GEOLOGY AND GROUND-WATER RESOURCES OF LANAI AND KAHOOLAWE HAWAII

TERRITORY OF HAWAII
1900

H. T. STEARNS

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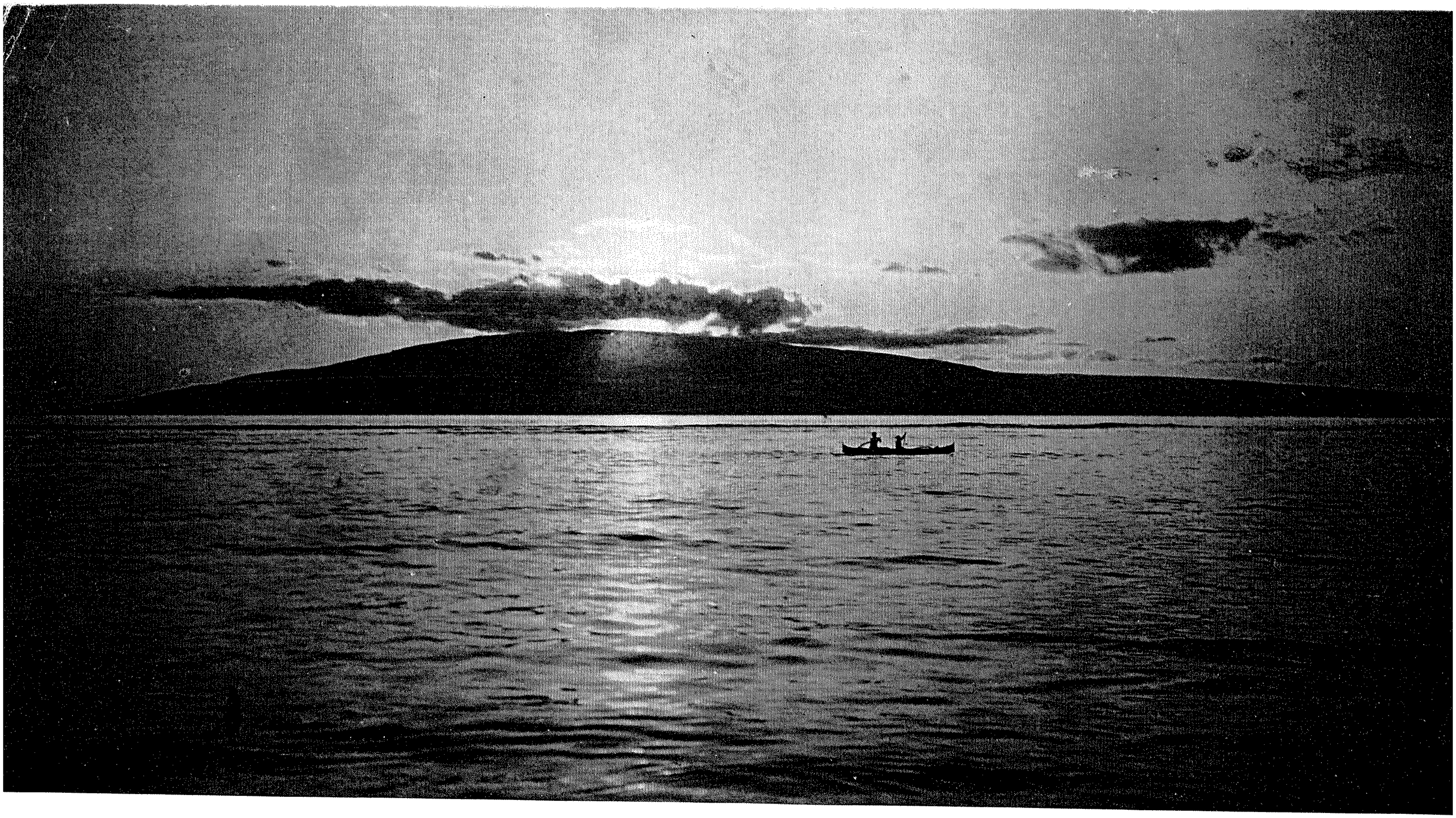

Lanai from West Maui. (Photograph by Ray Baker.)

TERRITORY OF HAWAII
JOSEPH B. POINDEXTER, *Governor*
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DIVISION OF HYDROGRAPHY
MAX H. CARSON, *Chief Hydrographer*

BULLETIN 6

GEOLOGY AND GROUND-WATER RESOURCES OF THE ISLANDS OF LANAI AND KAHOOLAWE, HAWAII

By HAROLD T. STEARNS
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WITH CHAPTERS ON

THE PETROGRAPHY OF LANAI AND KAHOOLAWE

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GEOPHYSICAL INVESTIGATIONS ON LANAI

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Prepared in cooperation with the Geological Survey,
U. S. Department of the Interior

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PART 1

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

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

By Harold T. Stearns

ABSTRACT

Lanai lies 59 miles southeast of Honolulu, Oahu, has an area of 141 square miles, and is 3,370 feet high. (See fig. 1 and pl. 1.) Lanai City is the only town of importance. The island produces pineapples and cattle. The surface above about 1,200 feet is generally covered with lateritic soil, which reaches a maximum depth of about 50 feet. Below this level the island is partly devoid of vegetation and is strewn with boulders, the result of having been once submerged by the ocean to this depth. Traces of various emerged and submerged shore lines are described, the highest fossiliferous marine deposits being 1,070 feet above sea level. Lanai is an eroded extinct basaltic volcano built during one period of activity. No secondary eruptions occurred as on most of the other islands. It has three rift zones and a summit caldera. The summit plateau has resulted from collapse along the northwest rift zone. Elsewhere there is much evidence of faulting. About 100 faults and 275 dikes were recorded, but they are so close together in places that it was not possible to show them all on the map.

The climate is semitropical, the mean annual temperature of Lanai City, altitude 1,620 feet, being 68° F. Because Lanai lies to the lee of Maui Island it is dry. The mean annual rainfall ranges from 38 inches on the summit to less than 10 inches on the coast. The windward (northeast) side is carved by streams into deep canyons. Maunalei Gulch has the only perennial stream, and it does not reach the sea. Ground water, the lifeblood of Lanai, is scarce. Lanai City obtains some of its water supply by a tunnel from gravel in Maunalei Gulch. This water apparently rises from the dike complex in this gulch. The rest of the supply comes from a recently constructed shaft tapping the dike complex not far downstream. The total quantity of high-level ground water discharged by springs and tunnels ranges from about 600,000 gallons a day in wet weather to about 250,000 gallons a day in dry weather. The basal water, although potable, is fairly high in salt. Several sites are recommended for developing and conserving ground water.

INTRODUCTION

Location and area.—The island of Lanai, County of Maui, lies 59 miles southeast of Honolulu, Oahu, and 9 miles west of Lahaina, Maui. Its form as seen from West Maui is shown in the frontispiece. It has a maximum north-south length of 13¼ miles, an east-west width of 13 miles, and an area of 141 square miles (fig. 1). Of the eight principal islands of the Hawaiian group only Niihau and Kahoolawe are smaller. (See insert map, fig. 1.) The highest point,

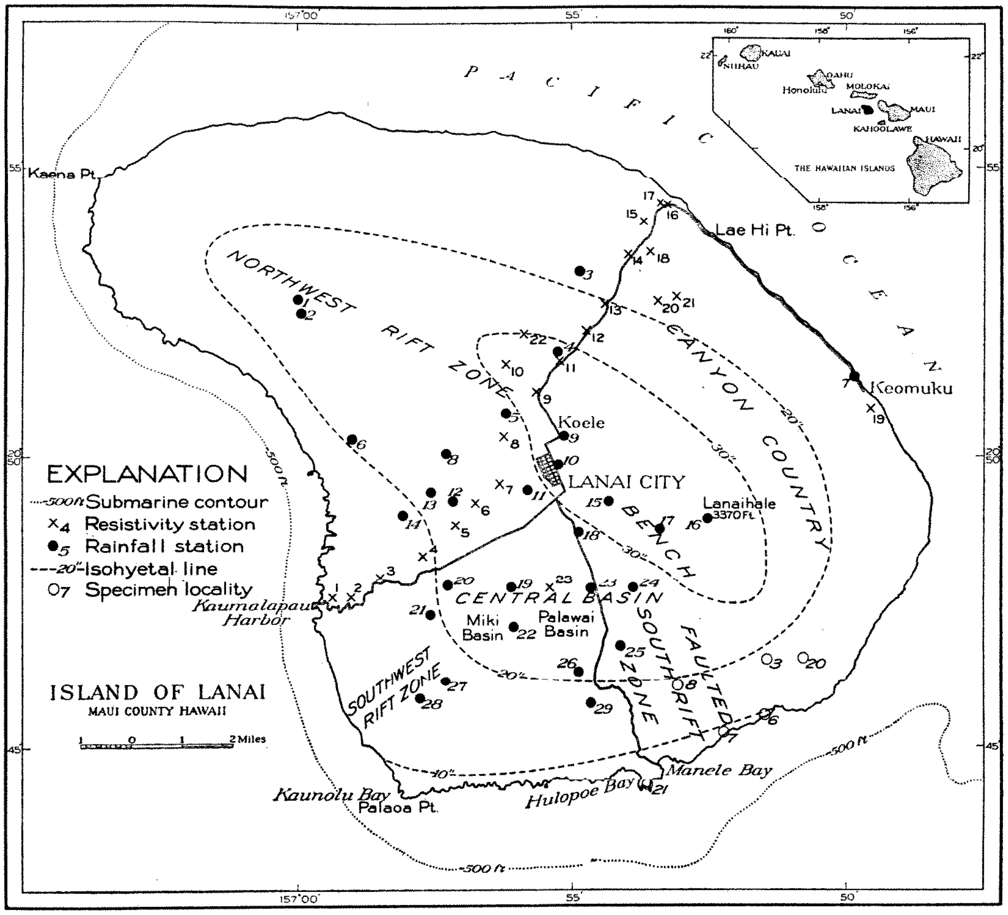

FIG. 1. Map of Lanai showing lines of equal rainfall, rainfall and resistivity stations, geomorphic divisions, and 500-foot submarine contour line. Insert map in upper right corner shows location of Lanai in the Hawaiian group.

Lanaihale, has an altitude of 3,370 feet (pl. 2, *A*). All the principal islands except Kauai and Niihau are visible from Lanai in clear weather. Lanai City is at 157° 55′ W. longitude and 20° 50′ N. latitude. The distribution of the area of Lanai with respect to elevation follows:

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

Altitude in feet	Area in square miles	Percent
0– 500	33.9	24.1
500–1,000	29.7	21.1
1,000–1,500	42.7	30.4
1,500–2,000	26.0	18.4
2,000–2,500	5.2	3.7
2,500–3,000	2.7	1.9
3,000–3,370	.6	.4
	140.8	100.0

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[1] Wentworth, C. K., The geology of Lanai: B. P. Bishop Mus. Bull. 24, p. 9, 1925.

HISTORICAL SKETCH.—The following sketch by Wentworth[2] summarizes the chief historical events:

> Lanai was first settled by the Hawaiians about 1400 A.D.—several hundred years after the first Polynesian migrations to Hawaii. The island was first seen by Europeans in 1779, when a part of Captain Cook's Expedition, under the command of Captain Clerke, passed along its south and west coasts. Sailing ships are known to have passed near to Lanai in 1786 and 1787. Vancouver, who explored other islands in the group about 1790, did not land on Lanai. The island is described briefly by the Reverend William Ellis, who saw it in 1823. Several ships are believed to have been wrecked on Lanai during the early part of the nineteenth century.
>
> Active missionary work on the island was begun by ministers from the mission station at Lahaina, Maui, in 1835, at which time the native population was reported to be 1,200. At about this time there was a penal colony for women near the northwest point of Lanai.
>
> In 1855 elders of the Church of Latter Day Saints acquired land from one of the chiefs and settled on the island. Walter Murry Gibson, a leader in the church, arrived in 1861, and in a few years acquired control of much of the best land. After considerable difficulty with the church authorities at Salt Lake City, these lands were inherited at Gibson's death in 1888, by his daughter, Mrs. Talula Lucy Hayselden. A sugar company organized by her husband, Frederick H. Hayselden, and others, failed in 1901. Between 1901 and 1903 the control of Lanai was acquired by Charles Gay and his associates and in 1910 by the Lanai Co. Between 1838 and 1910 the native population decreased from 1,200 to less than 130, partly by removal to other islands.
>
> By 1922 the Lanai Co., which in 1917 came under the exclusive control of Frank F. Baldwin and Henry A. Baldwin, had acquired control of the whole island except the ranch lands of Charles Gay and about 500 acres remaining under native titles. The entire property of the Lanai Co. was purchased in December 1922 by the Hawaiian Pineapple Co. of Honolulu.

Around the old native village sites and especially at Kaunolu and Manele are traces of rock terracing representing considerable industry. These terraces are reported to have been sweet potato gardens. Much of the soil appears to have been washed away leaving rocks behind. Perhaps the soil was washed from some of the terraces during the time of cultivation, a loss which would have made the natives build more and more terraces. Most of these artificial terraces are in areas of emerged marine deposits suggesting that the black marine silts were particularly favorable for sweet potato culture or that these areas had much more soil prior to soil erosion than areas which did not receive marine sediments.

POPULATION AND ROADS.—Lanai has a population of 2,356 according to the 1930 census. Lanai City, altitude 1,620 feet, lying near the center of the island, is the principal settlement and probably

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[2] Wentworth, C. K., op. cit., pp. 3–4. For an account of the early history and archaeology of Lanai, see The island of Lanai, a survey of native culture, by K. P. Emory: B. P. Bishop Mus. Bull. 12, 1924.

contains eight-tenths of the population (pl. 2, *A*). The houses of Miki Village were moved to Lanai City in 1937. A few houses are grouped about the port of Kaumalapau. Manele Harbor, the former shipping point, has been abandoned. The Lanai ranch headquarters are at Koele, about a mile north of Lanai City. Scattered along the northeast shore near the old village of Keomuku are several families who depend for a living upon fishing, the production of charcoal, and the growing of watermelons.

Hard surface roads connect Kaumalapau, Lanai City, and Koele. Dirt roads passable with an auto extend from Lanai City to Manele and to a point several miles southeast of Keomuku. A block system of dirt roads exists in the pineapple fields near Lanai City. The rest of the island is readily traversable on horseback.

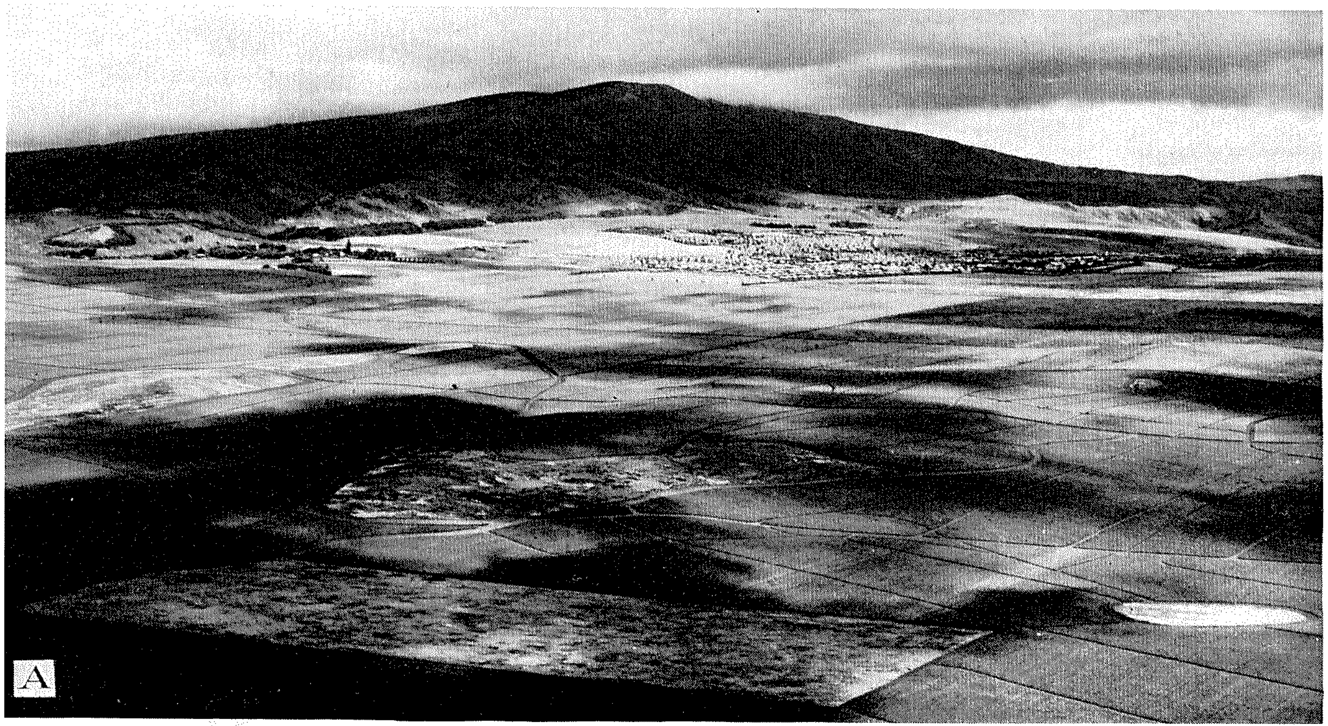
INDUSTRIES.—Lanai's chief industry, the growing of pineapples, was started in 1922 by the Hawaiian Pineapple Co., who invested $5,000,000 in developing the industry on Lanai. Production has increased to the point where the average annual value of fresh pineapples for the past decade has been about $1,400,000, according to data furnished by that company, the only producer. Lanai now produces the major supply of this company.

During July and August, when most of the pineapples ripen, work is carried on night and day. The fruit is hauled by trucks to Kaumalapau, from which place it is shipped by barge to the cannery of the Hawaiian Pineapple Co., in Honolulu. As many as 100,000 crates containing more than 1,300,000 pineapples have been shipped from Kaumalapau in 24 hours. In 1936 new land was being cleared for pineapple production. Conditions on Lanai are so favorable that pineapples weighing 6 to 8 pounds are common, and some reach weights of 12 to 14 pounds.

In 1936 there were 2,300 cattle, 130 horses and mules, and about 350 swine on the island. A few sheep and goats are at large in the more inaccessible areas.

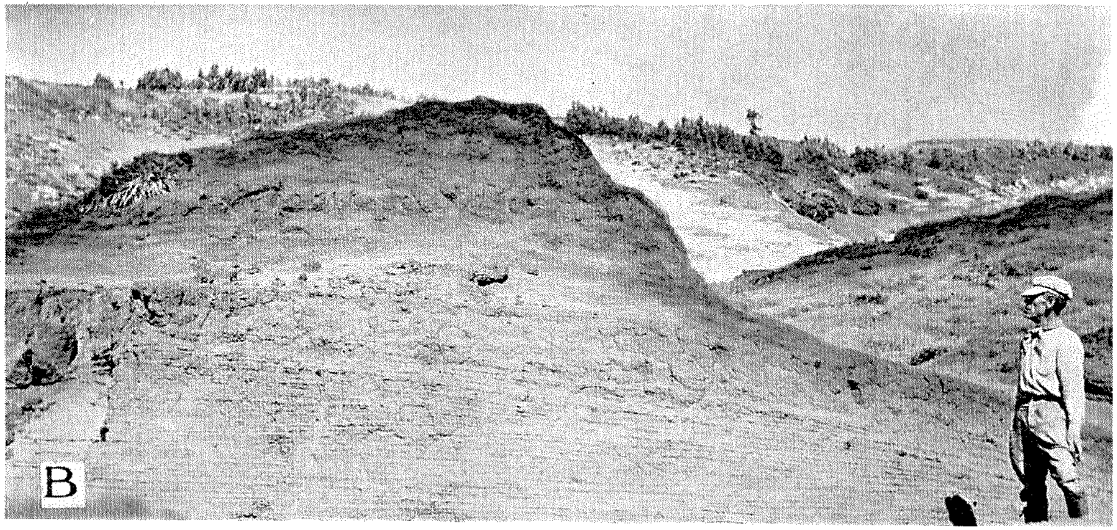
FAUNA AND FLORA.—Asiatic deer were introduced many years ago and their offspring live in the more rugged and less visited east side of the island. Mongolian pheasants, doves, and quail are numerous as the mongoose has never been introduced. Norway rats do considerable damage to pineapples in certain areas, and an effort is now being made to exterminate them. The poisoning of the rats has apparently indirectly poisoned many domestic cats which run wild in large numbers.

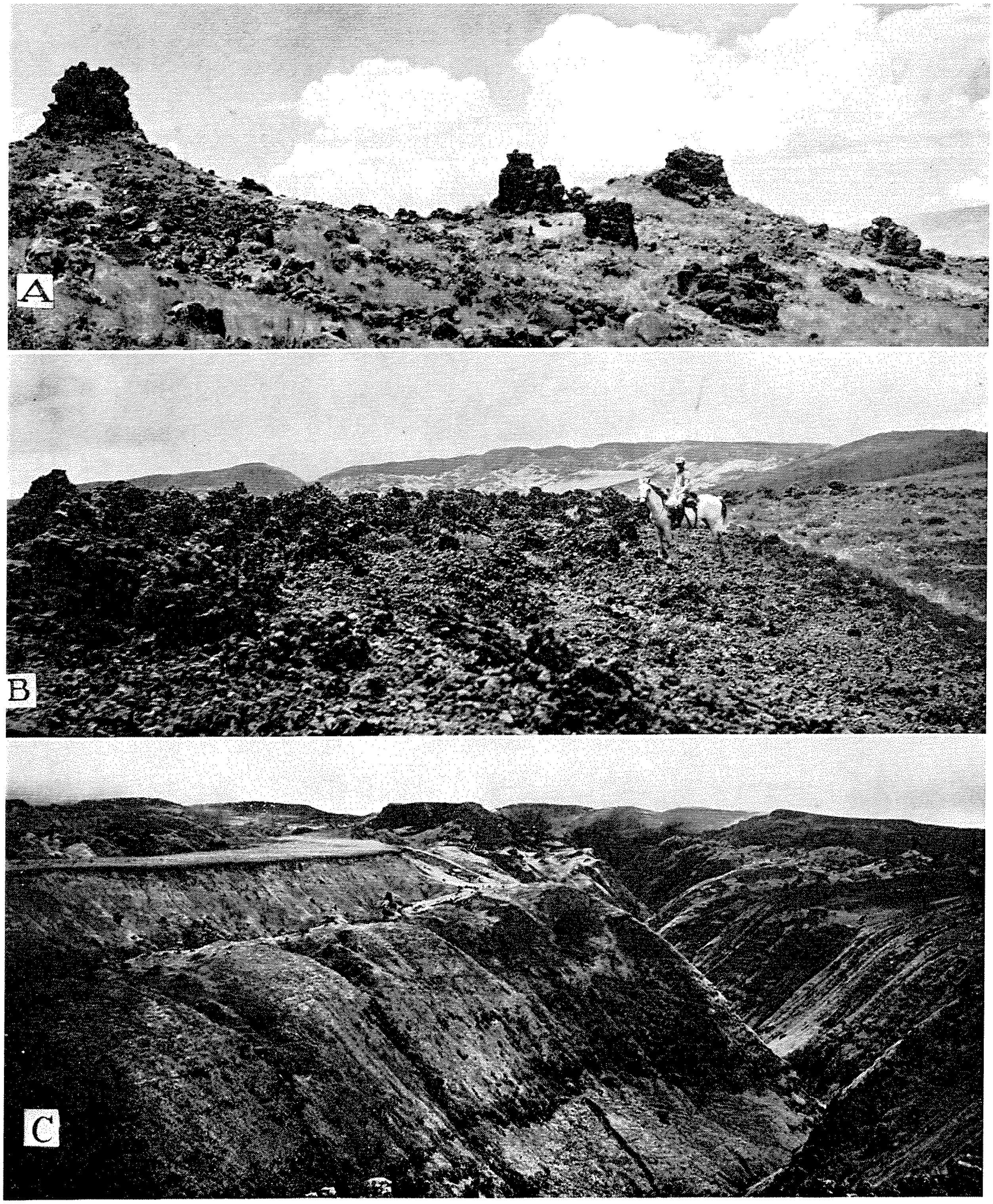
The summit of the island is still sparsely covered with native trees. At lower levels dry stumps and scattered trees indicate that



Pl. 2*B*. Mound of wind-deposited soil near head of Kapua Gulch. The lower part is laminated and the upper part is nearly structureless.

Pl. 2*A*. Airplane view of the summit plateau of Lanai. Pineapple fields in the foreground, Lanai City on the right, Koele on the left, and the peak of Lanaihale in the background. (Courtesy of Inter-Island Airways.)





PL. 3. *A*, Pinnacles of basalt in the denuded area along the Keomuku road. (Photograph by J. H. Swartz.) *B*, Pinnacles in the canyon country resulting from solution of lime-cemented rotted basalt. *C*, Wawaeku Gulch, typical of the canyon country. Note the narrow terrace of residual soil on the left.

the forest extended farther seaward prior to the introduction of livestock. The obviously fresh appearance of most of the wind-eroded areas, formerly soil-covered, is additional evidence of the recent deforestation of Lanai. George Munro, former manager of the Lanai Co., introduced many plants to reclaim the bare lands. At the same time he practically exterminated the wild goats which had been largely responsible for the destruction of the vegetation. Several of the introduced grasses have spread extensively and now cover much of the former bare ground.

HISTORY AND PURPOSE OF THE INVESTIGATION.—This report represents the completion of another unit in the systematic study of the geology and ground-water resources of the Hawaiian Islands by the Geological Survey, United States Department of the Interior, in cooperation with the Division of Hydrography of the Territory of Hawaii. The work was done under the general supervision of O. E. Meinzer, geologist in charge of the division of ground water of the Federal survey. The survey was made at this time particularly to locate additional supplies of ground water to meet the constantly increasing demand for municipal water at Lanai City. Field work was done for 31 days, between June 13 and August 4, 1936. Geophysical prospecting for ground water was carried on by J. H. Swartz, aided by J. Y. Nitta, both of the Federal Geological Survey, from June 13 to August 13, 1936.

ACKNOWLEDGMENTS.—Both Dr. Swartz and I are greatly indebted to the Hawaiian Pineapple Co. for its hearty cooperation in furnishing assistants, cars, boats, horses, and subsistence to the personnel of the Geological Survey. Because of the extreme helpfulness of Dexter Fraser, plantation superintendent of the Hawaiian Pineapple Co., Lanai, and Ernest Vredenburg, manager of the Lanai Ranch Co., the work was carried on effectively and rapidly, and we are heartily grateful to them. Their cooperation made working on Lanai a pleasure. On behalf of Dr. Swartz and myself I take this opportunity of expressing our appreciation for the hospitality and helpfulness of all the others with whom we came in contact, especially H. B. Caldwell, J. T. Munro, H. G. Munro, J. K. Clapper, J. Morren, and J. S. Hasegawa. I am indebted also to J. Y. Nitta for his careful preparation of the illustrations in this report. The manuscript was criticized by M. H. Carson, W. O. Clark, W. D. Collins, S. H. Elbert, J. E. Hoffmeister, T. A. Jaggar, S. B. Jones, A. H. Koschmann, G. R. Mansfield, F. K. Morris, J. T. Munro, C. K. Wentworth, and N. D. Stearns. Their criticisms were very helpful.

PREVIOUS INVESTIGATIONS.—Early papers describing the geology of the Hawaiian Islands mention Lanai only briefly. Wentworth[3] spent 6 weeks in 1924 studying the geology of the island with particular reference to available water supplies. H. S. Palmer spent 4 days on Lanai with Wentworth and prepared for the Hawaiian Pineapple Co. a manuscript report on the water supply. Most of Palmer's conclusions have been published by Wentworth in his report. Conclusions reached in the present work differ in most important particulars from those reached by Wentworth. No attempt to point out these differences has been made in this report.

W. O. Clark, geologist of the Hawaiian Sugar Planters' Association, has spent altogether about 3 weeks on Lanai. His findings are covered by two reports to the Hawaiian Pineapple Co.; one in 1930 recommends an extension of the upper Maunalei tunnel to develop additional water; the other in 1936 recommends a shaft to the basal water table at about 300 feet altitude in Maunalei Gulch and states that the water encountered would be potable if mixed with the water from the lower Maunalei tunnel. This shaft is described herein. Descriptions of the ancient shore lines on Lanai have already been published.[4]

GEOMORPHOLOGY

ORIGIN AND FORM

Lanai consists of a single volcanic dome or shield-shaped mass of basaltic lavas modified only a little by erosion since the volcano became extinct. Its present form is shown in the frontispiece and by the contour lines on plate 1. Five fairly distinct land units are recognized, namely, (1) the central basin; (2) the canyon country; (3) the northwest rift zone; (4) the southwest rift zone; and (5) the faulted south rift zone (fig. 1). A rift zone is an elongated area containing a definite fissure system from which lava has repeatedly issued. When eroded so that the dense basalt filling the cracks is exposed it is called a dike complex. The island is elongated to the northwest and southwest because of copious outpourings of lava along the rifts having these trends. These rift zones are not impressive features of the landscape of Lanai but are described in detail in this report because of their importance in controlling the movement of water and to give the reader a thorough understanding of the internal structure of the island.

Central basin.—The central basin consists of two closed depres-

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[3] Wentworth, C. K., The geology of Lanai: B. P. Bishop Mus. Bull. 24, 72 pp., 1925.

[4] Stearns, H. T., Pleistocene shore lines on the islands of Oahu and Maui, Hawaii: Geol. Soc. America Bull., vol. 46, p. 1954, 1935; Ancient shore lines on the island of Lanai, Hawaii: Idem, vol. 49, pp. 615–628, 1938.

sions, Palawai Basin, with an area of about 3½ square miles, and the nearby Miki Basin, with an area of about half a square mile. The features of Palawai Basin, although considerably smoothed by erosion, deposition, and weathering, are still those of a typical caldera. A reconstruction of this caldera in the stage at the close of volcanic activity is shown in plate 9, *A*. Palawai Basin is 144 feet deep if measured from the lowest point in the divide between it and Miki Basin, which has an altitude of 1,236 feet, and the bottom, whose altitude is 1,092 feet. Palawai Basin opens to the southeast toward the fault-block area and the wide graben (a downthrown block between two faults) through which the last flows of lava from the caldera found their way seaward (fig. 2).

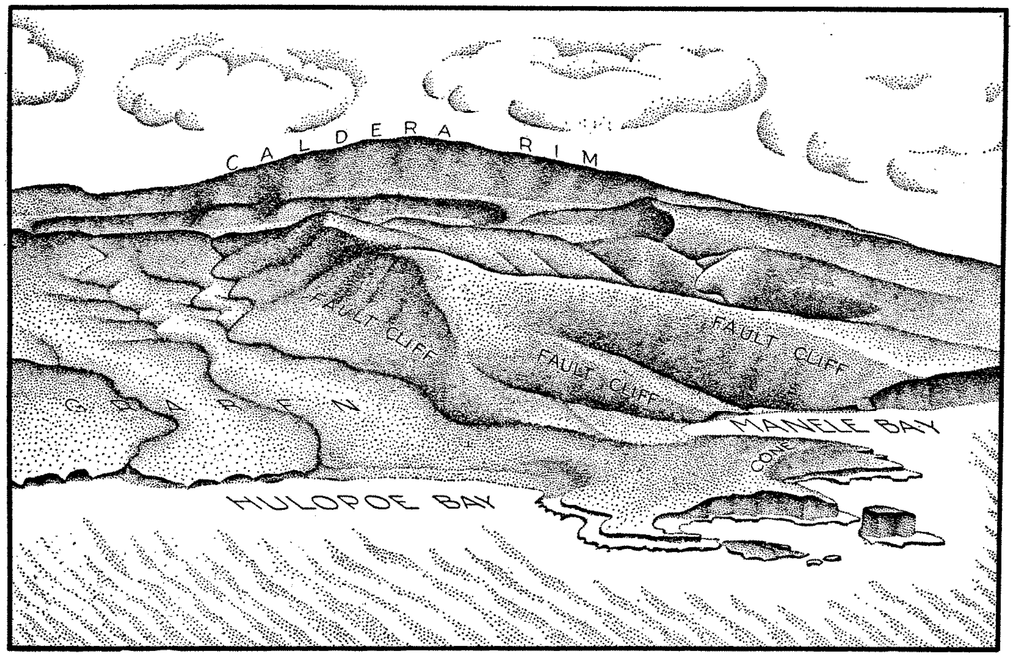

FIG. 2. The summit caldera of Lanai showing the high fault escarpments extending from the caldera to Manele Bay bounding the east side of a graben or fault trough through which the last flows of lava from the caldera found their way seaward. The wave-cut platform bordering Manele cone is shown in the foreground. Redrawn from an airplane photograph.

Miki Basin, an undrained depression at the west edge of the ancient caldera, is probably a partly filled pit crater similar to Kilaueaiki at Kilauea Volcano, on the island of Hawaii. It is only 39 feet deep if measured below the divide separating it from Palawai Basin but about 75 feet deep if measured from the lowest point on its rim elsewhere.

The island is sufficiently old so that red residual or lateritic soils

10 to 20 feet thick cover much of it. Partial filling of the basin has resulted from soil being washed into it, but most of the debris has come from the east wall as shown by the extensive alluvial fans at the mouths of the canyons opening into the basin (pl. 1). In 1898 a Mr. Payne dug a pit 90 feet deep in Palawai Basin at an altitude of 1,300 feet near the mouth of Kapohaku Gulch that is reported to have encountered only soft material, but it is not known whether all of this was alluvium.

Practically all the cliffs facing the summit plateau are due to faulting, but they have lost much of their original sharpness by weathering and erosion. The cliffs on the east side of Palawai Basin forming the Bench, those of the main crest, and those of the low bluffs on the east side of Lanai City running northwest toward the "North End" are some of the prominent fault escarpments. The main fault escarpment reaches a height of about 1,200 feet and the road to Keomuku crosses it about a mile north of Lanai City.

The Bench bordering the east side of Palawai Basin is a mile wide and lies about 500 feet above the basin (fig. 1). It appears to be a remnant of a formerly more extensive caldera floor comparable to the crescentic platforms in Mokuaweoweo caldera on Mauna Loa Volcano, Hawaii. It was formed prior to the collapse that produced the inner crater now known as Palawai Basin. If the Bench were simply a downfaulted block, the lava beds in it should match the upper layers under Lanaihale. The layers appear to be more massive, typical of those ponded or confined within a caldera floor. Thus, they probably bury part of the former downdropped summit block as illustrated in section B–B′, plate 1.

Canyon country.—The canyon country comprises the north and east side of the island, the segment between Maunalei and Kawaiu gulches. It is exceedingly rugged and cannot be crossed parallel to the coast a short distance inland even on foot. Field work in this area was carried on by climbing one ridge to the summit and then descending on another. Most of the gulch walls are bare, hence the rocks are well exposed. The only mature topography on the island is in the upper part of the canyon country. This is caused by several factors, namely, (1) the original slope was steep, thus producing high stream gradients, some of the lava beds having dips as much as 18°; (2) this area is favored by rainfall; (3) it was protected by a high fault cliff from eruptions in the caldera, hence lava flows ceased coursing down this slope before they stopped flowing over any other part of the island (pl. 9, *A*); (4) the original form of this sector caused a convergence of drainage in this area.

The lower slopes of the canyon country are much less eroded because the streams diverge as they flow seaward, and because they cross areas of low rainfall. Erosion was retarded on the lower slope between Halepalaoa Landing and Kawaiu Gulch because this area was veneered with lava flows from local cones and craters near the end of volcanic activity.

Northwest rift zone.—Rising gradually to the northwest from Palawai Basin for about 6 miles is a smooth flat area 1½ to 3 miles wide bounded on the northeast side by a fault scarp which dies out northwestward. This flat lacks definite stream channels and in places contains shallow broad undrained depressions. At an altitude of 1,700 feet it changes to a broad seaward-sloping ridge which plunges below the ocean at Kaena Point. This flat and ridge mark the site of the northwest rift or fissure zone of the Lanai Volcano (pl. 8, *B*). The ridge has not collapsed whereas the flat area is composed of parallel fault blocks plunging southeastward toward the former central crater or Palawai Basin. The whole northwest rift unit has been only slightly eroded chiefly because of the low rainfall and gentle slopes in the area.

Smooth low round hills project above the flat in half a dozen places. They are probably small cones from which lava poured about the time volcanic activity ceased, though they are not shown as such on plate 1 because no evidence other than their topographic form supports this origin. They closely resemble the hill formed at the source of the pahoehoe lava flow of 1920 in the southwest rift zone of Kilauea Volcano, Hawaii.

Southwest rift zone.—A smooth ridge 3 miles long and one-half to 2 miles wide extends southwestward from Palawai Basin. Its crest slopes to the southwest from an altitude of 1,343 feet near Miki Basin to 1,083 feet at the top of Kaholo cliff (pl. 1). Lava flows dip away from this ridge, suggesting that it was a source of lava. Also numerous dikes or fissure feeders trending southwestward are exposed in Kaholo cliff, the sea cliff which terminates the southwest end of this ridge, thereby proving that the ridge is a rift zone (pl. 4, *B*). A shallow horseshoe-shaped amphitheater with a low hill on its northeast rim lies on the crest of the ridge. Because the ridge has undergone little erosion this amphitheater is shown on plate 1 as Ulaula Crater, although no other evidence than its form was found to indicate its origin. Several lava flows appear to have flowed from it, but no petrographic studies of the material were made.

Faulted south rift zone.—Trending a little east of south from

Palawai Basin toward the coast are several ridges which are fault blocks arranged en échelon, that is, parallel to each other but each one slightly offset (fig. 2 and pl. 1). Closely spaced dikes are exposed in the sea cliffs of this area, indicating that it is of rift-zone origin and that many flows may have originated here. West of Manele the coast is only slightly cliffed. No ridge marks this rift, possibly because of the great amount of slumping along it. On the east side of Manele Bay the fault cliffs reach heights of 500 feet, and in their midst is the large pit crater, Kaluakapo (pl. 1). The area is very arid, and streams have cut only small canyons. Most of the relief bears no relation to the stream pattern. West of Manele Bay the canyons are shallow and the fault-block topography is absent. The lavas of this area are younger than those east of Manele Bay as they overlap them in the canyon draining into Manele Bay.

RESEMBLANCE TO KILAUEA VOLCANO.—The Lanai Volcano resembles the active volcano of Kilauea[5] on Hawaii in having about the same height, a broad shallow caldera or crater of collapse on its summit within which are partly sunken crescent-shaped floor segments or benches, numerous faulted blocks, several pit craters, only a few cinder cones, shallow rift-zone grabens or fault trenches, a spillway from one side of the caldera only, the whole pile produced by quiet outpourings of very fluid aa[6] and pahoehoe chiefly from narrow fissures accompanied by little or no spatter. It differs notably from Kilauea Volcano in that ash deposits are absent.

EFFECT OF FAULTING ON STREAM PATTERN

Aside from the interior drainage on the plateau that is a result of collapse, the most striking effects of faulting are shown by the course of the two largest streams, Maunalei and Hauola (pl. 1). Perhaps cracks rather than faults caused the abrupt turn from northwest to northeast near the heads of these streams. Apparently for a distance of about a mile east of the main fault escarpment the northeast slope was shattered by parallel cracks and small faults probably formed concurrently with the main scarp. These cracks and low escarpments or ledges directed the drainage northwestward oblique to the slope of the mountain in the same manner as the cracks on Kilauea Volcano, Hawaii, direct drainage today. The tributaries of Hauola and Maunalei streams apparently fol-

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[5] For a detailed systematic description of the structure and products of Kilauea Volcano see Stearns, H. T., and Clark, W. O., Geology and water resources of the Kau District, Hawaii: U S. Geol. Survey Water-Supply Paper 616, 1930.

[6] Aa is the lava comprising beds of spiny clinker with its massive part generally filled with irregular vesicles or holes. Pahoehoe has round vesicles, a billowy surface and commonly tubular caverns but little or no clinker.

lowed these cracks until they found sags or low spots where they cut across and flowed seaward down the normal slope.

FORMS DUE TO WIND

UNCONSOLIDATED DUNES.—Two types of unconsolidated dunes occur, those along the beach consisting of yellowish calcareous sand grains mixed with various quantities of black basaltic sand and those in the uplands consisting of red or brown soil and partly decomposed basalt particles. The beach type forms a definite ridge 10 to 20 feet high along a considerable part of the north and east coast. In very few places has this sand been blown beyond the beach flat and then for short distances only. A large amount of gray sand has drifted from Manele Bay southwestward to Hulopoe Bay partly burying a grove of algaroba trees. This gray sand stands in sharp contrast to the adjacent yellow sand of Hulopoe Beach and owes its gray color to the presence of large quantities of black basaltic particles.

The upland dunes or mounds seldom reach 10 feet in height. They are not conspicuous because they have the same color as the adjacent soil and many are now partly covered with grass. They occur almost entirely on the north and east slopes and in the wind-scoured north end. The lower parts of these dunes may be bedded, and the upper parts are unstratified or poorly stratified (pl. 2, *B*). The unstratified silt appears to be dominant. This earth type of dune results from wind erosion of the formerly deep soil on the uplands and subsequent deposition. It usually appears to be concurrent with the destruction of the vegetation which resulted from overgrazing by livestock, as shown by the burial of roads and trees.

