molokai, showing ground-water conditions. The position of the section is shown in figure 15.

plex springs. From 1919 to 1942, the average minimum discharge of Pulena Stream was 4.4, and of Waiakeakua Stream (including Waiokeela Stream) was 2.1 million gallons daily. Other springs issue from inter-dike compartments north of the gaging stations, in the walls of the main valley and in tributaries.

Minimum daily discharge of windward streams, East Molokai (in million gallons)[a]

Fiscal year[b]	Waikolu Stream	Pelekunu Valley		Wailau Valley		Total
		Pelekunu Stream	Lanipuni Stream	Pulena Stream	Waiakeakua Stream	
1919-1920	3.8	1.8	2.0	3.0	1.3	11.9
1920-1921	2.4	1.8	1.9	3.0	1.6	10.7
1921-1922	2.8	2.2	1.9	5.0	2.1	14.0
1922-1923	4.7	2.6	2.6	5.0	2.2	17.1
1923-1924	5.3	2.3	3.0	3.8	2.2	16.6
1924-1925	4.1	2.2	2.6	5.0	1.9	15.8
1925-1926	3.2	2.0	2.2	4.7	1.5	13.6
1926-1927	3.4	1.9	1.8	3.0	1.8	11.9
1927-1928	3.8	2.0	3.3	...	2.6	....
1928-1929	3.2	...	2.6	6.8	1.7	....
1929-1930	...	...	...	...	...	....
1930-1931	4.8	...	...	...	...	....
1931-1932	6.1	...	...	...	...	....
[c]1937-1938	7.7	3.3	3.6	4.6	3.2	22.4
1938-1939	7.2	3.1	1.7	5.4	2.0	19.4
1939-1940	6.1	3.0	2.6	5.0	2.6	19.3
1940-1941	5.8	2.9	2.2	3.4	2.2	16.5
1941-1942	6.3	2.5	2.3	3.4	1.9	16.4
Average	4.7	2.4	2.4	4.4	2.1	15.8

[a] Data from U. S. Geol. Survey, Water Supply Papers 516, 535, 555, 575, 595, 615, 635, 655, 675, 695, 710, 725, 740, 755, 865, 885, 905, 935, 965.

[b] July of one year to June of the succeeding year.

[c] No records from July 1932 to June 1937.

QUALITY OF GROUND WATER

Only two chemical analyses of ground water from the island of Molokai are available. They are listed in the following table, columns 1 and 2. For comparison there is given in column 3 an analysis of sea water in the adjacent channel between Molokai and Oahu.

The water of drilled well 1 (column 2 of the table) contains about one-seventh as much chloride as does the sea water. In contrast, the amounts of sodium are approximately one-half, sulfate two-thirds, magnesium twice, and calcium five times the amounts in the sea water, respectively. Obviously, these radicles in the water of drilled well 1 cannot be solely the result of mixing of pure fresh water with sea water. In part, they have probably been derived by solution from the enclosing rocks. The high temperature of the water in that well (page 61) suggests, however, heating of the ground water by rising volcanic volatiles, and some of the dissolved material has probably been brought upward with the volatiles. The sulfate is probably of magmatic origin. Most of the soda, magnesia, and lime were probably leached from the rocks traversed by the rising hot gases and solutions. It has been shown that these oxides are readily leached from the basaltic rocks at Kilauea Volcano, on the island of Hawaii, by similar weakly acid solutions arising from the admixture of volcanic gases and ground water.[44]

The composition of the water from dug well 30, at Kawela, shown in column 1 of the table, appears to be normal for Hawaiian ground water, as shown by comparison with analyses of well water from Oahu.[45]

Much of the surface and ground water on East Molokai is weakly acid, resulting in a high rate of corrosion of steel pipes. The acid is

Chemical analyses of water
(in parts per million)

	1	2	3
Silica (SiO_2)	25.4	.....	8.
Alumina (Al_2O_3)	3.17	.....	1.2 (Alumina and iron oxide)
Iron oxide (Fe_2O_3)	0.43	.....	
Calcium (Ca)	11.0	393.	427.
Magnesium (Mg)	6.9	395.	973.
Sodium (Na) or Sodium and Potassium (Na + K)	8.3	820.	12,535.
Chloride (Cl)	15.0	2,890.	20,713. (Chloride and nitrate)
Nitrate (NO_3)	0.14	.....	
Carbonate (CO_3)	.....	None	.....
Bicarbonate (HCO_3)	.....	44.	.....
Sulfate (SO_4)	5.6	244.	2,852.
Fluoride (F)	0.1	.....	.....
Total hardness	66.1	2,602.	4,934.
Total solids	119.	.....	37,700.
Loss on ignition	36.	.....	73.
pH	6.0	.....	.....
Date of collection	Nov. 15, 1945	Dec. 9, 1945	Dec. 31, 1929

1. Dug well 30 (Kamakana well), Molokai. Analyst, R. H. Tanimoto, Board of Health, Territory of Hawaii.
2. Drilled well 1, West Molokai. Analyst, A. B. Joy, Pacific Chemical and Fertilizer Co.
3. Pacific Ocean midway between Molokai and Oahu. Analyst, Dearborn Chemical Co. Stearns, H. T., and Vaksvik, K. N., Hawaii Div. Hydrography Bull. 1, p. 361, 1935.

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[44] Macdonald, G. A., Solfataric alteration of rocks at Kilauea Volcano: Am. Jour. Sci., vol. 242, pp. 496-505, 1944.

[45] Stearns, H. T., and Vaksvik, K. N., Geology and ground-water resources of the island of Oahu, Hawaii: Hawaii Div. Hydrography, Bull. 1, pp. 361-364, 1935.

largely humic acid derived from the summit swamps. The following list of acidity determinations was supplied by Molokai Ranch, Ltd. Water from dug well 30, at Kawela, has a pH of 6.0.

ACIDITY OF TUNNEL AND STREAM WATER

Source of water	pH	Date of sampling
Tunnel 8	6.2	Sept. 17, 1937
Tunnel 9	6.2	Do.
Kawela Stream	6.8	Sept. 14, 1937
Kamoku Stream	5.2	Do.
Kalihi Stream	6.4	Sept. 17, 1937
Ohialele Stream	5.6	Sept. 14, 1937

USE OF WATER FROM THE LARGE WINDWARD VALLEYS

During the past half-century, several proposals have been made to bring the abundant water of the large windward valleys of East Molokai to the dry leeward slopes and the Hoolehua Plain. On the Hoolehua Plain, in particular, large areas of rich soil exist but lack sufficient irrigation water for most agricultural uses. It has been estimated that if the water available in the windward valleys could be brought to the Hoolehua Plain, it would be sufficient to irrigate 5,000 to 12,000 acres, depending on the type of crops. Several projects have been advanced for tunneling through the intervening ridges and leading the water of the windward streams to the agricultural areas.

Although earlier suggestions of a general nature appear to have been made, the first well-supported plan of this sort seems to have been that by Lindgren.[46] He presented three alternate suggestions. (1) Utilization of Wailau water alone, by means of a tunnel 12,800 feet long which would tap Pulena Stream at 670 feet altitude, and discharge in Mapulehu Gulch at 660 feet altitude. (2) Utilization of both Wailau and Pelekunu water, by means of a tunnel 14,500 feet long which would tap Pelekunu Stream at 700 feet altitude, and lead the water to Pulena Stream in Wailau Valley, and thence to Mapulehu Gulch. (3) Utilization of both Wailau and Pelekunu water, by means of a tunnel 15,000 feet long tapping Pulena Stream at 650 feet altitude and leading the water to Pelekunu Stream at 635 feet altitude, and thence by means of a tunnel 26,500 feet long to a point at 610 feet altitude 1.2 miles east of Kawela Gulch. The positions of the tunnels are shown in figure 17. The water would

[46] Lindgren, W., The water resources of Molokai, Hawaiian Islands: U. S. Geol. Survey, Water Supply Paper 77, pp. 55-56, 1903; also unpublished report to American Sugar Co., 1900.

have been carried from the tunnels to the agricultural areas on Hoolehua Plain, at 450 feet altitude, by a series of ditches, flumes, and siphons. It was estimated that the use of Wailau Stream alone would make available about 8 million gallons of water a day, and Pelekunu and Wailau together would supply about 14 million gallons. It was expected that the tunnels would also develop large amounts of ground water. The tunnel projects were considered too costly by Lindgren, who recommended instead the development of ground water along the southern coast, and pumping to the agricultural areas.

In 1919, Frederick Ohrt recommended a series of tunnels 18,640 feet long to divert water from Waikolu Stream at 580 feet altitude and to deliver it to a point on the cliff above the reservoirs at Kalaupapa, for use as domestic water and to generate electric power. He suggested that if the construction of a tunnel system along the north coast to supply water to the Hoolehua Plain should in the future prove feasible, these tunnels could be incorporated as part of the large system.[47] H. A. R. Austin, in 1929, recommended adoption of Ohrt's proposals, and indicated the belief that it would eventually prove feasible to construct a series of tunnels along the north coast

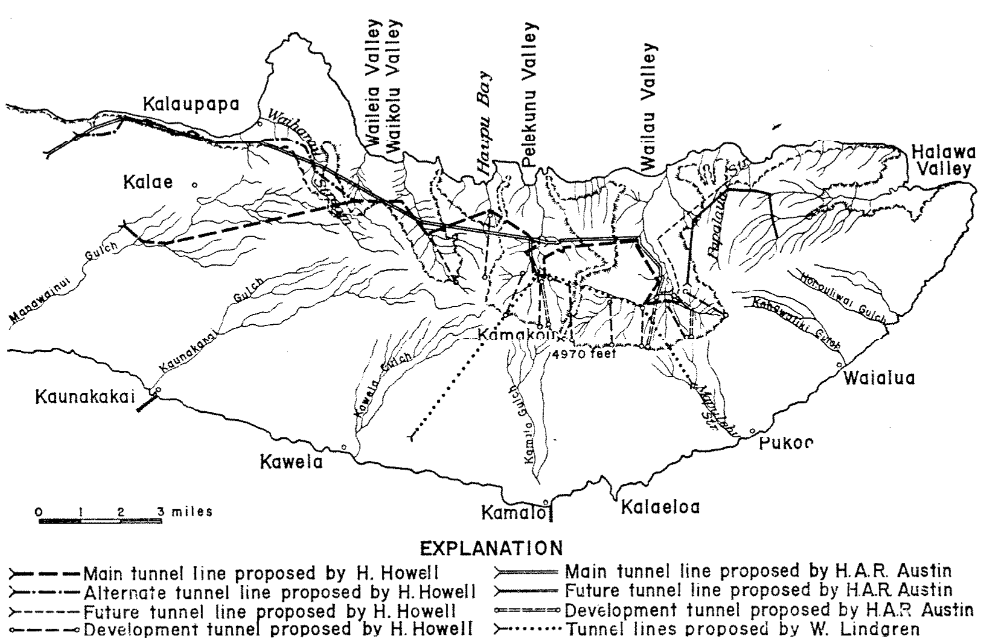

Figure 17. Map of East Molokai, showing proposed routes of tunnels to lead water from the wet windward valleys to the dry leeward slopes.