CONSOLIDATED DUNES.—Consolidated dunes consisting of calcareous or limy beach sand cover sufficient areas on the northeast or windward side to be shown on plate 1. That they accumulated at a time when the sea was lower is shown by the fact that some are now partly submerged (pl. 5, *A*). After the dunes were formed their grains were cemented together by lime deposited from percolating rain water. As on the islands of Oahu, Maui, and Molokai, the consolidated dunes are far more extensive than the unconsolidated recent dunes, indicating either one or more of the following conditions: (1) a longer period of accumulation; (2) stronger winds at the time of their accumulation; or (3) more abundant supplies of sand. The dunes extend 2 miles inland from the coast near Maunalei Gulch and up the slope to an altitude of 950 feet. Their surface is commonly pitted and in some places it bristles with formidable spines as a result of solution. Along the coast the pits usually contain salt deposited from evaporating sea water and spray.

On the ridge southeast of Wahane Gulch and 2 miles south of Lae Hi Point at an altitude of 680 feet are several acres of unusually rough country consisting of closely spaced spiny and pitted pinnacles 2 to 4 feet high made of brown hardened soil and partly decomposed basalt. Limy nodules several inches across are scattered among the pinnacles (pl. 3, *B*). These bizarre features appear to have resulted from the cementation of sand by lime carried downward by percolating water from the overlying calcareous dunes as they weathered away. When the dunes disappeared and cementation ceased, solution attacked the hardpan material and etched it as it had etched the dunes, but the resulting forms are different because the material is more insoluble. In a few places several inches of the former dune material remain as a cover, affording a clue to the origin of this peculiar topography.

EFFECTS OF WIND EROSION.—The deep gullies in the badlands make stream erosion appear a far more effective agent of denudation than wind erosion even in the largest so-called wind scars. However, wind probably prepares the way for the gullies by removing the top soil, thereby making seed germination practically impossible. The numerous small scars seen were due almost entirely to wind erosion. These evidently represent the first stage in the development of badlands. As the scar grows larger stream patterns develop, and the streams then rapidly erode deep gullies in the soil and underlying partly decomposed lava.

On the northeast slope of the island the canyons are bordered by terraces 20 to 60 feet in height, which were caused by the more rapid recession of the soil cap and rotted rock in relation to the underlying hard rock, a result of wind and water erosion (pl. 3, *C*). Along some canyons such as Wahane, the soil cap has receded a quarter of a mile, and in the higher altitudes where the divides are narrow the soil cap has been removed entirely. Generally pinnacles of rock and badland topography lie in the wake of the stripped terraces. It is difficult to believe that all this stripping has taken place since the introduction of livestock. During most of the year strong trade winds are tearing away the surface grain by grain and during the winter rains this material is washed into the canyons. It is undoubtedly a rapid process. The partial burial of trees at the mouths of the canyons and the building of the shore flat in historic time are evidence that great quantities of this soil have been washed from the hills in recent years.

The north end of the island is known as the "blown country" because of the devastation there by the wind. Rows of trees planted as windbreaks grow scarcely fast enough to keep their heads above the wind-blown silt they catch in their branches. Here and there the top of a post indicates a buried fence. In other places the soil has been scooped out from under the fence leaving stretches where the posts are dangling in the air. All the trees are bowed before the wind. This forlorn area vividly portrays the ravages resulting from overgrazing in a wind-swept country. One bizarre and fantastic group of pinnacles is locally known as the Garden of the Forgotten Gods. These pinnacles consist of hard pillars of rock which have withstood weathering and now stand in relief because of the removal of 10 to 30 feet of residual soil by stream and wind erosion (pl. 3, *A*). Some of these groups of pinnacles suggest the rugged surface of a youthful aa lava flow, but their origin is clearly shown by the various stages of exposure of the pinnacles.

MARINE FEATURES

MARINE CLIFFS.—The most impressive cliff on the island is Pali Kaholo or Kaholo cliff, south of the port of Kaumalapau (pl. 4, *B*). It starts at the gulch near the port and rises in the next 2¼ miles to a height of 1,000 feet and then dies out at Kaunolu Gulch 1¾ miles farther southeast. In places it is ornamented with fantastic pinnacles and deep grooves made by stream erosion. Although one might suspect that the cliff was caused by the seas eroding a fault escarpment, evidence was not found of a fault with the trend of the cliff, although several fault traces are exposed in it which trend obliquely or at right angles to the coast (pl. 1). The coast faces west and southwest toward the open Pacific and is often pounded by rough seas. The most destructive storms generally reach Lanai from this direction. Additional evidence that marine erosion is very effective on this side of the island is the presence of a marine cliff reaching a height of 350 feet 7 miles north of Kaumalapau. High marine cliffs are cut in the lava rock of the west coasts of Oahu, Niihau, and Kauai, indicating that marine abrasion is very effective on the leeward side of unprotected islands in this latitude. It seems likely that Kaholo cliff is solely the result of marine erosion. As shown on page 21, Lanai has had a complicated history of emergences and submergences which have given the sea an opportunity to make fresh attacks on the land repeatedly.

The height of a marine cliff in a large measure depends on the steepness of the land surface, which in Lanai is mainly a result of the dip of the lava beds. Thus a higher cliff will be cut in a steep slope because the waves can drag the spoil down a steep submarine slope more readily than down a gentle slope. Furthermore, the waves are not spent when they reach the shore because they have only a narrow bench to cross, and undermining causes large segments to fall as landslides, which are much more readily removed than rock in place. The effect of a steep slope and of a gentle slope on the height a cliff will be cut by the sea is illustrated in figure 3.

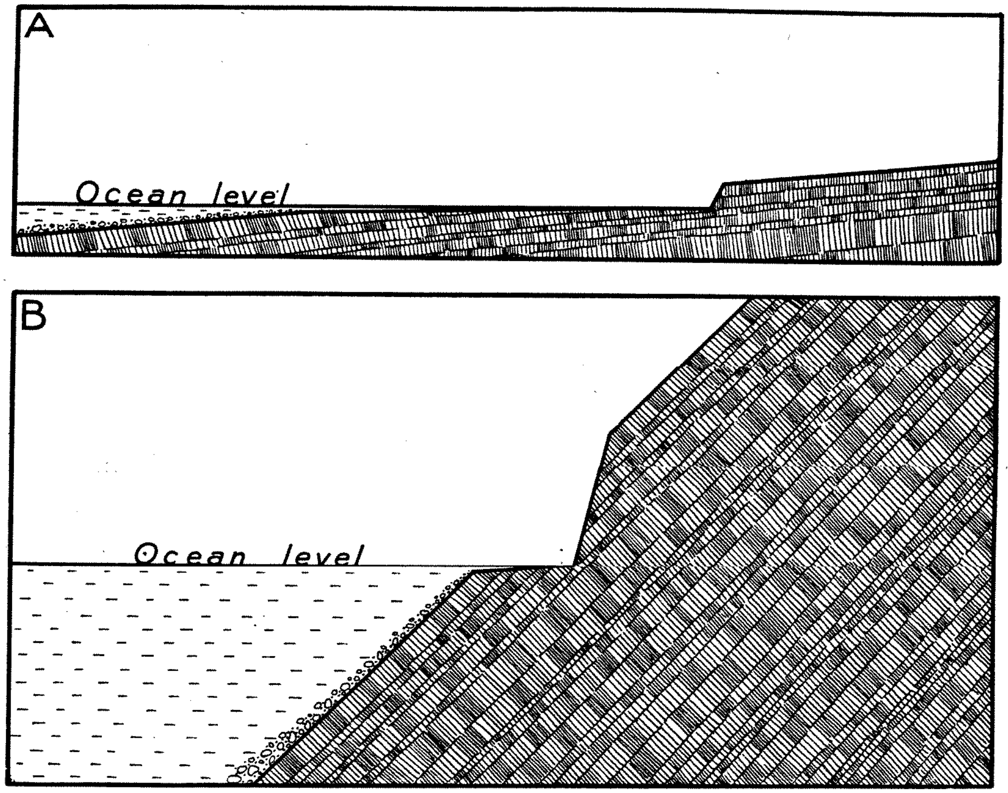
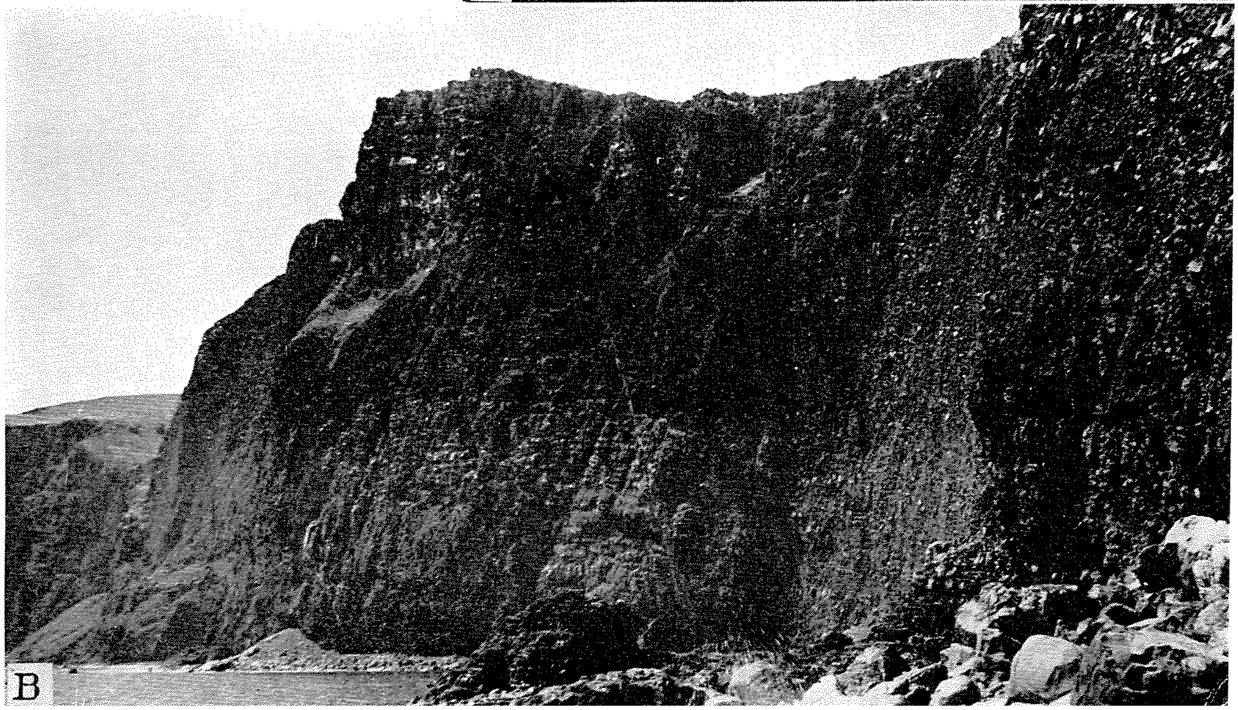
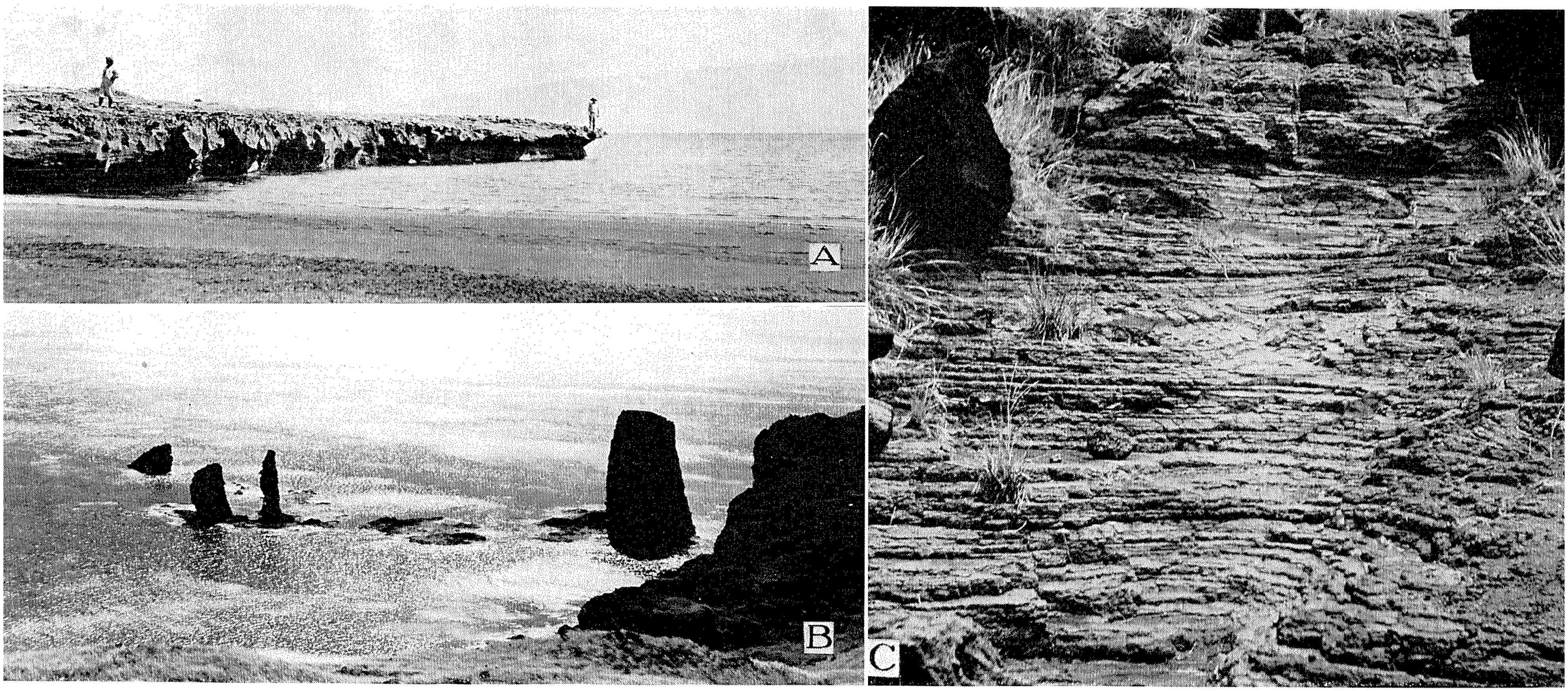


FIG. 3. Diagram illustrating how normally a higher cliff will be formed by wave attack on a steep slope than on a gentle slope. *A*, gentle slope; *B*, steep slope. The slope in *B* has been exaggerated.

In several places the lower part of Kaholo cliff overhangs, and the exposed fresh rock indicates that the present sea is rapidly undercutting the cliff. The absence of talus in most places shows that the sea is removing the blocks as fast as they fall. Only three talus fans were found at the foot of this cliff. That landslides are bringing in debris at these three localities faster at present than it can be removed by the sea may be explained in part by the fact that the cliff has receded into craters which have an irregular structure as compared with the relatively regular structure of the lava beds



Pl. 4. *A*. Streak of breccia indicating fault on the south side of Manele Bay. The rock on the right is shattered basalt and the rock on the left is talus accumulated along the escarpment created by this fault. *B*. Kaholo cliff, southwest coast of Lanai. The faint lines in the cliff are intersecting fault traces of the southwest rift zone.



PL. 5. *A*, Partly submerged consolidated dune at Lae Hi Point. *B*, Nanahoa or The Needles on the west coast of Lanai. They are marine stacks and remnants of a partly drowned interstream divide. *C*, Fine-grained laminated tuffaceous nonmarine* sediments in Kapoho Canyon. The blocks of basalt have fallen from the adjacent canyon rim. (*"Non" inadvertently omitted from title in list of illustrations on page ix.)

where talus does not exist. The rock that fills these craters is massive but cut by numerous columnar joints, and under it is a complex of throat breccia, cracks, fault blocks, and irregular dikes all making a poorly knit structure that fails more readily than the adjacent lava beds.

Between Kaunolu and Manele Bay most of the sea cliffs are low because the slope of the country is gentle. From Manele eastward to Kawaiu Gulch the cliffs are high again owing to the steep slope of the region and the shattering of the faulted and cracked lava beds.

From Kawaiu Gulch to Kaena Point the east and north coast is not cliffed, although it faces trade-wind seas. Such coasts are cliffed on most of the other Hawaiian Islands. This lack of cliffing is caused by two conditions: (1) The coast has not been exposed to wave action as long as the cliffed west coast. During the long erosional period when the canyons on the northeast side were cut and the high cliffs were made on the west coast the island was joined to Maui and Molokai as shown in plate 9, *B*, and the present north and east coast was dry land. (2) The shore is a coast of deposition. In spite of the fact that 8 miles of the northeast coast faces Pailolo Channel, the opening between Molokai and Maui (pl. 11, *B*), and catches the full brunt of the trade-wind surf, it is not cliffed. The steady trade winds blowing through Pailolo Channel create a current that washes debris toward the coast of Lanai and makes this shore one of the greatest receiving grounds of flotsam and jetsam in Hawaii. The presence of large numbers of Japanese glass floats which drift through the channel from the fishing grounds near the Aleutian Islands is evidence of this current. Further, the largest streams on Lanai drain to this coast and their debris is now carried alongshore by currents as shown by the extension of this coast in historic time.

STACKS.—Numerous stacks and pinnacles occur along the coast, the most scenic of which are "The Needles," or Nanahoa, 2½ miles north of Kaumalapau (pl. 5, *B*). Such stacks are made by the sea cutting through partly drowned narrow stream divides. This gives them their linear arrangement at right angles to the coast. The stacks at the point west of Manele Bay, however, are remnants of a volcanic cone (fig. 2).

BEACHES.—A practically continuous beach extends from Kaena Point on the west tip around the windward (northeast) coast to Kamaiki on the southeast side. The sand of this beach is a mixture of reef detritus and comminuted basalt. Consolidated beach sand occurs in small amounts at widely separated localities, the chief deposit being at Pohakuloa, on the northeast coast. Excellent beaches form the shores of Hulopoe and Manele bays, and at the latter several layers of beach rock are exposed. Although elsewhere such rock is generally useful for building and paving stone, that on Lanai is too poor a quality to be used for these purposes. The rest of the coast is bordered by a lava cobble beach interrupted in places by bare rock benches a little above tide or by sea caves, many of which are enlarged lava tubes in pahoehoe.

In many places the strand is composed of firmly cemented boulder conglomerate, especially on the fringing benches. It is so firmly cemented that a mile northwest of Kaunolu, pot holes are cut in it, and in the cemented talus at the foot of the cliff a mile east of Manele two natural bridges have been eroded. In all outcrops the cemented boulders could not be traced appreciably above storm-wave levels. The close association of these conglomerates with present sea level seems to indicate that the cementation is a chemical process operating today, probably as a result of calcium carbonate and possibly other salts being deposited from evaporating spray or sea water. In places where calcareous grains are available the process is apparently accelerated.

FRINGING REEFS.—The only fringing reef of any importance is along the windward coast. A small reef occurs also at Kamaiki. The reef has a maximum width of about 3,000 feet. The water over much of it is muddy most of the time, largely because of overgrazing, soil-stripping, and later stream erosion. However, the muddy condition does not extend to the seaward edge of the wider parts of the reef, and corals continue to grow there.

Reef organisms, particularly coral heads, grow in abundance along much of the west and south coasts and can be seen easily through the clear blue water on a calm day. Coral heads as much as 6 to 8 inches in diameter have grown on the rocks of the breakwater at Kaumalapau since it was built in 1924. In a few places coral heads were found growing above mean sea level in pools in the fringing rock benches.

FRINGING BENCH.—A bench ranging from a few feet to 100 feet wide, cut in lava rock by waves, skirts an appreciable part of the west and south coasts of Lanai (fig. 2). It ranges from a few inches to about 12 feet above mean sea level and is awash in all rough seas. The origin of this bench has been discussed in detail elsewhere.[7]

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[7] Stearns, H. T., Shore benches on the island of Oahu, Hawaii: Geol. Soc. America Bull., vol. 46, pp. 1467–1482, 1935.

In some places it is a relic bench of a stand of the sea about 5 feet higher than the present sea, in other places it is a product of present day shore processes, and in still other places it is a result of both these causes. On the west side of the first canyon east of Manele Bay this bench is 6 to 20 feet wide and is planed across a mass of very dense columnar jointed lava. It is 10 to 12 feet above sea level at the seaward end, but 50 feet shoreward it is only about 3 feet above estimated sea level. It is remarkably smooth considering the closely spaced joint blocks it truncates. The rapid decrease in height of this bench paralleling the rapid decrease in height of the waves as they round the point and enter the bay at the mouth of this valley shows clearly that the height of the bench is a function of the roughness of the sea.

ANCIENT SHORE LINES.—A series of emerged and submerged shore lines was found on Lanai, as on Oahu, Maui, and Molokai. They have been described in full elsewhere,[8] and need only brief mention here.

The highest fossiliferous marine sediments yet found in the Hawaiian Islands were discovered on Lanai at an altitude of 1,070 feet in a small swale 3,200 feet south of Puu Mahanalua and 5,700 feet north of Manele Bay (pl. 1). Stripping of the soil above this level suggests that the sea once washed the island to an altitude of about 1,200 feet. This high stand is named the Mahana stand. Resistivity surveys made by Swartz show that the bedrock floor at the mouth of Maunalei Gulch is at least 300 feet below sea level, indicating that Lanai has been submerged at least 300 feet since this canyon was cut. Apparently, therefore, Lanai was drowned a total of at least 1,500 feet and has now re-emerged about 1,200 feet.

It is possible, however, that the valleys of Lanai were carved prior to the Lualualei shore line which is now drowned more than 1,200 feet on Oahu. If Lanai is submerged the same amount as Oahu, then Lanai may have stood at least 1,200 feet higher than at present during the canyon-cutting epoch. During the high Mahana stand it may have been submerged as much as 2,400 feet.

Fossiliferous limestone was also found at an altitude of 625 feet on the south rim of Kaluakapo Crater. This limestone and the presence of rock platforms suggest a halt at about this level as the sea receded from the Mahana stand.

A conspicuous shore line, named the Manele, occurs at an altitude of 560 feet. The type locality in Kaluakapo Crater is shown on

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[8] Stearns, H. T., Ancient shore lines on the island of Lanai, Hawaii: Geol. Soc. America Bull., vol. 49, pp. 615–628, 1938.

plate 1. It is shown by fossiliferous marine conglomerate and broad wave-cut terraces at this level (pls. 1 and 6, *B*). Evidence that this shore line definitely existed after the present canyons were cut is afforded by sediments of the sea partly filling many of the canyons. Fossils collected from these deposits in Kawaiu Canyon are Pleistocene in age.[9] The shore line may be a halt in the recession of the sea from the Mahana stand, or a lower level of the sea may have intervened between the Mahana and the Manele stands.

Rock platforms and fossiliferous conglomerates at altitudes of about 325 and 375 feet suggest that temporary shore lines or halts occurred at these levels as the sea fell from the Manele shore line.

Concordant benches of marine conglomerate and several rock platforms at an altitude of about 250 feet make it appear that a halt occurred at this level, also. This corresponds to the Olowalu shore line, first discovered on West Maui.

A submerged shelf along the northeast coast is suggestive of a drowned shore line about 300 feet below sea level correlative with the Kahipa low stand of the sea on Oahu. This probably followed the emerged 250-foot shore line as on Oahu. Then the island was submerged about 400 feet as shown by the benches of marine conglomerate and wave-cut platforms 100 feet above sea level. They are particularly conspicuous between Manele and Kaunolu bays and mark the Kaena shore line.

The sea then fell to about 60 feet below present level, the Waipio shore line, and great quantities of wind-blown calcareous sand drifted inland from the bared ocean floor to form extensive dunes along the northeast coast. The dunes subsequently hardened to the white limestone now so apparent on the northeast slopes. Again the ocean crept up on the land to 25 feet above the present level and drowned some of these dunes as at Lae Hi Point (pl. 5, *A*). Benches of fossiliferous conglomerate and wave-cut terraces 25 to 30 feet above the present sea level attest this new invasion of the sea. Finally the sea receded to its present level, with probably a short pause at 5 feet above the present strand.

The major sequence and the magnitude of the movements of the sea in relation to the island are shown graphically in figure 4. Very little evidence exists on which to base the units of time, hence the units have no definite length of time in years. The only evidence available is the relative amounts of weathering and erosion and this is very difficult to evaluate. No attempt was made to show in this graph the duration of the halts in the movement or some of the

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[9] Stearns, H. T., op. cit., p. 621.

shore lines that are poorly preserved. Undoubtedly, the record is still very incomplete, but the graph does show a rhythmical decadence in movement. Zero in the units of time is the end of the epoch when the canyons were cut to essentially their present form. Two units of time have been assigned to the period occupied by the Lualualei submergence. This submergence may have required much more time relative to the later shifts.

In the following table the shore lines are listed in order of age with the oldest at the bottom.

Pleistocene shore lines on the island of Lanai, Hawaii

Approximate altitude (feet)	Name	Evidence on Lanai	Type locality (island)
0	None	Present shore line.	
+5	Kapapa	Wave-cut bench indicating a shore line at this level	Oahu
+25	Waimanalo	Wave-cut platforms and benches of fossiliferous marine conglomerate	do.
—60±	Waipio	Partly drowned hardened dunes overlain with fossiliferous marine conglomerate of the Waimanalo stand	do.
+100	Kaena	Wave-cut platforms and benches of fossiliferous marine conglomerate	do.
—300	Kahipa	Submarine shelves	do.
+250±	Olowalu	Wave-cut platforms and benches of fossiliferous marine conglomerate	Maui
+325±	None	Wave-cut platforms and deposits of fossiliferous marine conglomerate	Lanai
+375±	do.	do.	do.
+560	Manele	Well-preserved fossiliferous beach conglomerates and wave-cut cliffs and platforms	do.
+625±	None	Poorly preserved fossiliferous conglomerate and wave cut platforms	do.
+1,200±	Mahana	Shingle and soil stripping below this level and none above	do.
—320	None	Drowned valleys indicate 320 feet of submergence but the total submergence may have been as much as 1,200 feet, the amount recorded on Oahu.	

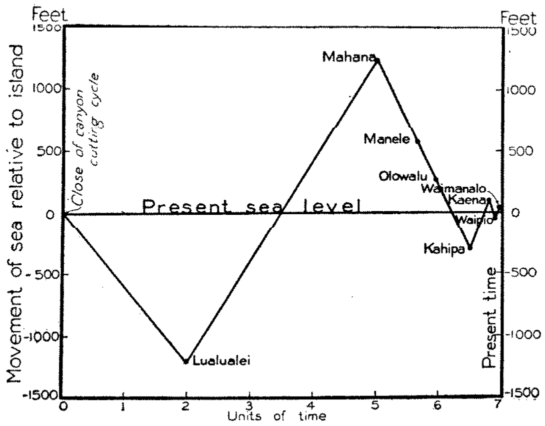

FIG. 4. Graph showing the rhythmical movement of the sea relative to the island of Lanai. Names of the prominent shore lines are given.

It may be that the shore lines after the Olowalu, because of their concordance on Oahu, Maui, Kauai, and Lanai, are eustatic and resulted from changes in the volume of the ocean as a result of advances and recessions of the ice caps and the concurrent changes in the form of the ocean floor. The floor of the Pacific has changed greatly in late geologic time and such changes have considerably affected the ocean level. The earlier shore lines, however, probably indicate considerable movement of the land. It is more likely, therefore, that the record left is that of an unstable land mass in a fluctuating ocean.

GEOLOGY

GEOLOGIC CONDITIONS AND THEIR EFFECTS ON THE RECHARGE AND MOVEMENT OF GROUND WATER

In a basaltic island like Lanai a thorough knowledge of the geology is essential to predict where, how much, and what quality of ground water is to be found. The minor structural features differing between and within the individual lava flows, owing to the diverse conditions under which the lava accumulated and cooled, constitute the texture of the mass. The cavities, pores, and other openings within these lava flows determine the quantity of water that can be stored in the great underground reservoir and are more or less comparable to the interstices in the gravel of a stream bed.

In addition to the minor structural features in the flows there are the major structural features of the volcanic edifice which cut across the flows. They are the fault breccias and the dike complexes, which lie in three definite systems radiating from Palawai Basin. The dikes are a few inches to several feet wide and consist of rock that cooled in cracks under the pressure of the overlying rocks. Except in their upper parts they have low permeability. Because of this fact they confine ground water in the polygonal segments of porous lavas which they enclose to altitudes of 1,000 feet or more above sea level in the middle of the island. These dike-walled compartments form reservoirs within the main reservoir of the island, and the rain water percolating into them either overflows as springs into the canyons that have cut into the compartments, as in Maunalei Gulch, or leaks through the dike walls to join the lower zone of saturation in the surrounding lavas (fig. 5). It is highly essential, therefore, in a study of the occurrence of the ground water that the location of these dike systems be determined.

The part played by fault breccias in the movement of ground water in a basaltic island is little understood. Well-cemented gouges[10] occur in some fault breccias. They may impound water in the same manner as dikes wherever they are sufficiently numerous and intersect one another. Doubtless they also guide water to the water table because they cut nearly vertically through the rocks, hence offer a direct path downward for the percolating water. Further, in places they break the dike compartments, allowing the water to escape and lowering the head in the dike complex. Along some fault scarps are thick talus breccias, and these also may serve as conduits for ground water.

The caldera complex of the central crater also has a role in ground-water movement. This complex is not exposed. By analogy with crater complexes on some of the other islands of Hawaii, the throat breccias, ponded lavas, fault breccias, and intrusives of such complexes may make up a large body of rock with a relatively low permeability 1,000 feet or more below the surface. It is essential that the position of this body of rock be determined in order to avoid it in water developments.

Consolidated dune and marine limestones and gravel, sand, and silt deposits exist on the island in addition to the volcanic rocks. The limestones do not contain available water but the earthy deposits yield valuable supplies.

GENERAL CHARACTER AND AGE OF ROCKS

The igneous rocks consist of basaltic lava flows and dikes with very small amounts of pyroclastic or fragmental material. The sedimentary rocks are in part earthy deposits derived from the weathering and erosion of the igneous rocks, and in part calcareous

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[10] Gouge is a term used to designate the rock powder produced by the friction of the moving blocks along the fault surface.

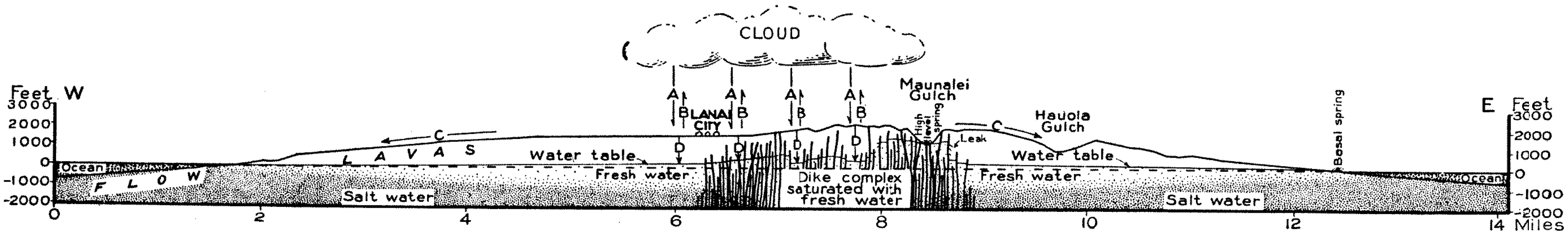

FIG. 5. The source and disposal of rainfall on Lanai. *A*, rainfall; *B*, fly-off or evaporation and transpiration; *C*, run-off; *D*, run-in or recharge of zone of saturation; mean sea level indicated by a broken line. Simplified section showing the confined water in the dike complex, the origin of high-level and basal springs, and the fresh water of the basal zone of saturation floating on salt water with the percentage of salt indicated by dots. Faults omitted and thickness of basal zone of saturation exaggerated.

or limy sediments that consist of emerged fossiliferous marine limestone, foraminifera, and fragments of calcareous marine organisms comminuted by erosion and deposited by the wind or the sea.

The lava beds range in thickness from 1 foot to 100 feet and average about 20 feet. Lava flows thicker than 50 feet are exceptional and are usually confined within crater walls or banked against fault scarps, whereas those less than 5 feet thick are generally on the slopes of cones. Pahoehoe flows predominate near the summit and along the crest of the rift zones, but elsewhere aa is abundant. Typical cinder cones were not found, the dominating cones being wholly composed of lava flows. Cones consisting of spatter and a mixture of cinder and spatter are common on the southeast slope, also pit craters from which no lava flowed. Beds of firefountain deposits[11] ranging from a few inches to 3 feet in thickness occur rarely. The dikes are all basaltic and range from a few inches to 6 feet in thickness. They are chiefly pahoehoe, although several containing aa were observed (p. 40). Throat breccias, the rubble which accumulates in craters, form only a small percentage of the island but are conspicuous because they break the continuity of the flow bedding. Bands of fault breccias, numerous in certain cliffs, average about 6 inches in thickness, although a few reach 30 feet. Elongated outcrops of exhumed talus breccias that formed along fault escarpments reach widths of several hundred feet.

Fossils are abundant in the emerged marine limestone conglomerates and show that these rocks were deposited in Pleistocene time. Most if not all of these limestones lie on the canyon floors, indicating that they were deposited late in the history of Lanai. The absence of fossils associated with the igneous rocks leaves the geologic age of these rocks uncertain. The absence of residual soil beds interstratified with the lavas makes it apparent that the flows accumulated rather rapidly, at a rate probably comparable to that of present day accumulation on Kilauea or Mauna Loa volcanoes, Hawaii. Ash becomes soil rapidly, but very little was produced by the Lanai Volcano. Rain, an important factor in the formation of soil, has probably always been scanty on Lanai. Thus the absence of soil does not necessarily mean that the Lanai Volcano was extraordinarily active during its building.

If the lower emerged limestones are related to the shifts of sea level induced by world-wide glaciation, as seems probable, then the canyons were carved during early Pleistocene or late Tertiary time.

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[11] These deposits consist of the whole gamut of products of the lava fountains, such as glassy pumice, broken ribbons, and spatter.

Thus the building of the island may have started in late Tertiary time. From their study of the evolution of land snails in Hawaii, Hyatt and Pilsbry conclude: "That the eastern or Molokai-Lanai-Maui region formed a single large island up to late Pliocene or even to Pleistocene time is evident from the very close relationship of the faunas of those islands."[12]

It is concluded on this meager evidence that the Lanai Volcano became extinct in late Tertiary or early Pleistocene time. A detailed description of the rock units follows. Their distribution is shown in plate 1.

TERTIARY AND EARLY PLEISTOCENE(?) VOLCANIC ROCKS

The volcanic rocks on Lanai consist of lava flows, intrusive rocks, pyroclastic rocks, and volcanic breccias. In a few places the basalt can be subdivided into several members but because elsewhere they merge one into the other it was impossible to map them separately.

BASALT FLOWS

CHARACTER AND STRUCTURE.—The basalt of the volcanic series makes up at least 95 percent of the bulk of the island. The individual flows range in thickness from 1 to 100 feet and average about 20 feet. The basalt is gray, blue, red, brown, and black. The clinker phases of the aa flows have a reddish color. Much of the variation in color is produced by weathering. Pahoehoe predominates near the summit and aa along the periphery of the island. This distribution is usual in volcanoes because the lava is generally pahoehoe at the source and commonly changes to aa as it flows, whereas aa never changes to pahoehoe. In one place a single thick bed may be laid down while a short distance away the lava may overflow the same place several different times. This process was well shown during the lava flow of 1935 from Mauna Loa. Further, a layer of pahoehoe may bury a layer of aa or vice versa during the same eruption, hence the change from one type to the other is not necessarily proof of a different eruption. These layers may represent time intervals of several minutes or several days (pl. 6, *A*). The lava flows of any one eruption are distinguished from those of another not by the bedding but by the differences in the mineralogic or textural characteristics or other physical features, or by thin deposits of soil between them. In some outcrops the flows may have followed one another so rapidly and be so similar in texture and

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[12] Hyatt, A., and Pilsbry, H. A., Manual of Conchology, vol. 21, p. XIX, Philadelphia, 1911.

composition that they are not distinguishable with certainty.

The basalts on Lanai are all of the Kilauean type and were extruded in very fluid condition. The few massive lens-shaped columnar-jointed flows exposed in Kaholo cliff and in the cliff east of Manele are crater fills. Fine-grained basalts with and without phenocrysts or large crystals of olivine, feldspar, and augite occur. Probably 40 percent of the flows have olivine phenocrysts. Porphyritic feldspar and feldspar-olivine rocks, those with large crystals in a fine-grained groundmass occur, but they are not abundant. Flows containing augite phenocrysts are as scarce as in the early basalts on the other islands. One was noted at an altitude of 1,950 feet on the east bank of the east fork of Kapoho Gulch. Rocks rich in olivine phenocrysts occur near the Naha trail at an altitude of 500 feet, in the sea cliff about 5 miles north of Kaumalapau, on Kaonohiokala Ridge 1¼ miles west of Keomuku at an altitude of 500 feet, and on the east rim of Kawaiu Gulch at an altitude of 800 feet. Most of the flows are very vesicular or full of pores but some, especially the solid parts of the aa flows, are dense. A few are platy. Their dips range from 2° to 18°, with the average probably about 9°.

Water-bearing properties.—The basalt flows are almost everywhere permeable and serve both as the principal intake formation and the bearer of the ground-water supply of Lanai. Some of the aa flows contain thick beds of very permeable clinker, and many of the pahoehoe flows (pl. 12, *A*) contain numerous tubes through which water can move rapidly in large volumes.

Unconformities.—An unconformity is a horizon represented by a time interval in the geologic record commonly but not always indicated by a lack of parallelism of the beds. Four unconformities were found in the basalt, two indicated by talus accumulated at the base of fault scarps, the other two by unsorted, unstratified debris or hillwash.

A series of great en échelon faults can be traced from Manele Bay to Palawai Basin. The lava beds west of these faults are younger and lap against the talus which accumulated at the base of the westernmost fault scarp as shown in section C–C′, plate 1. The best exposure of this unconformity is in a small tributary to the canyon on the east side of the road to Manele 8,000 feet due north of Manele trig. station. It is known that at this place lavas from Palawai Crater accumulated against the growing talus apron at the foot of a fault scarp over 400 feet high because the talus interfingers with the lava. This angular unconformity is shown on plate 1. No soil was found on the talus where it was overflowed by the lava, indicating that the fault scarp was essentially contemporaneous with the lava flows. This contact closely resembles the unconformity between the lower and middle basalts of the Waianae volcanic series in Heleakala Ridge, Oahu.[13]

In the sea cliff 2,900 feet northwest of the southwest point in Kaunolu Bay two series of lavas separated by an angular unconformity are exposed (pl. 1). The two series are separated by a prism of talus 20 feet wide at the beach. The contact of the talus with the overlying pahoehoe strikes N. 25° E. and dips 31° SE. The upper lavas are about 250 feet thick and comprise a non-porphyritic pahoehoe flow 35 feet thick and two massive overlying aa flows. A streak of rotted glass crust marks the top of the pahoehoe. The unconformity is plainly visible from a boat and appears to be caused by lavas from the north, possibly from Ulaula Crater, overflowing an east-facing fault escarpment. The lavas flatten out near Kaunolu Bay. This fault appears to form the west side of a sunken block that extends eastward to the Manele fault. The upper lavas are faulted 1,400 feet northwest of the point, indicating that faulting continued during the filling of the graben.

A layer of hillwash several inches to 4 feet thick crops out at the bottom of an aa flow in the upper series 1,700 feet northwest of the point, on the west side of Kaunolu Bay, showing that short time intervals occurred during the accumulation of these lavas.

Two series of lava separated by several inches to 2 feet of red hillwash crop out in the sea cliff 3,500 feet south of Kaumalapau Landing. This unconformity has an easterly trend and dips 12° NW. The hillwash consists of pahoehoe crust fragments overlain in turn by small fragments of aa clinker, angular dense rock, and pumice. The crust fragments were derived from the underlying bed, but the other fragments appear to be hillwash rather than explosion debris, although they may have originated from an explosion and may have been washed to this place later. The hillwash decreases in thickness to the southeast or up the slope of the surface on which it accumulated. The lower series of lavas has a westerly dip of 5° whereas the upper series is nearly horizontal, implying that the upper lavas came from the east or northeast and overflowed the north slope of the southwest rift-zone ridge. A similar but less continuous red layer of debris overlies the bottom aa flow in the upper series. It is probable that the time interval represented by the unconformity is

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[13] Stearns, H. T., and Vaksvik, K. N., Geology and ground-water resources of the island of Oahu, Hawaii: Hawaii Div. of Hydrography, Bull. 1, p. 80, 1935.

short, and that the hillwash debris was washed from the adjacent ridge onto lava flows lapping against it because these layers closely resemble the debris which now accumulates in the kipukas, or islandlike areas not covered by later lava flows, on the slope of Mauna Loa, Hawaii, and because no soil was formed.

An unconformity is exposed in the sea cliff extending 1,000 feet eastward from Kawaiu Valley. The upper series has a dip of 3° and rests on beds with a dip of 17°. A bed of vitric or glassy ash, indicating firefountains in the vicinity, separates the two lavas in one place but eastward interfingers with the upper beds. No sign of erosion or weathering occurs, indicating that very little time elapsed between the pouring out of the two series of flows. It appears that the upper flows came from vents to the north and overflowed the lavas in the ridge of the south rift zone. Possibly the discordance is solely the result of faulting, which may have caused the eastern side to be downthrown so that the upper series accumulated in a fault depression.

The talus breccias at the unconformities near Manele and Kaunolu bays cut across the island from the coast toward Palawai Basin. If they are not cemented too firmly they may serve as conduits to allow ground water a direct route to the sea. The thin layers of hillwash at the unconformity south of Kaumalapau Landing are too thin to serve as perching formations. Unless they thicken inland they probably play no role in the movement of ground water.