[47] Ohrt, Frederick, Unpublished report to the Superintendent of Public Works, Territory of Hawaii, 1919.

to deliver water of the windward streams to the Hoolehua Plain at an altitude of 450 to 500 feet.[48]

In 1923, J. Jorgensen proposed the construction of a series of tunnels along the north coast to deliver the water of Wailau, Pelekunu, and Waikolu Streams to the Hoolehua Plain at an altitude of 500 feet.[49] He estimated that the three streams would yield an average flow of about 55 million gallons daily, but in order to utilize high-stage discharges in excess of 55 million gallons, he proposed that the tunnels have a capacity of 100 million gallons daily, the excess to be stored in reservoirs in the Hoolehua area. He suggested that sufficient water for irrigation and power development could be diverted to Kalaupapa. Howell doubts whether the proposed storage capacity, or the capacity of the tunnel during freshet stages, would be sufficient to provide water throughout some of the longer drought periods.[50]

In the summer of 1935 H. T. Stearns investigated the geologic structure and hydrologic conditions in the windward valleys in anticipation of the Bureau of Reclamation survey, and proposed to Mr. Hugh Howell that water-development tunnels utilizing the new principal of storing water in the dike complexes be used to make up the deficit in surface run-off during dry periods.

In December, 1935, the U. S. Bureau of Reclamation commenced an investigation, under the supervision of Hugh Howell, into the location and amount of suitable agricultural land, the location and amount of available water for irrigation, and methods for delivering this water to the land. Howell's report outlines a program for the construction of tunnels to lead water from Wailau, Pelekunu, Waikolu, and other minor streams, to the Hoolehua Plain, and to supplement the low-stage flow of the streams with water from development tunnels driven into the dike complex in the heads of the big valleys.[51] The proposed locations of the transportation and development tunnels are shown in figure 17.

The transportation tunnel would start at the east at Wailau Stream, with a possible future extension to Papalaua Stream. From Wailau Valley, the tunnel would penetrate the ridge just north of Olokui Peak to Pelekunu Valley, extend thence to the head of Haupu Valley, to Waikolu Valley, and to the head of Waileia Valley.

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[48] Austin, H. A. R., Unpublished report to the Superintendent of Public Works, Territory of Hawaii, 1929.

[49] Jorgensen, J., Unpublished report on utilization of streams of the windward coast of East Molokai for irrigation of the Hoolehua homesteads, 1923.

[50] Howell, Hugh, Final report on water supply studies, Hawaii, F. P. No. 45, Island of Molokai (abridged) : U. S. Bureau of Reclamation, p. 10, 1938.

[51] Howell, H., op. cit., 62 pp.; also mimeographed report, unabridged, 111 pp., 1938.

Thence westward two alternative routes were proposed. The preferred route would strike almost directly westward, collecting water from Waihanau Valley, and emerging at a point about 0.3 mile south of Kualapuu village. The alternate route would strike northwestward to Waihanau Valley, and thence extend along the northern coast just inland of the great coastal cliffs, debouching about 2 miles northwest of Kualapuu. The capacity of the tunnel would increase from 30 million gallons daily at the eastern end to 80 million gallons daily west of Waikolu Valley. The total length of the tunnels, following the preferred route, would be 18.3 miles; and total cost of the project was estimated at 5 million dollars. It was proposed to deliver to the agricultural areas a minimum of 55 million gallons of water daily, for the irrigation of about 12,000 acres of land. It was believed that during most of the time the streams would supply 55 million gallons daily or more. Additional ground water of unknown amount would be developed by the transportation tunnels crossing the dike complex. During periods when the stream discharge is less than 55 million gallons daily, it was proposed to make up the deficit to 55 million gallons from the discharge of water development tunnels driven into the dike complex at the heads of the big valleys. Nine such tunnels were proposed, ranging from 1.0 to 1.9 miles long. The positions of the proposed development tunnels are shown on figure 17. Based on the results obtained at the Waiahole tunnel system on Oahu, H. T. Stearns concluded that if the tunnels were allowed to flow constantly, each could be relied on for a minimum flow of 1 to 3 million gallons daily, but if the tunnels were plugged and drawn upon only for short periods a considerably greater yield could be expected.[52] Thus, although several possible sites for the reservoirs in the Hoolehua area were indicated, it was proposed that the principal storage would be underground, in the dike complex.

In 1944, H. A. R. Austin[53] proposed the construction of a series of tunnels 96,800 feet long, to lead the water of Wailau, Pelekunu, and Waikolu Valleys to the farm lands of the Hawaiian Homes Commission on the Hoolehua Plain. The route of the tunnel differs from that proposed by Howell mainly in following the northern coast west of Waihanau Valley, but also in being straighter in its more easterly parts. The proposed route is shown in figure 17. The straightening was accomplished partly by the use of a short feeder tunnel in Pelekunu Valley, and a 48-inch concrete siphon to cross

[52] Stearns, H. T., Preliminary report on ground water in Wailau, Pelekunu and Waikolu: in Howell, H., op. cit., pp. 21-22.

[53] Austin, H. A. R., Unpublished report to Molokai Water Board, on investigations relative to the proposed Molokai Water Project, Jan. 31, 1944.

that valley. Water was to be delivered to the Hoolehua area at the 650 foot level, instead of at 750 feet as proposed by Howell, because it was believed that the corresponding lowering of the intakes would make available about 20 percent more stream water. The main tunnel would have a capacity of 35 million gallons daily at its eastern end, increasing by stages to 72 million gallons daily at its western end.

The minimum amount of water delivered by the tunnel would be 35 million gallons daily, as compared to a minimum of 55 million gallons daily as proposed by Howell, because it was believed that an attempt to maintain the higher minimum would necessitate draft from the development tunnels in the dike complex over too great a proportion of the time, resulting in drainage of the inter-dike compartments. To maintain a minimum daily discharge of 35 million gallons three water development tunnels were proposed, each about 5,000 feet long, penetrating the dike complex. Two would be situated at 800 feet altitude in the head of Wailau Valley, and one at slightly higher altitude in Pelekunu Valley. Their proposed locations are shown in figure 17. The tunnels would be bulkheaded to conserve water in the inter-dike compartments, and it was estimated that the deficiency in stream flow could be made up by an average total draft on the development tunnels of 10.8 million gallons daily for an average of 17 days per month during the 6 months of low stream flow, May to October, of a normal year. During the rest of the year draft on the development tunnels would generally be unnecessary, and a minimum delivery of 40 million gallons daily could probably be safely supplied. Additional development tunnels could be constructed later if so desired. Also, the draft on the tunnels could be increased after a few years if performance warrants it. The large amounts of ground water encountered in digging the transportation tunnels would rapidly decrease, owing to drainage of the inter-dike compartments, and it was believed that eventually the water developed by these tunnels would probably be only about enough to compensate losses from the tunnels.

Storage of 100 million gallons would be provided in reservoirs in the Hoolehua area, waterproofed by mixing soil and cement and tamping with sheep's-foot rollers. It is believed that the plan would make possible irrigation of 6,816 acres of land. The estimated total cost of the project, including reservoirs, distribution system, and administration, was $6,185,000.

It was suggested that water could be delivered from the tunnel to Kalaupapa, eliminating the need of the present pipeline to

Waikolu Valley. It was also suggested that at a later date tunnels could be constructed from Wailau Valley to intercept the water of Papalaua and Halawa streams, the water being delivered to Wailau Valley at about 2,000 feet altitude and dropped to about 750 feet altitude for the generation of electric power.

Shortly afterward, in a supplementary report,[54] Austin outlined a lower-cost project, involving construction of only the portion of the main transportation tunnel from Waikolu Valley westward, and one development tunnel. The main tunnel would be 52,900 feet long. The development tunnel would extend 2,000 feet eastward into the ridge between Waikolu and Pelekunu Valleys, and thence 5,000 feet southward across the trend of the dike complex. It was estimated that this system would deliver about 5 million gallons of water daily to the Hoolehua area, at a total cost of $2,815,000 for the project. This tunnel would be more than half as long as that proposed in the preceding project, but would deliver only about one-seventh as much water. Thus, although the total cost of the project would be much less, the actual cost per gallon of water delivered would be much greater.

FUTURE DEVELOPMENTS

A large amount of ground water remains to be developed in the island of Molokai. However, the area in which ground water can be developed, and particularly the areas in which specific types of development are possible, are decidedly limited. Figure 15 shows the areas of the island underlain by the several types of ground water.

The basal water beneath all, or nearly all, of West Molokai is brackish. No perched water is present. Fresh water confined between dikes may possibly occur in a small area in the vicinity of Puu Nana, but the likelihood is not great. Brackish basal water also underlies the Hoolehua Plain. There appear to be no prospects of developing fresh water anywhere west of Kualapuu hill. Likewise, wells on the Kalaupapa Peninsula would yield brackish or salt water.

In East Molokai the small amounts of perched water which are present are already largely developed. The spring area along the upper part of the South Fork of Kaunakakai Gulch is not utilized, but the dry-weather discharge of the springs is so small and the area so difficult of access to a pipeline, that development would probably not be economically feasible. Tunneling there would prob-

[54] Austin, H. A. R., Letter to Frank West, Chairman, Hawaiian Homes Commission, Feb. 11, 1944.

ably increase the discharge little or not at all. Likewise, further tunneling in the area east and northeast of Kalae would probably not appreciably increase the amount of perched water discharged. Tunnels along buried ash beds in the upper member of the East Molokai volcanic series, in the area west of Waikolu Valley and south of Waileia and Waihanau Valleys, would probably develop some perched water, but the amount would probably be too small to justify the expense of tunneling. Tunnels at Haleloulu Spring, 0.9 mile southwest of Puu Kolekole, at Kahananui Spring, and Ahaino Spring probably would develop little additional water. No economically important bodies of perched water are known in the area east of Wailau Valley.