CONES AND CRATERS

Exclusive of the main summit craters, Palawai and Miki basins, 47 cones and craters were found on the slopes. These minor cones are composed of lava flows generally with subordinate amounts of spatter and cinder. Some of these cones have shallow craters in their summits, but the craters referred to below are pit craters or depressions of collapse from which little or no lava flowed. Some are circular in plan and cup-shaped in cross section and contain massive columnar-jointed masses of lava; others contain only breccia or the rubble which accumulated in them concurrent with the collapse and afterwards. The cones and craters are shown by separate patterns on plate 1 except those in the cliffs along the coast, which are too small to show at all. The patches of breccia shown northeast of Lanai City on plate 1 are in Maunalei Gulch and mark the sites of eroded pit craters. A fine cross section of a small lava dome and its feeding dikes is exposed in Kaholo cliff, 6,000 feet northwest of Kaunolu Bay. The eruption began with a firefountain that produced a thin layer of vitric tuff. Then there followed copious outpourings of pahoehoe in thin layers. Another cross section of a lava cone is exposed at Manele. The lava layers are only 2 to 5 feet thick and contain considerable spatter. A fissure vent bordered by spatter and lying directly inland from Kamaiki Point has been modified considerably by marine erosion. No cones consisting exclusively of cinders were found, although many contain beds of cinders several feet thick. In the northwest wall of Naio Gulch in line with the upper part of Maunalei Gulch a cross section of a cone is exposed in which the pyroclastic debris is largely altered to palagonite, a waxy yellow mineral substance. In this exposure one can see with unusual clearness that the crater has been filled with later lavas.

Cross sections of pit craters filled by later lava flows are common. One is exposed in the bend of Maunalei Gulch and three in a line are exposed in the north wall of Lopa Gulch about 1,750 feet above sea level.

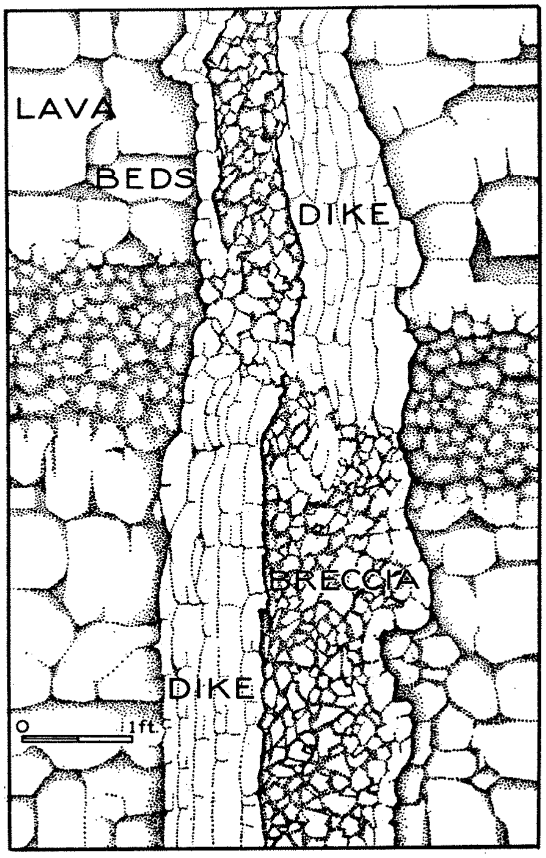

FIG. 6. Platy dike displaced and brecciated by a fault in the west fork of Kapoho Gulch.

In the west fork of Kapoho Gulch numerous thin layers of hillwash between lava flows and several dikes brecciated by faulting were observed. The arrangement of the breccia, which was produced by the faulting of a platy dike, at a place about 500 feet above the confluence of the forks is shown in figure 6. Because no soil produced by decomposition in place was intercalated with the lava beds in this area the layers of hillwash and the unconformities are interpreted as indicating local unconformities caused by lava flows spilling over cone slopes and low fault terraces. The steep slopes of such buried and partly buried topographic features could have readily yielded, by gravity and wash, the debris that is interstratified with the lava beds. Because none of the fragments in the hillwash were appreciably weathered prior to incorporation it is believed that the time intervals represented by the layers of hillwash were short.

The largest pit crater found is Kaluakapo, about half a mile northeast of Manele Bay. It has a maximum diameter of 4,000 feet, and its probable structure is shown in plate 1, section C–C′. Puu Nene, another crater about 2,000 feet across, is now aggraded to a level plain. The amphitheater-shaped depression 4,000 feet across with Puu Ulaula on its north rim in the southwest rift zone is believed to be a crater from which considerable lava flowed.

The other cones and craters are not sufficiently large or different to warrant separate descriptions.

The craters serve as collecting basins, thereby increasing recharge. The ash beds associated with the cones are too thin and cover areas too small in such a dry island to perch water as they do in the Kau district, Hawaii.

DIKE SYSTEMS

Northwest rift zone.—The form of the northwest rift zone is described on page 11. It is a belt of land about 2 miles wide extending from Palawai Basin to Kaena Point. On the island of Hawaii the southwest rift of Kilauea Volcano is bordered by low fault escarpments arranged en échelon. There, in the shallow sunken area between the scarps are numerous narrow cracks, three cinder cones, and several low spatter cones and inconspicuous lava domes. If volcanism were to cease long enough for soil to form, the cracks would soon be obliterated by soil. The weakly knit spatter cones would erode into knobs with only the denser material left, and the lava domes would become practically indiscernible. The cinder cones would be the last to lose their identity. The northwest rift of

Lanai fits this picture of a deeply weathered rift zone except that it did not happen to have any cinder cones. The few fault escarpments that could be identified with reasonable certainty are shown on plate 1. Doubtless other smaller ones formerly existed.

The rift zone is not exposed at the coast except for a short stretch on its south side; hence little can be said about the distribution of the dikes and the complexities that may have been produced by faulting.

No dikes were found in the first 6½ miles of sea cliff north of Kaumalapau. In the next half mile four dikes 6 inches to 3 feet thick trending between N. 35° E. and N. 55° E. were found. They are probably stray dikes near the margin of the rift zone. The westernmost dike in the group dies out part way up the cliff. Along its strike and 2,000 feet inland is a low hill called Kaapahu that consists of massive nonporphyritic basalt underlain with 3 to 6 inches of ash. Because of the extensive marine stripping in this area, no positive evidence that this was a vent could be found. A mile farther northwest along the coast and 2½ miles south of Kaena Point, or a short distance from where the sea cliff dies out, a group of eight dikes is exposed, all of them trending nearly due east. The widest is 5 feet across.

An increase in the amount of pahoehoe and a decrease in the amount of aa was noted as the rift zone was approached. Also a few thin ash streaks appeared, indicative of approach to a rift zone where firefountains had played.

In the vicinity of Lanai City the northwest rift zone may be as much as 4 miles across. It is wider near the summit because the northwest rifts in the early (pl. 8, *B*) and collapse (pl. 9, *A*) stages of the Lanai Volcano did not coincide exactly. This is fortunate because all the high-level water in Maunalei Gulch is apparently held up by dikes intruded mostly during the early stage of the volcano.

A chain of 15 vents is exposed in Maunalei Gulch and its tributaries. More than half are pit craters, and the rest are spatter cones. They are at various horizons in the gulches, hence are of different ages but all apparently belong to the early phase of the volcano. About 18 dikes are exposed in the canyon walls. Those below the pump station crisscross, but the general trend is northwestward. In the small side canyon near the bend in Maunalei Gulch a dike 10 feet thick is exposed. It appears to be locally thickened at this place. Four northwestward trending dikes in this group are exposed near the bend in Hauola Canyon. Five dikes trending northwestward are exposed in the pipe-line tunnel between Koele Village and Maunalei Gulch (pl. 1), hence there can be little doubt that the ridge back of Koele was a scene of volcanic activity.

The cones and craters near Kamaiki Point shown on plate 1 erupted from fissures apparently on a southward extension of the northwest rift system. Westward along the coast from Kamaiki Point are numerous dikes trending northwest, which have been grouped for convenience of description with those in the south rift, although they may well belong in an extension of the northwest rift.

The northwest rift is the most important developed water-bearing structure on Lanai because it is the source of the water in the tunnels and shaft supplying Lanai City. The dikes range from a few inches to 10 feet in width, and many are tight and capable of confining water, as illustrated in figure 5. The upper Maunalei shaft was driven to tap the water confined in this dike complex. This rift is, however, considerably shattered by faults that probably allow the water to escape from some of the compartments. The resistivity survey shows that the water table is only about 6 feet above sea level northwest of Koele, and in view of the fact that the dikes tend to diverge seaward, there is progressively more opportunity for the fresh water to escape northwestward from Koele. Consequently the northwest end of the island does not appear to be a favorable place to develop ground water, especially as its rainfall is low.

SOUTHWEST RIFT ZONE.—The southwest rift zone is a soil-covered ridge extending from Palawai Basin to Kaholo cliff (fig. 1). Ulaula and Miki craters lie along this rift (pl. 1). The central part of the ridge is older than the adjacent lavas, as shown by the unconformities described on page 28. A complete section across this rift is exposed in Kaholo cliff, and because few places in Hawaii expose so well the structure of the upper 1,000 feet of a rift zone, a detailed description of this rift zone from Kaunolu northwestward is given below. (See also pl. 1.) The distances were obtained by pacing, and because of the roughness of the shore some measurements are inaccurate. However, when a point on the map could be identified the pacing was started again; hence the errors are not cumulative.

In Lanai as in all the islands in Hawaii yet studied, the volcanoes are built over three rifts, from one of which less lava has issued than from the others. The southwest rift produced less lava than the northwest, as shown by the size of the ridge built by lavas poured from it. Because the number of dikes, faults, and joints normally increase with depth in a rift zone, a high cliff crossing a rift zone ordinarily exposes more of these features than a low cliff.

But in Kaholo cliff this does not hold true, as more dikes and faults occur half a mile or more south of the crest, where the cliff is only about 500 feet high, than at the crest, where it is 1,000 feet high. Also there are very few dikes or faults north of the crest. The major cracking in this rift lies southeast of the crest and probably marks the west boundary of the collapsed block occupying the area between Kaunolu and Manele. In the 3,600-foot stretch along the coast, starting at a point 2,500 feet west of Kaunolu, 85 dikes are exposed or one to each 42 feet. In the next 3,600 feet only 38 dikes or one every 92 feet crop out. The dikes average 12 inches in thickness and are mostly vertical or nearly so. The average trend is about N. 35° E., heading apparently for the north side of Palawai Basin. A total of 124 dikes is exposed in this rift zone, which is about 1.5 miles across.

About 43 faults and cracks are exposed in this cliff, most of them with displacements of only a few inches, indicating that they were essentially narrow cracks such as those in the southwest rift zone of Kilauea, on Hawaii. A few blocks moved several feet and probably produced ledges 10 to 30 feet high. But as no fault ledges show on the surface now, any that may have been formed were obliterated by later flows, or, if they reached the present surface they have been destroyed by subsequent erosion. Some of the cracks may have been filled with lava which drained away before cooling. Many of them are filled with rubble from their walls and one was noted into which ash had sifted. Most of the breccia in these cracks is tightly cemented. The lava beds in the badly cracked area are so jumbled that the layering is barely discernible. A detailed record of the structure is given in the table below:

Section from north to south along the shore across the southwest rift zone (pl. 1)

Distance (feet)	Structure	Strike (°)	Dip (°)	Remarks
0	....	....	....	Point on west side of Kaunolu Bay.
1,400	Fault. Beds.	N. N. 30 E.	E. 18 SE.	Zone of loose rubble 25 feet wide filled with infiltered lime in cliff 125 feet high. Displacement appears to be small, but the rocks are badly shattered on the west side of the rubble in the upper part of the cliff, making it difficult to match the layers above the aa. All beds are pahoehoe except one, which is a thick aa flow and which pinches out a short distance east of this fault.

Section from north to south along the shore across the southwest rift zone (pl. 1)—*Continued*

Distance (feet)	Structure	Strike (°)	Dip (°)	Remarks
1,700	2 cracks.	....	E.	Both cracks 2 feet wide filled with rubble; slight downthrow on the east side. Another aa flow with a few inches to 4 feet of hillwash at its base is exposed in cliff here.
2,500	Dike.	N. 10 E.	....	Irregularly jointed and vesicular dike; replaced in one spot by rubble. Numerous dikelets in the adjacent pahoehoe indicate that the dike magma intruded all the nearby cracks.
2,700	Crack.	N.	70 E.	Compact breccia zone 2 feet wide, probably a filled crack because no appreciable displacement occurs.
2,800	Crack.	N.	70 E.	Breccia zone 1 foot wide consisting chiefly of olivine basalt fragments derived from the adjacent walls and mostly subangular.
2,900	Fault.	N. 5 E.	70 E.	Major fault of unknown displacement with downthrow to the east and unconformity. Breccia zone 10 to 20 feet wide containing irregular blocks as much as 2 feet across and much vesicular rock and clinker. Conspicuous from a distance because of a streak of green material in its center. The streak consists chiefly of one kind of fairly dense rock and is possibly a dike brecciated by subsequent movement into gouge. The beds in this cliff are mostly of the frothy broken type of pahoehoe with only a few aa beds, and these are similar to those that form near a rift zone where the lavas are very fluid and highly gas-charged. The unconformable beds above the layer of hillwash noted at 1,700 feet die out at top of cliff here.
3,000	Crack.	N. 25 E.	45 NW.	Breccia zone 2 feet wide pinching out 25 feet above sea level. Fairly evenly spaced between this location and the next station are 17 north-northeastward trending faults and cracks dipping east crossed by four smaller ones dipping west. The westward-dipping faults cut some of the dikes but not all, indicating that the movement was contemporaneous with the eruptions forming the fissures. The blocks between the faults are downthrown various small amounts to the east. Two dikes and several lava tubes filled with dense lava and resembling small intruded pods occur in this stretch also.

Section from north to south along the shore across the southwest rift zone (pl. 1)—*Continued*

Distance (feet)	Structure	Strike (°)	Dip (°)	Remarks
3,600	Throat breccia.	....	....	Side of cylindrical mass of coarse throat breccia about 200 feet across and widening upward like a funnel. About 250 feet above the sea it is overlain by a massive crater fill of lava. The layers above it indicate that other flows spilled into the crater from the north and completely filled it. Three dikes in the adjacent basalt flows are cut off at the contact of the breccia and the basalt, but one dike striking N. 25° E. cuts the breccia. A few streaks of yellow ash crop out in this area.
4,200	Fault.	N. 25 E.	70 (SE?)	Shear zone 1 to 3 feet wide with drag dips in the beds on the east side. In the last 400 feet 22 dikes and one N.-S. fault noted.
4,400	Throat breccia and dikes.	....	....	Throat breccia rests on aa and contains blocks as much as 2 feet across; cut by two dikes trending N. 20° E. and two shear zones; apparently a remnant of a crater breccia now nearly eroded away. In the last 200 feet nine dikes striking N. 10° to 25° E. were noted.
4,600	Fault.	N. 30 E.	....	Nearly vertical breccia zone 2 to 3 feet wide.
5,000	Dikes.	....	....	Twelve dikes in the last 400 feet.
5,300	Throat breccia.	....	....	Breccia 150 feet across filling a pipe at least 250 feet high and cut by four dikes and sills with a dense platy crater fill above it. The reentrant in the cliff here is evidently caused by this vertical crater structure yielding more rapidly to marine erosion than the nearly horizontal lava beds on either side. Most of the crater fill has spalled off, forming a talus apron at the beach.
5,600	Dikes.	....	....	Eleven dikes in last 300 feet.
5,800	Fault.	N. 40 E.	....	Fault cut by two thin shear zones trending N. 15° E.
6,500	...do.....	N.	....	Fault enlarged by stream erosion into a deep groove.
6,700	....	....	....	One weakly developed shear zone in this stretch.
7,200	Dike.	N. 30 E.	....	Dike 1 foot wide including streaks of breccia caused by slight movement. Dissected lava dome in middle of cliff, which is 600 feet high here. Fifteen dikes in last 500 feet.

Section from north to south along the shore across the southwest rift zone (pl. 1)—*Continued*

Distance (feet)	Structure	Strike (°)	Dip (°)	Remarks
7,400	Fault.	N. 25 W.	65 SW.	A 6-inch shattered dike trending N. 25° E. terminates against the breccia along this fault. Slight displacement.
7,500	...do.....	N. 25 W.	65 SW.	Slight displacement; breccia zone 2 inches wide.
	3 dikes.	N. 30 E.	....	
7,600	Dike.	N. 5 E.	....	
	Dike.	N. 20 E.	....	
	...do.....	N. 50 E.	....	
	...do.....	N. 25 E.	....	
7,900	...do.....	....	....	Irregular dikes.
	...do.....	N. 25 E.	....	
8,200	...do.....	N. 10 E.	....	
8,300	...do.....	N. 40 E.	....	Dike, 6 inches wide, fractured.
	...do.....	N. 25 E.	....	Noticeable decrease in the shattering of the lava beds.
	...do.....	N. 55 E.	....	
8,500	Crack.	N. 10 E.	65 NW.	
	Dike.	N. 25 E.	....	A block of compact yellowish pumice in the slide here that came from the 2-foot layer at the level of the bottom of the lava dome exposed above in the cliff. The pumice indicates firefountains at the beginning of the eruption.
	...do.....	N. 30 E.	....	
	...do.....	N. 65 E.	....	
8,600	2 cracks.	E.	70 S.	
9,000	3 dikes.	N.	....	
9,600	6 dikes.	N. 30 to 60 E.	....	
	7 dikes.	N. 10 to 40 E.	....	Massive fill at the top of the cliff contributing to talus apron huge blocks of coarse-textured basalt showing numerous olivine crystals under the hand lens and doubtless the source of the olivine in the beach sand here. The rest of the rocks along this coast are mostly without olivine phenocrysts. Five dikes occur in the cliff above this slide. The cliff is 1,000 feet high.
9,700	Crater fill.	....	....	
	Dike.	N. 60 E.	....	
	...do.....	E.	....	
10,200	...do.....	N. 70 W.	....	Slight displacement.
	3 dikes.	E.	....	
10,400	Dike.	N. 40 E.	....	Unshattered pahoehoe in this stretch.
10,600	...do.....	N. 80 E.	....	
	...do.....	N. 40 E.	....	
10,700	...do.....	N. 75 W.	....	Shattered dikes.

Section from north to south along the shore across the southwest rift zone (pl. 1)—*Continued*

Distance (feet)	Structure	Strike (°)	Dip (°)	Remarks
14,000	Crack.	....	....	Breccia zone 4 to 12 inches wide showing slight displacement. It is filled with salts deposited from sea spray as high as about 30 feet above sea level. An ashy streak 2 to 6 inches thick on aa flow.
	Fault.	N. 50 W.	70 NE.	Breccia zone 2 to 4 inches wide with very little displacement.
14,500	Crack.	N. 50 W.	60 SW.	Crack barely discernible.
	Beds.	N. 70 E.	7 N.	Breccia zone 2 to 4 inches wide with very little displacement.
15,700	Fault.	N. 50 W.	50 SW.	
19,400	Unconformity.	....	....	North side of southwest rift zone ridge. End of traverse.

The high Kaholo sea cliff allows water in the highly permeable lava beds in this dike complex to drain into the sea. The area is drained also by the numerous cracks and faults of the rift zone which break the dikes and beds. Further, with its surface well soil-covered and with a rainfall of only 10 to 20 inches, the recharge must be slight. The cliff is dry except for a few damp spots.

South rift zone.—The south rift zone is a belt about 2 miles wide of narrow fault blocks extending S. about 15° E. from the east side of Palawai Basin. At the coast a marine cliff cuts across it, exposing an excellent cross section. The broad sunken block, Manele graben, extending west from Manele and veneered with lava flows from Palawai Crater conceals the west part of this rift zone (section C–C′, pl. 1). A group of cones lies to the east of it on an extension of the northwest rift zone southeast of Palawai Basin, and these cones merge into those in the south rift zone because of their proximity. Some of the dikes in the south rift zone have trends indicating that they may be intrusions along cracks of the northwest rift zone. Although the Lanai Volcano contains three rift zones, it was built chiefly over two rift zones which form a very wide angle, like many other Hawaiian volcanoes. These two are the northwest rift zone and the south rift zone.

The following section was measured by traverse on foot along the fringing bench and in a row boat where the bench was missing. Obviously strikes and dips taken from a boat with a Brunton compass are not exact, and some of the trends of the dikes and faults are therefore incorrect. Errors in distance also were made because of rowing some of the traverse. However, the errors are not cumulative because the traverse was started again at each point that could be identified on the map. In spite of these errors the picture is essentially correct. The number of dikes and faults is impressive in view of the fact that the sea cliff reaches a maximum height of only 300 feet and that erosion has been so slight that probably the maximum depth of exposure in the rift is not more than 500 feet below the original surface. In the first 15,400 feet of the traverse 65 dikes, 28 faults, 2 throat breccias, and 6 cracks were recorded. The series of lavas exposed in this part of the section are faulted below sea level west of Manele Bay, and about 4,000 feet of the coast line to the west is not appreciably cliffed. Otherwise probably many more dikes and faults would be exposed. In the remainder of the traverse 25 dikes and 2 faults were noted. Two faults and 21 dikes are exposed in the younger lavas in the 5,000-foot stretch of low sea cliff east of the starting point of the traverse. Thus a total of 111 dikes and 32 faults are exposed along the south coast of Lanai. This gives a basis for picturing the great number of faults and dikes

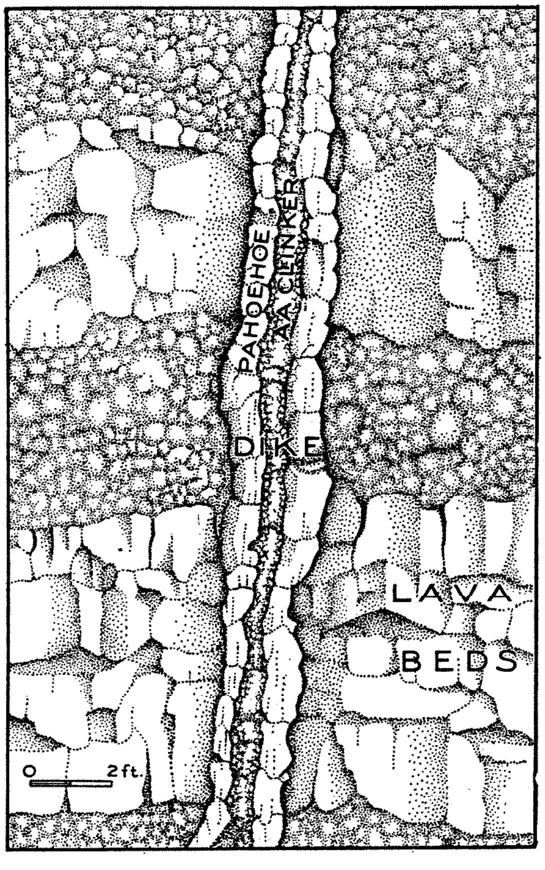

FIG. 7. Dike of pahoehoe enclosing later aa in the sea cliff cutting the south rift.

that must occur several thousand feet below the surface of this rift zone.

The average trend of the dikes is about N. 30° W. All are nearly vertical, and only a few exceed 18 inches in width. Two sets of faults occur, one striking about N. 25° W. and dipping 65° SW. and the other striking about N. 40° W. and dipping 65° NE.

A few dikes are unusual enough to justify individual descriptions. An 18-inch platy dike 1,200 feet up the gulch draining Kaluakapo Crater and striking N. 65° W. contains in its center a 6-inch band of ropy highly vesicular pahoehoe. Figure 7 shows the details of a dike 9,200 feet from the beginning of the traverse. (See p. 43.) It consists of two bands of cross-jointed dense pahoehoe basalt cutting massive and clinkery beds of basalt. Vertical cracks cut the cross-joints. A vertical band of typical aa basalt with irregular stretched vesicles bordered by clinker forms the center of the dike. Another dike containing aa crops out 27,650 feet from the beginning of the traverse. They remove any possible doubt that aa can exist as such underground and form dikes. The presence of aa in these dikes, however, does not indicate that aa is erupted at the initial outbreak of the flow, as some might assume, for in both of these dikes pahoehoe has preceded the aa.

The dike 27,700 feet from the starting point of the traverse is unusual. As shown in figure 8, it consists of an irregular platy structure 3 feet wide with bands of vesicles parallel to the walls. Here and there occur pockets of a peculiar breccia consisting of frag-

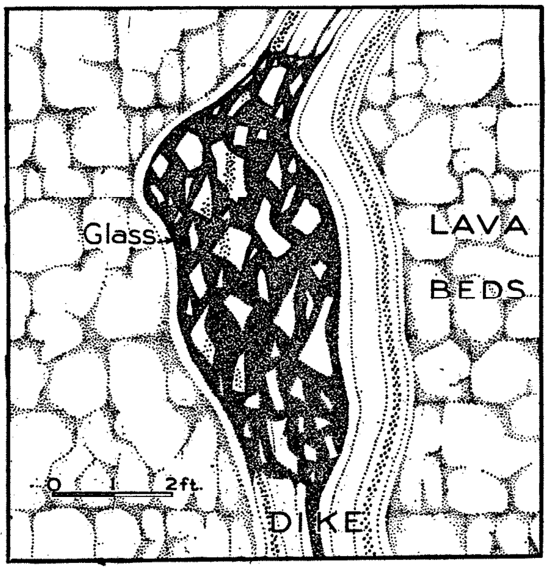

FIG. 8. Fragments of a platy dike in a matrix of glass indicating breaking of the border before the lava had ceased rising through the dike.

ments of the dike material as much as 8 inches across in a matrix of tachylyte or black glass. It appears that the liquid lava receded after most of the dike had solidified. This lack of support caused the platy walls of the dike to collapse. Then the lava rose again, this time filling the interstices in the blocks and cooling so quickly that it formed glass.

It is a striking fact that few dikes are faulted and few lie along fault planes. Such dikes are the exception rather than the rule. The lava beds on both sides of all dikes were carefully matched to ascertain whether movement had occurred. Some dikes contain small amounts of breccia, wall debris that fell into them at the time of the cracking and intrusion.

A detailed record of the traverse is given in the table below. Most of the dikes and faults are plotted on plate 1. This traverse can be made only at considerable cost and in calm weather, hence the justification for publishing the field notes in full. The fringing bench is traversable only for short stretches, so that a large boat anchored off shore and a row boat were used. The numerous landings which were necessary were accomplished only by the aid of skilled boatmen.

Section from east to west along the shore across the south rift zone (pl. 1)

Distance (east to west in feet)	Structure	Strike (°)	Dip (°)	Remarks
0	Unconformity.	....	....	1,000 feet east of Kawaiu Stream.
	Dike.	N. 10 W.	....	
	...do.....	N. 40 W.	....	
	...do.....	N. 10 W.	....	
	...do.....	N. 5 W.	....	
	Fault.	N. 5 W.	70 W.	Downthrow of 20 feet on west side. An ash bed is exposed on both sides of fault and although displaced 20 feet by the fault, the ash lies along the fault making a connection between the two parts of the offset bed.
	Dike.	N.	....	
	...do.....	N. 10 W.	....	
	Dike.	N. 20 W.	....	
	...do.....	N. 30 W.	....	
1,000	Fault.	N.	85 W.	Kawaiu Valley. Downthrow of 5 feet on west side.
	Dike.	N. 40 W.	....	
	...do.....	N. 20 W.	....	
1,100	...do.....	N. 40 W.	....	
	Dike.	N. 30 W.	....	
	...do.....	N. 30 W.	....	
1,700	...do.....	N. 30 W.	....	Ash streaks pinch out in top of cliff here.

Section from east to west along the shore across the south rift zone (pl. 1) —*Continued*

Distance (east to west in feet)	Structure	Strike (°)	Dip (°)	Remarks
2,400	Throat breccia.	....	....	50 feet wide with nearly vertical contacts. No displacement of beds on either side indicating hole was either stoped or blown out. Average diameter of blocks about 3 inches, but some are as much as 5 feet. About 40 feet above the base of the cliff the breccia is overlain by several inches to 3 feet of soil and partly rotted rock, and above this is a massive columnar-jointed lens of dense basalt in which Hawaiian petroglyphs are carved.
2,900	2 dikes.	N. 50 W.	....	
	Dike.	N. 15 W.	....	
	...do.....	N. 25 W.	....	
	Dike.	N. 15 W.	....	
	...do.....	N. 35 W.	....	Makole Gulch. Only aa in this stretch. About 1,300 feet up the gulch on the east bank is a circular mass of dense rock which is probably a crater fill.
	...do.....	N. 60 W.	....	
3,300	2 dikes.	N. 40 W.	....	
	Dike.	N. 60 W.	....	Known to be intruded along a fault as it has a band of breccia on the east side, and the lava beds are thrown down 15 feet on the west side. Pahoehoe at base of aa here.
	2 dikes.	N. 10 W.	....	
3,700	3 dikes.	N. 30 W.	....	Breccia along dikes but no appreciable displacement.
4,200	Fault.	N. 25 W.	70 SW.	Downthrow of 25 feet on west side.
	Dike.	N. 45 W.	....	
	Crack.	N. 25 W.	....	
	Dike.	N. 35 W.	....	
	...do.....	N. 30 W.	....	
5,500	Fault.	N. 20 W.	65 SW.	Apparently a small displacement.
	...do.....	N. 40 W.	72 NE.	Downthrow of 40 feet on east side.
	Dike.	N. 40 W.	....	
	Fault.	N. 40 W.	65 NE.	Downthrow of 12 feet on east side.
	Dike.	N. 35 W.	....	2 feet thick.
6,200	Fault.	N. 50 W.	75 NE.	Dies out in cliff about halfway up.
	...do.....	N. 15 W.	67 SW.	4 inches of breccia along it.
7,000	Fault.	N. 20 W.	60 SW.	Slight displacement.
	2 dikes.	N. 40 W.	....	
	...do.....	N. 35 W.	....	
	Fault.	N. 40 W.	60 NE.	Breccia 1 foot thick; downthrow 30 feet on east side.
	Dike.	N. 40 W.	....	
	Fault.	N. 35 W.	70 NE.	Breccia 6 inches wide with possibly a slight downthrow on west side; lava beds dip about 8° E. and about 15° W. indicating axis of arch.

Section from east to west along the shore across the south rift zone (pl. 1) —*Continued*

Distance (east to west in feet)	Structure	Strike (°)	Dip (°)	Remarks
7,200	Fault.	N. 55 W.	72 NE.	Breccia 3 to 6 inches wide on these two fault planes, which cross each other. The western one is downthrown 10 feet to the east by the eastern one, indicating the western is older. A pahoehoe bed indicates a downthrow apparently of 10 feet to the west along the western fault.
	...do.....	N. 10 W.	62 SW.	
7,400	Crack.	....	E.	No displacement.
7,700	Crack.	N. 30 W.	63 SW.	Small displacement.
	...do.....	N. 40 W.	57 NE.	Slight displacement.
7,800	Dike.	N. 45 W.	....	
8,500	Fault.	N. 50 W.	62 NE.	Breccia 2 feet wide; downthrow 60 feet on the east side.
8,900	Dike.	N. 30 W.	....	
	...do.....	N. 40 W.	....	
	2 dikes.	N. 50 W.	....	
	...do.....	N. 40 W.	....	
	...do.....	N. 50 W.	....	
9,200	Fault.	N. 50 W.	70 NE.	Shattered dike along it, slight displacement.
	Dike.	N. 50 W.	....	
	...do.....	N. 45 W.	....	
	Fault.	N. 40 W.	SW.	Slight displacement.
	2 dikes.	N. 50 W.	....	
	Fault.	N. 35 W.	75 SW.	Downthrow of 2 feet on the west side.
	Dike.	N. 40 W.	....	2 feet thick with a 6-inch vertical band of clinkery aa in middle bordered by platy pahoehoe lava containing vertical rows of vesicles that increase in size toward the middle of the dike (see fig. 7).
9,400	Dike.	N. 40 W.	....	2 feet wide; east edge of landslide.
9,600	Fault.	N. 10 E.	70 NW.	East side of crater fill.
	Crater fill and breccia.	....	....	In the cliff directly above this point is a coarse-grained basalt with a few olivine phenocrysts. Beneath it is pahoehoe that appears to have spilled into the crater from elsewhere. Under the pahoehoe is a prism of faintly bedded breccia with caves developed in it by weathering. Much fine debris including fragments of dense glass occur in the breccia. All the rocks below the crater fill are oxidized red and intruded by several dikes.
10,000	2 dikes.	N. 20 W.	....	Lower half of cliff aa and upper half pahoehoe.
	Dike.	....	....	Pinches out in cliff.

Section from east to west along the shore across the south rift zone (pl. 1)
—*Continued*

Distance (east to west in feet)	Structure	Strike (°)	Dip (°)	Remarks
	Dike.	N. 25 W.	....	
	...do.....	N. 20 W.	....	
	...do.....	N. 25 W.	....	
10,400	...do.....	N. 40 W.	....	No displacement, although dike has a patch of breccia along it.
	Dike.	N. 40 W.	....	2 feet thick.
	Fault.	N. 40 W.	70 NE.	Downthrow of 2 feet on the east side.
	Crack.	....	....	Filled with yellow ash.
10,900	Fault.	N. 30 W.	65 SW.	Bed of yellow ash 6 to 12 inches thick about 50 feet below top of cliff on the east side is apparently thrown down below sea level on the west side, indicating a displacement of more than 150 feet.
	Dike.	N. 30 W.	....	6 inches thick.
	Fault.	N. 30 W.	50 SW.	Slight downthrow on west side.
	Crack.	N. 40 W.	70 NE.	No appreciable displacement although band of breccia is present. Considerable aa in cliffs here.
	...do.....	....	E.	
11,500	....	....	....	Gulch draining Kaluakapo Crater. On the west bank is a pod of platy, fine-grained basalt 35 feet wide containing tiny scarce olivine crystals. Basalt is bordered by clinker and appears to be a flow filling a depression, because in one place 10 feet of bedded talus underlies it.
11,700	Fault.	N. 70 W.	70 SW.	Slight downthrow on west side; very frothy mixture of broken pahoehoe and aa here.
	Dike.	N. 25 W.	....	Rubble along dike, but both dike and rubble die out halfway up cliff.
	...do.....	N. 30 W.	....	
12,300	Fault.	N. 40 W.	65 SW.	Downthrow of 30 feet on west side.
	Crack.	N. 40 W.	65 SW.	
12,800	Fault.	N. 40 W.	65 SW.	Breccia 6 inches wide along fault.
13,200	Ash layer.	N. 50 E.	16 SE.	2-6 inches thick; strike approximate.
14,000	Fault.	N. 10 W.	60 SW.	East side of Manele Bay. Gouge 2 feet thick along the plane, and slickensides developed on small fragments. On the west side bedded talus dipping westward overlies a shattered pahoehoe bed having a drag dip of 30° W. The lava beds on the east side strike N. 80° E. and dip 24° S., but next to the fault these dips are reversed by the drag. Downthrow of at least 200 feet on the west side. Fault evidently has moved since the talus accumulated.

Section from east to west along the shore across the south rift zone (pl. 1) —*Continued*

Distance (east to west in feet)	Structure	Strike (°)	Dip (°)	Remarks
15,200	Dike.	N. 25 W.	....	Cuts pahoehoe dipping 18° SE.
	...do.....	N. 10 W.	....	2 feet thick.
15,400	Fault.	N. 13 W.	SW.	Fault indicated by the topography.
16,400	Cone.	....	....	Manele Landing. No rock exposed in last 1,000 feet. Between this place and the next point on traverse there is little or no sea cliff, and starting at the 15,400-foot station the lavas are later than those to the east and partly fill the depression caused by the faults described above. Rifting continued during the accumulation of these lavas, however, as shown by the record below. Station 23,900 below is on the east side of an unnamed bay where the west boundary of Palawai land division intersects the coast 4,400 feet in a straight line from Manele Landing.
23,900	Dike.	N.	....	
24,000	3 dikes.	N. 10 W.	....	6 to 18 inches wide.
25,100	3 dikes.	N. 10 W.	....	
26,400	Dike.	N.	....	2 feet thick and joins flow 40 feet below top of cliff.
26,600	...do.....	N.	....	Cliff here is all aa but one flow.
27,200	...do.....	N.	....	100 feet east of Huawai Gulch.
27,400	Fault.	N. 25 W.	85 NE.	Downthrows a 5-foot bed of pahoehoe 40 feet on the east side. Faulting shattered a dike and produced a band of breccia 8 feet wide.
	2 dikes.	N. 10 W.	....	One is 1 foot wide and other is 3 feet wide and composite.
	...do.....	N.	....	8 inches wide.
27,600	...do.....	N. 10 W.	....	3 inches wide.
	Dike.	N.	....	2 feet wide with vertical core of aa lava 8 inches wide.
27,700	...do.....	N. 20 E.	....	This dike contains local patches of breccia consisting of dike fragments 4 to 8 inches across surrounded by glassy lava. (See fig. 8.)
27,900	Dike.	N. 10 E.	....	This dike contains some breccia in it although it is not faulted. Lava beds dip 6° SW.
28,400	3 dikes.	N. 10 E.	....	All in Poopoo Islet. All but 30 feet of cliff section at Poopoo Bay is pahoehoe.
28,700	2 dikes.	N. 10 E.	....	
29,400	Dike.	N. 10 E.	....	

Section from east to west along the shore across the south rift zone (pl. 1) —*Continued*

Distance (east to west in feet)	Structure	Strike (°)	Dip (°)	Remarks
31,900	3 dikes.	N. 10 W.	....	Distance between last point and this one is measured along a straight line and not along the coast. These dikes all run into a bay at this point.
32,200	Fault.	N. 7 E.	80 E.	Downthrow of 100 feet on the east side and other complexities. (See p. 55 and fig. 9.) One dike striking N. 10° E. 2,300 feet to the west.

No springs or seeps were found where the south rift reaches the coast. Recharge is small on this rift, and faults are numerous, hence the rift probably confines little water.

THROAT BRECCIAS

CHARACTER AND STRUCTURE.—The throat breccias exposed on Lanai consist of the cemented rubble that accumulated in pit craters. They are well exposed in the sea cliffs that cut the south and southwest rift zones where craters have been exposed by marine erosion and also in Maunalei Gulch and in the lower Maunalei tunnel. Throat breccia probably underlies much of Palawai and Miki basins and some of the other craters shown on plate 1. It consists of angular and subangular fragments of basalt ranging in size from rock powder to blocks 5 feet or more across. It commonly lacks bedding, especially in small craters, and differs in this respect from ancient talus breccia formed at the base of cliffs during the growth of the volcano. It is circular or subcircular in plan, indicating that it fills a volcanic throat or pipe, and there is some evidence showing that at least the smaller throats decrease in size downward. Generally one or more dikes pass through the breccia, and they show that the breccia is not cemented talus of the present cliffs. The cementing material of the throat breccias of Lanai was not studied under the microscope, but that of Oahu consists chiefly of iron-stained silica. Commonly, it is more firmly cemented than the talus breccia of the present cliffs except in the upper 50 or 100 feet of the throat. However, in Naio Canyon talus of the present canyon wall lies on and alongside of throat breccia, and the two are so nearly alike that they are differentiated with difficulty. The throat breccia contains practically no weathered debris because it formed at a time when the lavas were fresh. But surficial weathering obscures this condition so that the two breccias are easily confused.

Throat breccias are generally readily distinguished from fault breccias in that fault breccias commonly consist of finer and more angular fragments, fewer kinds of rock, and form narrow bands which have a linear rather than a circular plan. In most breccias along faults of displacements of 10 feet or more is a streak of gouge or rock powder. Where the displacement is less or where the breccia fills a crack, the throat and fault breccias may be nearly identical in appearance and are separated only by their form when mapped. On Lanai no band of breccia more than 30 feet wide was seen in a crack. Throat breccias are usually several hundred feet across. Explosive breccias are sheetlike in their distribution and are therefore generally easy to distinguish from throat breccias. However, no positive method of identifying these breccias in single small exposures without contacts has yet been found. It is believed that throat breccias make up less than 1 percent of Lanai's volume. Those too small to show on plate 1 are described in the rift-zone traverses.

WATER-BEARING PROPERTIES.—No water was recovered from the throat breccia in lower Maunalei tunnel. In general throat breccias are so well cemented and contain so much fine rock powder that they are not very permeable. However, because they fill pipes cutting the lava beds, water probably tends to move between the breccia and the wall. Most of the breccias in dry areas on Oahu are firmly cemented. If they become saturated during their formation and remain so they may not become cemented. Two tunnels developed water in throat breccias on Oahu, hence some are permeable. Therefore, those in the zone of saturation in Lanai may prove to be excellent water bearers.

FAULT BRECCIAS

DISTRIBUTION AND CHARACTER.—Fault breccias are restricted to the three rift zones and the ancient caldera. The principal faults are shown on plate 1. Usually narrow bands of breccia a few inches to several feet wide occur along these faults. The breccia consists mostly of fragments of extrusive basalt and is commonly not very diverse, often consisting chiefly of pieces of the adjacent lava flows. In a few places the fragments are dominantly intrusive rock, indicating that movement has shattered a dike. The fragments are angular, generally less than a foot across, and roughly average about 2 inches. A gray or green streak of compact gouge or rock powder is usually found within the band of breccia, rarely dipping less than 60° or more than 75°. At the portal of Waiapaa tunnel (no. 3, pl. 1) the breccia, being more resistant to erosion than the adjacent lava beds, forms a cliff 50 feet high.

Water-bearing properties.—Most of the exposed fault breccias are compact and have low permeability. If they are just as impermeable in the zone of saturation and if they are numerous they should confine water as dikes do. However, their character as a water bearer in the zone of saturation is not known. They cut the lava beds nearly vertically, and form continuous nearly upright wall-like channels which, if permeable, offer conduits for water to percolate downward. The late faults cut across the dikes in the rift zones and tap water that would be normally confined in the dike complex. Thus they may be detrimental rather than beneficial in the recovery of ground water.

QUATERNARY SEDIMENTARY ROCKS

NONCALCAREOUS SEDIMENTS

Distribution and character.—The consolidated and unconsolidated noncalcareous sediments, those lacking significant amounts of calcium carbonate, are confined chiefly to the basins on the plateau, the windward coast, and in lesser amounts to the larger valleys, such as Maunalei and Hauola. They contain no fossils and consist chiefly of stream-laid gravel, sand, and silt, with lesser amounts of talus and landslide deposits. They are mapped together on plate 1. Unconsolidated sediments crop out over most of these areas shown on plate 1, but usually partly consolidated and consolidated sediments underlie them. Narrow valley fills of alluvium were omitted from plate 1. Possibly some of the deeper sediments below an altitude of 1,200 feet include some marine noncalcareous deposits.

Alluvium.—The alluvium is chiefly brown, but where the included cobbles are thoroughly rotted it has a reddish color. At the mouths of some streams it consists chiefly of thin-bedded brown silt which is the soil washed from the denuded areas. Most of the gravel is well rounded, but the cobbles and boulders are subangular. Even in the stream beds the gravel is poorly assorted and carries much fine material. The older conglomerate likewise contains much silt, which indicates accumulation in muddy torrential waters. It is usually more weathered at high altitudes than at low altitudes, apparently due more to greater rainfall than to greater age. Many of the rotted conglomerates on the Palawai Bench (pl. 1) can be cut like cheese.

In several places in Kapoho Canyon are sediments which were described[14] as sandstones laid down in the 560-foot stand of the sea. This interpretation was based on their fine grain and the close correlation between the altitude of the uppermost bed, and the level of this sea. These deposits are tuffaceous and contain considerable pumice from firefountains. If these deposits are later than the canyon, the presence of pumice indicates that eruptions followed the canyon-cutting cycle. Such cones should be fairly well preserved if on the land, but no recent cones were found.

Another hypothesis will account for these sediments. They may have accumulated in closed basins, presumably craters, during the closing phase of volcanic activity on Lanai. Later Kapoho Stream may have taken a course through these craters and dissected the deposits. This would require part of the basalt walls of the canyon to be erosional and part to be crater walls. There is some evidence to support this hypothesis.

The deposit in the south fork about 500 feet above the junction consists of 5 feet of talus breccia containing blocks up to 2 feet across resting on basalt. On this breccia and pinching out up the dip of the bed is 2 feet of cross-bedded silt mixed with talus blocks. This is overlain with 3 feet of poorly bedded pumice containing subangular and angular diverse basalt fragments up to 3 inches across mostly near the bottom. The bottom layer consists of 5 inches of pumice fragments averaging 1/3 of an inch across that are broken ribbons from firefountains. Above this 3-foot bed is 8 feet of debris consisting largely of subangular blocks of basalt up to 3 feet across in a matrix of silt and firefountain debris. All of the pumice is palagonitized. This deposit appears to be largely hillwash that accumulated slowly at the foot of a cliff. The dips change from 8° near the wall rock to 3° downstream where the deposit becomes better stratified. Unconformable on this material in several places is a boulder conglomerate with well-rounded cobbles laid down by Kapoho Stream. The firefountain deposit at this place can be best explained as laid down in a basin as hillwash rather than by a stream such as Kapoho, otherwise well-rounded cobbles and boulders should be present as in the overlying alluvium.

At the junction the basal member of the deposit consists of a gray breccia about 6 feet thick containing palagonitized fragments of spatter and pumice up to 2 inches across scattered among irregular blocks of basalt in a fine-grained gray ashy matrix. Above this is

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[14] Stearns, H. T., Ancient shore lines on the island of Lanai, Hawaii: Geol. Soc. Am. Bull., vol. 49, p. 622, 1938.

about 75 feet of horizontal thin-bedded tuffaceous sandstone. The upper 25 feet is definitely thinner bedded and richer in palagonite. Some layers are fine ashy mud. The whole deposit could have readily been laid in a closed depression following a nearby eruption. These beds can be traced in a horizontal position nearly to the canyon wall. If this were a subaerial ash deposit the layers should have steep dips next to the canyon walls.

The basal breccia is 5 feet thick and rests directly upon the palagonitized crust of a pahoehoe flow containing numerous olivines and scattered feldspar crystals about 100 feet above the mouth of the north fork. The lack of an erosional unconformity or soil at the contact proves that the basalt and tuffaceous sediments are contemporaneous. In the north bank the pahoehoe is 6 feet thick and strikes N. 80° W. and dips 30° S. It is underlain with 15 feet of poorly bedded coarse breccia which contains pumice and large chunks of spatter and angular blocks of older basalt. Soil is notably absent from the interstices. The lava and breccia lie unconformably on a vertical cliff truncating nearly horizontal beds of aa and pahoehoe. If this cliff were made by Kapoho Stream there can be no doubt that the lava and tuffaceous sediments indicate post-erosional volcanic activity on Lanai. But this wall may be a crater wall in which case the presence of the stream is a coincidence. The chief point in favor of the cliff being a crater wall is the absence of soil in the breccia under the lava. The talus of the present canyon wall does not contain appreciable spatter or pumice but contains soil filling the interstices of the talus blocks.

At an altitude of 700 feet on the south bank of the north fork a cliff of aa and pahoehoe is exposed with a thick talus banked against it striking N. 65° E. and dipping 35° S. This cliff is part of a crater wall more than 100 feet high between the north and middle forks. Some of the beds in the talus contain considerable pumice in the interstices. The talus is being cut away and is definitely older than the canyon. The configuration of the terrane shows quite clearly that the middle and north forks joined in this crater and then cut an outlet to the sea. The streams have exposed in the floor of the crater horizontal-bedded tuffaceous sediments similar to those at the junction of the north and south forks that are described above. The tuffaceous sediments are overlain unconformably here as at the downstream locality by a boulder conglomerate deposited by the present streams.

Thus, while these tuffaceous sediments map as canyon-filling deposits in Kapoho Canyon there is considerable evidence pointing to them being waterlaid deposits in ancient craters through which Kapoho Stream has established its course. The chief point in favor of this hypothesis is the lack of well-rounded boulders such as would be intermingled with the tuffaceous sediments if the ash had been deposited by this stream after the present canyon had been cut. The absence of recent cones also supports this hypothesis, although they may have been offshore and now eroded away.

A thick thoroughly rotted talus deposit that dips to the west crops out in the gulch 2,000 feet southeast of Puu Mahanalua. On the west side of this talus and filling a depression is an unconformable horizontally bedded silt deposit containing blocks as large as 10 feet in diameter that have rolled down from the west rim of the depression. Bombs even as small as 6 inches in diameter hurled out during a volcanic explosion and falling in ash will produce sags in the bedding. But in this deposit the sags in the bedding are due to the great weights of the blocks. The absence of sags under the small blocks indicates that they are talus blocks and not bombs.

Interstratified with the beds is a layer of white chalky nodules of very light weight ranging from a fraction of an inch to 3 inches in diameter. This layer is possibly tuffaceous, although it could not be determined as such under a hand lens. Henry Gibson reports this was used by Hawaiians as chalk. It may be a hydrated aluminum silicate, or some similar weathering product. The whole deposit appears to have accumulated in a fault basin or crater possibly during the Mahana or 1,200-foot stand of the sea.

TALUS.—The talus at the base of steep cliffs bordering the Palawai Basin country is characterized by large angular and subangular blocks. Some black basaltic solution-pitted boulders at the foot of the Bench, especially near Waiopaa Gulch, have resisted weathering and now stand in relief. A few measure 10 feet across and on many are Hawaiian petroglyphs depicting men and animals.[15] Much of the valley fill in the large canyons such as Maunalei contains considerable talus. The deposits range in thickness from a few inches to several hundred feet, the thickest being in Maunalei Gulch, where, according to resistivity surveys made during this investigation, they are about 320 feet thick.

Peculiar deposits of large angular blocks resembling rock glaciers are in many of the shallow gulches especially along the south coast (pl. 7, *A*). The rocks may have been left by the sea as it receded,

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[15] Emory, K P., The island of Lanai, a survey of native culture: B. P. Bishop Mus. Bull. 12, pp. 94–97, 1924.

but they are not appreciably rounded and in places are talus with the fine debris removed.

WATER-BEARING PROPERTIES.—The noncalcareous sediments vary a great deal in their permeability. At Maunalei tunnel no. 1 (pl. 1) the loose recent stream-laid bouldery conglomerate yields water abundantly, whereas a short distance downstream at the pumping station a test hole 5 feet square and 110 feet deep in the valley fill yielded only 10 gallons a minute when pumped in 1929. In general the noncalcareous sediments are of low permeability, especially on the plateau, and are much less permeable than the basalt. If it were not for this fact sea water would rapidly contaminate the water supply of the dug wells in the coastal flat on the northeast coast. In this flat small irrigation supplies can probably be recovered by skimming tunnels or trenches, but in the alluvium of the plateau the recharge is so small that no water will be found.

CALCAREOUS SEDIMENTS

The calcareous or limy sediments lie chiefly on the valley floors and on a few flats between Kaholo cliff and Kamaiki Point. Only the larger outcrops are shown on plate 1, and some of these had to be exaggerated to show on the map. They occur chiefly at certain levels, evidently having been laid down as near-shore deposits at various halts during the emergence and submergence of the islands. The largest area lies along the shore just west of Manele Bay. In Kawaiu Gulch the sediments reach a maximum thickness of about 150 feet.

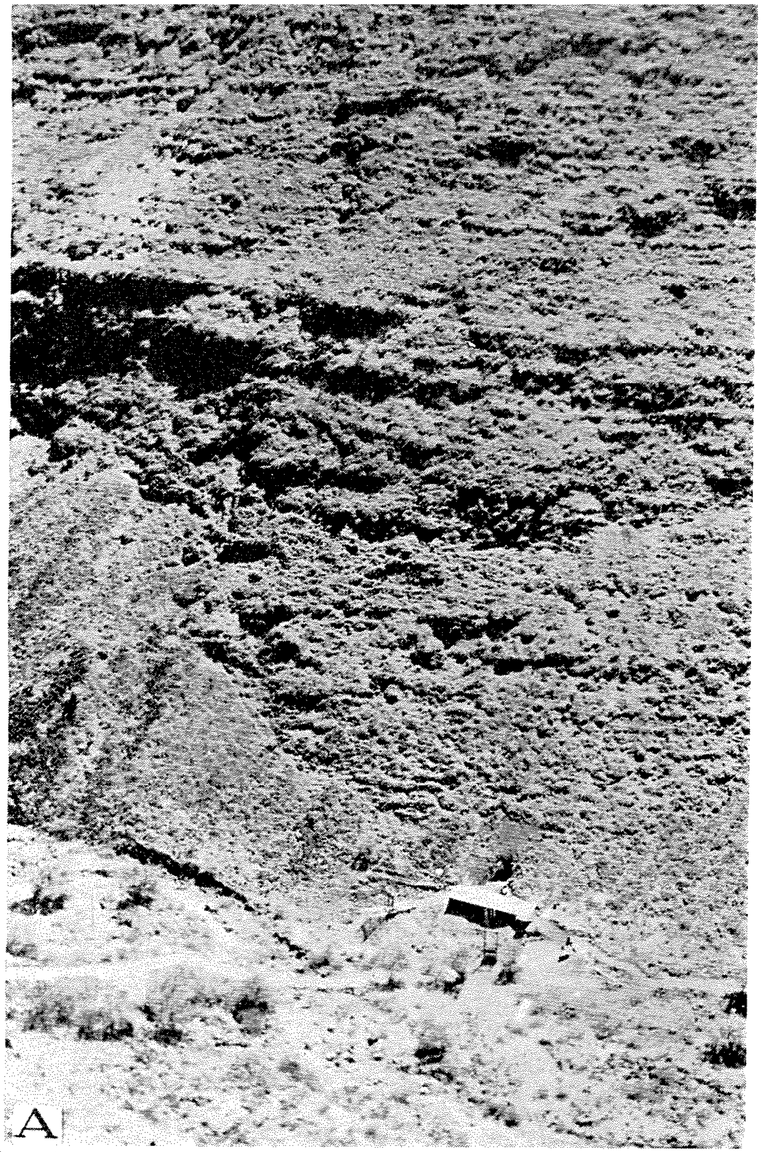
Most of the sediments are only a few feet thick and are calcareous conglomerate consisting of lava rock, pebbles, and cobbles in a matrix of coral, coralline algae, and shells, or their weathered products (pl. 7, *B*). Much of the lava rock is angular or subangular and in some of the gulches, such as Kawaiu, originated as talus. The lava blocks appear to have been wedged into chinks between reef organisms soon after falling into the water and thereby prevented from rolling about and becoming rounded. A few small ledges of reef were seen that were practically free of lava cobbles, the largest being in Kawaiu Gulch. Round pebbles of coral are common locally.

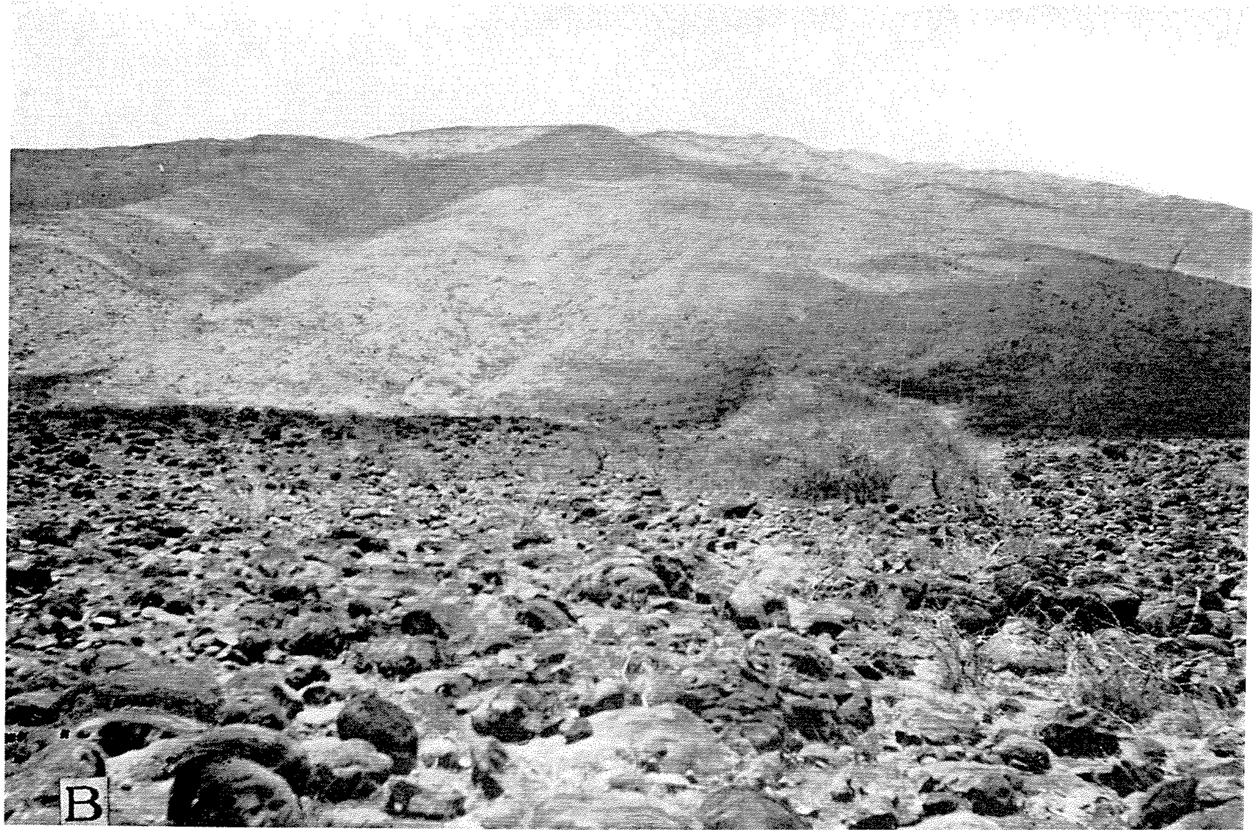
The calcareous sediments are not water bearing and in general are nearly impermeable.

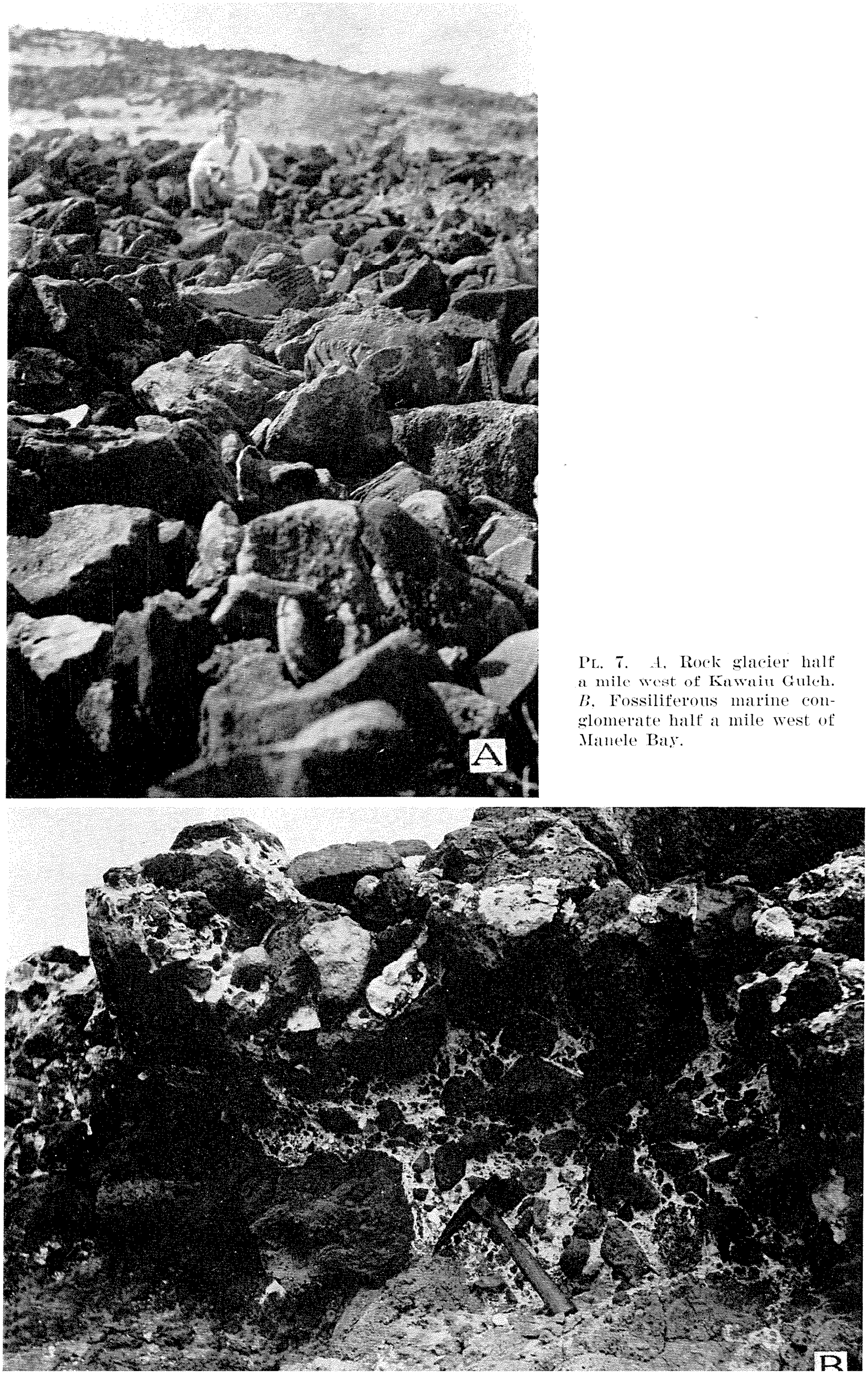
CONSOLIDATED DUNES

The consolidated dunes cover only a few square miles of the windward slope of the island as shown on plate 1. The largest extend up

Pl. 6. *A*, Shaft no. 1, lower Maunalei Gulch, showing thin layers of basalt in the canyon wall. (Photograph by J. H. Swartz.) *B*, Wave-rounded boulders and low marine cliff, northeast side of Naha Gulch. They mark the Manele or 560-foot shore line.







Pl. 7. *A*, Rock glacier half a mile west of Kawaiu Gulch. *B*, Fossiliferous marine conglomerate half a mile west of Manele Bay.

the slope of Lae Hi Point. They consist mostly of hard thin-bedded and cross-bedded limestone whose surface is weathered into small pits and pinnacles. Usually the dune is coated with a secondary structureless or laminated white limestone. Small remnants here and there and scattered, hard, irregular, structureless, bonelike blocks indicate that a considerable part of these dunes has been dissolved away. On plate 1 they are shown as disconnected masses extending inland from below present sea level, but formerly the several stretches of dunes were probably continuous. Most if not all appear to have been laid down during the Waipio or minus 60±-foot stand of the sea. No fossils were found in them. They range in thickness from a few inches to about 25 feet and are readily discerned by their light color in contrast to the adjacent red and brown soil on the lava rock.

They yield no water, and because of their low permeability are not valuable as an intake formation.

STRUCTURE

The major structural features of Lanai are three broad flat constructional arches that have resulted chiefly from the outpouring of lava along three sets of fissures that form the three rift zones and converge at Palawai Basin. The crest of the longest or northwestward-trending arch does not coincide with the northwestward-trending ridge of the island because the keystone of the arch has been downfaulted. The central plateau and Palawai Basin occupy this sunken area. The south rift-zone ridge has likewise been downfaulted. The intrusion of hundreds of dikes into the rift zones has probably caused a slight and doubtfully measurable change in the dip of the beds. Each eruption in the rift zones is preceded by fissuring of the lava beds. The magma filling these fissures displaces the beds sidewise. Some fragments from the fissure walls are carried upward in the fluid lava while others probably sink into the lava reservoir and are remelted. During the life of the volcano the deep magma is probably slowly remelting the previously hardened basalt in the rift zones, but at shallow depths, this process is insignificant. These processes, the withdrawal of lava due to outpouring elsewhere, and the slow settling of narrow slivers of rock in the rifts to compensate for the removal of the underlying rock cause the arches to collapse. The topographic expression of this settling process would be more apparent if it were not for new lavas pouring out from cracks within the rift zone and filling up the troughs made by the narrow dropped blocks. This process can be seen in operation today in the southwest rift zone of Kilauea.[16]

FAULTS

CENTRAL BASIN FAULTS.—The central basin has been eroded so little that fault scarps more than 20 feet high still retain their topographic form although their original sharpness is lost. The major faults are shown on plate 1. A fault is well exposed at the portal of Waiapaa tunnel (no. 3, pl. 1) in the northeast side of the basin. It consists of 5 feet of breccia with a distinct seam of slickensided gouge cutting through it, striking N. 35° W. and dipping 75° SW. This is one of the branches of the main fault bounding the northeast side of the bench of Palawai Basin on which a displacement of more than 1,200 feet occurred. Topographic evidence indicates movement of more than 500 feet along the fault bounding the southeast side of the Bench. Only a small amount of movement along the faults bordering the south side of the basin is recorded in the topography, but as considerable lava has poured seaward from this side of the caldera (sec. B–B′, pl. 1) it is likely that these flows have buried most of the fault scarp so that the total movement may have been several hundred feet.

FAULTS NORTH OF KAUMALAPAU.—A breccia zone a few inches to a foot wide striking N. 70° W. and dipping 75° S. indicating a fault is exposed in the sea cliff 2.25 miles north of Kaumalapau. A slight downward displacement probably occurred on the south side of this fault. Nine-tenths of a mile farther north is a zone of breccia 30 feet wide cut by a smooth slickensided seam of gouge striking N. 10° W. and dipping 70° W. The cliff has collapsed along the line of the breccia, thus producing a trough-shaped gully. The lava beds on the south side are flat, and those on the north side dip about 4° S. as if dragged down by the fault. Large masses of aa are included in the breccia. The beds are shattered adjacent to the fault, and none of them could be matched. This implies a displacement of at least 270 feet unless the beds are so shattered that their identity is lost. It seems strange, however, that such a large displacement did not cause a scarp that can be traced inland. Possibly flows accumulated on the downthrown block as rapidly as the displacement occurred. A fault with a dip of nearly 90° and a strike of N. 15° W. and of only slight displacement is exposed in the sea cliff 1,000 feet farther north.

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[16] Stearns, H. T., and Clark, W. O., Geology and water resources of the Kau District, Hawaii: U. S. Geol. Survey Water-Supply Paper 616, pp. 87–88, 1930.

A breccia zone 10 to 20 feet wide, indicating a fault striking N. 15° E. and dipping 52° NW. is in the sea cliff 4.25 miles north of Kaumalapau. About 100 feet farther north is another fault striking N. 15° E. and dipping 57° NW., with a downthrow of 3 feet on the east side. The slice of rock between the two faults has collapsed, producing a trough in the cliff. The displacement along the first fault could not be determined because of the gap in the bedding produced by the trough.

A fault striking northward and dipping 77° W. with a downthrow of possibly 20 feet to the west crops out in the cliff 4,000 feet northwest of Kaumalapau. In a few places along the strike are pockets of breccia from 1 to 10 feet across. About 100 feet to the west another fault striking N. 10° E. and dipping 52° W. occurs with possibly an inch downthrow to the west. The breccia is mainly loose aa rubble.

Just around the point 1,000 feet farther northwest another fault is indicated by a breccia streak 1 to 3 feet wide, striking N. 25° E. and dipping 77° SE. A 6- to 20-inch yellow vitric-ash streak stops abruptly against the west block and, as seen from a boat, the east block appears to be dropped 30 feet. About 300 feet to the northwest a streak of breccia 1 foot wide indicates another fault of slight displacement.

The last 4 faults described above enclose a shallow graben about 1,000 feet wide. Apparently the wind blew ash into this depression and, as the upper lava beds do not seem to be displaced as much as the lower beds, lava flows probably filled it after the ash accumulated.

Rift-zone faults.—Three faults are exposed in the northwest rift zone, and the topography indicates about 15 more. In the southwest rift zone, 43 faults and breccia-filled cracks were seen. In the sea cliff cutting the south rift zone 32 faults and 6 cracks are exposed. Twelve other faults were seen in this rift zone between the coast and Palawai Basin and the topography indicates at least four more.

The fault at the end of the traverse of the south rift zone (p. 46) has had a complex history (fig. 9). The first movement formed an east-facing cliff of unknown height. Rubble and fine firefountain debris accumulated on the west or back slope of this ridge or block. Subsequent movement accompanying an eruption faulted this talus down to the east, and pahoehoe lava rose to the surface along the fault as shown by the dike merging into the pahoehoe overlying the talus. Probably the lava also rose through the fault on the east

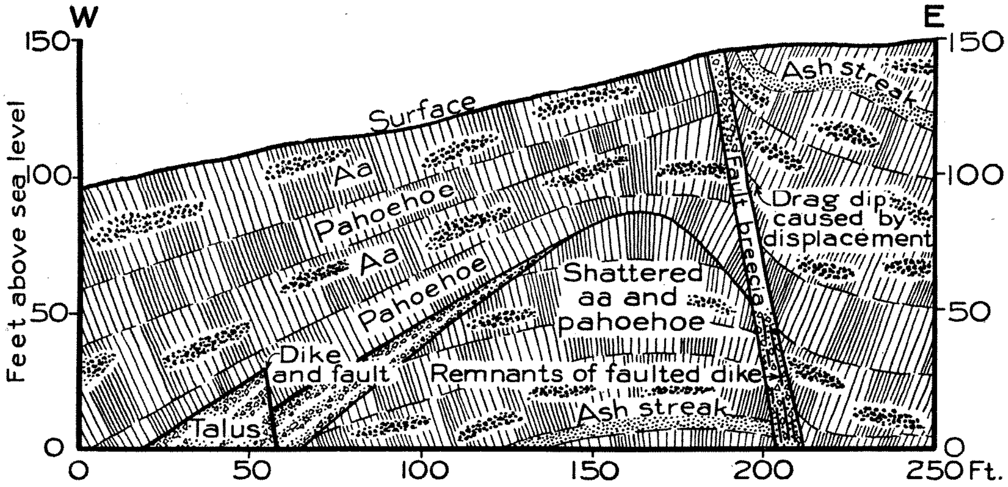


FIG. 9. Unconformity and fault on the south coast of Lanai.

side of the block, producing a shattered dike there. The pahoehoe is only 5 feet thick on top of the ridge of older lavas but 30 feet thick on the east side, indicating that the lava accumulated in the depression caused by the first epoch of faulting. Then other flows covered the ridge, and again the fault on the east side of the ridge moved, dropping these lavas down to the east, as shown by the drag dips, and shattered a dike that intruded the fault. The ash bed and the upper beds of lava on the east side of the fault cannot be matched with those on the west side, indicating that subsequent erosion has removed some of the rock from the west side, or that some flows accumulated on the dropped block which were not thick enough to overflow the fault escarpment. However, both conditions may have occurred.

About 100 faults are exposed in the entire island, and the topography indicates at least 30 more. Most of these faults are described in the rift-zone traverses, and the major ones are shown on plate 1. Doubtless many others exist in the northwest rift and in Palawai Basin that are not exposed.

CROSS SECTIONS

The growth of a volcano such as the one that built Lanai is too complex to be shown in a small illustration. Further, Lanai is not sufficiently eroded for all of its many geologic details to be revealed. However, one may infer the internal structure of Lanai from the structure observed in its high cliffs and from that exposed in the active volcano of Kilauea and the dissected volcanoes on the other islands of Hawaii. This inferred structure, greatly simplified and with many of the faults and dikes omitted, is shown in three sections in plate 1. The pre-collapse lavas are shown by one pattern in order to illustrate the major structural changes that took place later. The reader should not be misled into believing that there are any such sharp lines of demarcation bounding these or any other groups of lavas shown in these sections. Neither do they differ visibly in their physical appearance. Two layers are shown in solid black to bring out the effects of faulting. The thickness of the groups of lava is diagrammatic only, and an unknown thickness of marine sediments has been omitted from the undersea parts of all the sections. These sediments are probably thickest in the areas represented by the northeast ends of sections A–A′ and B–B′.

Section A–A′.—As shown on plate 1, section A–A′ crosses the northwest rift zone nearly at right angles. The faults here are based on the topography. The lavas are separated into three groups to show the geologic history of this rift zone. The main bulk of the lava flows is represented diagrammatically as having been erupted prior to the collapse of the rift zone. The top layer on the outer slopes of the section represents a group of lavas that were poured out of fissures in this rift zone during the period of collapse and that overflowed pre-existing fault cliffs and reached the sea. The fissure vents are now occupied by dikes. These flows probably buried some fault blocks as shown in this section, and have thickened locally in the fault depressions. Probably subsequent faulting produced narrow northwestward-trending depressions in this series. The third or latest group of lavas is represented by two layers, neither of which flowed down the east or west slopes of the volcano because they were confined in the fault-block depressions. However, they may have drained toward Kaena Point along these depressions. By analogy with the southwest rift zone of Kilauea Volcano or with the other Lanai rift zones for which data are available the structure is probably much more complicated than that shown in the drawing.

Section B–B′.—As shown on plate 1, section B–B′ extends from Kaunolu to Keomuku, across Palawai Basin and the summit, Lanaihale. The main bulk of the lavas was poured out prior to the collapse of Palawai Basin. The central crater, which during this time was probably a little west of Lanaihale, is shown diagrammatically in this section in a downthrown block buried by the lavas that formed Palawai Bench. The collapse that carried down this first group formed Palawai caldera, and later eruptions apparently buried them with Bench lavas that ponded against the Lanaihale escarpment on the east, burying the downthrown blocks in the same way that the lavas poured out since 1855 covered most of the fault blocks in the floor of Kilauea caldera. These lavas are shown in the section as overflowing the south rim of the caldera and filling the graben that extends toward Manele. Their thickness is exaggerated in order to show their relation to the other lavas. It is not known whether the Bench lavas or the later lavas above the Bench lavas filled this graben. Probably a third group of lavas was erupted, which was confined to the caldera floor. These are represented in the section by a distinct pattern, and their thickness is unknown. They would correspond to the lavas that have been slowly filling Kilauea caldera layer by layer in historic time. Above this group is shown a layer of alluvium that has been eroded from the fault escarpments and deposited since eruptions ceased. The chief difference between the caldera lavas and the Bench lavas is that the caldera lavas were erupted when the south rim of the caldera was too low to confine them to a level high enough to overflow the Bench again. However, they may have flowed seaward and may now overlie the Bench lavas in the Manele graben.

The Bench lavas are shown on the left side of the section as interfingering with the southwest rift-zone lavas. This was done because the section cuts across the side of this rift-zone ridge. They do not stop as abruptly as shown in this section but probably interfinger in an intricate manner.

Probably much more breccia and many other complications occur than are shown in this section, especially where there has been faulting.

SECTION C–C′.—Extending across the south and southwest rifts and showing the observed intricate faulting is section C–C′, plate 1. The amount of movement along the faults has been exaggerated, and many of the smaller faults and numerous dikes have been omitted because they would complicate the section unnecessarily. The structural details under Kaluakapo Crater are not known, and the throat breccia may not extend as deeply as shown.

Five groups of lavas are shown in this section. The first group is the same as in the other sections and represents the lavas extruded prior to the collapse. The southwest rift-zone lavas are represented in the left side of the section by a separate pattern. They are shown interfingering with the Bench and south rift-zone lavas and partly filling the Manele graben. The bottom layer is depicted as broken by subsequent faulting and in places thickened as a result of filling fault depressions.

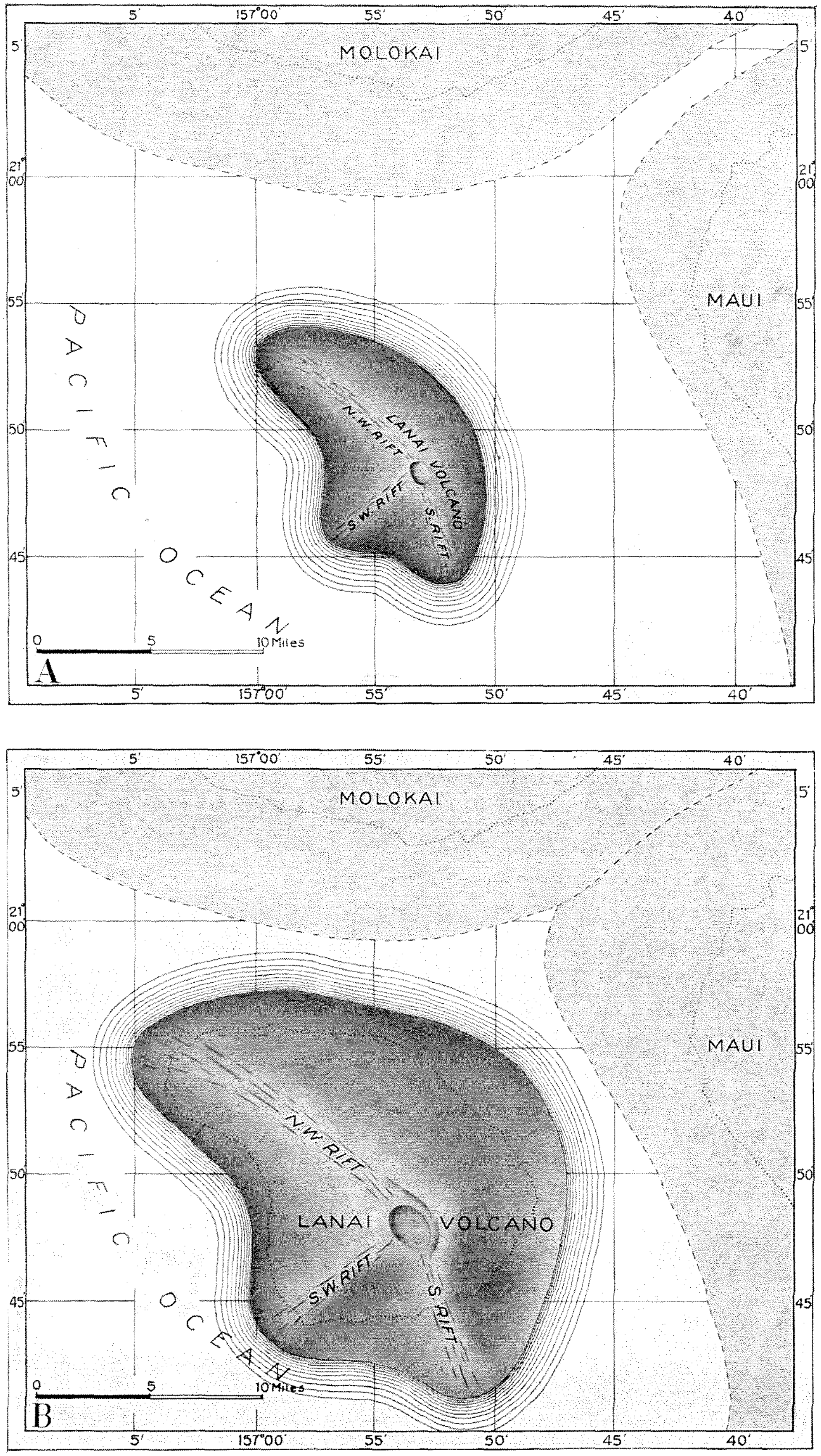
Overlying the pre-collapse lavas are the lavas extruded from the south rift during and after the collapse. They may have completely buried the first group; but there is no satisfactory field evidence to support this view, nor is there proof that they do not interfinger with the Bench lavas from Palawai caldera. Because the same pattern is used to indicate the lava in Kaluakapo Crater as elsewhere, it should not be thought that the lava in the crater overflowed the adjacent ridge.

The Bench lavas are shown as chiefly the ones filling the Manele graben. This was done because a thick section of Bench lavas crop out at the head of the graben near the rim of Palawai Basin unconformably upon the south rift zone lavas. However, a group of lavas locally erupted within the graben is shown by a distinct pattern. The cone at Manele Bay and dikes in the sea cliff crossing the graben are proof that lavas were poured from vents within the graben. Thus the Manele graben was partly filled with lavas from the south rift, from the southwest rift, from Palawai Basin, and from fissure vents in the graben itself. Possibly the upper beds in the graben are correlative with the caldera lavas shown in section B–B′.

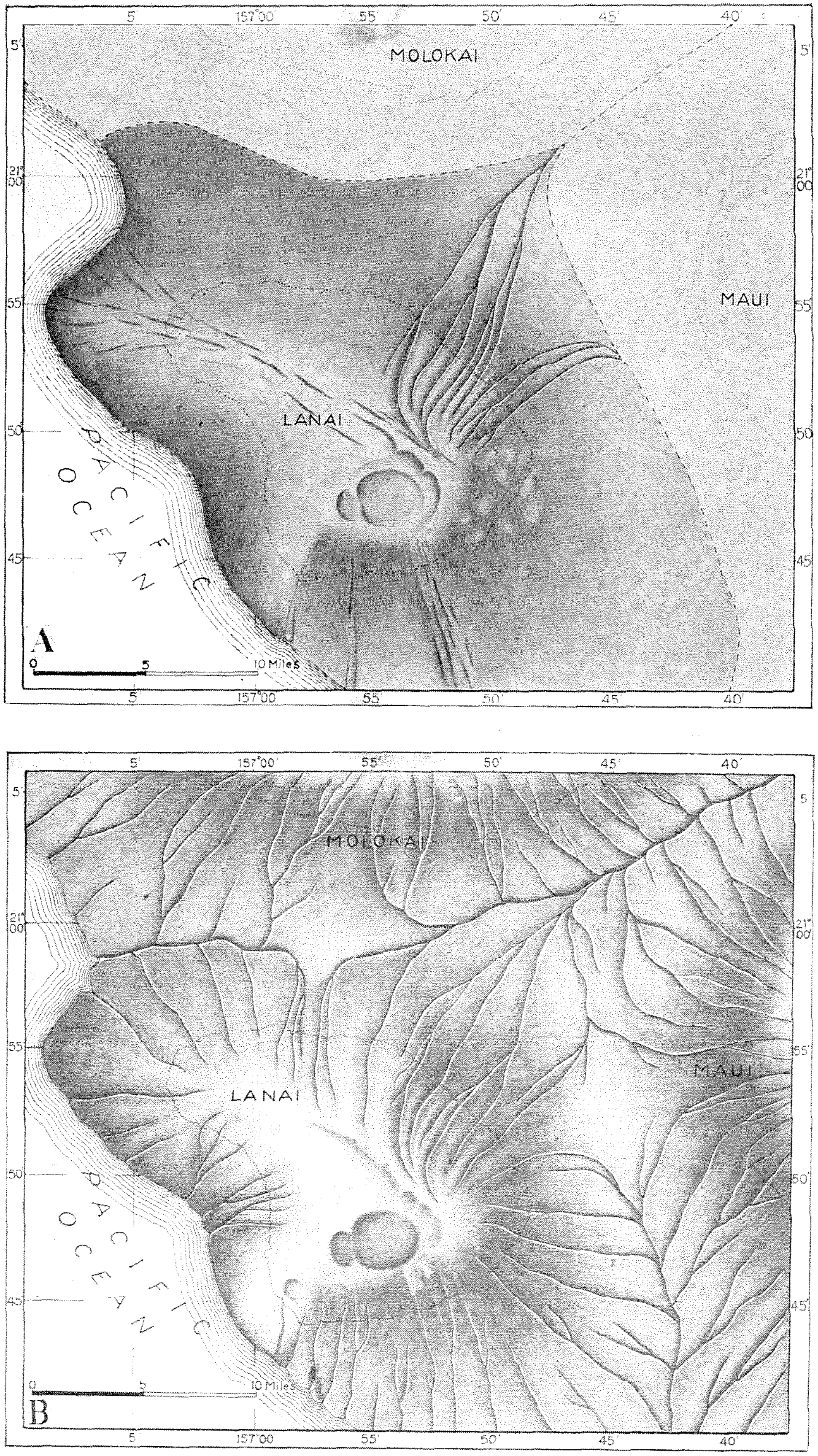
GEOLOGIC HISTORY

1. Building of dome-shaped island at least 4,500 feet above present sea level by the outpouring of basalt flows from northwest, southwest, and south rift zones with the center of activity at their intersection a little southwest of the present summit (pl. 8, *A*).
2. Collapse along the south and northwest rift zones, and subsidence at their intersection forming a caldera now known as Palawai Basin (pl. 8, *B*).
3. Diminished volcanic activity, with most of the lava filling the sunken areas along the south and northwest rift zones. Scattered eruptions on the southeast flank near Kamaiki Point. Establishment of streams on the northeast side, as this area was protected from lava flows by the high cliffs of the caldera. Maui and Molokai were probably joined to Lanai at this time (pl. 9, *A*).
4. Cessation of volcanism.
5. Establishment of stream pattern over entire island and formation of canyons on northeast slope.
6. Long period during which high marine cliffs were formed on the west and southwest coasts and stream erosion (pl. 9, *B*).