A large portion of East Molokai is underlain by fresh basal water (fig. 15). Anywhere within that area the development of basal wells is limited only by the depth of the water table beneath the surface, that is, by the economic limit of the depth of the well and the amount of pumping lift. The basal water would probably nowhere be encountered more than a few feet above sea level. Close to the southern coast the basal water is brackish, but short distances inland large amounts of fresh water are available to wells. Maui-type wells offer the least danger of becoming salty. In drilling wells, care should be exercised not to drill too far below the water table, particularly where the height of the basal water table above sea level is small. It would be wise to obtain competent geologic advise on specific projected sites before undertaking any large developments.

Large amounts of fresh water, at altitudes from sea level to more than 2,000 feet above sea level, remain undeveloped in the dike complex of East Molokai. The possibility of development tunnels penetrating the inter-dike compartments in the heads of the big windward valleys has already been treated. Similar tunnels driven into the dike complex from the heads of Mapulehu, Kamalo, or Kawela Gulches, or other localities on the southern slope, would develop large amounts of water. However, to insure sufficient head of water in the inter-dike compartments above tunnel level, the tunnels should not be higher than about 1,000 feet altitude. Such a tunnel started at 1,000 feet altitude in Mapulehu Gulch would enter the dike complex within half a mile, but tunnels started at 1,000 feet altitude in Kamalo or Kawela Gulches would probably extend more than 2 miles before reaching the dike complex. H. A. R. Austin has suggested a development tunnel, at 2,500 feet altitude at a location near Kamiloloa Spring, extending toward Waikolu Valley and under Kaulahuki hill, which he believed might encounter dikes.[55] The tunnel would, however, probably be at too high an altitude to develop much water from the inter-dike compartments.

It should be borne in mind that any tunnel developing water in the dike complex is removing water from storage. If the water is removed faster than it is replaced by recharge, the storage will be depleted, and the level of water in the inter-dike compartments eventually will be lowered to the level of the tunnel, at which time the daily yield of the tunnel will be greatly decreased. For that reason, tunnels in the dike complex should be plugged by means of one or more bulkheads at impermeable dikes, fitted with valves, and allowed to flow only when the water is actually needed. A study of pressure gages installed in the bulkheads will indicate whether, and at approximately what rate, the level of stored water in the inter-dike compartments behind the bulkheads is being lowered. Whenever pressures indicate that the head of stored water is being lowered too much, the rate of flow from the tunnel should be reduced. In that way water can be conserved in the dike complex for use in time of need.[56]

The need of large amounts of water for irrigation on the Hoolehua Plain has long been recognized. Large amounts of water are available, but there is no cheap way of delivering it to the area where it is needed. The possible sources of water are the large windward valleys, or a series of wells on the southern slope of East Molokai. The necessary large amounts of water could be obtained by Maui-type wells along the southern slope east of Kawela, but delivery to the Hoolehua agricultural areas would entail expensive pipe lines and the cost of pumping. The better solution appears to be the construction of a series of tunnels, such as those proposed by Howell and Austin, to bring the water in from the windward valleys. (See pages 81–84).

Another possibility is the construction of a pipe line to carry water from an intake at about 1,000 feet altitude on Waikolu Stream, around by way of the coast to Hoolehua. The pipe could be laid along a narrow bench excavated in the windward cliff, crossing Waileia and Waihanau Valleys with siphons. An intake at 1,000 feet altitude on Waikolu Stream would impound most of the low-stage flow of the stream, or probably never less than 2 million gallons daily. This could, if desired, be augmented by a development tunnel in the head of the valley. It should be possible

[55] Austin, H. A. R., Unpublished letter to Frank West, Chairman, Hawaiian Homes Commission, Feb. 11, 1944.

[56] Stearns, H. T., and Vaksvik, K. N., Geology and ground-water resources of the island of Oahu, Hawaii: Hawaii Div. Hydrography, Bull. 1, p. 435, 1935.

by this means to deliver 2 million gallons of water daily to the Hoolehua Plain at an altitude of 650 feet, through a 12-inch pipe line approximately 12 miles long.

Water from the windward valleys could be delivered to the southern slope for irrigation by means of tunnels such as those suggested by Lindgren. The shortest route would be that from Wailau Valley to Mapulehu Gulch. Water from such a tunnel at Mapulehu Gulch could be brought out along the eastern wall of the valley to a point at about 650 feet altitude near the end of the spur, then dropped several hundred feet for the generation of electricity.

PAGE 88

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PETROGRAPHY OF MOLOKAI

By

Gordon A. Macdonald

ABSTRACT

The lower member of the East Molokai volcanic series consists predominantly of olivine basalt, with smaller amounts of basalt and picrite-basalt. In the lower part of the section the picrite-basalts are of the primitive type, containing numerous large phenocrysts of olivine. In the upper part of the section appear picrite-basalts containing many large phenocrysts of augite as well as olivine. The upper member consists principally of oligoclase andesite, with minor amounts of andesine andesite and trachyte. A chemical analysis of a typical oligoclase andesite is given. In and near the caldera complex many of the lavas were partly chloritized, and amygdules and nodules of calcite and quartz were deposited, probably by rising igneous volatiles. In the same area the lavas are intruded by small masses of olivine gabbro.

The lavas of the West Molokai volcanic series are olivine basalts, picrite-basalts of the primitive type, and basalts. The latter are considerably more abundant than in other Hawaiian volcanoes. A few basalts contain a small amount of hypersthene.

Following a long period of erosion on East Molokai Volcano, an eruption of mafic olivine basalt built the Kalaupapa Peninsula at the foot of the great northern cliff; at about the same time an eruption of similar magma off the eastern coast of Molokai built the Mokuhooniki tuff cone.

At West Molokai Volcano, the parent olivine basalt underwent only minor differentiation. But in East Molokai Volcano it was differentiated toward the end of the eruptive cycle into augite-rich picrite-basalts, andesites, and trachytes. The suite as a whole is typical of mid-oceanic volcanoes.

INTRODUCTION

The petrographic study is based largely on the examination in thin section of 121 specimens, from localities scattered over the entire island, supplemented by field studies and the laboratory examination of hand specimens. The specimens were collected by H. T. Stearns, D. J. Cederstrom, and the writer, during the course of geological and ground-water investigations of the island. A chemical analysis of a specimen of oligoclase andesite was made by Sadamoto Iwashita, in the laboratories of the University of Hawaii.

The compositions of feldspars were determined largely by immersion methods, but partly by extinction angles. Optic axial angles were estimated from the appearance of optic axis or acute bisectrix interference figures.

Rocks in which the average feldspar is labradorite are classed as basaltic; those in which it is andesine or oligoclase as andesites; and those in which it is albite, as trachytes. The andesites are divided into andesine andesites and oligoclase andesites, depending on the composition of the average feldspar. Basaltic rocks in which olivine forms less than 5 percent are classed as basalts. Those in which olivine forms 5 percent or more, and feldspar 30 percent or more, are classed as olivine basalts. Those (essentially holocrystalline) rocks in which feldspar comprises less than 30 percent are classed as picrite-basalts.

PREVIOUS INVESTIGATIONS

The earliest, and only other extensive investigation of the petrography of Molokai is that by Möhle,[1] who studied about 50 specimens of lava and several of tuff collected by Schauinsland. Although Möhle states that the localities were scattered over the entire island, most of the specimens came from the great northern cliff of East Molokai or its immediate vicinity. The lavas were divided into three groups. Those of the first group were described as normal olivine-bearing basalts, characterized by large feldspar phenocrysts. Their olivine content was not large, but moderately uniform. All but one came from the cliff behind Kalaupapa Peninsula. The rocks of the second group were reddish-brown lavas in which olivine was nearly or totally absent. They were believed to represent flow crusts. In the third group pyroxene was said to be present in only small amount, or absent altogether, its place being taken by abundant olivine. One contained irregular flakes of biotite. The first two of these groups may correspond with the olivine basalts and basalts of the present paper, but the writer has found no rocks which correspond to Möhle's description of those of his third group, either on Molokai, or on any other of the Hawaiian Islands. A dense dark basalt from Kalae was described by Möhle as containing a few four- and six-sided cross-sections of nepheline, and was classed as "nepheline basanitoid." No rock of this sort has been found on Molokai during the present investigation, and either the locality or the determination of nepheline must be regarded as erroneous. A small "bomb," about the size of a hen's egg, was reported to consist of

[1] Möhle, F., Beitrag zur Petrographie der Sandwich- und Samoa- Inseln: Neues Jahrb., Beil. Bd. 15, pp. 71-82, 1902.

orthorhombic pyroxene, olivine, monoclinic pyroxene, and picotite, and was compared to similar bombs from Oahu. No rock of this sort has been found during the present study. It is possible that both these specimens were mislabeled, and actually came from the late volcanics (Honolulu volcanic series) on Oahu. A specimen of olivine gabbro was not unlike some of those described in the present report.

Lindgren[2] paid little attention to the lavas of Molokai, describing them briefly as principally normal "feldspar basalt," containing olivine, and in part also phenocrysts of soda-lime feldspar. From the west fork of Wailau Valley he described boulders of a coarse-grained intrusive rock, termed by him olivine diabase, composed of calcic plagioclase, augite, olivine and magnetite. The rock is undoubtedly the same as that described on a later page of this report as olivine gabbro.

Cross[3] reviewed the work of both Möhle and Lindgren, but added no new descriptions.

Powers[4] recorded the presence of basalt with abundant olivine, "feldspar basalt" with conspicuous phenocrysts of plagioclase, and nonporphyritic olivine-free basalt at West Molokai Volcano. East Molokai Volcano he believed to consist "largely of feldspar basalt with rare alkali trachyte". He compared the lavas to those of Kohala Volcano on Hawaii. He described a basaltic rock, containing feldspar phenocrysts "sometimes one or two inches long and 1/4 inch thick," larger than any observed by the writer. The lava forming the Kalaupapa Peninsula was recognized as olivine basalt.

[2] Lindgren, W., The water resources of Molokai, Hawaiian Islands: U. S. Geol. Survey, Water-Supply Paper 77, pp. 14-15, 1903.

[3] Cross, W., Lavas of Hawaii and their relations: U. S. Geol. Survey, Prof. Paper 88, pp. 24-25, 1915.

[4] Powers, S., Notes on Hawaiian petrology: Am. Jour. Sci., 4th ser., vol. 50, pp. 259, 269, 271, 1920.