7. Gradual submergence of at least 1,500 feet and probably considerably more, resulting in the drowning and sedimentation of the valleys. Submergence culminated with the formation of a shore line about 1,200 feet above present sea level (pl. 10, *A*). Continued marine abrasion along the west and south coasts and growth of coral, but no reefs.
8. Gradual emergence with possibly a very short halt 1,070 feet above present sea level.
9. Continued emergence with a short halt 560 feet above the level of the present sea, forming the Manele shore line (pl. 10, *B*). Possibly the emergence was somewhat more and then the island was resubmerged to an altitude of 560 feet.
10. Emergence of about 850 feet more and the development of a bench about 300 feet below present sea level corresponding to the Kahipa shore line on Oahu. Soundings indicate that probably narrow necks of land again connected West Maui and East Molokai to Lanai (pl. 11, *A*).
11. Resubmergence of about 400 feet and the deposition of marine sediments about 100 feet above present sea level corresponding to the Kaena shore line on Oahu.
12. Re-emergence of about 160 feet corresponding to the Waipio shore line on Oahu and the formation of calcareous dunes on the windward (northeast) slope. Vigorous marine erosion on west and south coasts.
13. Resubmergence of about 85 feet, partly drowning the dunes at Lae Hi Point and forming of a shore line correlative with the Waimanalo shore line on Oahu.
14. Re-emergence of 25 feet to present shore line with probably a short halt at about 5 feet above present sea level. Continued stream and marine erosion and nearly complete filling of ancient caldera with alluvium (pl. 11, *B*). Introduction of livestock. Overgrazing greatly accelerating wind and stream erosion, causing great areas of barren land and nearly annihilating the fringing reef organisms. Formation of narrow coastal plain along the northeast coast.

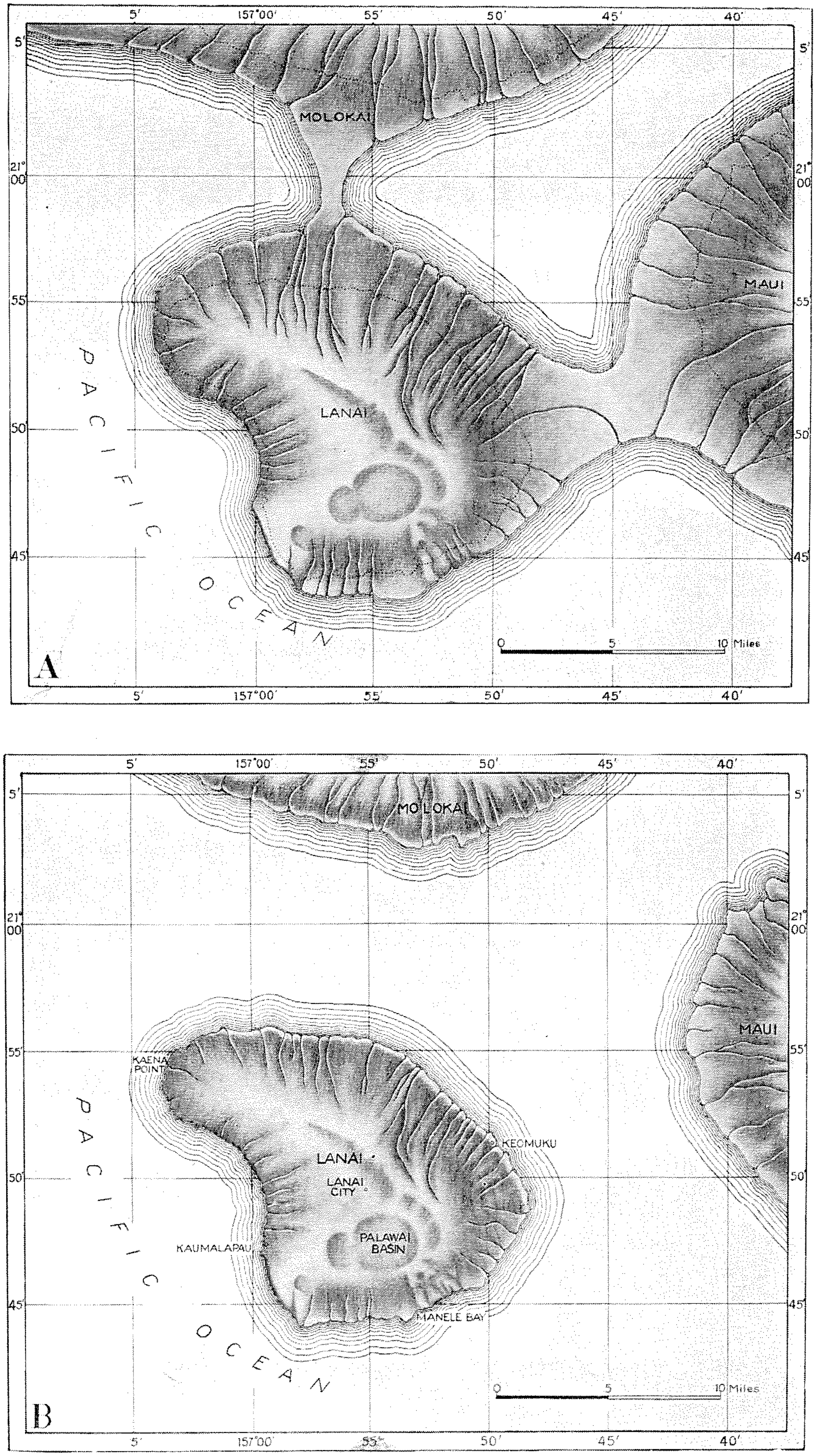


PL. 8. *A*, First stage in the development of Lanai showing an active phase of the volcano prior to the collapse of the summit. *B*, Second stage in the development of Lanai showing the beginning of the collapse stage while still an active volcano. Dotted lines indicate present shore lines of Lanai, Maui, and Molokai. Broken lines show probable outlines of Maui and Molokai.



PL. 9. *A*, Third stage near the end of volcanic activity, showing collapse along the rifts and the beginning of drainage on the northeast slope. The caldera wall protected this slope from lava flows. *B*, Fourth stage showing the probable appearance of Lanai joined with Maui and Molokai during the canyon-cutting cycle and prior to submergence. Drainage below present shore line hypothetical.

PL. 10. *A*, Fifth stage in the development of Lanai showing its form during maximum submergence or during the Mahana or 1,200±-foot stand of the sea. *B*, Sixth stage in the development of Lanai showing its form during the Manele or 560-foot stand of the sea. Dotted lines indicate present coast lines of Lanai, Maui, and Molokai.



PL. 11. *A*. Seventh stage in the development of Lanai showing its form during the Kahipa or minus 300±-foot stand of the sea. The isthmuses connecting Maui and Molokai to Lanai are approximate. Dotted lines indicate present coast lines of Lanai, Maui, and Molokai. *B*. Eighth stage in the development of Lanai showing its emergence to present sea level and its form today.

PETROGRAPHY

By GORDON A. MACDONALD

Very little is known of the petrography of Lanai. Sidney Powers states that the island "appears to be composed of olivine and feldspar basalt in about equal amounts,"[17] but beyond that brief statement he makes no mention of the composition of the lavas. Washington has published a single chemical analysis,[18] but does not describe the rock. (See p. 167.) Wentworth briefly describes 39 hand specimens, but gives no microscopic data.[19]

Only six specimens, collected by H. T. Stearns, have been available to the writer for microscopic study. Such meager representation is inadequate, but in view of the total lack of petrographic descriptions of any of the Lanai lavas, the few specimens studied will be described below.

The lavas of Lanai are basalts, the flows ranging in thickness from 1 to 100 feet, and averaging about 20 feet. Most of them contain phenocrysts of olivine, from 1 to 3 mm in diameter, and many also carry phenocrysts of plagioclase. Augite phenocrysts are present in a few rocks, but are relatively scarce. Nonporphyritic lavas are moderately abundant.

Pyroclastic rocks form only a small part of the mass of Lanai. Vitric tuffs, composed of glassy ejecta from firefountains, are locally present. Some of these vitric tuffs are altered to palagonite.

Typical of the basalts of Lanai that have been studied microscopically is specimen 3, collected about 0.1 mile south of the trail, and 1 mile S. 72° E. of the top of Puu Manu.[20] This is a medium-gray aa, with a few vesicles reaching a maximum diameter of 1½ mm, and a few small phenocrysts of brownish-green olivine as much as 1 mm across. Microscopically, phenocrysts of olivine and microphenocrysts of hypersthene are set in an intergranular to intersertal groundmass with an average grain size of about 0.06 mm. The grains of olivine show only a small amount of resorption, but are altered around the edges to iddingsite, and one grain is surrounded by a narrow reaction rim of finely granular monoclinic pyroxene. The hypersthene occurs in colorless euhedral to subhedral grains up to 0.5 mm long. Olivine and hypersthene constitute respectively about 2 percent of the rock.

The groundmass consists of subhedral to anhedral, lath-shaped grains of plagioclase, zoned from calcic to sodic labradorite (40%); very pale brown, subhedral to anhedral grains of pigeonite, with +2V of about 45° (45%); euhedral to anhedral grains of iron ore, including both rod-shaped grains of

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[17] Powers, S., Notes on Hawaiian petrology: Am. Jour. Sci., 4th ser., vol. 50, p. 260, 1920.

[18] Washington, H. S., Petrology of the Hawaiian Islands; I. Kohala and Mauna Kea, Hawaii: Am. Jour. Sci., 5th ser., vol. 5, pp. 486–487, 1923.

[19] Wentworth, C. K., The geology of Lanai: B. P. Bishop Mus. Bull. 24, pp. 35–38, 1925.

[20] The location of the specimens is shown on figure 1.

ilmenite and equant grains of magnetite (7%); and very pale brown, interstitial glass with a refractive index distinctly below that of balsam (4%). A few of the largest grains of feldspar attain the dimensions of microphenocrysts, with a length of 0.7 mm, but there is a complete gradation in size into those of the groundmass.

Specimen 7, collected on the southern coast 0.8 mile southwest of Makole Bay, is a medium-gray, dense lava with a very few phenocrysts of brownish-green olivine up to 1.5 mm across. The flow is very massive, and fills a small crater exposed in the sea cliff. The source of the flow may have been local. The olivine is very slightly altered to iddingsite around the edges and along fractures. Euhedral to subhedral microphenocrysts of hypersthene attain a length of 0.5 mm, and are slightly rounded by resorption and enclosed in a narrow reaction rim of finely granular pigeonite. A few grains of plagioclase reach the dimensions of microphenocrysts, but there is a seriate gradation into the groundmass feldspars. These large feldspar grains show normal zoning, from intermediate bytownite to intermediate labradorite.

The groundmass is intergranular to intersertal, with an average grain size of about 0.12 mm. It is made up of intermediate labradorite and pigeonite in about equal quantities, with iron ores, both ilmenite and magnetite, and very pale brown, interstitial glass (10%). The pigeonite shows a +2V of about 35°. Tiny, acicular crystals of apatite are enclosed in the interstitial glass.

Specimen 8 is a fragment of olivine basalt from the fault breccia exposed about 50 feet west of the gulch, 0.43 mile S. 73° E. of Puu Mahanalua. It is a light-gray, moderately vesicular pahoehoe, with a few small phenocrysts of olivine reaching a little over a millimeter in diameter. The groundmass is hyalopilitic, with lath-shaped microlites of sodic labradorite, tiny granules of monoclinic pyroxene, and grains of iron ore embedded in an abundant glassy base heavily clouded with a finely dispersed dust of iron ore.

Specimen 21, collected near the end of Puupehe Point, just southwest of Manele Bay, is a medium-gray pahoehoe containing only a few phenocrysts of feldspar. Microphenocrysts of iddingsite are present, completely replacing former grains of olivine. Iddingsite is also found in the groundmass. It forms about 8 percent of the rock. The plagioclase phenocrysts (2%) show normal zoning from intermediate to sodic labradorite. The groundmass is intergranular, with an average grain size of about 0.03 mm. It is made up of sodic labradorite (30%); clinopyroxene (30%); iron ore, both magnetite and ilmenite (25%); and 5 percent of interstitial feldspar with a refractive index close to that of balsam, probably oligoclase. (See p. 151.)

In the bed of Kapoho Stream, about 0.1 mile below the trail crossing, pahoehoe is exposed underlying sedimentary tuff (p. 50). The rock (20) is medium gray, with a few small phenocrysts of olivine and feldspar reaching a length of 2 mm, and rare phenocrysts of pyroxene. The vesicles are few and small, reaching a maximum diameter of 2 mm, but mostly less than 0.5 mm across. The olivine crystals are euhedral, and many are highly tabular. One such crystal seen in cross section measures 3.25 mm long by 0.1 mm wide. It is slightly altered around the edges to iddingsite. Olivine constitutes about 5 percent of the rock. Plagioclase phenocrysts (8%) are euhedral to subhedral, and show Carlsbad and albite twinning and normal zoning from calcic labradorite to labradorite-andesine. Some of the larger crystals have been bent and fractured, probably during eruption. Hypersthene microphenocrysts

(2%) are euhedral to subhedral, and reach a maximum length of 0.7 mm. They show a large negative optic axial angle.

The groundmass is intergranular to intersertal, with an average grain size of about 0.06 mm. It is composed of labradorite-andesine (30%); pigeonite, with an optic angle of about 35° and $Z \wedge c = 40°$ (35%); interstitial feldspar (5%), with a small (+)2V, and a refractive index close to that of balsam (see p. 151); iron ore, including both ilmenite and magnetite, with the latter apparently the more abundant (10%); and very pale brown interstitial glass, with a refractive index distinctly below that of balsam (5%). This rock is classified as an olivine basalt, but in average feldspar composition it approaches an andesite.

Another basalt, the feldspar composition of which shows an approach to the andesites, is represented by specimen 6. This is a dense, medium-gray, aphyric lava which overlies a throat breccia in a pit crater exposed in the sea cliff just east of Makole Bay. The source of the flow was probably local. Under the microscope the rock is intergranular to intersertal in texture, with weakly developed fluidal orientation of the feldspars. The grain size averages about 0.1 mm. A very few grains of olivine are present, and are almost wholly altered to iddingsite. Plagioclase makes up 40 per cent of the rock. A few of the largest grains show normal zoning from intermediate labradorite to andesine-labradorite, but most grains are andesine-labradorite. Very pale brown, subhedral to anhedral grains of pigeonite (40%) show a +2V of about 30°. Iron ore (10%) includes both magnetite and ilmenite. Very pale brown interstitial glass (10%) has a refractive index distinctly below that of balsam. Many patches of glass show a very faint, irregular polarization.

The only other rock of possible andesitic composition which was noted by Stearns during the course of the field work is a light-colored lava which crops out near the coast on the broad spur between Kapoho and Kawaiu gulches. No specimen of this rock was collected.

The lavas of Lanai, as represented by the few specimens described above, are closely similar to the early lavas of all the other Hawaiian volcanoes. They appear to represent the undifferentiated parent magma of the province, poured out as frequent, highly fluid flows during the principal period of growth of the volcano. It is not until the later stages of the Hawaiian volcanoes, toward the end of the period of filling of the caldera and later, that differentiation progresses far enough to produce types of lava markedly different from the early "primitive," or Kilauean type of olivine basalts. The fact that volcanism on Lanai ceased before the caldera had been completely filled, is in accord with the lack of lavas showing appreciable differentiation from the "primitive" basalt.

GROUND WATER

CLIMATE

Temperature.—The climate of Lanai, like that of the other islands of Hawaii, is subtropical rather than tropical. The mean annual temperature of Lanai City, altitude 1,620 feet, is 68.1° F., and that of Koele, altitude 1,780 feet, is 67.9° F. Both stations are leeward of the crest and owe their low temperatures not only to the altitude but to frequent cloudiness. The mean temperature along the coast is somewhat higher, especially on the leeward (southwest) side, where nearly every day is cloudless. However, the cool sea breezes blowing over such a small island have insufficient time to be thoroughly heated, hence even these areas are not unbearably hot. The island is too low to be noticeably heated adiabatically by the descent of the wind. The absolute maximum recorded at Koele is 88° F. and the absolute minimum is 49° F. On December 23, 1935, the temperature fell to 48° F. at Lanai City.

WIND.—Lanai lies in the belt of the northeasterly trade winds, which are very persistent. However, being partly sheltered by West Maui and East Molokai, all of the island is not exposed to these winds. Southerly or "kona" winds interrupt the trades at times, especially during the winter. No anemometer records are available, but the numerous wind scars, the universal leeward bend in the tree trunks, and the wind-pruned tops of the trees in the region facing the channel between Molokai and Maui are evidence of constant high trade-wind velocities.

RAINFALL.—The areal distribution of the rainfall is shown by isohyetal lines in figure 1. The average annual rainfall ranges from less than 10 inches along the coast to 38 inches on the summit. Although only half as high, Koele has nearly the same rainfall as the summit, Lanaihale, because it lies close to the crest. Rainfall is influenced as much by closeness to the crest as by high altitude on mountains less than 6,000 feet high in the Hawaiian Islands.

The similarity in variations in the rainfall of Koele, on the leeward side of Lanai, to those of Wailuku, on the windward side of Maui, is brought out by the cumulative departure from the 10-year progressive averages of these two stations as shown in figure 10. The variations in the rainfall at Mahana station, altitude 1,400 feet, and Honolua ranch, altitude 25 feet, both on the northwest slope of West Maui, as shown in this figure are very different from the variations at Koele, indicating that the similarity with Wailuku as brought out by these curves is not a coincidence but is due to certain comparable factors governing the rainfall.

Because the island is small and relatively smooth, the geographic distribution of its rainfall is not as spotty as on the larger rugged islands. The rainfall varies widely from year to year, as at Koele, where it ranges from 15 to 52 inches, and at Keomuku, from 1.7 to

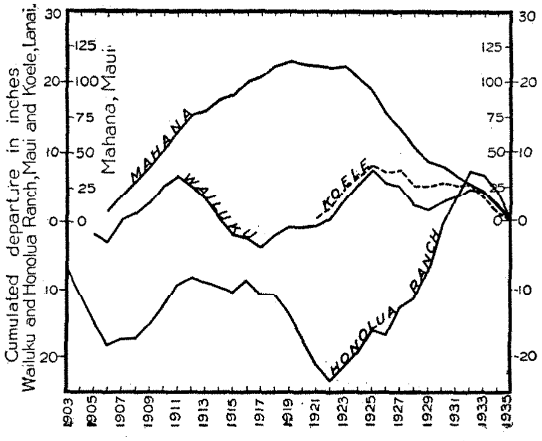

FIG. 10. Cumulative departure from the average of the 10-year progressive average of the rainfall at Wailuku, Honolua ranch, and Mahana, West Maui, in comparison with Koele, Lanai.

33 inches. There is a well-marked dry season during the summer, but as shown by the comparative mean monthly distribution of rainfall at various stations in figure 11 a less-marked rainy season occurs in the summit area. December is the wettest month and July the driest month at most stations. Heavy downpours during a single kona storm commonly account for a considerable part of the annual rainfall, and in some of the arid sections a single rain may contribute as much as 80 percent of the annual total. Because the island is not sheltered by other islands on the southerly side, kona storms are unobstructed. Sudden local heavy showers called

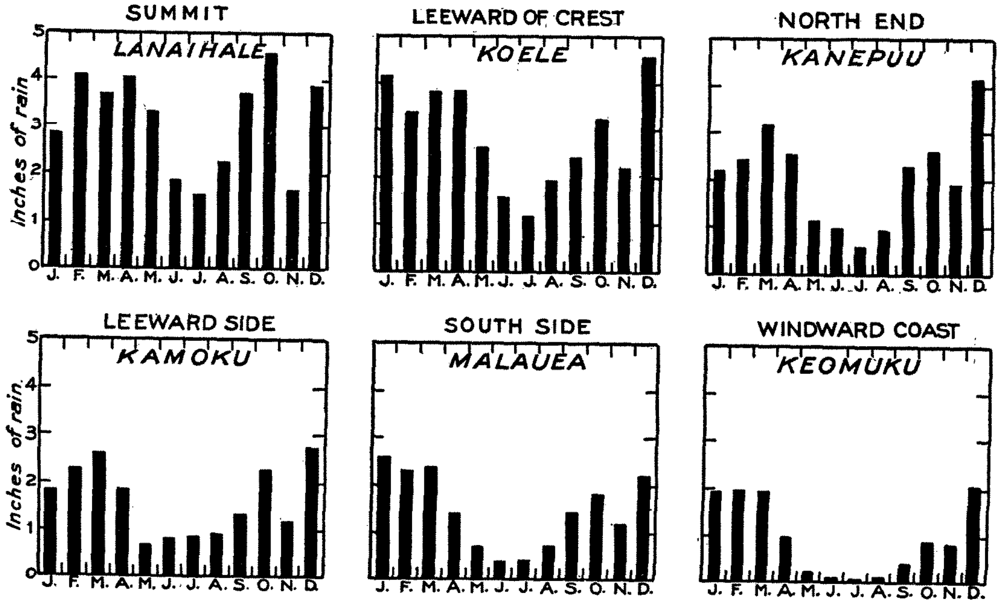

FIG. 11. Comparative mean monthly distribution of rainfall on Lanai.

"naulu" fall during times when neither the trade winds nor the kona winds blow. A naulu shower is caused by a cloud that forms off the south or west coast and then moves inland, dropping its moisture apparently as a result of local convection currents. Naulu showers are reported to occur chiefly in the afternoon during hot weather.

The rainfall stations on Lanai are shown on figure 1, and their monthly and annual records, as furnished by the Hawaiian Pineapple Co., are given in the following tables.

Rainfall at all stations on Lanai, in inches, 1912-39

(Records furnished by Hawaiian Pineapple Co. For location of stations see figure 1.)

1.—**Kanepuu** (northwest end of plateau), altitude 1,600 feet

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1913													16.57
1914													26.78
1915													20.52
1916													40.88
1917													28.06
1918													25.83
1924	0.23	0.20	1.47	7.78	3.48	.....	0.39	0.18	0.96	2.20	1.23	11.67	29.79
1925	4.01	1.29	2.48	1.67	.48	0.41	1.00	.38	.71	5.72	.24	7.64	26.03
1926	1.89	.44	.92	.17	.81	7.80	.....	.33	1.00	4.18	.11	.68	18.33
1927	4.74	4.01	1.68	7.96	.86	.83	.07	.90	.90	.03	2.64	16.75	41.37
1928	.90	.92	.84	3.51	.86	.....	1.44	.33	8.00	1.37	.60	.68	19.45
1929	.....	2.06	1.23	1.78	1.66	.05	.98	.28	1.65	1.22	10.09	3.99	24.99
1930	9.57	.73	4.13	.40	.01	.04	1.21	3.59	9.90	4.19	7.29	1.90	42.96
1931	.27	.20	1.45	2.01	2.00	.37	.45	1.19	5.71	2.60	.15	.03	16.43
1932	.80	8.17	1.95	3.03	.07	2.86	.28	1.28	1.23	.44	.60	3.04	23.75
1933	.34	3.68	1.11	.83	.81	.30	.26	.70	.....	.10	.05	5.72	13.90
1934	1.47	2.72	.91	.36	1.55	.20	.72	.90	1.65	1.53	1.34	3.00	16.35
1935	1.45	.32	6.20	.10	2.70	.70	.05	.82	.40	2.05	2.87	.80	18.46
1936	1.44	2.08	1.17	1.60	.50	.20	.....	.....	2.15	6.90	.82	.30	17.16
1937	3.86	7.80	16.47	1.19	.20	.22	1.00	.46	.....	1.10	.35	5.70	38.35
1938	1.65	3.50	3.15	1.18	1.72	.10	.63	3.08	.....	1.18	.85	1.65	18.69
1939	2.20	1.60	4.81	7.18	.45	.83	.05	.27	1.88	7.11	1.25	3.14	30.77
Mean	2.18	2.48	3.12	2.55	1.13	.93	.54	.92	2.26	2.62	1.91	4.17	25.25

2.—**Kaena** (northwest end of plateau), altitude 1,640 feet

1914	3.99	4.00	1.72	3.55	3.65	0.08	0.93	1.15	2.78	0.48	1.61	5.82	29.76
1915	.....	1.13	1.68	1.26	2.00	2.19	.78	1.25	2.36	.53	2.09	8.19	23.46
1916	19.98	2.03	4.67	.....	.....	.....	1.07	.....	.47	.80	.10	1.34	30.46
1917	1.60	7.32	2.07	1.95	1.83	4.43	1.13	.54	.55	4.48	1.31	2.30	29.51
1918	4.02	2.71	4.10	8.30	.13	.....	.75	2.54	.45	.....	2.51	1.15	26.66
Mean	5.92	3.44	2.85	3.01	1.52	1.34	.93	1.10	1.32	1.26	1.52	3.76	27.97

3.—**Field 5389**[a] (north slope near Halulu Gulch), altitude 1,150 feet

1934											0.25	1.75	
1935	3.17	0.35	7.08	.....	.08	.25	.....	1.05	.06	1.56	.37	.32	14.29
1936	1.18	3.00	2.05	2.55	.06	.12	.....	.....	.72	9.04	2.80	.25	21.77
1937	5.66	8.26	13.29	.82	.94	.....	.....	1.34	.....	.87	.....	5.07	36.25
1938	1.35	4.21	.88	.14	.87	.....	.80	2.72	.....	1.40	.....	.53	12.90
1939	2.61	1.17	2.05	5.90	.....	.....	.....	.....	.....	10.25	.34	.78	23.10
Mean	2.79	3.40	5.07	1.88	.39	.70	.16	1.02	.16	4.62	.63	1.45	21.66

[a] Field 5390 (1,200 ft.) prior to Jan. 1937.

Rainfall at all stations on Lanai, in inches, 1912–39—*Continued*

4.—**Field 5392** (near Puu Mahana), altitude 1,850 feet

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1928									0.02	1.02	0.40	0.18	
1929	5.09	2.58	2.15	0.55	1.33	.....	0.37	0.17	.39	2.24	9.96	5.43	30.26
1930	10.23	.39	5.35	.....	.....	.....	1.10	.72	6.66	2.46	4.58	.31	31.80
1934											.60	1.82	
1935	3.45	.77	6.59	.....	.63	.85	.....	1.61	.57	2.73	.60	.....	17.80
1936	1.70	3.99	1.99	3.50	.13	.35	.....	.....	2.49	11.30	2.85	.35	28.65
1937	7.75	13.02	17.58	.30	1.32	.....	.....	2.62	.....	2.43	.....	6.14	51.16
1938	2.06	4.05	2.52	1.03	3.89	.....	1.65	3.03	.....	4.00	.....	2.95	25.18
1939	2.29	1.00	3.27	8.42									
Mean	4.65	3.68	5.64	1.97	1.22	.20	.52	1.36	1.45	3.74	2.36	2.15	30.81

5.—**Field 5334**[b] (central plateau), altitude 1,520 feet

1932	1.41	8.11	1.65	0.30	0.43	1.95	.38	0.78	1.88	.....	.....	6.05	22.94
1933	.30	5.29	2.81	1.18	.35	.71	.29	.85	.....	.....	0.26	.....	12.04
1934	1.72	4.11	.90	1.08	1.21	1.53	.37	4.32	4.95	1.68	1.67	1.25	24.79
1935	3.06	1.39	7.20	.....	1.97	1.22	.....	2.25	3.98	4.43	.96	.68	27.14
1936	2.65	5.05	1.81	4.77	.65	.76	.29	.75	2.61	10.50	2.45	.20	32.49
1937	8.04	12.30	15.81	.20	2.28	.....	.10	2.40	.51	2.39	.13	5.35	49.51
1938	1.69	4.76	3.63	3.74	5.36	.43	.46	3.53	.17	3.09	.23	1.37	28.46
1939	3.35	2.13	5.92	7.35	1.09	.98	.12	.63	1.64	7.52	1.36	2.74	34.83
Mean	2.78	5.39	4.96	2.33	1.67	.94	.25	1.94	1.96	3.70	.88	2.21	29.02

6.—**Field 5327** (Honopu Gulch), altitude 1,010 feet

1935	2.67	0.68	8.80	.....	1.45	.88	.....	1.34	3.90	4.10	0.65	0.48	24.95
1936	2.98	4.53	1.29	2.91	.43	.46	.86	.39	2.06	8.20	1.74	.45	26.30
1937	8.33	13.70	16.40	.....	.92	.....	.....	.42	.....	1.75	.....	4.75	46.27
1938	1.22	4.40	1.66	2.62	1.38	.....	.38	2.87					
Mean	3.80	5.83	7.04	1.38	1.04	.34	.31	1.26	1.99	4.72	.80	1.89	32.51

7.—**Keomuku** (east shore), altitude 5 feet

1913													5.59
1914	2.61	1.10	5.58	1.35	1.50	.....	.....	.....	0.90	.....	0.86	6.24	20.14
1915	.....	.....	.75	.....	.....	.....	.....	.....	.....	.....	.....	4.75	5.50
1916	11.99	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.50	12.49
1917	2.00	.....	.....	1.06	.28	.....	.....	.....	.33	0.32	.20	1.64	5.83
1918	2.93	2.67	1.25	1.80	.33	.....	.....	.....	.....	.....	3.00	.....	11.98
1924	.....	.....	.80	5.45	.....	.....	.....	.....	.25	.10	.....	4.20	10.80
1925	.....	1.00	1.90	.....	.....	.....	.....	.....	.....	2.10	.....	3.80	8.80
1926	.....	.....	.....	.....	.....	.97	.....	.....	.....	1.65	.....	.50	3.12
1927	.....	2.70	1.21	1.98	.....	.....	.....	.....	.....	.....	.....	6.70	12.59
1928	.....	.....	.....	.....	.....	.....	.....	.....	.....	.30	.....	.....	.30
1929	.....	2.60	.60	.....	1.33	.....	.....	.....	.....	.....	7.38	3.50	15.41
1930	9.27	.....	.....	.....	.....	.....	.....	.....	4.62	.....	.....	.....	13.89
1931	.....	.....	.....	.62	.....	.....	.68	0.66	.....	2.05	.....	.....	4.01
1932	.....	8.57	1.42	1.69	.....	.....	.....	.....	.55	.....	.19	.19	12.61
1933	.....	5.28	.....	.60	.....	.....	.....	.....	.....	.....	.....	4.40	10.28
1934	.33	1.50	.....	.....	.....	.....	.....	.....	.....	.19	.06	1.17	3.25
1935	4.37	.....	5.37	.....	.....	.....	.....	.....	1.00	.86	2.30	.31	14.21
1936	.44	3.13	2.96	1.50	.....	.....	.....	.....	.36	5.75	1.95	.....	16.09
1937	7.03	8.00	12.74	.30	.55	.....	.....	.74	.....	.....	.....	4.20	33.56
1938	.....	3.37	1.48	.....	.....	.....	.....	2.35	.....	.19	.....	.16	7.55
1939	.....	.....	4.63	5.24	.....	.....	.....	.04	.65	6.05	.04	.65	17.30
Mean	1.95	1.90	1.94	1.03	.20	.05	.03	.18	.41	.93	.76	2.04	11.15

8.—**Field 5316**[c] (west edge of central plateau), altitude 1,470 feet

1936									1.15	7.48	1.78	0.15	
1937	7.27	11.31	13.13	0.19	1.88	.....	0.32	0.88	.35	1.02	.90	5.32	42.57
1938	1.70	4.55	3.37	2.91	3.29	.28	1.20	3.24	.57	1.52	.26	.74	23.63
1939	2.67	2.92	5.14	6.95	.84	.64	.12	.51	2.77	8.74	1.09	2.63	35.02
Mean	3.88	6.26	7.21	3.35	2.00	.31	.55	1.54	1.21	4.69	1.01	2.21	33.74

[b] Airport (1,540 ft.) prior to Apr. 1936; Field 5335 to Oct. 1936.
[c] Field 5314 (33 Road) prior to Sept. 1938.

Rainfall at all stations on Lanai, in inches, 1912–39—*Continued*

9.—Koele (central plateau), altitude 1,744 feet

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1905			2.00	2.05	2.20	0.60	1.30				0.51	8.50	
1906	4.75	0.60	1.99	2.83	.50	.05	.....	0.11	1.16		3.50	8.60	
1911					1.77	.88	1.43	.99	3.61	1.22	.41	1.32	
1912	.68	3.10	2.33	2.68	.45	1.15	1.84	1.03	.72	.81	.38	.61	15.78
1913	.98	1.72	5.34	.16	6.98	2.45	.42	4.11	.61	4.34	2.03	2.39	31.53
1914	5.17	3.36	7.92	4.16	5.94	1.04	1.85	4.32	5.40	.71	1.76	6.80	48.43
1915	1.39	1.54	3.60	3.11	3.07	5.06	1.23	.70	2.23	1.60	4.05	7.42	35.00
1916	22.26	2.81	5.70	3.61	4.62	.43	1.82	.81	.65	3.04	2.47	4.04	52.26
1917	6.31	2.42	2.83	7.97	6.94	1.36	1.88	2.30	4.62	4.18	2.96	4.13	47.85
1918	4.77	5.96	5.41	10.80	1.83	1.43	.68	2.74	1.40	.43	4.03	1.84	41.32
1919	.34	.20	3.00	2.54	3.47	3.57	.75	1.33	.99	1.50	2.75	1.76	22.20
1920	*6.32*	*.68*	*.89*	*2.32*	*2.43*	*.92*	*1.88*	*1.43*	*.67*	*2.94*	*.94*	*9.94*	*31.36*
1921	5.78	1.91	1.57	2.60	4.65	.77	1.10	.63	1.81	4.20	3.06	7.49	35.57
1922	1.88	2.00	1.02	1.66	.49	1.61	1.69	3.08	3.75	5.14	1.69	.21	24.22
1923	11.02	5.34	4.69	9.41	.99	2.99	1.36	1.62	1.99	.95	.99	6.65	48.00
1924	.90	1.75	2.47	8.20	4.55	.05	1.93	.44	1.65	2.33	1.16	9.75	35.18
1925	2.35	2.88	2.15	1.75	.45	.68	3.16	.80	1.73	4.55	.75	8.21	29.46
1926	2.50	1.11	2.81	1.53	1.24	6.30	2.69	3.85	4.49	4.99	.79	.88	33.18
1927	5.19	4.53	4.09	13.79	4.75	2.41	.19	1.10	2.30	.75	2.03	14.70	55.02
1928	1.13	2.50	1.82	3.48	1.87	.48	1.20	.72	1.41	1.47	.99	.25	17.32
1929	6.23	4.87	2.74	2.37	1.83	.06	1.34	2.15	2.08	3.43	10.80	7.97	45.87
1930	7.72	1.39	3.88	.81	.48	.30	1.30	2.30	4.87	5.12	4.28	.70	33.15
1931	.51	.25	3.06	2.92	4.04	.95	.99	4.16	4.93	4.57	1.58	1.12	29.08
1932	1.48	11.82	2.60	1.12	.21	1.91	.98	.76	3.13	.73	1.14	4.54	30.42
1933	1.00	7.40	3.15	1.30	.79	.87	.45	1.10	.28	.25	1.26	7.83	25.68
1934	2.75	4.77	1.98	2.36	2.47	2.58	.48	4.72	5.46	3.75	2.20	1.80	35.32
1935	4.24	1.15	7.60	.22	2.15	2.01	1.08	3.79	4.82	5.06	3.62	.76	36.50
1936	2.56	4.88	3.20	6.42	1.25	1.70	.72	.45	3.97	10.15	3.08	.55	38.93
1937	6.77	11.42	13.85	1.02	2.97	.45	1.50	2.39	.77	4.98	.17	6.18	52.47
1938	2.08	6.03	6.19	6.01	7.63	1.44	.98	4.05	.27	2.87	.37	1.73	39.65
1939	4.13	2.01	5.48	7.37	1.58	1.69	.20	.98	2.14	8.59	1.28	3.21	38.66
Mean	4.25	3.46	3.85	3.88	2.73	1.55	1.24	1.97	2.46	3.27	2.16	4.58	36.08

10.—Lanai City (central plateau), altitude 1,650 feet

1930	9.07	1.59	4.58	0.04	0.04	0.13	1.61	2.71	6.28	5.14	4.83	0.44	36.46
1931	.47	.36	3.25	2.98	3.92	.71	2.85	4.45	4.49	4.22	.84	1.46	30.00
1932	1.63	11.91	2.50	1.71	.50	2.23	1.03	1.14	3.24	1.02	1.20	5.36	33.47
1933	.50	6.26	3.10	1.15	.32	.60	.54	1.05	.08	.60	1.09	7.39	22.68
1934	2.98	4.87	1.95	2.34	3.18	3.07	.75	2.90	6.49	3.26	2.17	1.51	35.47
1935	4.42	.92	5.63	.30	1.56	2.02	1.34	2.69	3.90	6.25	2.01	.61	31.65
1936	2.85	3.44	2.31	4.53	.99	1.25	.59	.38	2.19	9.73	3.11	1.20	32.57
1937	7.08	10.97	13.63	1.37	3.26	.60	1.64	2.15	1.00	3.52	1.32	5.96	52.50
1938	2.12	5.81	4.92	5.23	5.70	.65	1.71	3.50	.32	3.38	.35	2.09	35.78
1939	2.68	2.39	5.36	7.87	1.68	1.88	.20	1.13	3.42	7.03	1.56	3.01	38.21
Mean	3.38	4.85	4.72	2.75	2.11	1.31	1.22	2.21	3.14	4.42	1.85	2.90	34.87

11.—Field 5311[d] (central plateau), altitude 1,544 feet

1936									1.17	7.50	1.98	0.20	
1937	5.49	10.07	12.50	0.24	2.11	.....	0.60	0.70	.37	1.78	.67	5.34	39.87
1938	1.56	4.61	3.72	4.22	3.01	0.34	2.76	3.04	.....	2.89	.....	.99	27.14
1939	2.07	3.15	6.40	7.58	1.36	2.00	.....	.95	2.87	7.92	.86	2.68	37.84
Mean	3.04	5.94	7.54	4.01	2.16	.78	1.12	1.56	1.10	5.02	.88	2.30	34.95

12.—Field 5530[e] (west side of central plateau), altitude 1,540 feet

1926						0.84	0.68	1.35	3.92	2.74	.....	0.29	
1927	1.98	5.13	1.93	4.81	1.02	.68	1.05	.42	.....	.13	1.79	14.48	33.42
1928	.88	.85	.54	2.75	.99	.....	.24	.25	1.75	.43	.71	.08	9.47
1929	5.49	4.69	1.17	1.18	1.21	.12	1.23	.85	3.02	2.27	9.79	5.43	36.45
1930	9.05	.57	3.63	.14	.44	.86	.39	2.17	5.07	4.47	3.78	.09	30.66
1931	.15	.10	2.02	1.89	2.33	.43	1.57	2.00	2.01	3.00	.37	.19	16.06
1932										2.55	.79	3.77	
1933	1.20	4.99	1.41	.69	.....	.70	.19	.55	.....	.....	.14	.....	9.87
1934	1.18	3.62	.84	.44	2.46	2.14	.78	2.38	2.02	1.56	1.67	1.20	20.29
1935	2.42	.32	6.28	.....	.77	.34	.....	1.39	2.77	3.17	.60	.22	18.28
1936	2.69	4.34	1.11	2.96	.36	.37	1.61	.10	1.83	8.73	1.65	.08	25.83
1937	6.11	10.56	14.39	.....	1.00	.....	.....	.82	.....	1.95	.....	5.49	40.32
1938	1.70	4.65	3.72	2.46	1.05	.....	4.30	2.14	.88	3.09	.27	1.00	25.26
1939	3.36	3.26	4.49	7.68	.85	1.73	.26	.93	2.14	7.98	1.17	2.41	36.26
Mean	3.02	3.59	3.46	2.08	1.04	.63	.95	1.18	1.95	3.00	1.62	2.48	25.18

[d] Field 5312 prior to Aug. 1938.

[e] Experimental Plot L-3 (1,540 ft.) prior to 1932; Field 5527 (1,450 ft.) 1932-May 1939.