TERTIARY VOLCANIC ROCKS

EAST MOLOKAI VOLCANIC SERIES

LOWER MEMBER

General characteristics.—The lower member of the East Molokai volcanic series comprises the great mass of little-differentiated basaltic lavas which built the primitive shield volcano. By far the most abundant type of rock is olivine basalt, but there also occur flows of basalt containing little or no olivine, and others of picrite-basalt containing very abundant phenocrysts of olivine or olivine and augite. The flows are both aa and pahoehoe in type. Locally, there are found between the flows thin beds of vitric ash and ashy soil.

The lavas of the caldera complex are of the same type as those outside the caldera, and originally differed from them only in greater massiveness and thickness owing to ponding. Within the area of the former caldera, however, the lavas are characterized by a large amount of secondary mineralization, presumably the result of the rise of abundant volatiles in the volcanic focus. Normally, on the outer slopes of the volcano the lavas are not amygdaloidal, even a thin layer of calcite in the vesicles being rare, but in the caldera area amygdules and vesicle linings are very common. The commonest secondary mineral is calcite, but quartz and chalcedony are nearly as abundant. In addition to vesicle linings and amygdules, quartz and chalcedony occur as irregular nodules, up to 6 inches or more across. Accompanying the deposition of secondary quartz and calcite, many of the lavas were partly chloritized, the chlorite being derived partly from ferromagnesian minerals and partly from interstitial glass. Similar hydrothermal alteration and secondary mineralization are found in the Kailua area on Oahu, which is interpreted as the ancient caldera of the Koolau Volcano,[5] and less conspicuously in the caldera area of the Waianae Volcano on Oahu.

The general character of the lower member of the East Molokai volcanic series is well shown in the following stratigraphic section, measured along the trail which leads from Kalae down the great northern cliff to the Kalaupapa leper settlement (plate 1).

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[5] Stearns, H. T., and Vaksvik, K. N., Geology and ground-water resources of the island of Oahu, Hawaii: Hawaii Div. Hydrog., Bull. 1, pp. 88-90, 1935; Stearns, H. T., Supplement to geology and ground-water resources of the island of Oahu, Hawaii: Hawaii Div. Hydrog., Bull. 5, pp. 48-50, 1940.

Stratigraphic section of East Molokai volcanic series along the trail from Kalae to Kalaupapa

Member		Thickness (feet)
Upper member	Andesite aa, dense and nonporphyritic	16
	Baked red soil	0–½
	Andesite aa, dense and nonporphyritic	57
	Andesite aa clinker	8
	Andesite aa, nonporphyritic	10
	Andesite aa clinker	6
	Andesite aa, dense and nonporphyritic	10
	Andesite aa clinker	8
	Andesite aa, with a few feldspar phenocrysts up to 2 mm long	29
	Andesite aa clinker	27
	Andesite aa, dense and nonporphyritic	28
Lower member	Red ashy soil	¼–1
	Olivine basalt aa clinker, weathered red at top	4
	Olivine basalt aa, with moderately abundant olivine phenocrysts up to 5 mm long	8
	Aa clinker	3
	Olivine basalt aa, with moderately abundant olivine phenocrysts up to 3 mm long	5
	Aa clinker	4
	Olivine basalt aa, with scattered phenocrysts of olivine and feldspar up to 4 mm long	12
	Olivine basalt pahoehoe, with abundant feldspar phenocrysts up to 1 cm long, and a few of olivine and augite up to 5 mm long. Many flow units averaging about 5 feet thick	71
	Olivine basalt aa, with abundant feldspar phenocrysts up to 5 mm long	26
	Aa clinker	12
	Olivine basalt aa, with moderately abundant phenocrysts of feldspar, olivine, and augite up to 7 mm long	21
	Olivine basalt pahoehoe, with moderately abundant phenocrysts of olivine and feldspar up to 6 mm long, and a few of augite. Several thin flow units	22
	Basalt pahoehoe, nonporphyritic; many flow units averaging about 4 feet thick; in many places clinkery and transitional to aa	49
	Olivine basalt aa, with a few phenocrysts of olivine up to 3 mm long	4
	Aa clinker	3
	Basalt aa, with moderately abundant feldspar phenocrysts up to 5 mm long	3
	Aa clinker	2
	Basalt aa, like above	3
	Olivine basalt aa, with moderately abundant olivine phenocrysts up to 5 mm long, and less abundant feldspar phenocrysts up to 2 mm; contains large irregular masses of clinker	17
	Talus	60
	Aa clinker	3
	Olivine basalt aa, with moderately abundant phenocrysts of olivine and feldspar up to 3 mm long	3
	Aa clinker	5
	Olivine basalt aa, like above	9
	Red decomposed vitric ash	0–½
	Olivine basalt pahoehoe, with moderately abundant phenocrysts of feldspar up to 4 mm long, and a few of olivine up to 2 mm; the flow units averaging 4 to 5 feet thick	25
	Olivine basalt aa, with moderately abundant phenocrysts of olivine up to 8 mm long, and a few of feldspar up to 3 mm	6
	Picrite-basalt pahoehoe, with abundant phenocrysts of olivine up to 7 mm long and augite up to 1 cm; several thin flow units	15

Stratigraphic Section—(continued)

Lower member

Aa clinker	3
Picrite-basalt aa, with abundant phenocrysts of olivine and augite up to 5 mm long	6
Aa clinker	2
Picrite-basalt aa, with abundant phenocrysts of olivine and a few of augite up to 6 mm long	2
Aa clinker	4
Picrite-basalt aa, like above	12
Aa clinker	4
Picrite-basalt aa, like above	9
Olivine basalt pahoehoe, dense, with moderately abundant phenocrysts of olivine and feldspar up to 7 mm long	22
Picrite-basalt pahoehoe, with abundant phenocrysts of olivine and augite up to 8 mm long; many flow units averaging 4 to 5 feet thick	70
Picrite-basalt aa, same composition as overlying pahoehoe	9
Picrite-basalt pahoehoe, same composition as overlying aa	8
Red decomposed vitric ash	0–¼
Picrite-basalt pahoehoe, with abundant olivine phenocrysts up to 4 mm long	4
Red decomposed vitric ash	0–½
Basalt pahoehoe, with a very few phenocrysts of olivine and feldspar up to 1 mm long; thin flow units averaging about 4 feet thick	27
Aa clinker	7
Olivine basalt aa, with moderately abundant phenocrysts of olivine and feldspar up to 5 mm long	8
Olivine basalt aa, with moderately abundant phenocrysts of feldspar up to 3 mm long, and olivine up to 1 mm	14
Olivine basalt pahoehoe, with scattered phenocrysts of olivine up to 3 mm long and feldspar up to 2 mm	4
Aa clinker	3
Olivine basalt aa, like overlying pahoehoe	5
Aa clinker	1
Picrite-basalt aa, with abundant phenocrysts of olivine up to 6 mm long; dense and massive	21
Picrite-basalt pahoehoe, with abundant phenocrysts of olivine up to 5 mm long and moderately abundant phenocrysts of augite up to 8 mm	16
Picrite-basalt aa, with abundant olivine phenocrysts up to 7 mm long; massive and dense	27
Picrite-basalt aa, like above but clinkery	9
Basalt pahoehoe, with moderately abundant feldspar phenocrysts up to 1.5 mm long	6
Basalt pahoehoe, like above but with rare phenocrysts of olivine up to 4 mm long	6
Olivine basalt pahoehoe, with moderately abundant feldspar phenocrysts up to 3 mm long, and scattered olivine phenocrysts up to 1 mm	4
Olivine basalt pahoehoe, like above	8
Olivine basalt pahoehoe, like above, locally clinkery at top	9
Olivine basalt pahoehoe, like above	9
Olivine basalt pahoehoe, with moderately abundant olivine phenocrysts up to 5 mm long; locally clinkery at top and transitional toward aa	8
Aa clinker	4
Olivine basalt aa, with moderately abundant olivine phenocrysts up to 4 mm long, and feldspar phenocrysts up to 2 mm	4
Olivine basalt pahoehoe, with scattered olivine phenocrysts up to 1 mm long	8
Aa clinker	6
Olivine basalt aa, with moderately abundant olivine phenocrysts up to 6 mm long, and feldspar phenocrysts up to 2 mm	8

Stratigraphic Section—(continued)

Lower member	Aa clinker	3
	Olivine basalt aa, with moderately abundant phenocrysts of feldspar up to 2 mm long, and less abundant olivine phenocrysts up to 3 mm	5
	Talus	10
	Olivine basalt pahoehoe, with moderately abundant feldspar phenocrysts up to 2 mm long, and scattered olivine phenocrysts up to 5 mm	5
	Talus	60
	Olivine basalt aa, dense, with moderately abundant phenocrysts of olivine up to 5 mm long, and feldspar up to 3 mm	28
	Aa clinker	9
	Basalt aa, with scattered phenocrysts of feldspar up to 4 mm long	5
Talus, to base of cliff		516
	Total thickness of section	1610

Olivine basalts.—Nearly all the olivine basalts of the East Molokai volcanic series are porphyritic. Most nonporphyritic rocks contain less than 5 percent olivine, and are therefore classed with the basalts. Rarely, however, rocks lacking megascopically visible phenocrysts contain enough olivine to place them in the group of olivine basalts.

Nearly all the specimens of olivine basalt contain phenocrysts of feldspar, which range in length from a millimeter to a centimeter, or rarely 1.5 cm. The feldspar phenocrysts consist of a calcic core, ranging in composition in different rocks from medium bytownite to calcic labradorite, enclosed in a thin more sodic shell having the same composition as the groundmass feldspar, medium or sodic labradorite. The calcic cores generally are of uniform composition from the center to the edge, though rarely they show weak normal zoning. In many rocks the cores were slightly rounded by resorption before deposition of the outer shell. In most rocks the feldspar phenocrysts are associated with others of olivine or olivine and augite. Rarely, however, feldspar phenocrysts alone are found. Thus, a specimen from near the summit of Olokui Peak contains large phenocrysts of sodic bytownite only, largely altered by weathering to an isotropic colorless material with a refractive index of 1.50, probably a clay mineral resembling allophane; and a specimen from 1,060 feet altitude in Kapuhi Stream, in the caldera complex, contains only phenocrysts of labradorite-bytownite, enclosed in narrow rims of medium labradorite.

Olivine phenocrysts are present in most specimens, ranging in size up to 8 mm, and rarely 1 cm. They have an optic axial angle close to 90°, indicating a content of about 85 percent forsterite.[6]

[6] Deer, W. A., and Wager, L. R., Olivines from the Skaergaard intrusion, Kangerdlugssuag, East Greenland: Am. Mineralogist, vol. 24, pp. 18-25, 1939.

They are generally rounded and embayed by magmatic resorption, and in many rocks they are altered around the edges and along fractures to iddingsite. In some specimens, such as one collected at 300 feet altitude in Kaunakakai Gulch, the iddingsite is enclosed in thin shells of fresh olivine which tend to restore the enhedral outlines of the crystals. The recurrence of iddingsite within rims of fresh olivine, associated with fresh olivine in the groundmass, indicates that it was formed prior to crystallization of the groundmass, probably as the result of high concentration of volatiles (and possibly reduced pressure) during and just preceding eruption.[7] In other rocks, however, both the phenocrysts and the groundmass olivine are partly altered to iddingsite or a material closely resembling it, and in these rocks the alteration appears to be probably the result of ordinary weathering. In some rocks in the caldera complex, olivine phenocrysts are replaced by pseudomorphs of chloritic and serpentinous material. Olivine phenocrysts occur alone in a few rocks, but in most rocks they are accompanied by feldspar phenocrysts and in some by augite phenocrysts.

Augite phenocrysts are common, although less so than olivine or feldspar. They are decidedly more numerous in the late lavas of the lower member of the East Molokai volcanic series, exposed widely over the southern slopes, than in the earlier lavas of that member which crop out in the lower parts of the big valleys and the great northern cliff. In some specimens they reach a length of 1 cm. They have an optic angle of 50 to 60°, moderately strong inclined dispersion, and $\beta = 1.700$ to 1.703. In some rocks they are partly rounded by resorption. In many rocks they show a thin outer zone of pigeonitic augite or pigeonite, the latter probably deposited coevally with the pyroxene of the groundmass. The trend in pyroxene crystallization is thus toward a more iron-rich pyroxene, as pointed out by Barth.[8]

Phenocrysts and microphenocrysts of magnetite occur in a few rocks, and rarely reach a diameter of 1 mm. In some they are well formed, but in others they are skeleton crystals enclosing a large proportion of groundmass material.

Particular mention should be made of a type of olivine basalt, found quite commonly near the top of the lower member, which

[7] Edwards, A. B., The formation of iddingsite: Am. Mineralogist, vol. 23, pp. 277-281, 1938.
Macdonald, G. A., Petrography of Kahoolawe: Hawaii Div. Hydrography, Bull. 6, pp. 155-156, 1940.

[8] Barth, T. F. W., Crystallization of pyroxenes from basalts: Am. Mineralogist, vol. 16, pp. 195-208, 1931; The crystallization process of basalts: Am. Jour. Sci., 5th ser., vol. 31, pp. 324-328, 1936.

contains abundant large crystals of all three of the common phenocrystic minerals, feldspar, olivine, and augite. The three are generally present in nearly equal abundance, and together comprise as much as 40 or 50 percent of the rock. The abundance of phenocrysts suggests that at the close of eruption of the lower member the basaltic magma of the reservoir had reached a temperature at which it was supersaturated in all the major silicate constituents.

The groundmass of the olivine basalts is intergranular or intersertal, with an average grain size ranging from about 0.03 mm to 0.1 mm. In general, the pahoehoe is intersertal, and the aa is intergranular; and the average granularity of the pahoehoe is somewhat greater than that of the aa. However, the variation is so great as to make this generalization very tenuous. The principal constituents of the groundmass are feldspar and monoclinic pyroxene, the latter being generally only a little the less abundant. The feldspar ranges from medium to sodic labradorite. In most specimens the pyroxene is pigeonite, with 2V close to 0°, but in a very few it is augite. Olivine occurs in the groundmass of all the olivine basalts. In many it is stained pale brownish-green by slight alteration, and in some it is altered to iddingsite or material closely resembling it. Black opaque oxides form 5 to 15 per cent of the rock. They generally include both magnetite and ilmenite, though in a few rocks magnetite alone appears to be present. Apatite appears in many specimens as minute highly acicular crystals generally enclosed in feldspar. Several specimens contain small flakes of biotite, pleochroic from pale straw yellow to deep reddish-brown. The biotite flakes are anhedral, lying between the other constituents, or project into vesicles. They were formed during a very late magmatic or post-magmatic stage. Interstitial glass is present in the rocks with intersertal texture. It is pale brown to colorless, the color generally becoming deeper with an increase in amount. Except in pahoehoe crusts, however, the proportion of glass does not much exceed 5 percent. Within the caldera complex some rocks contain interstitial chlorite, apparently derived in part from glass, and in part from ferromagnesian constituents of the groundmass.

Basalts.—The basalts are essentially like the olivine basalts, except that olivine is sparse or entirely absent. Gradations to the olivine basalts occur. A few specimens are nonporphyritic, but most contain scattered to moderately abundant phenocrysts of feldspar. The maximum size of the phenocrysts is less than in the olivine basalts, the greatest length observed being 7 mm. The cores of the phenocrysts are labradorite-bytownite to calcic labradorite; the thin rims are medium to sodic labradorite. Rarely, a few phenocrysts of olivine are present, and these may be partly altered to iddingsite. The groundmass is intergranular or intersertal, composed of medium to sodic labradorite, monoclinic pyroxene, magnetite, ilmenite, a little apatite, and glass. Olivine is lacking or present in very small amount. Where its nature has been determined, the pyroxene is pigeonite.

Within the caldera complex many of the rocks have been considerably chloritized. In a nonporphyritic basalt collected at 1,230 feet altitude along Pelekunu Stream the ferromagnesian minerals have been almost entirely destroyed, although the feldspar (medium labradorite) appears to have been little affected. There remains only an aggregate of feldspar, chlorite, iron oxides, and calcite. In a basalt from 1,440 feet altitude in Pulena Stream, a tributary of Wailau Stream, feldspar phenocrysts are altered to an aggregate of calcite, chlorite, and a clay mineral with low birefringence and a refractive index of about 1.54. The groundmass consists of plagioclase, iron oxide, and abundant chlorite. Residuals of fresh feldspar appear to be medium labradorite, but much of it is altered to a more sodic feldspar, apparently oligoclase.

PICRITE-BASALTS.—The picrite-basalts also are intergradational with the olivine basalts, differing from them principally in the greater proportion of ferromagnesian minerals. As in other Hawaiian volcanoes,[9] two types of picrite-basalt can be recognized. One of these is characterized by the abundance of olivine phenocrysts, either alone or with a few phenocrysts of feldspar or augite. The other contains phenocrysts of both olivine and augite, in roughly equal abundance, with or without a few phenocrysts of feldspar. The first type occurs associated with olivine basalt and basalt in the primitive lava shields of Hawaiian volcanoes, and has been termed the primitive type of picrite-basalt. The second type, termed the augite-rich type of picrite-basalt, appears later in the stratigraphic succession of those volcanoes erupting more highly differentiated lavas.

In the lower member of the East Molokai volcanic series, picrite-basalts of the primitive type appear low in the section, in the big valleys and in the northern cliff. Olivine phenocrysts reach a length of about 8 mm, and may comprise as much as 50 percent of the rock. They have a 2V close to 90°. Typically they are partly resorbed, and in many rocks they are partly altered to iddingsite. In some the iddingsite is enclosed in a shell of fresh olivine. The groundmass is like that of the olivine basalts.

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

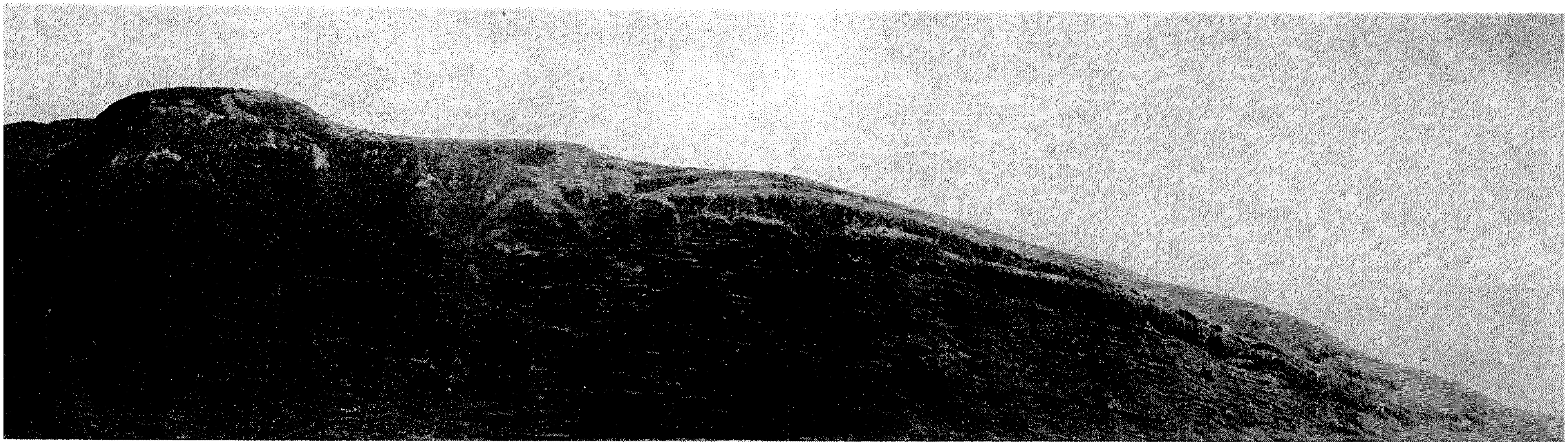

Plate 14A. East wall of Kamalo Gulch, from the west, showing thin-bedded basalts of the lower member of the East Molokai volcanic series overlain by the Kaapahu viscous dome and thick flow of andesite. Photo by G. A. Macdonald.

Plate 14B. East Molokai from Kaunakakai wharf, showing its general domical profile, cinder cones along the rift zone, the steep southern slope, and the alluvial flats along the coast. Photo by G. A. Macdonald.