Rainfall at all stations on Lanai, in inches, 1912–39—*Continued*

13.—**Woolshed** (west side of central plateau), altitude 1,300 feet

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1913													16.57
1914	4.13	1.42	0.19	2.98	2.55	.....	0.90	0.70	2.33	.....	3.36	8.24	26.80
1915	.....	.96	.62	.92	1.46	2.51	.42	.08	2.00	0.29	3.35	7.91	20.52
1916	19.40	3.56	2.97	.06	3.81	.....	2.50	.19	.15	4.23	.79	3.22	40.88
1917	3.59	1.48	2.56	1.04	3.76	2.94	.55	2.26	2.43	2.55	2.42	2.68	28.26
1918	4.43	2.93	1.91	8.09	.....	.28	.....	1.28	.30	1.69	4.25	.67	25.83
Mean	6.31	2.07	1.65	2.62	2.32	1.15	.87	.90	1.44	1.75	2.83	4.54	26.48

14.—**Kamoku** (west slope), altitude 1,075 feet

1924	0.45	1.08	1.72	4.58	3.12	0.17	0.61	0.50	0.80	0.47	0.59	8.50	22.59
1925	1.55	.58	.91	1.08	.02	.03	3.04	.12	.20	3.92	.26	8.69	20.40
1926	.97	.25	1.69	.41	.36	2.42	.65	1.22	3.18	2.13	1.11	.....	14.39
1927	2.31	1.93	1.87	3.26	.85	.60	1.11	.99	.99	.....	.61	11.35	25.87
1928	.25	.86	.40	3.79	.86	.14	.14	.....	.77	.03	.30	.10	7.64
1929	2.71	2.69	.06	.48	.30	.....	1.27	1.49	1.05	1.16	5.52	1.68	18.41
1930	5.41	.46	2.19	.02	.11	.58	.03	1.26	2.74	2.20	3.55	.03	18.58
1931	.10	.18	1.50	1.22	.53	.09	.17	.90	1.50	2.39	.08	.....	8.66
1932	1.00	5.15	1.40	.12	.11	1.28	.08	.70	1.01	.48	.60	.79	12.72
1933	.20	3.93	.85	.35	.22	.10	.10	.57	.....	.02	.05	2.29	8.68
1934	.15	1.43	.65	.05	.57	4.19	.06	2.00	2.65	3.09	1.21	1.30	17.35
1935	1.80	.64	5.10	.....	.55	.15	.60	.70	1.44	2.80	.99	.45	15.22
1936	1.80	1.85	.87	2.25	.28	.....	1.36	.....	1.67	6.60	1.28	.29	18.25
1937	6.70	8.50	16.00	1.58	.55	.16	.88	.24	.55	1.72	.50	4.55	41.93
1938	1.60	4.60	1.75	1.24	1.00	.....	1.82	1.88	.03	.72	.23	.63	15.50
1939	.97	1.10	3.15	7.68	.40	2.00	.17	.78	1.54	8.14	1.00	2.10	29.03
Mean	1.75	2.20	2.51	1.76	.62	.74	.76	.83	1.26	2.24	1.12	2.67	18.46

15.—**Field 5329** (northwest end of Bench), altitude 1,800 feet

1937						0.36	1.06	1.62	.....	2.57	1.22	5.16	
1938	1.95	5.53	3.72	5.51	2.72	.47	3.48	3.69	0.61	5.05	.17	1.55	34.45
1939	2.25	2.93	4.52	6.36	1.64	4.74	.10	.55	3.08	6.75	1.52	1.93	36.37
Mean	2.10	4.23	4.12	5.94	2.18	1.86	1.55	1.95	1.23	4.79	.97	2.88	35.41

16.—**Lanaihale** (summit), altitude 3,370 feet

1924	0.60	0.29	1.33	11.30	5.86	0.75	2.73	0.94	2.30	2.34	2.00	3.45	33.89
1925	1.90	6.01	2.85	1.27	1.85	1.45	1.99	1.02	3.92	6.28	2.09	5.71	36.34
1926	2.99	2.07	2.03	1.77	6.17	6.17	1.99	2.47	8.48	6.75	.68	1.70	43.27
1927	3.00	2.14	3.66	1.77	2.99	1.50	.66	1.12	4.96	1.85	3.21	11.55	38.41
1928	.85	2.31	1.64	7.39	.80	1.35	1.30	1.27	1.03	1.67	1.65	1.21	22.47
1929	5.36	6.12	3.74	2.27	1.75	.....	2.25	3.02	2.60	2.76	11.79	9.03	50.69
1930	6.12	1.75	4.11	1.99	.39	.76	2.00	2.80	6.05	8.38	4.48	1.30	40.13
1931	.67	.24	2.83	5.15	4.81	.69	1.50	4.24	5.03	6.15	1.22	3.34	35.87
1932	1.36	10.93	2.78	3.18	4.43	1.53	1.52	1.62	2.53	1.72	1.96	6.72	40.28
1933	1.52	6.32	1.68	1.84	1.53	1.30	1.02	.68	.69	.28	2.92	2.32	22.10
1934	2.42	4.32	3.59	3.29	4.72	3.58	.77	5.39	5.31	5.82	1.83	2.63	43.67
1935	3.10	1.50	4.92	.57	3.25	3.55	.35	3.00	7.05	4.82	2.05	1.20	35.36
1936	3.94	1.70	2.90	5.40	1.20	2.10	1.90	.37	3.90	4.85	3.60	1.00	32.86
1937	6.27	13.10	9.58	2.40	2.58	.50	2.67	1.85	1.51	8.60	.75	4.30	54.11
1938	1.85	4.34	6.67	8.95	9.00	2.22	1.77	3.60	1.86	5.36	.70	2.60	48.92
1939	3.18	2.00	5.42	6.60	1.61	2.44	.42	2.00	2.38	5.30	1.50	3.73	36.58
Mean	2.82	4.07	3.73	4.07	3.31	1.87	1.56	2.21	3.72	4.56	2.65	3.87	38.43

17.—**Waiapaa** (west slope of Lanaihale), altitude 2,125 feet

1914	4.05	1.24	3.32	7.28	5.90	5.15	2.28	.....	6.90	0.95	.....	10.86	47.93
1915	.....	1.93	2.77	.....	4.34	2.25	4.80	.....	.....	4.65	5.05	13.39	39.18
1916	21.75	2.60	6.88	.....	.....	.....	.47	0.58	2.60	5.90	1.10	6.63	48.51
1917	1.44	.....	6.90	2.06	.....	.....	10.80	3.10	2.90	.....	.....	3.00	30.20
1918	4.65	4.70	.....	.....	2.52	.....	1.20	.80	2.25	.....	4.80	.....	20.92
Mean	6.38	2.09	3.97	1.87	2.55	1.48	3.91	.90	2.93	2.30	2.19	6.78	37.35

18.—**Kapano** (north edge of Palawai Basin), altitude 1,340 feet

1936										7.71	2.50	0.75	
1937	6.97	7.90	11.97	0.64	1.41	0.04	1.18	1.18	1.00	2.78	.58	5.56	41.21
1938	1.36	4.97	4.38	3.93	2.56	.34	5.43	2.62	.69	3.43	.72	1.70	32.13
1939	1.81	2.36	4.18	6.90	1.80	2.96	.....	.39	2.46	6.65	.69	1.47	31.67
Mean	3.38	5.08	6.84	3.82	1.92	1.11	2.20	1.40	1.38	5.14	1.12	2.37	35.00

Rainfall at all stations on Lanai, in inches, 1912–39—*Continued*

19.—**Puu Masada**[f] (northwest rim Palawai Basin), altitude 1,240 feet

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1926									3.50	2.43	.....	0.32	
1927	1.46	4.60	1.80	4.65	2.83	0.76	0.96	0.85	.....	.23	1.00	13.85	32.99
1928	.28	.47	.59	2.34	.47	.05	.22	.60	.....	.43	.63	.12	6.20
1929	8.65	3.53	.15	1.04	2.03	.05	1.06	1.50	1.37	.98	9.69	4.57	34.62
1930	7.55	.65	4.10	.09	.14	.87	.87	.89	2.65	6.51	4.41	.05	28.78
1931	.....	.....	3.38	1.09	4.38	.05	.53	.99	2.69	4.80	.24	.70	18.85
1936										6.06	2.35	.38	
1937	5.43	7.75	12.10	.52	1.34	.19	.19	1.41	.87	2.36	.47	5.86	38.49
1938	1.81	4.87	2.58	1.13	1.02	.14	3.12	2.97	.98	2.06	.20	.72	21.60
1939	1.37	3.68	3.27	4.92	.79	.40	.....	1.12	2.76	5.65	.44	1.01	25.41
Mean	3.32	3.19	3.50	1.97	1.62	.31	.87	1.29	1.65	3.15	1.94	2.76	25.87

20.—**1240 Road** (west side of central plateau), altitude 1,310 feet

1936										7.04	1.83	0.23	
1937	5.65	8.75	12.34	0.46	2.02	0.05	0.46	0.89	1.07	3.25	.33	5.77	41.04
1938	1.29	5.27	2.52	.46	.53	.....	1.84	2.92	.20	1.64	.29	.79	17.75
1939	1.08	3.23	4.01	4.67	.70	2.03	.24	1.06	1.93	7.04	.61	1.62	28.22
Mean	2.67	5.75	6.29	1.86	1.08	.69	.85	1.62	1.07	4.74	.76	2.10	29.00

21.—**1388 Road** (west side of central plateau), altitude 1,250 feet

1937				0.39	1.90	0.03	0.28	0.46	1.23	2.61	.41	4.68	
1938	1.40	5.20	2.44	.17	.83	.....	1.51	2.59	.16	1.36	.21	1.02	16.89
1939	.84	2.44	3.16	4.78	.67	1.28	.15	.81	1.87	6.99	.50	1.67	25.16
Mean	1.12	3.82	2.80	1.78	1.13	.44	.65	1.29	1.09	3.65	.37	2.46	21.02

22.—**Miki Village** (Miki Basin), altitude 1,200 feet

1933	0.66	5.62	1.27	1.03	0.18	0.47	0.08	1.39	0.06	.....	0.12	.....	10.88
1934	1.17	3.98	.....	.58	4.89	1.04	1.05	2.15	3.72	1.40	1.15	1.86	22.99
1935	2.95	.38	3.92	.....	.....	.44	.69	.30	.33	1.82	1.80	.05	12.68
1936	2.25	3.69	1.06	3.04	.....	.41	.55	.....	2.09	6.49	2.15	.18	21.91
1937	5.75	6.49	8.09	.48	.49	.07	.63	1.01	.75	1.88	.18	5.21	31.03
1938	1.65	3.84	1.32	.41	1.64	.19	1.63	3.83	.97	.92	.19	1.11	17.70
1939	.75	2.82	3.19	4.65	.78	.85	.14	.70	2.83	6.46	.72	1.94	25.83
Mean	2.17	3.83	2.69	1.45	1.14	.50	.68	1.34	1.54	2.71	.90	1.48	20.43

23.—**Palawai Basin** (near center), altitude 1,140 feet

1932	0.75	8.79	2.08	0.06	0.89	0.29	0.37	1.76	2.20	1.18	0.45	1.62	20.44
1934					2.99	3.15	.70	3.95	4.37	1.49	1.21	2.16	
1935	2.70	.49	2.48	.....	.21	.53	1.77	.40	1.24	4.68	1.06	.31	15.87
1936	3.74	2.78	1.22	3.08	.13	.50	.77	.43	2.03	6.92	2.27	.60	24.47
1937	6.94	8.14	10.47	.47	1.56	.22	.62	1.00	1.07	2.02	.30	6.03	38.84
1938	1.64	5.48	3.27	2.40	1.92	.31	3.49	2.97	.72	1.32	.28	1.05	24.85
1939	.43	2.71	4.98	5.40	1.01	2.37	.24	1.50	2.76	5.37	.53	1.76	29.06
Mean	2.70	4.73	4.08	1.90	1.25	1.05	1.14	1.72	2.06	3.28	.89	1.93	25.59

24.—**Field 5410** (east side of Palawai Basin), altitude 1,240 feet

1937					0.23	0.04	0.34	0.65	0.51	2.63	0.33	4.31	
1938	1.20	4.53	3.53	1.55	2.37	.....	2.60	3.80	.....	.77	.15	1.66	22.16
1939	.50	2.36	4.08	7.39	.58	1.49	.....	.22	3.05	5.59	.48	1.16	26.90
Mean	.85	3.44	3.80	4.47	1.06	.51	.98	1.56	1.19	3.00	.32	2.38	24.53

25.—**Malauea (543)** (southeast rim of Palawai Basin), altitude 1,320 feet

1936										6.31	2.42	0.27	
1937	7.72	8.63	8.93	0.41	0.38	.....	0.21	0.18	0.65	2.06	.14	3.86	33.17
1938	1.31	4.57	2.18	1.20	.91	.....	1.20	3.19	.....	.65	.85	.24	16.30
1939	.01	1.80	2.39	5.17	.24	.46	.....	.03	3.10	6.13	.32	1.14	20.79
Mean	3.01	5.00	4.50	2.26	.51	.15	.47	1.13	1.25	3.79	.93	1.38	23.42

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[f] Experimental Plot L-4 prior to Oct. 1936.

Rainfall at all stations on Lanai, in inches, 1912–39—*Continued*

26.—Manele (south rim of Palawai Basin), altitude 1,190 feet

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1936										7.39	2.49	0.32	
1937	6.91	7.64	9.10	0.28	0.14	0.04	0.34	0.12	0.67	2.12	.15	4.76	32.27
1938	1.73	4.19	1.55	.34	1.23	.17	1.15	3.50	.35	1.13	.63	.45	16.42
1939	.53	1.63	2.89	4.71	.70	.57	.13	.31	3.81	6.26	.73	1.59	23.86
Mean	3.06	4.49	4.51	1.78	.69	.26	.54	1.31	1.61	4.22	1.00	1.78	24.18

27.—Palikaholo (548)[g] (southwest ridge), altitude 1,175 feet

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1932	.....	3.84	1.62	0.56	0.46	0.24	1.23	0.65	2.32	1.33	0.61	1.74	14.60
1933	0.84	5.34	1.08	.77	.33	.40	.....	2.43	.06	.....	.21	.....	11.46
1934	1.42	3.49	.....	.14	3.16	.86	1.44	1.03	2.48	1.08	1.58	1.96	18.64
1935	2.56	.20	5.23	.....	.....	.....	.87	2.08	.50	1.37	1.20	.....	14.01
1936	1.68	2.93	1.02	3.09	.....	.....	.65	.15	1.78	6.60	1.63	.33	19.86
1937	4.72	5.58	8.52	.28	.40	.....	.59	.61	.69	.53	.21	4.99	27.12
1938	1.46	4.62	1.10	.10	2.69	.....	.91	3.35	.61	.88	.27	.95	16.94
1939	.97	2.16	3.36	3.87	.28	1.07	.14	.55	2.25	6.44	.62	1.81	23.52
Mean	1.71	3.52	2.74	1.10	.92	.32	.73	1.36	1.32	2.28	.79	1.48	18.27

28.—Palikaholo (ranch gauge on southwest ridge, near Puu Ulaula), altitude 1,050 feet

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1913													13.57
1914	4.21	1.05	1.45	5.35	3.03	0.32	0.34	.....	2.43	0.57	1.03	6.22	26.00
1915	.....	.59	.71	.74	.79	2.37	.70	0.71	1.76	.87	3.36	6.78	19.38
1916	14.52	1.92	2.78	.....	2.20	.30	.92	1.73	.....	.41	.45	2.60	27.83
1917	2.45	1.65	1.30	.....	3.22	.66	.02	.45	1.70	2.38	1.93	1.87	17.63
1918	6.11	1.80	2.95	3.60	.....	1.25	.....	.43	.....	.60	4.38	.....	21.12
1924	.21	.29	1.76	4.72	1.48	.92	1.12	.69	.54	.09	1.55	6.74	20.11
1925	.....	.09	.73	.05	.....	.34	.99	.06	.86	2.76	.26	4.27	10.41
1926	.37	.20	.96	.19	.....	1.34	1.35	.59	1.85	1.30	1.11	.45	9.71
1927	1.65	2.53	1.92	3.02	.23	.83	.67	1.03	1.03	.....	.18	8.33	21.42
1928	.30	.60	.44	1.63	2.15	.....	.....	.....	.....	.....	.20	.....	5.32
1929	4.40	2.69	.05	.04	.91	.06	.79	.95	1.60	.66	5.90	1.96	20.01
1930	4.80	.41	3.04	.05	.09	.51	.20	.15	4.65	1.54	1.94	.02	17.40
1931	.10	.13	2.62	.76	.70	.....	.29	.83	1.41	4.53	.08	.....	11.45
1932	.07	.....	.....	.65									
1934										1.87	.58	1.80	
1935	1.90	.40	4.26	.....	.10	.20	.20	1.47	.52	1.60	1.16	.32	12.13
1936	1.46	2.00	.90	2.00	.42	.....	1.20	.....	1.74	5.00	1.70	.24	16.66
1937	5.93	6.77	10.68	.44	.36	.12	.98	.15	.43	1.78	.05	4.05	31.74
1938	1.56	3.91	.97	.15	1.85	.20	.57	2.55	.40	.60	.20	1.00	13.96
1939	.35	.70	3.10	5.10	.35	.82	.33	.47	1.68	5.60	.70	1.98	21.18
Mean	2.65	1.46	2.14	1.50	.99	.57	.59	.68	1.26	1.69	1.41	2.56	17.74

29.—Malauea (ranch gauge on south slope), altitude 1,050 feet

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1913													13.89
1914	4.20	1.38	7.25	2.14	2.60	0.10	0.58	.....	1.85	.....	1.17	6.59	27.86
1915	.40	.15	.70	1.69	.....	.....	.....	.....	3.74	0.70	6.35	.....	13.73
1916	21.63	2.05	3.20	2.69	.60	.53	.47	1.45	2.68	.....	.....	.....	35.30
1917	2.50	3.51	1.62	1.39	.85	.40	.54	1.07	1.60	2.95	.22	3.40	20.05
1924	.....	.87	2.30	4.63	1.82	.44	.67	.24	.35	.07	1.50	6.95	19.84
1925	.....	2.39	2.30	.02	.....	.47	.69	.01	.76	5.82	.....	4.25	16.71
1926	.73	.....	.39	.10	.....	3.10	.22	.50	1.49	.63	.64	1.53	9.33
1927	1.52	3.73	1.74	3.21	.74	.45	.52	1.76	1.77	.73	.45	1.73	18.35
1928	.....	.60	.69	1.59	.61	.....	.12	.46	.67	.....	.25	.67	5.66
1929	.....	1.13	.02	.03	.55	.....	.50	1.61	1.47	.18	7.06	3.07	15.62
1930	5.81	.23	2.27	.....	.02	.05	.02	.27	4.10	.55	1.12	.....	14.44
1931	.05	.10	.85	1.04	1.13	.....	.52	1.51	.51	3.47	.10	.....	9.28
1932	.28	5.53	1.43	.73	.07	.08	.16	1.13	1.05	1.15	.72	2.00	14.33
1933	.63	4.85	1.05	.91	1.09	.21	.05	1.32	.....	.13	.05	6.13	16.42
1934	1.20	3.43	1.89	.31	1.60	.40	.03	.24	.99	1.66	.42	1.60	13.77
1935	1.40	.70	4.49	.....	.10	.30	1.32	.52	.28	1.70	1.32	.30	12.43
1936	1.77	3.30	1.75	1.65	.30	.....	1.03	.....	2.38	5.30	1.75	.....	19.23
1937	7.20	7.05	9.50	.53	.08	.10	.16	.18	.21	1.60	.11	3.32	30.04
1938	1.50	4.00	1.13	.48	1.40	.05	.65	2.30	.28	1.04	.34	.35	13.52
1939	.35	.50	2.80	4.56	.25	.14	.08	.07	2.77	6.48	.34	1.77	20.11
Mean	2.56	2.28	2.37	1.38	.69	.34	.42	.73	1.44	1.71	1.20	2.18	17.14

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[g] Field 5513 prior to Oct. 1936.

The isohyetal lines in figure 1 are based on the mean rainfall at the stations listed above. The stations having short records were disregarded in drawing the lines. The quantity of water that falls as rain on Lanai, as computed from planimeter measurements of the rainfall map (fig. 1), averages 52,000 million gallons a year, or about 143.5 million gallons a day.

The rainfall is distributed as follows:

Average annual and daily rainfall and estimated ground-water recharge

Area in square miles	Percent of area of Lanai	Average annual rainfall		Average daily rainfall		Estimated ground-water recharge	
		Inches	Million gallons	Gallons	Gallons per square mile	Percent	Daily average in gallons
2.5	1.8	9	391	1,071,300	428,517	10	107,100
73.2	51.4	16	20,354	55,764,300	761,808	10	5,576,400
51.1	35.9	25	22,201	60,825,600	1,190,325	15	9,123,900
15.5	10.9	35	9,428	25,830,000	1,666,455	25	6,457,500
142.3	100.0	21.2	52,374	143,491,200	1,008,253	13	21,264,900

Some of the run-off from the summit area sinks on its way to the sea. No data are available to estimate the ground-water contribution from this source, but it would increase the total estimated recharge of about 21,000,000 gallons a day given in the table above. The wet years of 1937 to 1939 increased the average annual rainfall 11,000 million gallons. The rainfall records are too short to determine reliable averages.

Disposal of rainfall.—The ultimate source of essentially all ground water is rain. In figure 5 the source and disposal of rain is shown diagrammatically. Of the rain that falls a large quantity evaporates directly from the surface of the ground or from the surfaces of the vegetation on which it falls. Of the remainder a part runs off if the shower is heavy, and another part sinks into the ground. The more porous and permeable the ground the more rain it can absorb. However, all that is absorbed does not reach the water table, the surface of the zone of saturation. Instead, part is returned to the atmosphere by being drawn up through the capillary tubes in the soil, and another part is sucked up by the roots of plants and transpired through the leaves. In a dry island such as Lanai only a small part of the rain sinking into the soil reaches the water table.

No measurements of any surface streams are recorded. Streams seldom flow except when kona storms strike the island, which is only a few days in a year. Maunalei Gulch had apparently the only perennial stream on the island prior to its diversion.

No records of transpiration and evaporation are available for Lanai. Most of the vegetation on the slopes below the summit and plateau areas is dried up except during a few months each year, and even much of the vegetation on the plateau suffers. It is obvious that insufficient rain falls to take care of the transpiration requirements of the plants except over about 7 square miles of the summit area. This high area has frequent showers and is cloudy enough of the time to keep the ground muddy or damp most of the year.

Elsewhere when the rains come the soil is so dry that most of the rain that soaks into the ground is returned to the atmosphere later by evaporation and transpiration. Consequently there must be very little ground-water recharge except in the summit area. This conclusion is supported by the general absence of fresh-water springs entering the sea along the coast. At Lae Hi Point small quantities of brackish water flow into the sea, but elsewhere along the coast most of the dug wells yield water unfit for human consumption. Because Lae Hi Point lies down the dip of the lava beds of the summit area, the springs there probably come from recharge on the summit.

VALUE AND SOURCE OF WATER SUPPLIES

Ground water is the lifeblood of Lanai. Lanai City, Koele, and Kaumalapau are supplied by water from the tunnels in Maunalei Gulch and shaft no. 2 (pl. 1). Most of the water is pumped up the wall of Maunalei Gulch, through a tunnel to two reservoirs near Koele, from which it is distributed by gravity. The reservoirs store 500,000 and 3,000,000 gallons of water. The larger one is lined with concrete and was in use in 1936. Run-off near Koele is collected by ditches and stored nearby in an unlined reservoir having a capacity of 2,000,000 gallons for stock use. A pipe line carrying water chiefly for stock runs part way down Maunalei Gulch from the tunnels and then branches, one line going northward nearly halfway around the island, the other going southward nearly halfway around the island. During certain months sufficient water stands in plunge pools and natural basins in the rocks to supply the livestock, but this dries up in a few weeks after the rains cease.

The aboriginal population of about 3,150 prior to 1778 according to Emory[21] depended chiefly on dew collected on oiled tapas or whipped from heavy shrubbery. Water that accumulated in natural depressions was husbanded carefully, and a few wells were dug

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[21] Emory, K. P., The island of Lanai, a survey of native culture: B. P. Bishop Mus. Bull. 12, p. 122, 1924.

along the coast and were plastered on the seaward side with mud and straw to stop the infiltration of sea water. Even with this device these wells yielded water at low tide that was so brackish that it was usable only because the Hawaiians had by necessity become accustomed to it. Sometimes the Hawaiians also went to the small springs in the distant hills and carried home the water from them in gourds.

Since 1924, when the Hawaiian Pineapple Co. built Lanai City, the water supply has been barely adequate. The faucets in the laborers' homes had special devices to reduce the flow of water. The supply was insufficient for a sewer system. A shortage of water often occurred if a drought coincided with the harvesting season, when the number of laborers was increased. This shortage has been remedied as a result of the supplies discovered during this study.

BASAL GROUND WATER

DEFINITION

The basal ground water on Lanai, as distinguished from high-level ground water, is the great body of water that lies below the main water table or upper surface of the zone of saturation of the island.[22] It is the unconfined ground water occurring in the loose gravel and sand along the coast and under all the island except the rift zones in the basalt.

WATER IN THE SEDIMENTS ALONG THE COAST

Shallow wells have been dug to develop water for stock in many places in the sand flat bordering the north and east coast (fig. 1). This water is too brackish for human consumption except between Maunalei Gulch and Halepalaoa Landing, and even in this stretch it is not very satisfactory, although a few families of Chinese, Filipinos, and Hawaiians use it. Formerly a few irrigated watermelon vines with it, using small pumps operated by gas engines. Analyses of the water are not available, but its salt content[23] probably ranges from 25 to 200 grains per gallon (260 to 2,078 p.p.m.)

During floods considerable water probably sinks into the coastal flat and then slowly percolates into the ocean or becomes brackish through fluctuation of the water table in response to the tide. A short distance from the coast, in the poorly assorted alluvium, the effect of the tide is slight because of the low permeability of the

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

[23] The term "salt content" as used in this report means the amount of chloride found in the water in terms of sodium chloride. The abbreviation p.p.m. in parentheses is the amount of the (cl) radicle in parts per million.

alluvium. Hourly measurements of the old Gay well at Keomuku showed fluctuations of the water level of 0.09 foot only, and most of this appears to be due to changes in barometric pressure. The water table ranges from a few inches to about 2 feet above sea level, depending upon the distance from the coast and the permeability of the sand and gravel.

It is believed that most of the water in these sediments is floating on salt water, hence wells should be as shallow as possible. Probably only small quantities of water occur in this material. Several shallow dug wells will yield more water of usable quality than can be obtained from a single deep well in the same locality. Dug wells should be located directly inland as far as possible from places where ground water can be seen running into the sea at low tide. Open cuts or tunnels to skim the fresh water from the top of the zone of saturation are advisable where larger quantities are desired than can be developed by a dug well.

WATER IN BASALT

Permeability.—The cavities and crevices within and between both the aa and pahoehoe flows of the basalt form a great underground reservoir. These crevices and cavities, named in order of decreasing potential yield, are (1) interstitial spaces in clinker, (2) cavities between beds, (3) shrinkage cracks, (4) lava tubes, (5) cracks produced by mechanical forces after the flows have come to rest, (6) gas vesicles, (7) tree-mold holes. This order differs from that given for Oahu[24] because lava tubes on Lanai are much more numerous, and the beds have been shattered over large areas by faulting. The rocks exposed in the west coast are thin-bedded and filled with lava tubes and cracks. They rank among the most permeable basalts in the Hawaiian Islands (pl. 12, *A*). One naturally expects the sea water to rush far under the island through the spacious lava tubes of these cliffs. Fortunately the lava beds have fairly steep dips so that these cavities do not extend far inland before they rise above the water table. The openings are separated from those in the underlying beds by the less permeable or dense parts of the lava flows, which prevent sea water from freely mixing with the fresh ground water.

Form of water table.—The basal water table lies near sea level and has only a slight gradient, as in the other islands of Hawaii (fig. 5). A resistivity survey across the island, described at the end of this report, indicates that the water table rises only 6.7 feet in

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[24] Stearns, H. T., and Vaksvik, K. N., op. cit., p. 235.

4.5 miles between the west shore and the crest one mile northwest of Koele (resistivity station 9, fig. 1). In the first mile from the coast it rises 2.75 feet, indicating that the gradient is only 1.1 feet per mile farther inland. This gradient of 1.5 feet per mile is similar to that observed on Oahu and Maui.

The resistivity survey indicated a maximum head of 23 feet at station 11, northwest of Maunalei Gulch. It is believed that the high head in the locality of that station results from the water being confined in the dike complex. In the next 3.5 miles, between resistivity station 12 and the northeast coast, the basal water table has a gradient of slightly more than 1.1 feet per mile, similar to that near Koele.

The water table in the lower Maunalei shaft no. 1 (pl. 1) is about 2.5 feet above sea level, indicating a gradient of 1.6 feet per mile between it and the coast.

RELATION TO UNDERLYING SALT WATER.—The lavas on Lanai are saturated for an unknown depth below sea level but not everywhere with fresh water. A drilled well in the bottom of the lower Maunalei shaft indicates that the salt content increases with depth. This condition is found in all the other islands. The following statement about Oahu applies equally well to Lanai:

> Salt water probably filled the interstices in the rocks concurrently with the building of the volcano above sea level. Rain water percolating downward through the porous lava floated upon the salt water because of its lower specific gravity. When the island was small this rain water percolated laterally and quickly discharged into the sea, but as the island grew larger the friction increased in proportion to the distance the water had to move to reach the sea. Moreover, because the salt water in the interstices of the island is not a rigid body but is in hydrostatic equilibrium with the adjacent ocean level, the fresh water disturbed the equilibrium and caused the surface of the salt water to sag until the body of combined fresh and salt water in the rocks was in equilibrium with the sea.[25]

GHYBEN-HERZBERG PRINCIPLE.—The Ghyben-Herzberg principle[26] of the behavior of fresh water in contact with salt water in a pervious formation is illustrated in figure 12 and is expressed by the following formula:

"Let H equal total thickness of fresh water.
h equal depth of fresh water below sea level.
t equal height of fresh water above mean sea level.
Then H equals h plus t.

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[25] Stearns, H. T., and Vaksvik, K. N., op. cit., p. 237.

[26] 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.

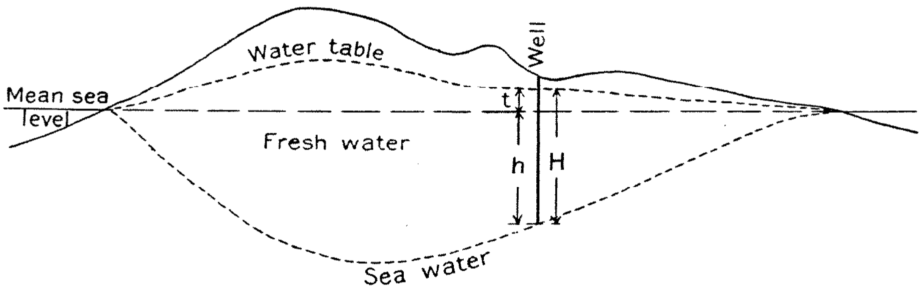

FIG. 12. Section of the island of Norderney, Germany, showing the application of the Ghyben-Herzberg principle. (From Herzberg.)

But the column of fresh water H must be balanced by a column of salt water h in order to maintain equilibrium. Wherefore, if g is the specific gravity of sea water and the specific gravity of fresh water is assumed to be 1,
$H = h + t = hg$ whence

$$h = \frac{t}{g - 1}$$

In any case $g - 1$ will be the difference in specific gravity between the fresh water and the salt water."[27]

The average specific gravity of the ocean adjacent to Lanai is unknown. The average specific gravity of sea water off Oahu is 1.0262 at 22° C. using the specific gravity of fresh water at 22° C. as 1.[28] Using this specific gravity, $h = 38.5t$. Other factors such as the change in density of the ocean with depth make this value approximate only, hence $h = 40t$ is in common use. If fresh water stands 2 feet above sea level in a well the depth of fresh water below sea level will be theoretically about 80 feet. Because of diffusion and mixing, the actual depth of fresh water is less than the theoretical depth. Rain water percolating to the water table in Maunalei shaft no. 1 contained 11 grains per gallon (114 p.p.m.) of salt, indicating that some of the salt in basal water may be derived from salt particles carried inland by the wind. Even with a head of only 2.44 feet the salt content in the lower Maunalei shaft is 36 grains (374 p.p.m.), which is unusually high for this static level. About a third of this salt may possibly be attributed to ocean spray, but the remainder must be from diffusion and mixing (fig. 5). The combined tidal and seasonal fluctuation of the water surface in this well appears to be only a few inches. This fluctuation is so small that it does not seem probable that mixing by variation in head is chiefly responsible

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[27] Stearns, H. T., and Vaksvik, K. N., op. cit., p. 238.

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

for this high salt content. Under these conditions the unusually high salt content must mean that very little fresh water moves past this well and that diffusion is effective in more or less stagnant bodies of basal water in porous rocks.

No artesian water, such as that of Oahu, will be found on Lanai because caprock is lacking.

WELLS

LOWER MAUNALEI SHAFT NO. 1.—A well of typical Maui type[29] to skim water from the basal zone of saturation was started on June 15, 1936, under the direction of W. O. Clark at an altitude of 294 feet in basalt in the south wall of Maunalei Canyon 2 miles from the coast (pls. 1 and 6, *A*). The shaft is 582 feet long, 7 feet wide, and 6 feet high. It was driven southeastward on a 30° incline to an altitude of 1.4 feet. Water was encountered on September 1, 1936, at an altitude of 2.44 feet. A drip from the roof in the shaft at 109 feet vertically below the surface contained 11 grains per gallon (114 p.p.m.) of salt, indicating that considerable salt deposited on the ground from ocean spray is carried to the basal zone of saturation by percolating rain water. The water at the bottom of the shaft contained 36 grains per gallon (374 p.p.m.) of salt on September 1, 1936. A pump sump with its floor at an altitude of 1.0 foot is at the bottom of the shaft. Extending southeastward from the sump is a tunnel 7 feet wide, 6 feet high, and 536 feet long with its floor at an altitude of 1.4 feet. A partial analysis of the water is given below:

Analysis of water from Maunalei shaft no. 1
(Data furnished by Hawaiian Pineapple Co. Sample collected September 1, 1936)

	Grains per gallon	Parts per million
Bicarbonate (HCO_3)	8.9	152
Chloride (Cl)	21.8	373
Total dissolved solids	58.6	1,002
Total hardness (as $CaCO_3$)	11.5	197
pH	7.9	

As soon as the sump was completed a hole was drilled to a point 25 feet below the water level. Water from the bottom of this drill hole contained 54 grains per gallon (561 p.p.m.) of salt prior to pumping. The first pumping test was made on September 22. The following table gives the pertinent data regarding the pumping tests. The skimming tunnel was being excavated during part of this period, which accounts for most of the decrease in draw-down. Also the static level rose 1 inch as a result of autumn rains.

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[29] Stearns, H. T., and Vaksvik, K. N., op. cit., p. 324.

Pumping tests at Maunalei shaft no. 1
(Data furnished by Hawaiian Pineapple Co.)

Date	Pumping test			Total quantity in gallons	Chloride as sodium chloride (NaCl)				Length of tunnel in feet
					Pump discharge		Drill hole		
	Draw-down (inches)	Rate in gallons per minute	Duration in hours		(Gr.p.gal.)	(P.p.m.)	(Gr.p.gal.)	(P.p.m.)	
1936									
Sept. 22	9¼	115	10	69,000	34	353	.....	.....	.....
23	......	110	24	158,400	34.5	359	54	561	50
24	9	200	24	288,000	35	364	.....	.....	63
25	9½	200	24	288,000	36.5	379	61.5	639	75
26	8	235	15	211,500	36.5	379	64	665	87
		100	9	54,000					
27	3¾	100	24	144,000	36.8	382	64.5	670	100
28	3½	100	24	144,000	36	374	65	675	115
29	3½	100	24	144,000	36.5	379	65.7	683	130
30	2½	100	24	144,000	35.8	372	65	675	142
Oct. 1	2½	100	24	144,000	36.3	377	63	655	150
(a.m.) 2	2½	100	12	72,000	36.5	379	55.5	577	160
(p.m.) 2					36.5	379	64	665	165
3	2½	100	12	72,000	36.3	372	62	644	170
4	2½	100	24	144,000	37	384	62.5	650	175
5	2½	100	24	144,000	37.3	387	62	644	195
6	2⅝	100	24	144,000	37	384	62.5	650	205
7	2$\frac{7}{16}$	100	24	144,000	37.3	387	62.5	650	216
8	2½	100	24	144,000	36.8	382	62	644	226
9	2¼	100	24	144,000	37.3	387	63.5	660	236
(a.m.) 10	2¼	100	12	72,000	37.3	387	63.5	660	246
(p.m.) 10	2⅝				36.5	379	58.5	608	250
12	1$\frac{1}{16}$	100	[a]4	24,000	35.8	372	57.5	598	266
13	2	100	18	108,000	36.8	382	58	603	274
14	2	100	4	24,000	35.8	372	55	571	280
15	2	100	18	108,000	37	384	56	582	295
16	2	100	4	24,000	34.8	362	51	530	300
17	2	100	18	108,000	35.5	369	53	551	310
18	2	100	4	24,000	34.8	362	50	520	320
19	2¼	100	18	108,000	35.8	372	51.5	535	335
20	[b]1¼	100	4	24,000	35	364	49	509	350
21	[b]1½	100	18	108,000	36.5	379	51	530	362
22	2⅜	100	4	24,000	34.8	362	49.5	514	377
23	1⅞	100	18	108,000	36	374	50	520	382
24	2	100	4	24,000	....	.....	48	499	392
[c]25	1⅛	100	18	108,000	35.5	369	50	520	395
28	1$\frac{1}{16}$	100	4	24,000	35.5	369	47	488	430
29	1$\frac{1}{16}$	100	18	108,000	35.5	369	48.5	504	440
30	1	100	4	24,000	34	353	47	488	453
31	1$\frac{1}{16}$	100	18	108,000	36	374	45	468	460
Nov. 1	1½	200	4	48,000	36	374	46	478	473
2	2	200	18	216,000	37	384	47.5	493	480
3	1¾	200	4	48,000	35.5	369	47.5	493	490
[d]4			18	216,000					
(a.m.) 6	2	200	12	72,000	37	384	55	571	497
(p.m.) [d]6					37.5	389	.....	.....	.....
9	1	200	22	264,000	35	364	49.5	514	504
10					35.8	372	.....	.....	512
12	2	200	22	264,000	36.5	379	55	571	520
14	1	200	22	264,000	37	384	57	592	523
16	1	200	22	264,000	36.8	382	56.3	585	531
18	1½	200	24	288,000	36.3	377	57.8	601	531
19	1½	200	24	288,000	36.3	377	57.8	601	531
20	1½	200	24	288,000	36.3	377	57.8	601	531
21	1½	200	24	288,000	36.3	377	56.5	587	531
22	1½	200	24	288,000	36.3	377	56.5	587	531
23	1	200	24	288,000	36.8	382	56.5	587	531
24	1⅝	200	24	288,000	37	384	.....	.....	531
25	1⅝	300	16	288,000	37	384	.....	.....	531
26	1⅝	300	24	432,000	37	384	57	592	531
27	1½	300	24	432,000	36.3	377	57.5	598	531
28	1⅝	300	24	432,000	36.3	377	57.5	598	531

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[a] Pumped 22 hours and shut down 26 hours from Oct. 12 to Nov. 4, 1936.

[b] Heavy rains caused the water table to rise, and the observers' notes do not clearly indicate whether this is the true draw-down.

[c] No pumping Oct. 26.

[d] No pumping Nov. 5, 7, and 8.

Pumping tests at Maunalei shaft no. 1—*Continued*

Date	Pumping test			Total quantity in gallons	Chloride as sodium chloride (NaCl)				Length of tunnel in feet
	Draw-down (inches)	Rate in gallons per minute	Duration in hours		Pump discharge		Drill hole		
					(Gr.p.gal.)	(P.p.m.)	(Gr.p.gal.)	(P.p.m.)	
Nov. 29	1⅝	300	24	432,000	36.3	377	57.5	598	531
30	1½	300	24	432,000	36.5	379	57	592	531
Dec. 1	1½	300	24	432,000	36.5	379	57	592	531
2	1⅜	300	24	432,000	36.8	382	58	603	531
3	1⅜	300	24	432,000	36.8	382	58	603	531
4	1¼	300	24	432,000	37	384	59.5	618	531
5	1½	300	24	432,000	37	384	62.5	650	531
6	1½	300	24	432,000	38	395	63	655	531
7	1⅜	300	24	432,000	38	395	68.5	712	531
8	1⅜	300	16	288,000	37.3	388	67.8	704	531
9	1½	300	24	432,000	37.8	393	[e]56.3	585	531
10	1½	300	24	432,000	37.5	390	69.8	725	531
11	1½	300	24	432,000	38	395	71.8	746	531
12	2	300	24	432,000	38	395	72.8	756	531
13	1¾	300	24	432,000	38.5	400	74.5	774	531
14	1⅞	300	24	432,000	39	405	76	790	531
15	2	300 200	12 12	216,000 144,000	39	405	77	800	531
16	1¼	200	24	288,000	38.5	400	76.3	793	531
17	1¼	200	24	288,000	38.8	403	77	800	531
18	1	200	24	288,000	39	405	75	779	.....
19	1¼	200	24	288,000	39	405	77	800	531
20	1 3/16	200	24	288,000	39.2	407	76.8	798	531
21	1 1/16	200	24	288,000	39	405	76	790	531
22	1¼	200	24	288,000	39.8	414	76.5	795	531
23	1¼	200	24	288,000	39	405	76.8	798	531
24	1¼	200	24	288,000	39.2	407	76.8	798	531
25	1¼	200	24	288,000	39.2	407	76.2	792	531
26	1 3/16	200	24	288,000	39.8	414	75.2	781	531
27	1¼	200	24	288,000	40.5	421	77	800	531
28	1 3/16	200	24	288,000	40.5	421	77	800	531
29	1¼	200	24	288,000	41.2	428	77.2	802	531
30	......	200	24	288,000	....	.....	.....	.....	531
[f]31	......	200	7	84,000	....	.....	.....	.....	531
1937 Jan. 4	......	200	12	144,000	....	.....	.....	.....	531
5	1¼	200	24	288,000	39.2	407	72.5	753	531
6	1½	200	24	288,000	39.5	411	72.5	753	531
7	1½	200	24	288,000	40	416	71	738	531
8	1½	200	24	288,000	40.2	418	70.5	733	531
9	1½	200	24	288,000	40.5	421	70.5	733	531
10	1½	200	24	288,000	40.5	421	71	738	531
11	1½	200	24	288,000	40.5	421	71.5	743	531
12	1½	200	24	288,000	40.5	421	73.5	764	531
13	1½	200	24	288,000	41.8	434	75.5	785	531
14	1½	200	12	144,000	....	.....	.....	.....	[g]531
Total				24,004,900					

[e] Sample probably diluted unintentionally by tunnel water.