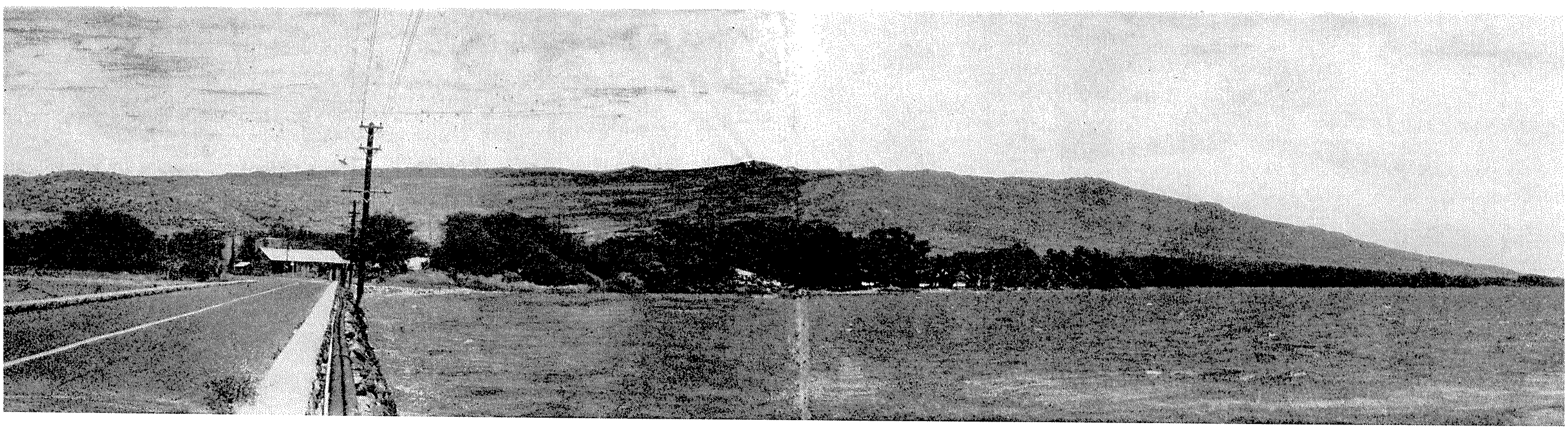

Plate 15A. Thin-bedded aa and pahoehoe lavas of the West Molokai volcanic series, near Halena. Small filled and partly filled pahoehoe tubes are clearly visible. Photo by C. K. Wentworth.

Plate 15B. Oligoclase andesite of the upper member of the East Molokai volcanic series, resting on residual soil at the top of the basalts of the lower member, in a roadcut 0.2 mile northeast of Waialua. Photo by G. A. Macdonald.

Augite-rich picrite-basalts occur in the upper part of the section, their range overlapping somewhat that of the primitive type (see stratigraphic section, page 93). Olivine phenocrysts resemble in size, composition, and alteration those of the primitive type. Augite phenocrysts reach a length of 1 cm. They have an optic angle of 50° to 60°, and moderate to strong inclined dispersion. Many are zoned, the outer part having a smaller extinction angle and smaller 2V than the core. Augite phenocrysts are generally about equal in abundance, or are slightly more abundant, than those of olivine, and together they constitute 40 to 60 percent of the rock. A few feldspar phenocrysts are present in some specimens, consisting of cores of medium or sodic bytownite enclosed in thin shells of calcic to medium labradorite. Through an increase in the abundance of feldspar phenocrysts these rocks grade into the type of olivine basalt rich in large phenocrysts of feldspar, olivine, and augite, described above. The groundmass is essentially the same as that of the olivine basalts, although in analyzed specimens from Haleakala Volcano, on Maui,[10] subtraction of the composition of the phenocrysts and recalculation of the remainder to 100 percent, shows the groundmass to be somewhat more femic than the ordinary olivine basalts.

UPPER MEMBER

General features.—The lavas of the upper member of the East Molokai volcanic series, which form a thin cap over the East Molokai basaltic shield volcano (pl. 14A), are predominantly oligoclase andesite. In a few specimens, otherwise essentially like the rest, the feldspar is sodic andesine. Trachytes have been identified at only two localities, but at other of the viscous domes in the wet summit area the rocks are too much weathered for certain identification. It is probable that some of these also are trachytes.

The rocks of the upper member of the East Molokai volcanic series closely resemble those of the Honolua volcanic series on West Maui,[11] and the Hawi volcanic series of Kohala Volcano on the island of Hawaii.[12]

Oligoclase andesites.—The typical oligoclase andesites are medium to light gray rocks, with moderately to well developed platy jointing parallel to the flow surface (pl. 15B). Platy joint blocks

[10] Macdonald, G. A., and Powers, H. A., Contribution to the petrography of Haleakala Volcano, Hawaii: Geol. Soc. America Bull., vol. 57, pp. 115-124, 1946.

[11] Macdonald, G. A., Petrography of Maui: Hawaii Div. of Hydrog., Bull. 7, pp. 320-325, 1942.

[12] Macdonald, G. A., Petrography of Hawaii: Hawaii Div. of Hydrog., Bull. 9, p. 196, 1946.

generally exhibit a distinct micaceous-appearing, almost schistose sheen, owing to the parallel arrangement of innumerable small tabular feldspar crystals. Rare pahoehoe flow-types occur, but much more abundant are flows of the aa type. In many of the latter, the fragments in the scoriaceous part of the flow are more rhomboid and less clinkery and spinose than in typical aa, and the flows approach the type characteristic of andesite volcanoes, known as block lava.[13] Porphyritic and nonporphyritic forms are nearly equally abundant. Of the 43 specimens studied, 19 are nonporphyritic and 24 porphyritic. The phenocrysts are preponderantly feldspar. Only 4 specimens contain phenocrysts of olivine, and two of these contain feldspar phenocrysts as well.

The feldspar phenocrysts range from sparse to moderately abundant. They are generally 1 to 2 mm long, but rarely attain lengths as great as 8 mm, and one specimen contains a phenocryst of labradorite-andesine 2 cm long, much rounded by resorption. They show normal zoning, the soda content increasing outward. The core is generally medium andesine, less commonly sodic andesine, and still less commonly calcic andesine. In one specimen, mentioned above, the core is labradorite-andesine, and in one it is sodic labradorite. The outer shell of the phenocrysts is calcic or medium oligoclase, of the same composition as the feldspar of the groundmass.

Olivine phenocrysts of megascopic size are generally rare and less than 2 mm in length. However, in one specimen, collected on the ridge 0.2 mile S. 85° W. of Pualanalana Bay, olivine phenocrysts reach a length of 3 mm, and form about 5 percent of the rock. They have $-2V = 75°$, corresponding to a forsterite content of about 55 percent. Although megaphenocrysts of olivine are rare, microphenocrysts are present in most of the specimens studied. They are generally partly, or even entirely, altered to iddingsite. In a few thin sections the iddingsite is surrounded by a thin envelope of fresh olivine, and in many the groundmass olivine is fresh, indicating that the altered microphenocrysts are probably of intratelluric origin.

Magnetite microphenocrysts, up to about 0.7 mm across, are present in about two-thirds of the specimens.

A few specimens contain microphenocrysts, up to about 0.5 mm long, of an acicular amphibole resembling riebeckite, but less strongly colored. This mineral has been found also in the oligoclase andesites of West Maui and Kohala. It has $X \wedge c$ small, $+2V$ large, birefringence very low, and distinct pleochroism with X = brownish-gray and Z = pale brownish-yellow.

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

The groundmass of the oligoclase andesites is generally trachytic. The principal constituents are feldspar and monoclinic pyroxene, with smaller amounts of olivine and opaque iron oxides. The feldspar is calcic to medium oligoclase. In some of the rocks some or all of the oligoclase has a small positive optic angle, and is probably potassic.[14] The pyroxene is colorless in thin section. In all specimens in which its properties were determined, it is pigeonite. The olivine is generally fresh, but in some rocks it is stained pale brownish-green by slight alteration. In most rocks the opaque mineral is largely or entirely magnetite, but in others both magnetite and ilmenite are present. Irregular flakes of hematite occur in some specimens. Fairly commonly, the larger grains of pyroxene exhibit sieve structure, and over small areas small irregular patches of pyroxene scattered amongst grains of the other minerals show common orientation. Numerous minute highly acicular grains of apatite are enclosed in the feldspar. Interstitial colorless glass is present in a few rocks, and in others there is a little interstitial chlorite. Small grains of the riebeckite-like amphibole are present in the groundmass of several specimens.

About half the rocks studied contain a few small flakes of brown biotite. In a specimen collected 0.25 mile southwest of the triangulation station on Ooa Hill it is unusually abundant, forming flakes up to 0.3 mm long, occupying interstices between the other minerals and projecting into vesicles. It obviously was formed in a very late magmatic or postmagmatic stage. It has $-2V = 20°$, $r < v$ strong, and strong pleochroism with $X =$ pale yellow to nearly colorless, $Z =$ deep reddish-brown.

A few small grains of greenish-brown hornblende are present in the groundmass of an oligoclase andesite flow exposed in an old railroad cut near the eastern edge of Kaluaapuhi Pond, and another at the eastern rim of the gulch 0.6 mile N. 37° W. of the northwestern corner of Puhiomu Pond. The latter specimen, and two others, contain pseudomorphs of finely granular magnetite replacing some prismatic mineral, possibly hornblende or possibly the riebeckite-like amphibole.

A chemical analysis of a typical specimen of oligoclase andesite is given in column 1 of the accompanying table. The specimen was collected along the highway from Kaunakakai to the airport, at 380 feet altitude, 0.35 mile N. 19° W. of benchmark 354. The rock is medium gray, dense, and nonporphyritic in hand specimen, with moderately well developed platy jointing, and a micaceous-appear-

[14] Macdonald, G. A., Potash-oligoclase in Hawaiian lavas: Am. Mineralogist, vol. 27, pp. 793-800, 1942.

ing sheen on the joint surfaces. In thin section microphenocrysts of feldspar and olivine are seen to grade in size into the groundmass. The olivine crystals are fresh and euhedral. The feldspar phenocrysts consist of cores of sodic andesine, enclosed in thin shells of medium oligoclase. A few grains of magnetite and the riebeckite-like mineral also attain the dimensions of microphenocrysts. The trachytic groundmass consists of medium oligoclase, monoclinic pyroxene, olivine, opaque iron oxides, minute needles of apatite, a few flakes of purplish-brown biotite, and a few grains of the riebeckite-like mineral. The iron oxides include both magnetite and ilmenite, with the former predominant. Many of the feldspar phenocrysts show a small optic angle, which appears to be the result of overlapping Carlsbad twin lamellae, as described by Sugi.[15] Many grains of the untwinned groundmass oligoclase also show a small positive optic angle, which is believed to indicate a small admixture of potash feldspar. The approximate mineral composition of the rock, estimated by means of traverses with a grilled ocular, is: plagioclase phenocrysts 8%, groundmass feldspar 50%, pyroxene 22%, olivine 5%, iron oxides 12%, apatite 2%, riebeckite-like mineral and biotite 1%.

CHEMICAL ANALYSES OF OLIGOCLASE ANDESITES

	(1)	(2)
SiO_2	53.14	51.35
Al_2O_3	14.60	16.34
Fe_2O_3	5.74	4.64
FeO	7.72	6.19
MgO	2.50	3.73
CaO	5.44	6.61
Na_2O	4.64	5.01
K_2O	2.20	1.94
H_2O+	0.38	....
H_2O-	0.22	....
TiO_2	2.74	2.74
P_2O_5	1.03	1.00
MnO	0.26	0.20
Total	100.61	....

Norms

	(1)	(2)
Q	2.22	....
or	12.79	11.12
ab	39.30	42.44
an	12.51	16.40
di	15.55	8.04
hy	3.95	3.96
ol	....	3.54
mt	8.35	6.73
il	5.17	5.17
ap	2.35	2.35

(1) Oligoclase andesite, upper member of East Molokai volcanic series; on highway from Kaunakakai to Hoolehua airport, at 380 feet altitude. S. Iwashita, analyst.

(2) Average oligoclase andesite of the Hawaiian Islands; average of 11 analyses, including one "oligoclase gabbro" (kauaiite). Macdonald, G. A., The Hawaiian petrographic province: in preparation.

Compared to the average analysis of oligoclase andesite of the Hawaiian Islands, shown in column 2 of the table, the Molokai

[15] Sugi, K., On the nature of some plagioclase apparently with small optical angle. . . .: Kyushu Imp. Univ., Fac. Sci. Mem., ser. D, vol. 1, pp. 1-22, 1940.

specimen is a little more silicic, as shown by the presence of quartz and absence of olivine in the norm, slightly richer in potash and iron oxide, and slightly poorer in alumina, magnesia, lime, and soda.

ANDESINE ANDESITES.—The andesine andesites are essentially identical to the oligoclase andesites except for the slightly more calcic nature of the plagioclase. Only four occurrences of this type of rock were found. The dominant feldspar is sodic andesine. All other constituents are the same as those of the oligoclase andesites. The rocks are much more like the oligoclase andesites than the typical andesine andesites of Haleakala Volcano on Maui, or Mauna Kea on Hawaii, and are to be regarded as merely the most calcic members of the oligoclase andesite group.

TRACHYTES.—Rocks definitely identified as trachyte have been found only at the viscous dome of Puu Kaeo, on the western rim of Waikolu Valley, and the small cinder cone Puu Anoano, 1.3 miles west-northwest of Kalae. Specimens from some of the other vents in the swampy area near the rims of Waikolu and Pelekunu Valleys may be trachyte, but are too weathered for certain identification. The presence of trachyte in the drainage basin of Wailau Valley is proven by the discovery by Powers[16] of a trachyte stream pebble near the mouth of that valley. The trachytes of Puu Kaeo and Puu Anoano are closely similar to those of West Maui.

The rock from Puu Kaeo is light gray and dense, with many tabular phenocrysts of feldspar, up to 2 mm long, arranged in a fluidal texture. The rock is considerably weathered. The centers of the feldspar phenocrysts are altered to a fine-grained aggregate of clay minerals, leaving only a thin rim of fairly fresh calcic albite. The trachytes of West Maui contain phenocrysts of calcic to medium oligoclase enclosed in a thin shell of albite,[17] and it is probable that the phenocrysts of the trachyte of Puu Kaeo originally had a similar composition. A few small phenocrysts of some former acicular mineral, possibly hornblende, much rounded and embayed by resorption, are now represented only by pseudomorphs of finely granular magnetite. Microphenocrysts of magnetite up to 0.2 mm across, and a few of olivine and augite, also are present. Those of olivine are partly altered to iddingsite. The groundmass is a very fine grained aggregate of calcic albite, monoclinic pyroxene, magnetite, and decomposition products. It is not impossible that the albite was derived from some originally more calcic feldspar, by weathering,

[16] Powers, S., op. cit., p. 271.

[17] Macdonald, G. A., Petrography of Maui: Hawaii Div. of Hydrog., Bull. 7, p. 324, 1942.

but this seems unlikely as the groundmass feldspar appears to be fairly fresh.

The trachyte of Puu Anoano is very similar to that of Puu Kaeo, even to the decomposition of the cores of the feldspar phenocrysts. The groundmass appears fairly fresh, and is a little coarser than that of the other rock. The iron oxide is largely magnetite, but a little of it appears to be ilmenite. The pyroxene is pigeonite.

INCLUSIONS IN LAVAS.—A few flows of oligoclase andesite contain angular to subangular inclusions of gabbro and dunite, up to about 2 inches across. A flow cropping out a mile northeast of Kapukaulua triangulation station contains inclusions of olivine gabbro, consisting of medium labradorite (60%), augite (28%), olivine (10%), and iron oxides (2%), arranged in a granitoid texture with an average grain size of about 1.5 mm. The dunite inclusions generally consist very largely of anhedral grains of olivine, with a small amount of iron oxide, probably magnetite. One specimen of dunite contains a few grains of augite.

INTRUSIVE ROCKS

Large numbers of dikes cut the lavas of the lower member of the East Molokai volcanic series in the rift zones and the caldera complex. They show the same variation in composition as the lava flows, of which they were the feeders. Many of them have glassy selvages a quarter of an inch to an inch thick, in which the texture is hyalopilitic. The central parts of the dikes have the same textures as the extrusive rocks.

Within the caldera complex there are several small stocks and other intrusive masses of olivine gabbro. Most of them are dense, but some show locally an open miarolytic structure resembling that of certain gabbros of West Maui.[18] The texture is granitoid (hypidiomorphic granular), and the average grain size ranges from 1 to 3 mm. The rocks consist principally of plagioclase, monoclinic pyroxene, and opaque iron oxides. Olivine is present in most specimens. In a few olivine is absent, but its place is probably taken by chlorite and serpentine alteration products. The plagioclase is generally zoned, ranging from sodic bytownite or calcic labradorite to sodic labradorite or in a few specimens calcic andesine. The pyroxene is augite, with $+2V = 55°$, and weak to moderate dispersion. In a specimen collected at 1,580 feet altitude in Pulena Stream (a tributary of Wailau Stream) the augite grades into pigeonitic

[18] Macdonald, G. A., Petrography of Maui: Hawaii Div. of Hydrog., Bull. 7, p. 328, pl. 43C, 1942.

augite, with an optic angle of about 40°. The iron oxides include both magnetite and ilmenite. A little hematite is present in a few slides. Small apatite grains are enclosed in the feldspar in some specimens, and in one it forms large prismatic grains as much as 2 mm long and 0.2 mm wide. In a few rocks, a small amount of interstitial chlorite is probably derived by alteration of glass. Several specimens contain scattered grains of reddish-brown biotite, and in a pebble from the mouth of Wailau Stream biotite comprises about 5 percent of the rock. A gabbro cropping out at 875 feet altitude in Pulena Stream contains a few small grains of brownish-green hornblende.

WEST MOLOKAI VOLCANIC SERIES

General features.—All of the lavas of West Molokai Volcano are basaltic. Olivine basalts are probably predominant in the lower part of the section, but basalts become very abundant in the upper part. Random sampling over the surface of the shield yielded nearly twice as many samples of basalt as of olivine basalt. The latest lavas, erupted at scattered points over the shield surface, are nearly all olivine basalts, however. A few picrite-basalts of the primitive type occur throughout the section, except among the very latest lavas. Many of the West Molokai lavas are very thin bedded, ranging from less than a foot to two feet in thickness (pl. 15A), and must have been erupted in an exceedingly fluid condition. In the upper part of a section in the face of the fault scarp three-quarters of a mile north of Puu Nana, the lavas are more consistently thin-bedded and poorer in olivine phenocrysts than any other series of flows seen by the writer in the Hawaiian Islands.

The latest lavas of West Molokai Volcano were erupted from a few scattered vents, among which are Waiele, Kaeo and Kaa cinder cones, and unlocated vents which produced flow-remnants cropping out at Kaawa hill, southeast of Kaeo hill, and just southwest of Kahaapilani hill (figure 18). On the lower end of the spur below Kaawa a prominent dike (plate 1) is seen to pass into a flow. These latest flows rest on a layer of tuffaceous soil 1 to 3 feet thick, generally baked at the top. All but two of these flows are olivine basalt; only the specimens collected 0.7 mile S. 74° E. of Kaeo hill and 0.2 mile S. 68° W. of Kahaapilani hill are basalts poor in olivine.

Olivine basalts.—More than half of the specimens of olivine basalt from West Molokai volcano are nonporphyritic. This abundance of nonporphyritic rocks is decidedly unusual among the primitive lavas of Hawaiian volcanoes. Of the porphyritic specimens, all contain phenocrysts of feldspar, rarely up to 5 mm long but generally less than 2 mm. Small olivine phenocrysts also are present in most porphyritic specimens, but in general are a little less abundant than those of feldspar. This dearth of olivine phenocrysts does not reflect a similar deficiency in the rock as a whole, for olivine is quite abundant in the groundmass.

The feldspar phenocrysts consist of cores of labradorite-bytownite or calcic labradorite, surrounded by thin shells of more sodic plagioclase with the same composition as that of the groundmass. Olivine phenocrysts have an optic angle close to 90°, are generally partly resorbed, and altered around the edges or even throughout to iddingsite. Both grade in size into the groundmass. Microphenocrysts of augite ($+2V = 55°$), grouped together in glomerocrysts, are present in only one specimen collected 0.15 mile inland from the western edge of Pakanaka Fishpond. Magnetite microphenocrysts, up to 0.2 mm across, are found in a few specimens.