[f] Pump shut down for repairs and not started again until Jan. 4, 1937.

[g] Tunnel was measured from head wall of shaft. It is 536 feet long if measured from floor of shaft.

As shown by the above records, the draw-down decreased steadily with the increase in the length of the skimming tunnel until the end of October 1936, when the tunnel reached a length of about 460 feet. After that the tunnel did not recover much water, probably because its floor is so flat that the slight draw-down at the sump did not draw water from the heading of the tunnel. The lens of potable water at this place is so thin that the floor of the tunnel was kept only slightly below the water table.

On November 25 the rate of pumping was increased from 200 to 300 gallons a minute and immediately the salt content of the water began to rise, indicating overdraft. On December 16 the rate of pumping was decreased to 200 gallons a minute, but the salinity continued to increase until December 30, when pumping was stopped. With the increased rate of pumping the salt content of the water in the drill hole increased more rapidly than that of the water in the sump but reached a maximum two weeks sooner. The salt content of the water in the sump increased only 4.25 grains per gallon (44 p.p.m.) during the period of heavy pumping, November 25 to December 29, and decreased 3 grains per gallon (31 p.p.m.) as a result of the shut-down at the end of the year, whereas the salt content of water in the drill hole rose 20.2 grains per gallon (210 p.p.m.) and decreased only 4.8 grains per gallon (50 p.p.m.) during the shut-down. As shown in figure 13, the salt content of the water in the drill hole is a better indicator of overdraft than the salt content of the water in the sump. A second boring, 45 feet deep, was made on September 20, 1936, in the tunnel floor about 150 feet from the sump, and salt samples were collected from it. Owing to the difficulties of obtaining samples of water without admixture of tunnel water, the data obtained are in part erratic. Disregarding diluted samples, there is a progressive increase in salt content during the test, from 113 grains per gallon (1,174 p.p.m.) on September 21, 1936, to 191 grains per gallon (1,984 p.p.m.) on January 13, 1937. The salt content in the water in this hole proved to be an even better indicator of overdraft than that of the water in the 25-foot boring.

It is apparent that this shaft and tunnel will not yield more than about 100,000 gallons a day without the salt content increasing materially. However, it is believed that more water can be obtained by driving a tunnel westward from the sump. This tunnel should increase the yield but will probably not decrease the salt content below about 34 grains per gallon (353 p.p.m.), as all the basal water in the vicinity apparently contains this amount of salt. More water could be obtained from the present tunnel if a pump were placed at the heading and the water pumped to the sump at the foot of the shaft. After these changes are made, if more water is needed, it is recommended that the present tunnel be extended indefinitely with sumps about every 500 feet to boost the water back to the sump at the bottom of the incline shaft. Such a method is necessary as the floor of the tunnel must be kept flat to skim only the very freshest water, which lies on top. The additional sumps

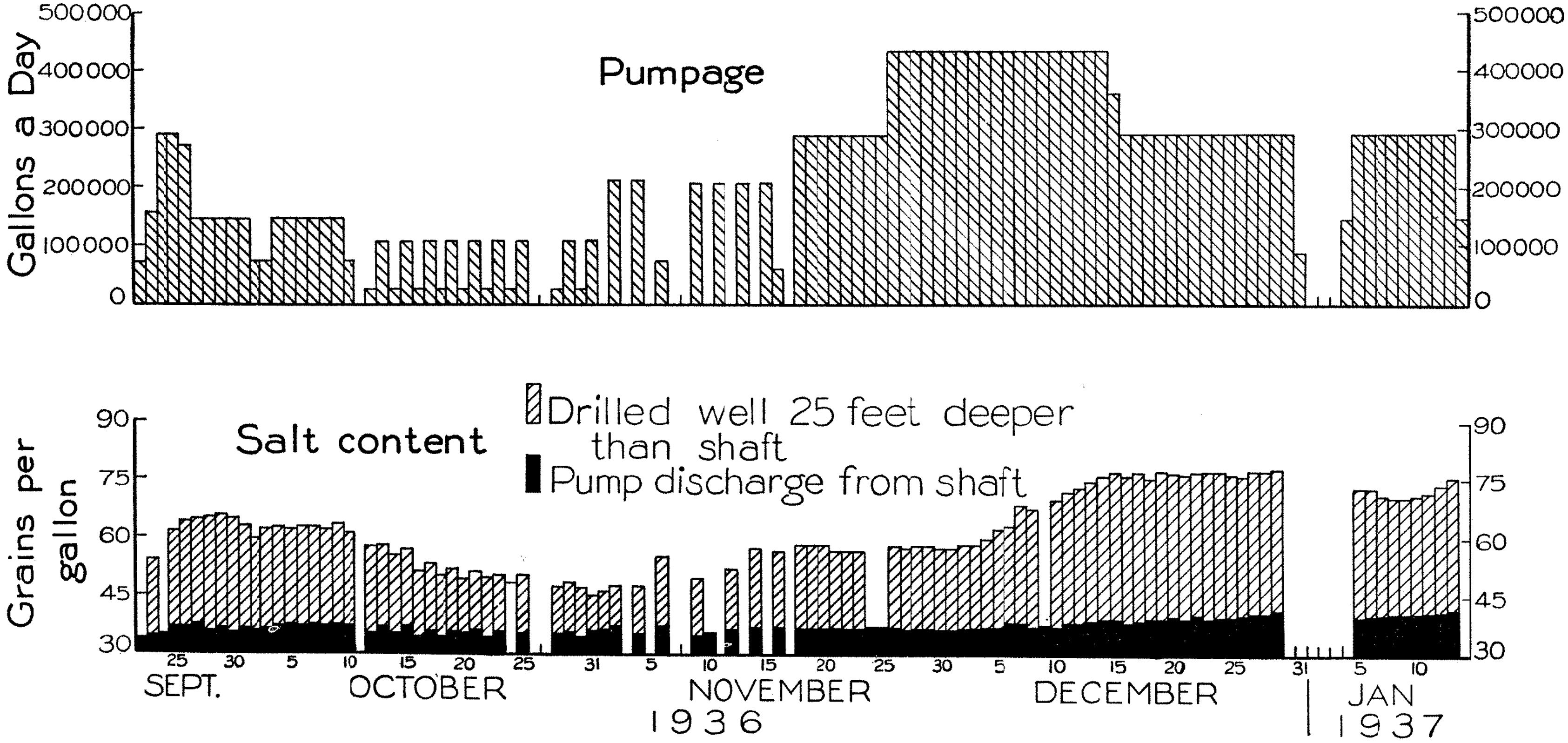

FIG. 13. Graph showing the effect on the salt content of the water of pumping at Maunalei shaft no. 1.

would distribute the draft, thereby preventing excessive mixing of the salt water with the fresh water at any one place.

An automatic recorder was in operation at the sump from August 29 to October 15, 1937. The water is not artesian but the water level fluctuates about 0.02 foot twice a day as a result of changes in barometric pressure. The highs occur between about noon and 5 p. m. and between about midnight and 5 a. m. Tidal fluctuations, if present, must be extremely small.

The monthly change in static level is slight, as shown by the measurements below. Those between October 22, 1936, and March 1, 1937, were made during the period of the pumping test but not while the pump was running.

Static level, in feet, in lower Maunalei shaft no. 1[a]
(Data furnished by Hawaiian Pineapple Co.)

Sept. 1, 1936	2.44
Oct. 22	2.51
24	2.48
28	2.45
29	2.45
30	2.44
31	2.44
Nov. 1	2.44
4	2.49
9	2.52
Nov. 12, 1936	2.52
Mar. 1, 1937	2.52
27	2.36
31	2.50
Apr. 1	2.47
May 1	2.38
June 1	2.40
July 1	2.39
Aug. 1	2.30
Sept. 1	2.40

The upper Maunalei shaft, which develops water confined by the dike complex, is described in the chapter on high-level ground water.

GAY WELLS.—The Gay drilled wells shown in plate 1 are near Keomuku. Well *A* is at an altitude of about 16 feet, is 60 feet deep, and 6 inches in diameter. The depth to water in January 1937 was 13 feet. This well was drilled prior to 1900 for the Maunalei Sugar Co. Soon after this company failed, Charles Gay used the well for irrigating alfalfa and pumped it at the rate of about 500,000 gallons a day until about 1927, when it was abandoned. On May 13, 1936, the Hawaiian Pineapple Co. pumped this well for 4 hours at the rate of 400 gallons a minute to determine the yield and quality of the water. The salt content averaged 79 grains per gallon (821 p.p.m.), as indicated by three samples taken while the pump was running. The altitude of the top of the casing is 6.86 feet. The measurements given on p. 112 indicate that the water level fluctuates little if any with the tide, even though the well is only about 800 feet from the shore. This rise in water level may have been due

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[a] Additional measurements will be found in the annual U. S. Geological Survey Water-Supply Papers entitled "Water levels and artesian pressure in observation wells in the United States."

mostly to barometric pressure because the water level in Maunalei shaft no. 1 rises about the same amount each day at the same time.

Well *B* is a battery of four wells, likewise drilled to irrigate lands of the Maunalei Sugar Co. It is reported that the wells ended in basalt. The irrigation ditch built in lava rock about 100 feet above sea level can still be discerned. It probably leaked badly.

SPRINGS

The only prominent basal-water spring flows during low tide from the basalt on the north side of Lae Hi Point (pl. 1). The yield is difficult to estimate but does not appear to exceed about 10,000 gallons a day. A sample collected by James Munro on April 1, 1937, contained 121.5 grains per gallon of salt (1,262 p.p.m.). Just east of the mouth of Kuahua Gulch cattle drink from springs along the beach in low tide.

When waves pass over a certain spot in Manele Bay a cylindrical body of water about 10 feet across may be discerned most of the time. It has the appearance of being produced by a large spring gushing from a hole in the floor of the bay. Stories are related that natives collected drinking water from it during the existence of Manele village probably because of its similarity to springs in the ocean elsewhere. In 1936 James Munro collected a bottle of water from this hole. He said it tasted like ocean water, and he did not bother to have it analyzed. W. O. Clark reports that coral heads grow around the opening. It is probable, therefore, that this is a submerged spouting horn rather than a fresh-water spring.

QUALITY AND QUANTITY

The basal water along the coast is brackish and unfit for human consumption except along the shore of the canyon country. Even there the salt content is about 79 grains per gallon (821 p.p.m.), as shown by the sample from the Gay well, which is considered one of the best wells. At the lower Maunalei shaft 1.75 miles inland the salt content was 36 grains per gallon (374 p.p.m.) prior to pumping. No data regarding quality are available for water elsewhere. Because the amount of salt spray decreases progressively inland, and because the resistivity survey showed a basal water table nearly three times as high under the central plateau as at the lower Maunalei shaft, basal water with much less than 36 grains per gallon of salt (374 p.p.m.) may be expected under the central part of Lanai. Along the west and south coasts between Kaena and Kamaiki Points the basal water is probably very brackish because coastal sediments such as those on the windward side are absent and the lava rocks exposed in the sea cliffs are highly permeable, so that sea water can mix freely with the fresh ground water. It is reported that the Maunalei Sugar Co. drilled holes at Manele Bay but found only salt water.

The average quantity of basal water recovered from dug wells and the lower Maunalei shaft when it was in use amounted to about 300,000 gallons a day. About 350,000 gallons a day are recovered from the high-level sources described below. Based on crude estimates of recharge (p. 72) the average quantity contributed by rainfall on Lanai is about 21,000,000 gallons a day. A very large part of this quantity can never be recovered because it can escape along many miles of shore line and because it is diffusing and mixing constantly with salt water under the island.

UNDEVELOPED SUPPLIES

Small quantities of basal water may be recovered by skimming tunnels or trenches in the basalt or sediments along the coast between Maunalei Gulch and Halepalaoa Landing. Coarse loose gravel should be avoided because it lets sea water in and fresh water out, too readily. The water could be used profitably to irrigate adjacent land as watermelons raised in this area command a good price.

To develop potable basal water elsewhere is an expensive undertaking, owing to the rapidity with which the land rises inland. Even in the deep canyons such as Maunalei the floor rises rapidly, and hence even a short distance inland a deep shaft is necessary. In addition, a long skimming tunnel barely below the water table is needed to develop potable water. The skimming tunnel in shaft no. 1 yields only about 200 gallons a day per foot, not because the rocks lack permeability, but because only a few inches of the tunnel is in the water.

Wells drilled to develop water would probably not be successful outside of the area of the dike complex, because the water table is low and only a small amount of fresh water is moving through the rocks.

HIGH-LEVEL GROUND WATER

OCCURRENCE

The present supply of Lanai City is high-level ground water. High-level ground water is that water which occurs appreciably above the basal water table. It is by far the most valuable water on the island even though it occurs in smaller quantities than the basal water. Of the four types of high-level perennial water found in the Hawaiian Islands only two types are known on Lanai. These are water confined by intrusive rocks and water perched on soil. It is believed that most if not all of the high-level water in Maunalei Gulch is confined by dikes and discharged there because the stream cuts the dike compartments (fig. 5). The perching structures of the seeps on the Bench are not exposed but near the Gay tunnel a soil bed at the base of alluvium appears to be the perching formation. Soil beds interstratified in the basalt are not known to exist, but thin layers of partly rotted basalt resting on massive basalt may be responsible for some of the small seeps. Ash beds are thin and discontinuous and do not perch water on Lanai. Thin streaks of breccia along some of the faults appear to be sufficiently compact and impermeable to confine water in much the same manner as dikes. If compact breccia does confine or perch water on Lanai it is a new type of occurrence of high-level water in Hawaii. These breccia streaks usually cut across all layers and where not too compact probably act as conduits, not barriers, thus offering percolating water an easy route to the water table. While no definite spring was observed perched or confined by them, fault breccias may be responsible for the seeps 350 feet upstream from the upper Maunalei tunnel.

TUNNELS

Lower Maunalei tunnel.—The lower Maunalei tunnel (no. 1, pl. 1) was driven in 1911 by the Lanai Co. to develop water for domestic and stock purposes. It starts at an altitude of 1,103 feet, is 1,000 feet long, and the many short laterals show various unsuccessful attempts to tap the underflow of Maunalei Stream. It starts in the east wall and after crossing under the stream bed three times ends near the west wall of the canyon about 60 feet below the surface. The first 240 feet is in hard throat breccia, the next 140 feet is in basalt chiefly pahoehoe, and the rest is in poorly consolidated stream-laid boulders and gravel. According to hearsay, written orders had been received on Lanai from the owners to cease work on the tunnel, but before word could be sent down to the workmen, water was struck at the heading. No tunneling was done after the water was found, and all of the water now falls from the innermost heading.

The discharge since 1926 has ranged from a minimum of 160,000 gallons a day, during September 1929, to a maximum of 497,000 gallons a day during April 1939, as shown in the table on next page.

Average daily discharge in gallons
(Data furnished by Hawaiian Pineapple Co.)

Lower Maunalei Tunnel

Year	1926	1927	1928	1929	1930	1931	1932	1933	1934	1935	1936	1937	1938	1939
January	208,000	244,000	252,000	180,000	267,000	302,000	308,000	266,000	246,000	248,000	192,000	204,120	331,786	359,640
February	194,000	224,000	244,000	189,000	260,000	296,000	402,000	282,000	206,000	288,000	220,000	235,440	429,475	390,780
March	180,000	200,000	234,000	198,000	300,000	316,000	496,000	266,000	244,000	192,000	197,000	263,160	453,780	454,315
April	190,000	238,000	226,000	207,000	302,000	343,000	298,000	252,000	230,000	220,000	197,000	318,945	430,560	497,340
May	190,000	232,000	215,000	216,000	274,000	347,000	283,000	246,000	244,000	196,000	196,000	274,320	403,920	379,296
June	190,000	226,000	208,000	213,000	248,000	288,000	283,000	246,000	233,000	196,000	184,000	274,320	365,940	348,480
July	191,000	220,000	200,000	210,000	248,000	302,000	283,000	208,000	208,000	196,000	180,000	....	329,040	348,480
August	194,000	220,000	196,000	208,000	370,000	316,000	283,000	207,000	208,000	196,000	174,000	318,240	322,272	348,480
September	196,000	220,000	193,000	160,000	310,000	316,000	283,000	206,000	220,000	196,000	172,000	271,090	318,240	348,480
October	198,000	254,000	190,000	224,000	272,000	346,000	283,000	230,000	220,000	207,000	220,000	267,860	357,660	356,940
November	194,000	286,000	186,000	272,000	272,000	318,000	283,000	205,000	260,000	207,000	220,000	267,860	342,720	348,480
December	190,000	316,000	183,000	273,000	302,000	220,000	284,000	205,000	208,000	198,000	208,000	314,640	362,880	399,240
Total	2,315,000	2,880,000	2,527,000	2,550,000	3,425,000	3,710,000	3,769,000	2,819,000	2,727,000	2,540,000	2,360,000	3,009,995	4,448,273	4,579,951

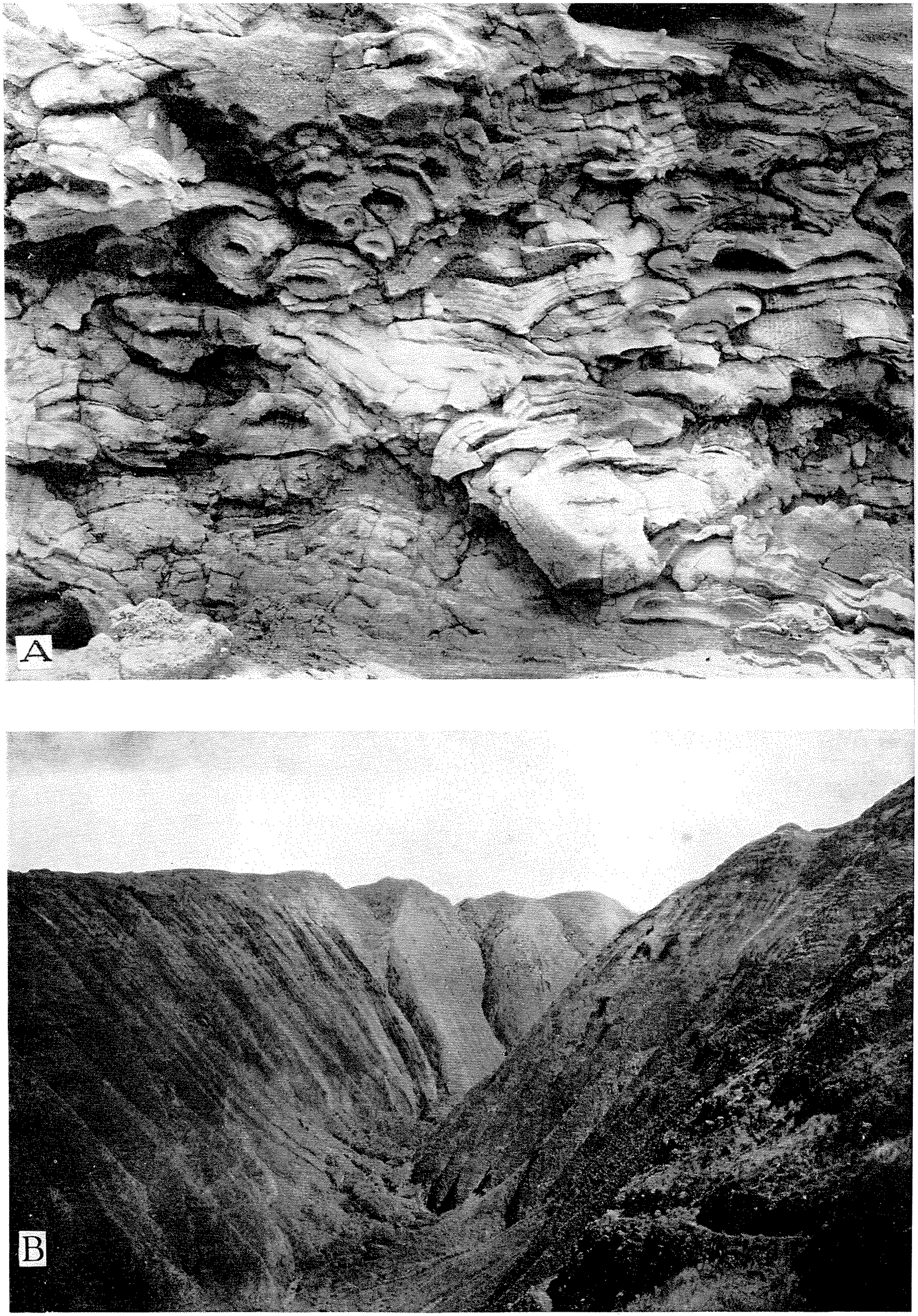
Upper Maunalei Tunnel

Year	1926	1927	1928	1929	1930	1931	1932	1933	1934	1935	1936	1937	1938	1939
January	....	45,360	48,960	53,200	....	81,960	81,360	79,920	72,000	57,024	55,728	55,728	68,233	67,800
February	56,160	....	....	....	55,872	81,960	81,360	79,920	72,000	56,592	57,758	63,072	68,250	68,250
March	56,160	60,480	....	....	56,200	81,960	81,504	79,920	72,000	55,728	57,110	56,448	68,450	68,250
April	54,720	60,480	....	....	72,000	81,960	84,504	79,920	72,000	57,024	58,492	56,736	67,800	67,550
May	54,720	....	....	....	65,000	81,960	81,504	79,920	76,754	55,728	57,024	62,784	68,500	67,300
June	56,160	....	....	....	68,000	....	81,504	79,920	81,864	55,728	55,728	69,120	68,250	67,300
July	54,720	45,360	44,640	....	68,000	....	81,504	72,000	49,392	57,024	55,123	....	68,050	67,300
August	....	....	....	51,400	68,000	....	96,400	72,000	60,988	57,024	54,518	....	68,820	67,300
September	....	51,840	....	52,800	68,000	74,160	90,000	72,000	62,894	55,728	56,505	67,392	67,550	67,300
October	48,960	....	....	52,800	68,200	76,636	91,584	72,000	60,264	59,702	57,110	67,392	68,050	67,300
November	53,280	....	....	52,800	73,090	75,600	86,400	72,000	58,233	60,997	54,864	67,392	67,800	67,300
December	51,840	47,520	....	57,600	76,520	81,360	86,400	72,000	57,024	57,024	56,246	68,300	67,900	67,300
Total	486,720	311,040	93,600	320,600	738,882	717,556	1,024,024	911,520	795,413	685,323	676,206	634,364	817,653	810,250

The alluvium yielding the water ends about 3,000 feet upstream from the portal. This formation has insufficient intake area to supply the water developed. Several dikes are cut by Maunalei Canyon near its head and it is believed that the water leaks from the dike complex into the gravel and thence into the tunnel. A small spring issues about 1,000 feet upstream from the heading of the tunnel but sinks in the gravel of the stream bed after flowing a short distance. James Munro has piped this water past the tunnel, and subsequent measurements prove that it does not contribute to the tunnel flow. Probably little water was recovered by the tunnel in addition to what normally rose as springs in the stream bed and flowed seaward. According to Henry Gibson, Maunalei Stream used to flow all the way to the sea most of the time and in sufficient quantities to irrigate land at the mouth. The abandoned taro patches along the stretches of the canyon just below the tunnel indicate that a perennial stream once existed. Now the bed is dry almost as far as the first spring upstream from the tunnel. Except during rains it is dry above this spring where the channel is on bedrock. A 5-foot well dug 110 feet deep in 1929 at the pump station at an altitude of 1,000 feet in Maunalei Gulch encountered valley fill with low permeability saturated with water, indicating that some of the underflow passes the tunnel. Its minimum yield was 10 gallons a minute.

The water from the upper and lower tunnels flows by gravity to the pump station. From there it is pumped up the canyon wall, a vertical lift of 800 feet, and through a tunnel by a Worthington plunger pump with a capacity of 168,480 gallons a day, to a reservoir which supplies Lanai City, Koele, and all the outlets in the pineapple fields and certain pastures. A stand-by pump with a capacity of 144,000 gallons a day and one with a capacity of 72,000 gallons comprise the equipment to meet emergencies. Prior to the installation of these pumps an attempt was made by Charles Gay to pump the water up the canyon wall with a series of windmills having wheels about 20 feet across. The experiment failed.

Maunalei Canyon lowers the adjacent water table in the same way as a tunnel or open cut would when it penetrates the dike complex (fig. 5 and pl. 12, *B*). The area effectively drained by this deep gash cannot be determined because the number and permeability of the unexposed dikes adjacent to the canyon is involved. Small quantities of water may be recoverable from the valley fill in the upper part of Maunalei Canyon. Although the test well at the pump station exposed only material with low permeability, narrow



Pl. 12. *A*. Pahoehoe near Kaumalapau showing tubes typical of this type of lava. *B*. Head of Maunalei Gulch from the trail to the pump house. (Photographs by C. K. Wentworth. Courtesy of B. P. Bishop Museum.)

ribbons of more permeable gravel may occur that were not encountered by the well.

Upper Maunalei tunnel.—The portal of the upper Maunalei tunnel (no. 2, pl. 1) is in the east bank of the stream, about 8 feet above the stream bed and about 2,800 feet upstream from the lower tunnel, at an altitude of about 1,500 feet. It is about 500 feet long and consists of numerous short drifts apparently made in an attempt to follow the water. The first 225 feet was driven under the direction of D. E. Root, the remainder under W. O. Clark. The northeast branch of the tunnel yields from 50,000 to 80,000 gallons a day. The rock was largely removed without the use of powder because the company was afraid dynamiting might shatter the lava and cause the water in the lower tunnel to disappear. In the innermost heading the rock is filled with dikelets of basalt glass 1 to 3 inches across. About halfway from the portal the tunnel cuts a dike. The rest of the rock is flow lava except for a streak of breccia. A detailed geologic survey of the tunnel was not made because no base map was available. The discharge is given on page 87.

Waiapaa tunnel.—The Waiapaa tunnel (no. 3, pl. 1) was driven about 1924 by the Hawaiian Pineapple Co. under the direction of Simes Hoyt and was stopped on the recommendation of W. O. Clark. It is dry at all times. The portal is at an altitude of about 2,220 feet, at the bottom of a 50-foot dry waterfall in the north fork of Waiapaa Gulch. The tunnel is driven N. 55° E. for about 465 feet. The first 5 feet is in compact fault breccia and the rest in practically horizontal pahoehoe basalt. The tunnel was driven at this place because the company believed that the small seeps nearby indicated a good prospect.

Gay tunnel.—The Gay tunnel (no. 4, pl. 1) is at an altitude of about 1,920 feet in the south bank of the north fork of Waiapaa Gulch about 15 feet above the bed of the stream. The tunnel is reported to have been dug by Charles Gay to develop water for stock, but it was unsuccessful. The tunnel is dry. It is driven S. 65° E. for about 60 feet with a short lateral 10 feet from the portal running S. 60° E. The tunnel is 8 feet high. It is now badly caved because of the soft material it penetrates and the lack of timbering. Near the portal the material appears to be badly decomposed bedrock but the rest of the tunnel rock is rotted fragmental debris, probably alluvium, although the fragments are not well rounded. Thick rotted alluvium is exposed in the adjacent bluffs, and in the bank opposite the tunnel basalt is exposed at the base of the alluvium.

Henry Gibson says he was told by his mother that the old Hawaiian trail reaching the bottom of the gulch about 100 feet upstream from the tunnel was built to obtain water from a perennial pool of water in the stream bed at this point, that this seep supplied the former native village at the mouth of the gulch, and that if a Hawaiian filled two 10 gallon cans from this seep in the afternoon, the next person arriving that day would have to remain all night to fill his cans. Apparently the pool yielded only about 30 gallons a day. The water was probably perched on lateritic soil at the base of alluvium. A lateritic soil one-half to one foot thick is exposed near the tunnel. This place does not appear to be favorable for developing water.

Mountain House tunnel.—Mountain House tunnel (no. 5, pl. 1) is reported to have been dug about 1918 under the direction of J. H. Foss. It is in the south bank about 100 feet above the bottom of the south fork of Paliakoae Gulch in the main Lanaihale fault escarpment at an altitude of about 2,700 feet. It is driven S. 40° E. for 15 feet on the upper part of a lens of massive columnar-jointed basalt containing a few olivine crystals one-half millimeter across. The vesicles contain tiny acicular crystals of an unidentified mineral. On August 3, 1936, the only water present was in a pool on the floor at the entrance, and no visible flow was observed. When water runs a pipe conducts it to cattle troughs. Probably a small seep was located at this point and the tunnel was driven to serve as an intake for the pipe and to collect as much seepage as possible. The tunnel is reported to yield several hundred gallons a day in wet weather. No extensive perching formation was found, hence this place is not recommended for further development.

Another tunnel several hundred feet long is reported to have been driven under a ledge of dense rock in the adjacent gulch bottom by the Lanai Co. in 1918 by tunnel men lent by the East Maui Irrigation Co. J. H. Foss states that he ordered the work stopped on this tunnel on his first inspection trip. James Munro reports that no water was recovered and that several years ago the portal was buried with debris.

UPPER MAUNALEI SHAFT NO. 2

The water of the lower Maunalei shaft was potable only when mixed with water from the lower Maunalei tunnel. To obviate this mixing a new shaft was started in December 1936 at an altitude of 851 feet. It was driven southwestward on a 30-degree incline from the upper part of Maunalei Gulch at a site selected by the writer

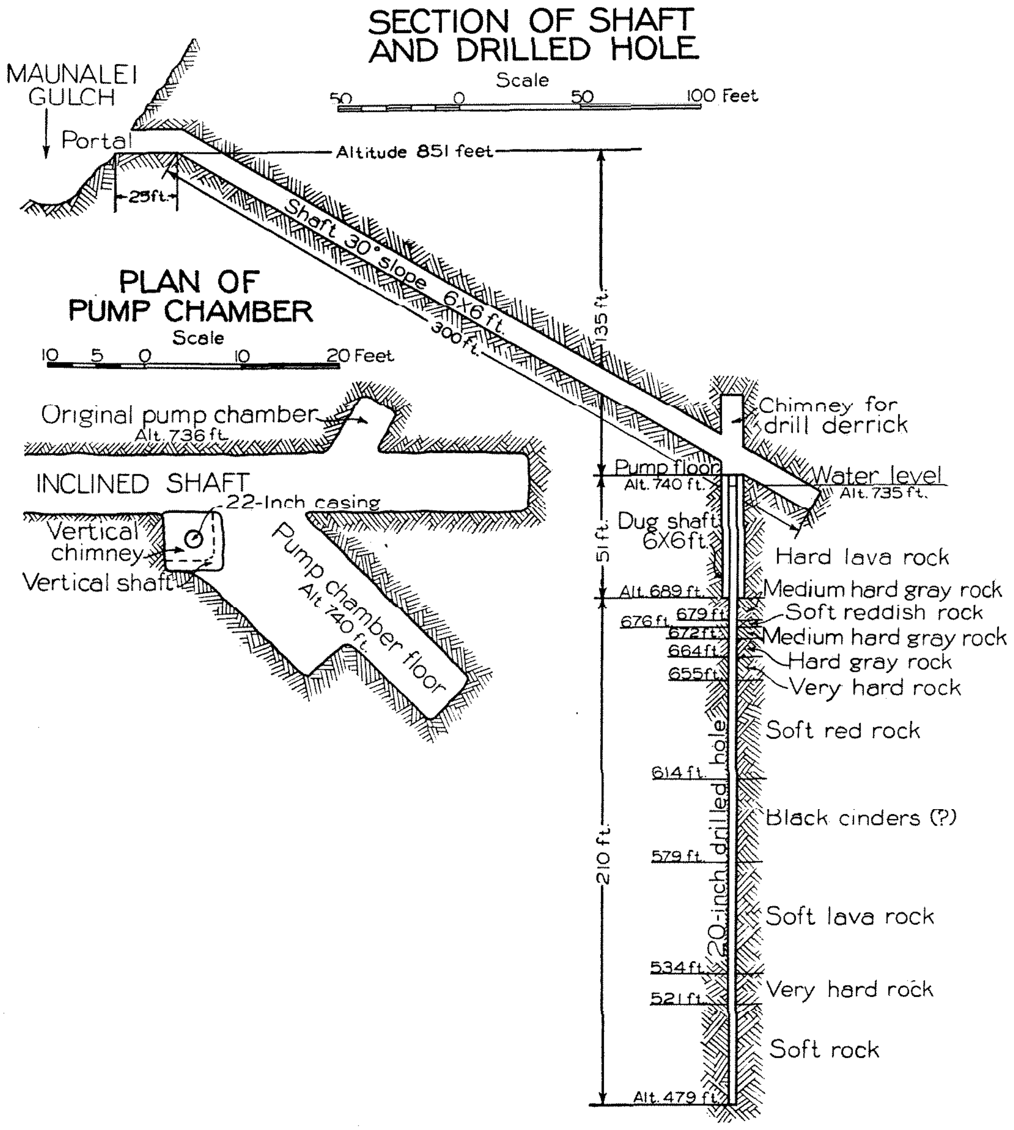


FIG. 14. Plan and profile of Maunalei shaft no. 2.

to develop water confined by dikes (pl. 1). It is not a Maui-type well because it is not based on the skimming principle. Wells developing water from between dikes and not utilizing the skimming principle will hereafter be called the Lanai-type well. A plan and section of the well are shown in figure 14.

After excavating 242 feet on the incline through basalt and one dike, water with only 3 grains of salt per gallon (31 p.p.m.) was encountered at an altitude of 735 feet in a dense body of rock. The upper 4 feet of this rock is platy and vesicular and seems to merge into overlying scoriaceous basalt. The platy lava grades downward into columnar-jointed rock. A pump with a capacity of 15 gallons a minute lowered the water 3 feet. Then a sump was excavated alongside the shaft, after which pumping at the rate of 20 gallons a minute lowered the water level only 2 feet. A pump with a capacity of 150 gallons a minute was then installed and the shaft was dug an additional 34 feet. James Munro reports that a dike was apparently cut at this depth, and so much water entered the shaft that work had to be abandoned.

It was then decided to drill a vertical hole in the sump and equip it with a deep-well turbine in order to dewater the sloping shaft. A chamber with a drill mast chimney 40 feet high was next excavated at the static water level. It exposed a 4-foot vesicular dike cut by a nearly flat-lying 2-foot dike dipping westward. Owing to the difficulty of obtaining a drilling rig at that time, a vertical shaft was excavated as deeply as feasible in the dense rock on the assumption that this could be done without additional pumping equipment because of the low yield of the dense rock. A little water was struck in this vertical shaft all the way down. At 25 feet a crack was encountered that raised the inflow to 40 gallons a minute. At a depth of 48 feet the inflow reached 250 gallons a minute, and work was stopped pending the arrival of a 700-gallon-a-minute deep-well turbine. Two jackhammer drill holes 2 inches in diameter were put down in the bottom of this shaft to depths of 33 and 37 feet. Soft red rock was encountered at 34 feet. When the shaft was pumped dry these two holes delivered good flows of water.

Meanwhile the demand for water at Lanai City made it necessary to pump from this shaft, hence excavation was stopped. Pumping for the city was started on July 23, 1937, at the rate of 144,000 gallons a day. The water level in the sloping shaft had dropped 4.75 feet by August 20, after 28 days of continuous pumping from the vertical shaft, during which 4,032,000 gallons were removed. The water level recovered 1 foot in the following 4½ days of no pumping, indicating that the local water level had dropped about 3.75 feet and storage had been drawn upon.

A 20-inch hole was bored in the bottom of the dug shaft on January 15, 1938, using a Hughes rotary bit. This was the first time rotary drilling of this type was tried in Hawaii. At first the heavy olivine and magnetite grains in the cuttings would not rise with the return water. This difficulty was overcome by introducing mud and installing a mud pump. Inclined crevices in the rock caused the drill to work off from the perpendicular. A hole 210 feet deep was completed on June 20, 1938, and a deep-well turbine installed at an altitude of 685 feet. The quantity of water pumped from the shaft for domestic use at Lanai City was 11,704,000 gallons in 1937, 9,180,000 gallons in 1938, and 8,328,940 gallons in 1939.

Unlike most other wells the draw-down induced by pumping and the subsequent rate of recovery is not indicative of the quantity of water available in this well. This is because the water percolating to the well comes in part from recharge and in part from ancient storage in adjacent compartments enclosed by dikes. The rate of percolation from these compartments is governed chiefly by the number of leaks through the dikes and not by the draw-down in the well. For this reason if the draft is large, many years may elapse before equilibrium is reached, the water level falling year after year. Eventually it may be necessary to continue the inclined shaft much deeper and drive lateral tunnels cutting across the dikes. If the shaft is sunk only as fast as the water level is lowered in the drilled well, large volumes of water will be saved that have accumulated during past centuries. So far the inflow has equaled the draft.

However, the rainfall is only about 35 inches annually in this region; hence the recharge is not great. Furthermore as the water level is lowered it may eventually reduce or stop the flow at Maunalei tunnel no. 1. Consequently the water should be carefully conserved. Three methods are feasible: (1) to sink the flood waters of Maunalei Stream in a pit near the shaft; (2) to pump water from shaft 1 into shaft 2, thereby artificially recharging the well; (3) to build bulkheads in the wider dikes cut by the horizontal tunnel if and when such a tunnel is excavated.

SEEPS

Perched water is so scarce on Lanai that even seeps are worth describing. The seep developed by Mountain House tunnel is described on page 90. Two small seeps that issue on the Bench and that were reported to be dry during June, July, and August, 1936, were not visited.

MAUNALEI GULCH.—On August 1, 1936, a spring was discharging about a gallon a minute about 300 feet downstream from the upper Maunalei tunnel. A massive dike 3 feet wide which crops out in the adjacent northeast wall probably holds the water at this high level.

About 350 feet upstream from the upper Maunalei tunnel both walls of the canyon are wet, and water drips from as high as 50 feet above the stream bed on the east wall. On this wall two fault traces indicated by thin breccia streaks dipping eastward cross another dipping westward. The water issues from the prism between the fault traces. The discharge is not more than a gallon or two a minute in dry weather.

WAIAPAA GULCH.—A small seep called Pulou Spring issues from the base of a ledge of massive black basalt at an altitude of about 2,450 feet in the south fork of Waiapaa Gulch. It yields normally only about a pint a minute and in dry weather ceases to flow. The water is piped to a cattle trough.

The largest dependable seeps are at an altitude of about 2,300 feet in the north fork of Waiapaa Gulch about 100 feet upstream from Waiapaa tunnel. The water issues from vesicular pahoehoe and drains into a concrete basin from which it is piped to a cattle trough. On August 3, 1936, the stream bed was very wet but no water was flowing into the basin although the basin contained water. Probably at night when the transpiration is less there is sufficient water to flow into the basin. In the adjacent small tributary gulch and about 10 feet lower is another similar concrete basin and wet spot that evidently yields water at times. The structure perching these seeps could not be determined, but it is probably a thin decomposition streak. The Waiapaa tunnel under them is dry.

QUANTITY AND QUALITY

The average quantity of developed high-level ground water is about 500,000 gallons a day. All the water is of excellent quality as shown by the following partial analysis.

Analysis of average of six samples of water collected from lower Maunalei tunnel between July 18 and September 11, 1936
(Data furnished by Hawaiian Pineapple Co.)

	Grains per gallon	Parts per million
Silica (SiO_2)	2.1	36
Bicarbonate (HCO_3)	5.5	940
Chloride (Cl)	1.3	22
Total dissolved solids	8.4	144
Total hardness (as $CaCO_3$)	3.3	56
pH	7.3	

RECOMMENDATIONS FOR DEVELOPING WATER

The following sites for a shaft and tunnel were recommended in 1936[30] for developing water on Lanai: (1) head of Hauola Canyon; (2) at or upstream from the present pumping plant near the head of Maunalei Gulch, altitude 1,000 feet; (3) near the bend of Mauna-

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[30] Letter to Hawaiian Pineapple Co. dated Nov. 19, 1936.

lei Gulch half a mile downstream from site 2, altitude about 800 feet; (4) Lanai City, altitude 1,600 feet.

Site 3 was recommended as the most feasible of the four sites. Shaft 2 was constructed there and has proved a success.