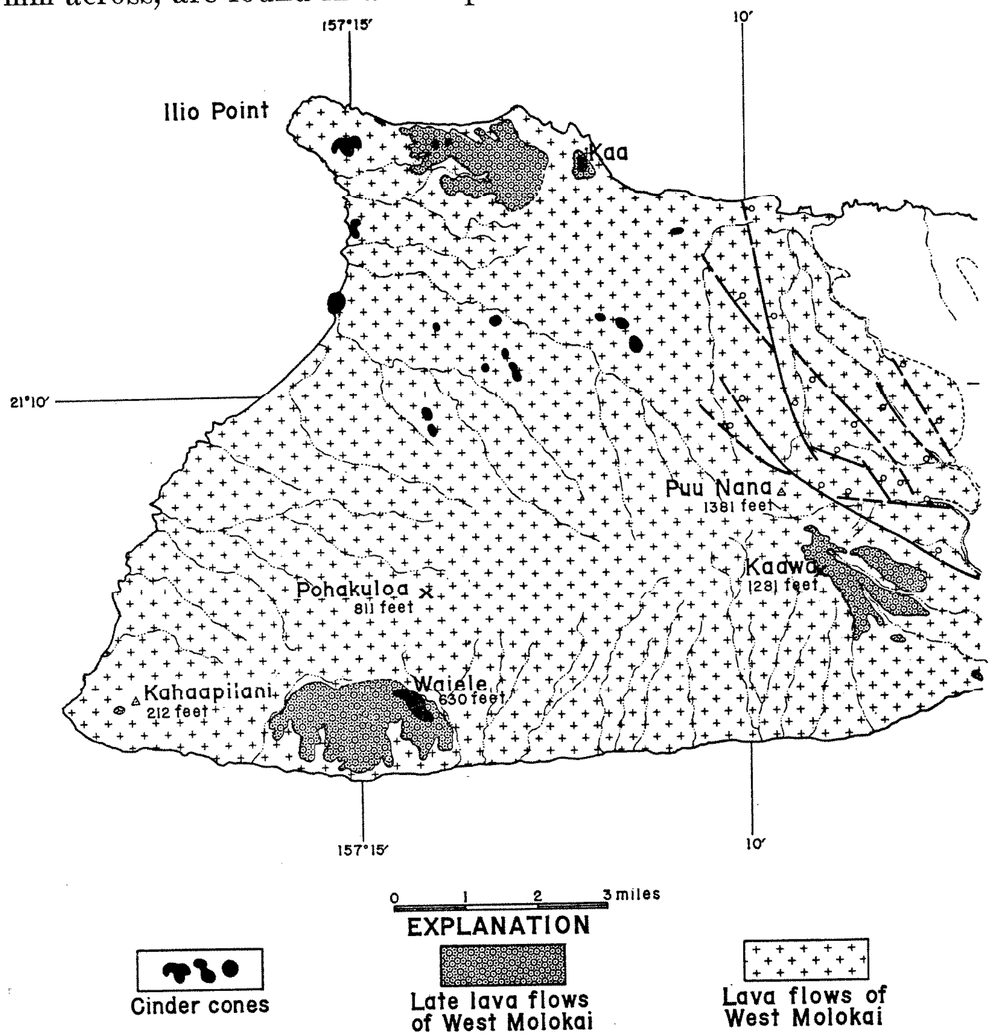

Figure 18. Map of West Molokai, showing position of late lava flows.

The groundmass is intergranular or intersertal. The average grain size generally ranges from 0.01 to 0.07 mm, but some of the latest lavas are unusually coarse grained, averaging 0.1 to as much as 0.4 mm in grain size. These very coarse-grained rocks are nonporphyritic. The groundmass (or the entire rock in nonporphyritic specimens) consists of intermediate to sodic labradorite, monoclinic pyroxene, olivine, magnetite, ilmenite, apatite, and interstitial glass. The apatite occurs as minute highly acicular crystals generally enclosed in feldspar. Small flakes of late-formed brown biotite are present in several specimens. In most rocks the pyroxene is pigeonite, but in a few, especially those of unusually coarse granularity, it is augite ($2V = 55°$). Some of these rocks, particularly the coarse-grained late lavas, contain an unusually large amount of groundmass olivine. A specimen of nonporphyritic lava from a thin flow in Kahalelani cone contains about 16 percent olivine; another collected 0.95 mile S. 42° E. of Puu Nana contains 15 percent; others collected respectively 0.25 mile north of Kaeo hill and 0.75 mile S. 34° E. of Waiele hill contain 20 percent. In some specimens the groundmass olivine is partly or largely altered to iddingsite or a mineral resembling it, probably by ordinary weathering. A nonporphyritic olivine basalt from an ancient Hawaiian adz quarry 0.2 mile northeast of Kaeo hill contains small vesicles which are lined or entirely filled with chlorite.

Picrite-basalts.—The picrite-basalts in the West Molokai volcanic series are all of the primitive type, containing abundant phenocrysts of olivine, but none of augite. The olivine phenocrysts range in size up to 8 mm long, and in abundance up to 45 percent of the rock. They are partly resorbed, and altered around the edges to iddingsite. Their optic axial angle is close to 90°. The groundmass is like that of the olivine basalts, already described. A specimen collected 2.65 miles S. 67° W. of Pohakuloa trig. station contains in the groundmass irregular patches and streaks of pegmatitoid matter, with an average granularity of 0.15 mm, as compared to 0.03 mm in the rest of the rock. Both augite and pigeonite are present in the pegmatitoid patches, together with the other normal groundmass minerals, whereas in the fine-grained portion of the groundmass all of the pyroxene is pigeonite. In some of the coarse patches the crystals are arranged radially.

Basalts.—The basalts are in general much like the olivine basalts, except for the absence or near-absence of olivine. Roughly a third of the specimens contain no olivine; in the rest it ranges from 1 to 4 percent. Also about a third of the specimens of basalt are nonporphyritic, but these are not necessarily those devoid of olivine.

Of the porphyritic specimens, most contain phenocrysts of feldspar. Many also contain scattered phenocrysts of olivine, with or without feldspar phenocrysts. Augite phenocrysts, with an optic angle of about 55°, are present in a few rocks. All of the phenocrysts are small, generally less than 2 mm long but rarely up to 3 mm. The feldspar phenocrysts have the same composition as those in the olivine basalts. The groundmass resembles in both composition and texture that of the olivine basalts.

In most specimens in which its nature has been determined the pyroxene of the groundmass is pigeonite. In three specimens, however, it ranges from augite with an optic angle of about 55° to pigeonite with an optic angle near 0°. In a specimen collected 0.9 mile S. 33° W. of Mokio Point the groundmass pyroxene is separable into larger grains with $2V = 45°$ to 55°, and more numerous smaller grains with 2V near 0°. However, in specimens collected 1.15 miles east of Ka Lae o ka Laau and at the summit of Puu Nana, such separation is not possible. Equipment to make accurate measurements was not available, but the gradation in size of optic angle appears to be essentially continuous.

HYPERSTHENE-BEARING BASALTS.—Three specimens of basalt contain rare phenocrysts of hypersthene, up to 2 mm long. These specimens came respectively from localities: 0.8 mile east of Ka Lae o ka Laau, 2.35 miles S. 70° W. of Pohakuloa trig. station, and 200 feet east of Pohakuloa trig. station. The last contains no other phenocrysts, but both the others contain as well phenocrysts of plagioclase, augite, and olivine. Olivine is present only as phenocrysts, and forms less than 1 percent of the rocks. The hypersthene grains are pleochroic from very pale pink to very pale green, and have $-2V = 80°$. In general they appear to be entirely unresorbed. Hypersthene forms less than 1 percent of the rocks. It is not present in the groundmass, which, in all three specimens, consists of medium labradorite, monoclinic pyroxene, magnetite, ilmenite, and a little interstitial glass.

Hypersthene-bearing basalts have been found also at West Maui Volcano.[19] They are fairly common among the lavas of Mauna Loa, on Hawaii,[20] and are predominant among those of the Koolau Volcano, on Oahu.[21]

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[19] Macdonald, G. A., Petrography of Maui: Hawaii Div. of Hydrog., Bull. 7, p. 317, 1942.

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

[21] Wentworth, C. K., and Winchell, H., The Koolau volcanic series, Oahu, Hawaii: Geol. Soc. America Bull., vol. 58, pp. 45–77, 1947.

QUATERNARY VOLCANIC ROCKS

KALAUPAPA BASALT.—The lava of the late eruption which built Kalaupapa Peninsula, at the foot of the northern cliff, is a dark gray rather mafic olivine basalt pahoehoe, with abundant phenocrysts of feldspar up to 4 mm long, and olivine and augite up to 2 mm long. The olivine has a —2V close to 90°, and is unaltered except for a faint yellowish stain around the edges. The augite has +2V = 60° and fairly strong inclined dispersion. The plagioclase phenocrysts are zoned from medium bytownite to medium labradorite. The groundmass is intersertal, and consists of medium labradorite, pigeonite, olivine, magnetite, ilmenite, and interstitial glass. The pigeonite is slightly purplish brown, and is probably titanian. The glass is pale brown, and is generally clouded with finely granular iron oxide. The phenocrysts grade in size into the groundmass, and no sharp line can be drawn between the two. The approximate bulk mineral composition of the rock is: feldspar 37%, pyroxene 33%, olivine 14%, iron oxides 12%, and glass 5%.

TUFF OF MOKUHOONIKI CONE.—Mokuhooniki Islet, off the eastern end of Molokai, is a tuff cone built by an eruption probably of about the same age as that which formed Kalaupapa Peninsula. The cone is composed largely of palagonite tuff, similar to that which forms the Diamond Head and Punchbowl cones on Oahu. A specimen was taken from a dike which cuts the tuff. It is a dark gray dense lava with abundant phenocrysts of olivine up to 1 mm long. The phenocrysts, which are entirely fresh and unresorbed, constitute about 30 percent of the rock. They lie in a glassy base rendered black and opaque by abundant finely disseminated iron oxide. The rock is probably a mafic olivine basalt, approaching picrite-basalt in composition.

MAGMATIC DIFFERENTIATION

The lavas of West Molokai depart little from the composition of the basalt which forms the great bulk of the Hawaiian volcanoes and represents the nonvolatile portion of the parent magma of the Hawaiian province. The small amount of differentiation which has taken place is easily accounted for by the sinking of early-formed crystals in the magma column. The large proportion of olivine-poor basalts in the upper part of the West Molokai shield probably represents a period during which eruptive fissures tapped only the uppermost part of the magma column, from which the olivine phenocrysts had settled out.

The lavas of East Molokai, on the other hand, include types which differ greatly in composition from the parent olivine basalt. Nearly the entire range of Hawaiian lavas is included, among the major types only the nepheline-bearing lavas being unrepresented. The origin of the various lava types is discussed at length elsewhere,[22] and space will not be taken here to repeat the discussion. It is sufficient to state that the other types can be derived from olivine basalt very largely by crystal differentiation.

[22] Macdonald, G. A., The Hawaiian petrographic province: in preparation.

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