A test hole is also recommended in Palawai Basin as close to the Bench as possible. It is probable that a sufficient number of dikes cut through this place to cause the water to stand considerably above sea level unless the faults present allow the water to escape at low levels.

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GEOPHYSICAL INVESTIGATIONS ON LANAI

By Joel H. Swartz

INTRODUCTION

During 1934 H. T. Stearns became interested in the possible use of geophysics in the study of ground-water problems in the Hawaiian Islands. An arrangement for a cooperative geophysical survey to test the feasibility of the application of such methods was made with the Geophysical Section, then in the Bureau of Mines but transferred to the Geological Survey on July 1, 1936, and in March 1936 J. H. Swartz, of the Geophysical Section, began a series of magnetometer and resistivity measurements on the island of Maui.

These preliminary studies showed that it was possible to determine by resistivity measurements the depth to salt water and from this depth to calculate the elevation of the basal water table and the thickness of the basal fresh-water lens. After these initial studies had been completed, the equipment was transferred to the island of Lanai, where measurements were made at 23 resistivity stations, most of which lay along a traverse extending across the island from Kaumalapau on the southwest to the mouth of Maunalei Gulch on the northeast. The results of this survey are presented herewith.

THEORY OF THE RESISTIVITY METHOD

PRELIMINARY CONSIDERATIONS

Electric current, potential difference.—It is now generally accepted that an electric current consists of a series of moving electrical charges. Such a current will always flow between any two points of a conducting body which have between them a *difference of potential*.[31] Conversely, any two points between which current is flowing must have between them such a potential difference.

Equipotential surface.—A surface may be passed through all points in a body which have the same potential. Such a surface is called an *equipotential* surface. Since there is no potential difference

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[31] The electric potential at any given point may be defined as the ability of an electric charge to do work in virtue of its position in an electric field at that point. It is measured with reference to some other point, usually at infinity. For convenience it may be defined as the work done against the field while bringing a unit positive charge from a point of zero potential to the given point.

between any of the points of such an equipotential surface no current can flow between them, *i.e.,* along the equipotential surface. Thus, the flow of current is perpendicular to the equipotential surfaces.

RESISTANCE AND CONDUCTANCE.—The amount of current flowing between two such equipotential surfaces in a body, for a given potential difference between these surfaces, will depend on the opposition to current flow offered by the materials between the two surfaces. This opposition to current flow is called the *resistance.*

To look at the same thing from another viewpoint, the ease with which the current flows through a body is called the *conductance.* The conductance is the reciprocal of the resistance. A body of infinite conductance would have zero resistance and conversely a body of zero conductance would have infinite resistance. Mathematically, if G is the conductance and R the resistance,

$$G = \frac{1}{R} \qquad (1)$$

OHM'S LAW.—The quantitative relationship between current, potential difference, and resistance was first stated by Ohm, whose experiments indicated that the current flowing in an electrical circuit is directly proportional to the potential difference across the circuit and inversely proportional to the resistance of the circuit. Stated mathematically, if E is the potential difference across the circuit, R the resistance of the circuit, and I the current flowing through the circuit, we have

$$I = \frac{E}{R} \qquad (2)$$

This relationship is called Ohm's Law, after its discoverer.

UNITS OF CURRENT, RESISTANCE, AND POTENTIAL DIFFERENCE.—The unit of current is the *ampere.* The ampere[32] has been defined as the unvarying current which will deposit 0.001118 grams of silver per second from a standard aqueous solution of silver nitrate. A current of one thousandth of an ampere is called a *milliampere.* The milliampere is a more convenient unit for geophysical work.

The unit of resistance is the *ohm.* The ohm has been defined as the resistance at 0° C. offered to the flow of a steady current by a column of mercury of constant cross-sectional area having a length of 106.300 centimeters and a mass of 14.4521 grams.

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[32] The definitions here given are those for the International units as established by the International Congress of Electricians in 1893 and later confirmed by the International Conference in 1908.

The unit of potential difference is the *volt*. One volt is the potential difference required to drive a current of one ampere through a resistance of one ohm. The *millivolt*[33] is a more convenient unit for resistivity measurements.

RESISTANCE AND RESISTIVITY.—The resistance of a body depends not only on the material[34] of which it is composed but also on the shape and size of the body and the direction of the current path through it. Thus a pound of copper will have a low resistance if made in the shape of a cube but a much higher resistance if drawn out into a fine wire.

We cannot therefore use resistance to compare different materials, since the resistance depends on factors other than the nature of the material. Instead we must have recourse to some property involved in resistance but which depends on the material alone.

Experiment has shown that the resistance of a body depends on three things: (*a*) the length of the current path through the body, (*b*) the area of cross-section of the current path, and (*c*) the material of which the body is composed. Quantitatively the resistance is directly proportional to the length of the current path and inversely proportional to the area of its cross-section. Stated mathematically, if L is the length of the current path, A the area of its cross-section, and R the resistance, then

$$R = \rho \frac{L}{A} \qquad (3)$$

where ρ is a factor of proportionality dependent only on the material of which the body is made. It is obvious that the factor ρ is the quantity sought since it controls resistance and is independent of the dimensions of the body or the direction of the current path.

The significance of the factor ρ becomes apparent if L and A are each made equal to unity, for then we get, from equation (3),

$$\rho = R \qquad (4)$$

which states the fact that ρ is the resistance offered by a body of the given material having a current path of unit length and of unit cross-section. For this reason ρ has been called the *specific resistance* or, more simply, the *resistivity* of the material. Because it depends solely on the material of which the body is made it can be

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[33] Both the term milliampere and the term millivolt are often abbreviated to the word "mil," the context determining which applies.

[34] The word material as here used includes all the characteristics of the material, both physical and chemical.

used to compare different materials on the basis of their resistance-determining properties.[35]

UNIT OF RESISTIVITY.—Solving equation (3) for ρ we get

$$\rho = R\frac{A}{L} \tag{5}$$

from which we see that $\rho = 1$ when R, A, and L all equal 1. Using the units of the cgs (centimeter-gram-second) system we get

$$1 \text{ resistivity unit} = 1 \text{ ohm} \times \frac{1 \text{ cm}^2}{1 \text{ cm}} = 1 \text{ ohm} \times 1 \text{ cm} \tag{6}$$

For this reason the unit of resistivity is called the *ohm-centimeter.* A larger unit, the ohm-meter,[36] is often convenient. Since one meter equals 100 centimeters, 1 ohm-meter equals 100 ohm-centimeters.

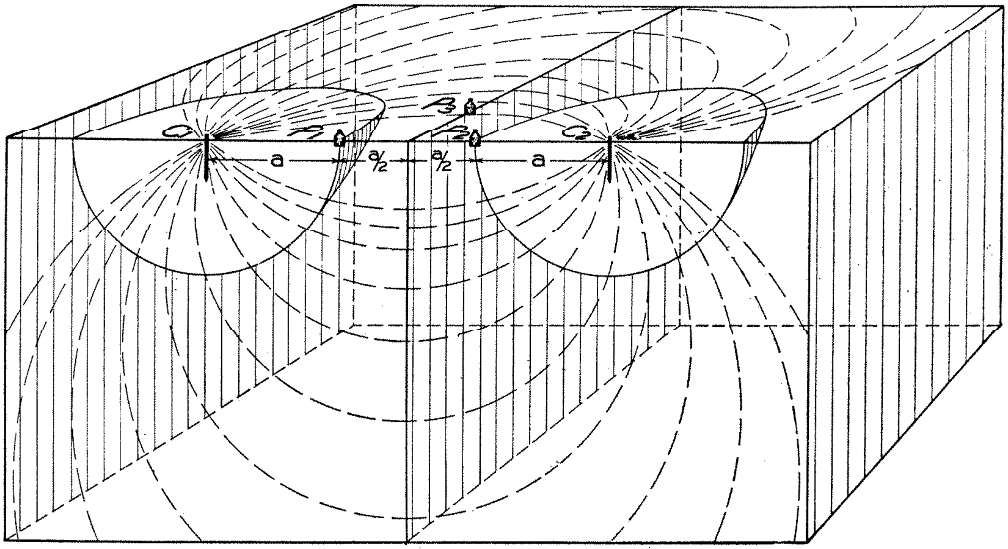

FIG. 15. Diagram showing electrical field for Lee Partitioning Method of measuring resistivity.

THE RESISTIVITY METHOD.—Since different materials have different resistivities, a determination of the resistivities of underground geological bodies may be used to help determine what these bodies are, as well as to locate desired bodies, such as oil, ores, and water.

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[35] Resistivity bears much the same relationship to resistance that density does to mass. The mass of a body depends not only on the material of which it is composed but also on its shape and size. Density on the other hand is a characteristic of the material of which the body is composed and is independent of the shape and size of the body. Quantitatively density is the mass of a unit volume of the material of which the body is made.

[36] It has been suggested that, since the unit ohm-meter might be confused with the meter for measuring resistance, known as the ohmmeter, it would be better to call these units the meterohm and centimeterohm. There is much to be said for this suggestion, although it has not yet received general acceptance.

If two stakes C_1 and C_2, figure 15, are driven into the ground and a current, I, passed between them through the ground, the voltage, E, set up between any two other points P_1 and P_2 between them, depends on three things: (1) the current strength I, (2) the spacing of the electrodes (*i.e.*, the distances C_1P_1, C_1P_2, C_2P_1, and C_2P_2), and (3) the resistivity of the materials underground. From a measurement of E, I, and the electrode spacings, the resistivity, ρ, of the underground materials may be calculated.

For a homogeneous earth it may be shown that

$$E = \frac{\rho I}{2\pi}\left(\frac{1}{C_1P_1} - \frac{1}{C_1P_2} + \frac{1}{C_2P_2} - \frac{1}{C_2P_1}\right) \tag{7}$$

or letting

$$K = \left(\frac{1}{C_1P_1} - \frac{1}{C_1P_2} + \frac{1}{C_2P_2} - \frac{1}{C_2P_1}\right) \tag{8}$$

we get

$$E = \frac{\rho I}{2\pi} K \tag{9}$$

whence

$$\rho = 2\pi \frac{E}{I} \cdot \frac{1}{K} \tag{10}$$

Partitioning Method.—In Lee's Partitioning Method, used in the Hawaiian measurements, one potential electrode P_c, is placed half-way between C_1 and C_2, as shown in figure 15. Two other potential electrodes, P_1 and P_2, are placed on either side of P_c at a point one-third of the distance from P_c to C_1 and C_2 respectively; *i.e.*, they are so placed as to be equidistant from each other and from C_1 and C_2. With this arrangement we have the following relationships:

$$C_1P_1 = 2P_1P_c = 2P_cP_2 = P_1P_2 = P_2C_2 = \frac{1}{3} C_1C_2 \tag{11}$$

If we let $\frac{1}{3} C_1C_2 = a$, and substitute the corresponding electrode spacing values in equations (8) and (10), we get, for the Partitioning Method,

$$K = \frac{1}{2a} \tag{12}$$

and

$$\rho = 4\pi a \frac{E}{I} \tag{13}$$

where E is the voltage between P_1 and P_c (or between P_c and P_2).

If E is measured in millivolts, I in milliamperes, and a in centimeters, ρ will be given in ohm-centimeters. If a is measured in feet, as is usually the case, its value must be multiplied by 30.48 to convert it into centimeters, and equation (13) becomes, on multiplying out the constants,

$$\rho = 383a\frac{E}{I} \tag{14}$$

Experience in the field has shown that a gives the effective depth with a high degree of accuracy. Hence measurements to different depths can be made simply by changing the value of a. A series of values of the resistivity will be obtained for such different depths. When the measurements are completed at a given point or station, a resistivity curve, such as shown in figure 16, is drawn by plotting each value of ρ as ordinate against the value of a at which it was obtained, as abscissa.

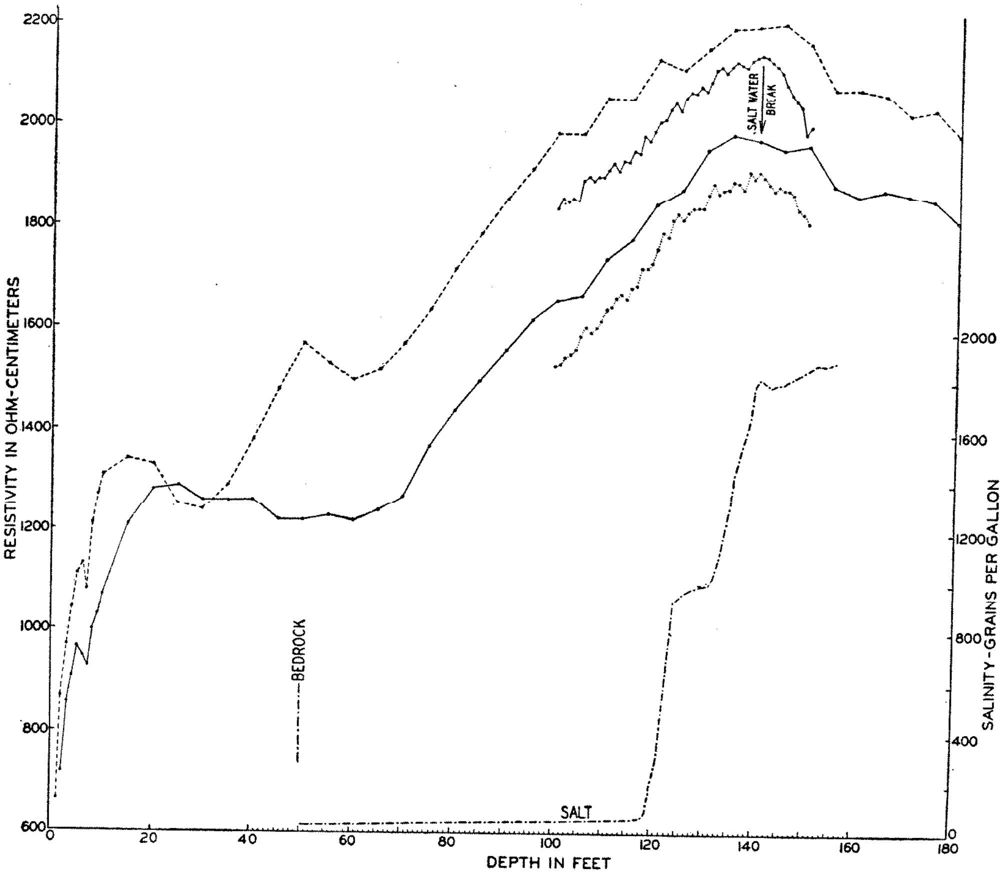

FIG. 16. Resistivity curves obtained at Kahului Fair Grounds on Maui, in comparison with a curve showing salt content of water in a test boring.

From the changes in this curve the changes in resistivity at different depths may be observed and the corresponding changes in geological character of the underground rocks or other geological bodies deduced.

As seen in figure 15, two curves are obtained at each station center in the Partitioning Method, one each for the materials lying on either side of the median or partitioning plane through the central potential electrode. This permits the use of one curve to corroborate the other, where the materials on both sides of the center are alike, or what is still more important, to detect their dissimilarity when the materials on opposite sides of the center are different, and to determine how they differ and the depths at which they differ.

In these curves an upbreak or counter-clockwise rotation of the curve slope usually occurs where a higher resistivity is met as depth is increased, a downbreak or clockwise rotation of the curve slope where a lower resistivity material is encountered.

DETERMINATION OF THE DEPTH TO WATER

Preliminary survey.—As described in a previous paper,[37] the initial survey on Maui indicated the feasibility of measuring the depth to salt water by resistivity methods and of calculating from this, on the basis of the Ghyben-Herzberg principle, the height of the fresh-water table above sea level and the corresponding thickness of the basal fresh-water lens.

This conclusion was verified by a test hole put down to salt water at the Kahului Fairgrounds, Kahului, Maui, through the courtesy of J. H. Foss and C. S. Childs and the cooperation of J. M. Heizer and Robert E. Hughes. The results there obtained will be discussed in some detail since they constitute a direct test of the validity of the resistivity method later applied on Lanai.

As seen in figure 16 the resistivity curves obtained at this location showed a characteristic downbreak[38] at a depth of 140 ± 1 feet below the surface, or 135.2 ± 1 feet below sea level. On the basis of this downbreak it was predicted that salt water would be encountered in the drill hole at a depth of 135.2 ± 1 feet below sea level. A series of water samples at one-foot intervals taken after the completion of the drill hole gave the salinity curve plotted in figure 16. As there shown, the top of salt water of approximate sea-water

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[37] Swartz, J. H., Resistivity studies of some salt water boundaries in the Hawaiian Islands: Trans. Am. Geophys. Union 18th Ann. Meeting, 1937, pp. 387-393.

[38] A clockwise rotation of the resistivity curve showing that a lower resistivity material has been encountered.

salinity lies, on the basis of the salinity curve, at a depth of 141 ± 1 feet below the top of the well casing or 134.4 ± 1 feet below sea level. This value is in close agreement with that of 135.2 ± 1 feet predicted from the resistivity measurements.[39]

CALCULATION OF THE HEIGHT OF THE WATER TABLE.—As stated in the discussion of the Ghyben-Herzberg principle (p. 77), for each foot the water table stands above sea level the depth to salt water below mean sea level will be about 40 feet.

In the Kahului Fairgrounds drill hole the depth to salt water obtained from the resistivity curve is 135.2 feet. Dividing this by 40 we get a value of 3.38 feet for the altitude of the basal water table above mean sea level. When the drill hole was put down the water table was found at 3.43 feet. Later measurements showed a tidal variation of about 0.18 feet with a mean height of approximately 3.34 feet. The close agreement between the calculated and observed values indicates the feasibility of determining by this method the elevation of the water table above sea level and the thickness of the fresh-water lens from the depth to salt water as given by the resistivity measurements.

RESULTS OF THE MEASUREMENTS

Resistivity measurements on Lanai were made at 23 stations, as shown in figure 1. Stations 1–9 and 11–17 lay along a traverse line crossing the island from Kaumalapau on the southwest to the mouth of Maunalei Gulch on the northeast. Station 18 is on the floor of Maunalei Gulch a short distance seaward of Maunalei shaft no. 1. Station 19 is at the Gay wells near Keomuku. Stations 20 and 21 are a short distance east of Maunalei shaft no. 1. Stations 10 and 22 are northwest of station 11 and test the extension of the high-level water found at station 11. Station 23 is in Palawai Basin, south of Lanai City. A summary of the resistivity results is given below:

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[39] While in this particular case the difference between predicted and observed results is less than one foot, it is not anticipated that resistivity determinations of the depth to salt water will in general be so close. There will always, of course, be a possible error equal to the depth interval used in the measurements, and it usually will not be economical to employ the one-foot interval here utilized. Furthermore, there will be occasional locations where denser rocks may occupy the position which would otherwise be held by the top of salt water of sea-water salinity, thus preventing the registration of the salt-water resistivity break until the resistivity measurements reach a greater depth at which porous rocks saturated with sea water are encountered. In addition, where the zone of mixture is considerably widened, either by pumping or other cause, the curve may at times become so rounded that it is difficult to determine the exact position of the salt-water break. With such factors in mind, it appears safe to expect, from the results here obtained, that except where conditions are definitely adverse, determinations of the depth to salt water of sea-water salinity may be made by resistivity measurements with satisfactory accuracy.

Depths to salt water and altitude of the water table as determined by the resistivity measurements

Station (fig. 1)	Altitude (feet)	Distance from coast (miles)	Coast from which measured	Depth reached (feet)	Depth to salt water as determined by resistivity measurements		Calculated altitude of the water table (feet)
					Below ground surface (feet)	Below sea level (feet)	
1 . . .	259.45	0.15	SW.	400	265	5	+ 0.1
2 . . .	454.10	0.55	SW.	700	510	56	+ 1.4
3 . . .	794.22	1.05	SW.	1,240	910	116	+ 2.9
4 . . .	1,183.87	1.85	SW.	1,800	1,310	126	+ 3.2
5 . . .	1,402.30	2.40	SW.	2,500	1,550	148	+ 3.7
6 . . .	1,537.80	2.80	SW.	2,800	1,705	167	+ 4.2
7 . . .	1,514.22	3.35	SW.	2,800	1,675	161	+ 4.0
8 . . .	1,522.25	3.60	SW.	2,800	1,725	203	+ 5.1
9 . . .	1,921.69	4.50	SW.	2,800	2,190	268	+ 6.7
10 . . .	1,867.57	4.25	SW.	3,250	2,080	212	+ 5.3
11 . . .	1,870.66	3.85	NE.	3,920	2,820	949	+23.7
12 . . .	1,587.21	3.05	NE.	3,920	1,725	138	+ 3.5
13 . . .	1,125.30	2.40	NE.	2,400	1,240	115	+ 2.9
14 . . .	610.22	1.40	NE.	2,200	670	60	+ 1.5
15 . . .	276.35	0.70	NE.	1,400	310	34	+ 0.9
16 . . .	20.71	0.20	NE.	1,000	48	27	+ 0.7
17 . . .	40.65	0.20	NE.	200	68	27	+ 0.7
18 . . .	113.03	1.15	NE.	2,000	150	37	+ 0.9
19 . . .	15.65	0.15	NE.	500	65	49	+ 1.2
20 . . .	808.29	1.65	NE.	2,600	a	a	a
21 . . .	666.57	1.35	NE.	1,520	790	123	+ 3.1
22 . . .	1,795.02	3.90	NE.	3,800	2,460	665	+16.6
23 . . .	1,106.19	3.75	S.	2,400	1,530	424	+10.6

[a] Depth to salt water masked by serious electrical disturbances caused by pipe lines near station center.

DEPTH OF ALLUVIUM IN MAUNALEI GULCH

Resistivity stations 16 and 18 in lower Maunalei Gulch permit an estimate of the thickness of the alluvium and of the depth to the floor of the valley.

Two types of resistivity criteria may be looked for in identifying the base of the alluvium and the top of the rock floor of the gulch in the resistivity curves: (*a*) The alluvium in general is more heterogeneous than the lava rocks underlying the valley floor. Hence the resistivity values for the two curves obtained at a single station are apt to be more irregular and divergent in the alluvium, and to tend to converge when the rock floor is reached. Also, since the alluvium is apt to vary lithologically in a lateral direction more rapidly than the lavas of the valley floor, the resistivity changes in the two curves at a single station may be expected to match somewhat better in the lavas below the valley floor than in the overlying alluvium. (*b*) In the Hawaiian Islands fluviatile alluvium is in general quite impermeable, much more so than the lava rocks which form the valley walls and floor. Since the alluvium must extend considerably below sea level in lower Maunalei Gulch, a drop in resistivity should be observed if the resistivity curve passes out of the relatively impermeable fluviatile alluvium into underlying porous lavas saturated with salt water.

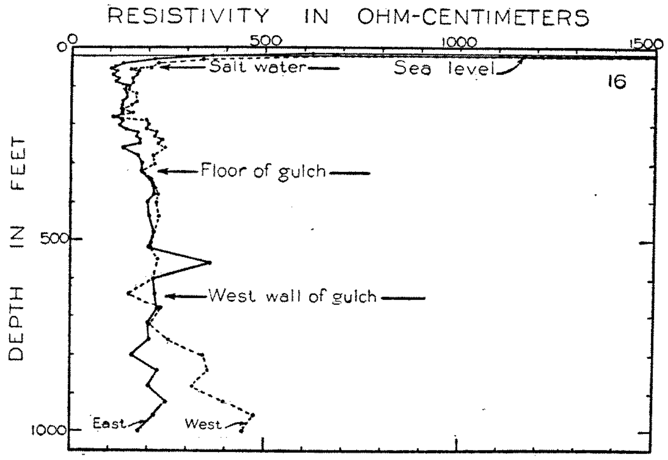

FIG. 17. Resistivity curves obtained at station 16 near mouth of Maunalei Gulch.

In figure 17 are shown the paired resistivity curves obtained at station 16 located in lower Maunalei Gulch, about 750 feet from the beach. The center lies a short distance east of the west wall of the gulch and is located on sand of apparently beach or dune origin. Surface resistivities are fairly high but drop within a few feet to extremely low values, around 500 ohm centimeters, suggesting that below a depth of about 27 feet the sand contains a considerable amount of salt water.

The two curves are divergent and irregular to a depth of 320 feet, where they converge and become rather closely congruent. The upper divergent portion of the curves undoubtedly begins in the alluvium. The lower convergent congruent portion is regarded as lying in the underlying lava rocks. The point of convergence, depth 320 feet, is therefore regarded as representing the valley floor, which thus lies 320 feet below the surface or 299 feet below sea level.

A marked divergence occurs between the two curves at a depth of 620 feet. This divergence is not a depth effect, but is a surface

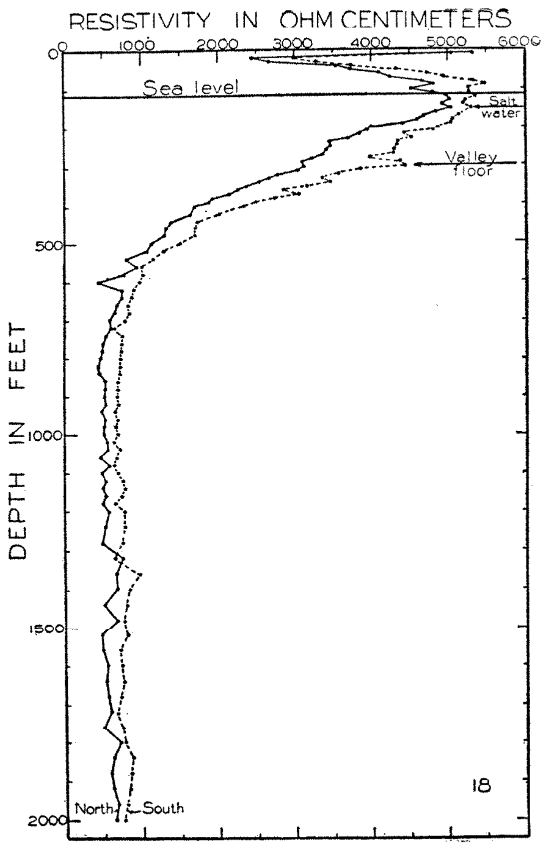

FIG. 18. **Resistivity curves obtained at station 18 a mile above mouth of Maunalei Gulch.**

effect caused by the movement of the west potential electrode off the thick alluvial fill of the valley onto the barely covered lava rocks forming the west wall of the gulch.

The resistivity curves of station 18 are shown in figure 18. These curves are very different in character from those of station 16, due to the much higher resistivities encountered. Station 16 is close to the sea and the curves are obviously much affected by the shallow depth to salt water. Station 18 is a mile farther inland and nearly a hundred feet higher in elevation.

Two marked resistivity downbreaks occur below sea level in the station 18 curves, an upper at a depth of 150 feet, and a lower at a depth of 300 feet. To harmonize with resistivity determinations at adjacent stations, the upper of these two must represent the salt-water break. The lower, that at a depth of 300 feet, must therefore be due to a stratigraphic change. It is most readily explained by the passage from less permeable alluvium above into more permeable lava rocks saturated with salt water below. The valley floor is hence placed at a depth of 300 feet below the surface or 187 feet below sea level.

These values give the old rock valley floor a slope of 113 feet to the mile between stations 16 and 18. This compares satisfactorily with the slope of 93 feet to the mile for the alluvial surface forming the present valley floor between these stations, the slightly greater slope of the old rock valley floor being in accord with the geological factors involved.

Assuming that the slope of 113 feet to the mile continues for some distance to the northeast, the valley floor would be 317 feet deep at the present shore line, 0.15 mile northeast of station 16. Since such a submergence of the old valley must have been accompanied by an inward migration of the shore line it follows that the old valley mouth now lies beneath the sea some distance off the present shore. Because there must be some drop in elevation along the old valley floor from a point beneath the present shore line to the old valley mouth now offshore the old shore line must now be at a depth greater than 317 feet below sea level. Hence the stand of the sea at the time Maunalei Gulch was originally eroded must have been somewhat lower than 317 feet below present sea level.

FORM OF THE WATER TABLE

SOUTHWEST SLOPE.—As shown in the table above, the basal water table beneath the southwestern slope of the island falls into two zones: a coastal zone with a steeper gradient, and an inland zone with a lower gradient. From the sea coast at Kaumalapau to station 3, a little over a mile inland, the water table rises 2.9 feet, an average gradient of 2.75 feet per mile. From station 3 to station 9, one mile north of Koele and almost at the crest of the island, it rises an additional 3.8 feet, an average gradient for this interval of only 1.1 feet per mile. The average gradient for the whole distance, from Kaumalapau to station 9, is 1.5 feet per mile.

NORTHEAST SLOPE.—Under the northeastern slope of the island the basal water table has a more nearly constant gradient. Between the sea coast at the mouth of Maunalei Gulch and station 12, a short distance east of the crest of the ridge, it rises to an elevation of 3.5 feet above mean sea level, an average gradient of 1.2 feet per mile, a value for the entire slope approximately equal to that of the inland zone of the southwest slope. The basal water table is thus lower, at corresponding distances from the sea coast, on the northeast than on the southwest slope of the island, and the average gradient for the slope as a whole is about 20 percent less for the northeast than for the southwest slope.

The measurements at station 21 indicate that the basal water table rises not only towards the southwest along the Keomuku-Koele road but also towards the south in the general direction of Lanaihale.

HIGH-LEVEL WATER.—The most important result of the survey was the discovery of the high-level water at stations 11 and 22, just northeast of the crest of the island along the Koele-Keomuku road. At station 11, as shown in figure 19, the basal fresh-water lens was found to be 973 feet thick, with a water-table elevation of 23.7 feet above mean sea level, a value nearly 400 percent higher than that for any other station along the Kaumalapau-Maunalei traverse.

To verify this result, station 22 was run at a point approximately one mile northwest of station 11 along a line parallel to the axis of the ridge forming the crest of the island. High-level water was found at this station also. As seen in figure 20, the salt water was encountered at this station at a depth of 2,460 feet below the surface

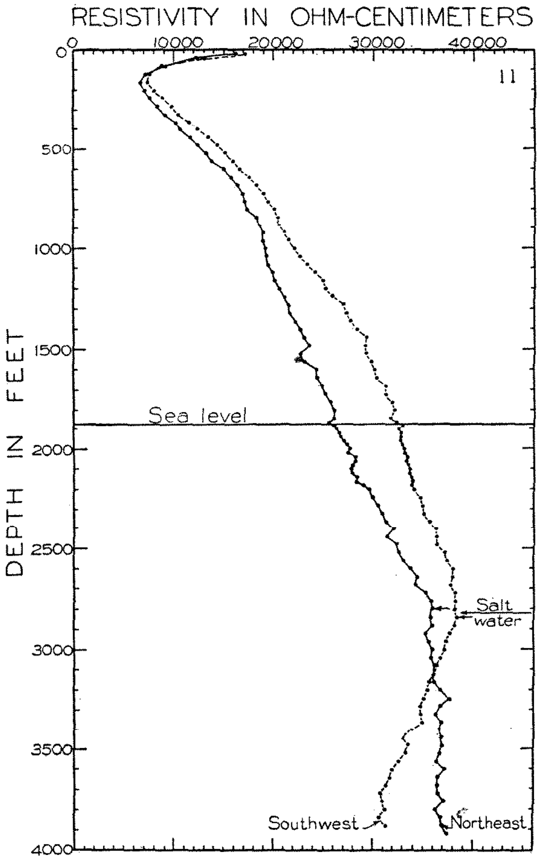

FIG. 19. Resistivity curves obtained at station 11 near crest of island along Koele-Keomuku Road.

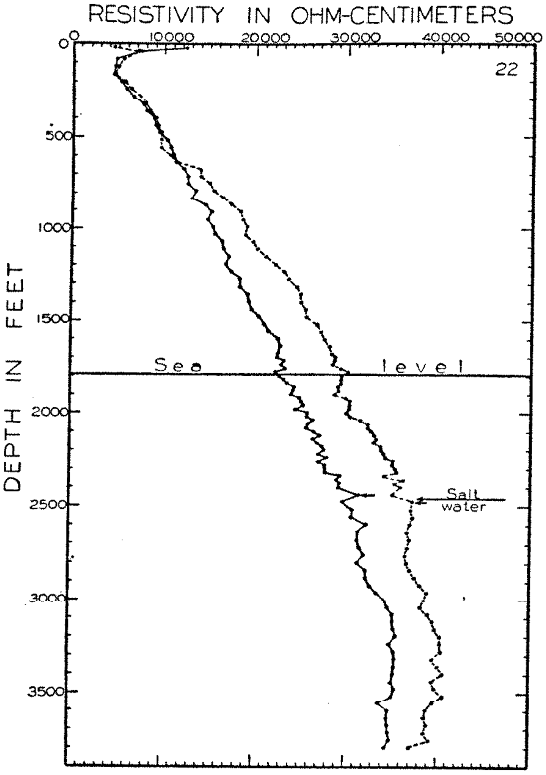

Fig. 20. Resistivity curves obtained at station 22 one mile northwest of station 11.

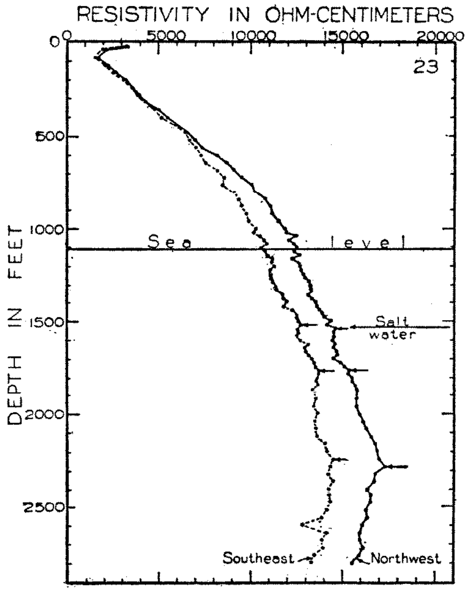

Fig. 21. Resistivity curves obtained at station 23 in Palawai Basin.

of the ground, or 665 feet below sea level, giving an elevation of 16.6 feet for the water table and a thickness of 682 feet for the basal fresh-water lens.

As was to be expected from its position to the northwest and therefore seaward of station 11, the water table, although definitely high-level in character and some 300 percent higher than that at the adjacent station 10, is lower than at station 11. Rough topography prevented a test of the high-level water to the southwest closer to Maunalei Gulch.

PALAWAI BASIN.—As shown in figure 1, a resistivity test was made in Palawai Basin at station 23 as nearly in the lowest portion of the basin as field pipe lines permitted. The resistivity curves there obtained are shown in figure 21.

In view of the caldera structure of this basin, a considerable stratigraphic complexity is to be expected in the rocks underlying this basin. It was not surprising, therefore, to find three important trend changes, all downbreaks in character, below sea level, at depths below the surface of 1,530, 1,770, and 2,260 feet respectively.

The break at 2,260 feet is the most marked downbreak, and is the first point at which the resistivity begins to decrease steadily in value. It is, therefore, definitely within the salt-water zone and could possibly represent the top of salt water. However, in view of the stratigraphic complexity of the rocks underlying a caldera, the probable presence of impervious rocks, the exceptional sharpness of the break, and the presence of two overlying resistivity downbreaks, it is regarded as much more likely that this break is purely stratigraphic in character, representing in all probability the depth at which the resistivity curve passes downward from an overlying less pervious series of lavas into underlying lavas of greatly increased porosity saturated with salt water.

The first major downbreak below sea level, that at depth 1,530 feet, is chosen as most probably representing the top of salt water. This break lies 424 feet below sea level and would correspond to a basal water table at an elevation of 10.6 feet above sea level.

It is recognized that the rocks underlying Palawai Basin are in all probability largely throat breccias and ponded lavas which may be quite impermeable. Hence, both this and the next lower break may be stratigraphic in character, representing changes in the lava sequence encountered, instead of a salt-water break. The water-table height of 10.6 feet here given is thus tentative in character. It represents the most probable value from the available resistivity and stratigraphic data.

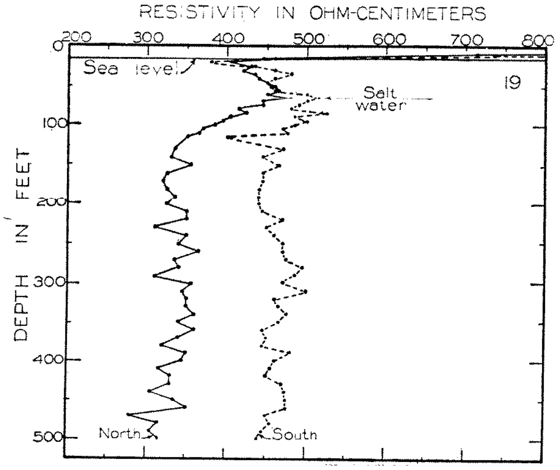

FIG. 22. Resistivity curves obtained at station 19 near Gay wells.

CORROBORATIVE EVIDENCE

GAY WELLS, KEOMUKU.—A resistivity test, station 19, was run at the Gay wells, Keomuku, on the northeast coast of the island where a measurement of the water table could be obtained (see fig. 1). The results of the measurements are shown in figure 22. While the curve is somewhat atypical in character, it shows a resistivity downbreak below sea level at a depth of 65 feet below the surface or 49 feet below sea level. If this is assumed to represent the top of salt water the corresponding calculated altitude of the water table is 1.23 feet.

A series of measurements of the altitude of the water table in the well nearby, made during the progress of the resistivity measurements, gave the following results:

Altitude of the water in the Gay well

Date	Time	Altitude of water (feet)	No. of readings
July 31, 1936	1:30 p.m.	+2.07	2
	2:30 p.m.	+2.09	2
	3:30 p.m.	+2.08	2
	4:30 p.m.	+2.06	3
August 1, 1936........	9:15 a.m.	+2.00	2
	11:20 a.m.	+2.04	2
	12:20 p.m.	+2.04	2
	1:25 p.m.	+2.09	3
	2:20 p.m.	+2.08	4
	3:45 p.m.	+2.09	6

These variations, small in value, are probably part tidal and part barometric in origin.

Depth 65 in figure 22 was measured at 2:45 p. m. on August 1, 1936, at which time, as seen in the table above, the water table stood 2.08 feet above sea level, a difference between calculated and observed values of 0.85 foot.

LOWER MAUNALEI SHAFT NO. 1.—A second test was afforded by the shaft no. 1. Excavation of this shaft was started only a day or two before the resistivity survey of the island was begun. A series of pipe lines at the shaft offered such serious electrical interference that it was impossible to make resistivity measurements at the shaft. However, it was found possible to make measurements at resistivity stations 14 and 21 located on opposite sides of the shaft and three quarters of a mile from it.

The resistivity curves obtained at these two stations are shown in figures 23 and 24. As there shown, the salt-water break at station 14 occurs at a depth of 670 feet below the surface, or 60 feet below sea level, indicating an altitude of 1.5 feet for the basal water table. At station 21 the salt-water break was found 790 feet below the surface or 123 feet below sea level, corresponding to a water-table elevation of 3.1 feet above sea level.

Interpolating, a value of 2.3 feet above sea level is obtained for the elevation of the water table in the shaft. The water table was reached by the shaft on September 1, 1936, at an elevation of 2.44 feet above sea level, in close agreement with the value of 2.3 feet later calculated from the resistivity measurements.

UPPER MAUNALEI SHAFT NO. 2.—The abrupt rise in the water table determined by the resistivity measurements between stations 9 and 11 suggested that the high-level water at stations 11 and 22 was confined by dikes which were acting as dams or retaining walls. Partial confirmation of this view was subsequently obtained by H. T. Stearns who found in the walls of Maunalei and Naio gulches a swarm of dikes that could form such a dike-walled reservoir.

Three possible sites were considered by Stearns for the new water-development shaft (p. 94). Palawai Basin was rejected because the resistivity data gave no evidence of high-level water there. The site selected by Stearns lay near the angle of upper Maunalei Gulch approximately along a line passing through resistivity stations 11 and 22 and about halfway between station 11 and lower Maunalei tunnel. (See fig. 1 and pl. 1.) It was chosen in the expectation that water at that site would be encountered at an elevation intermediate between the 23.7-foot elevation of the water table shown by the resis-

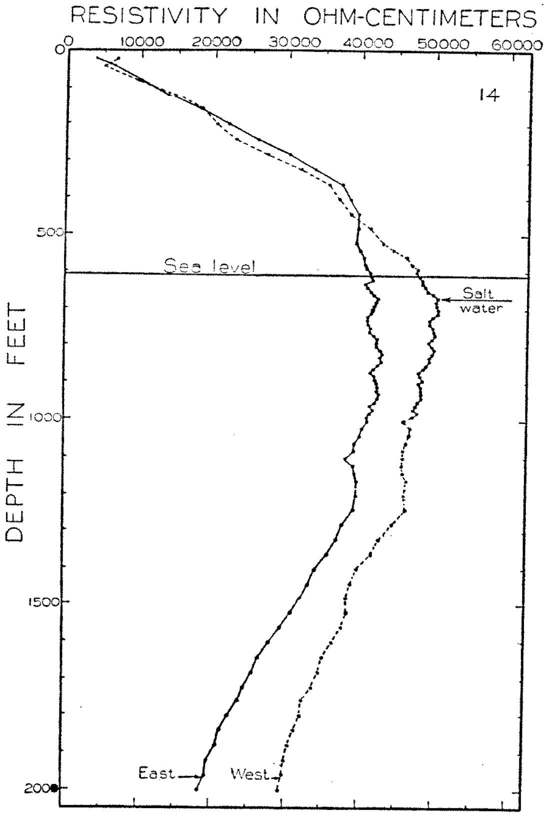

FIG. 23. Resistivity curves obtained at station 14 near lower Maunalei shaft no. 1.

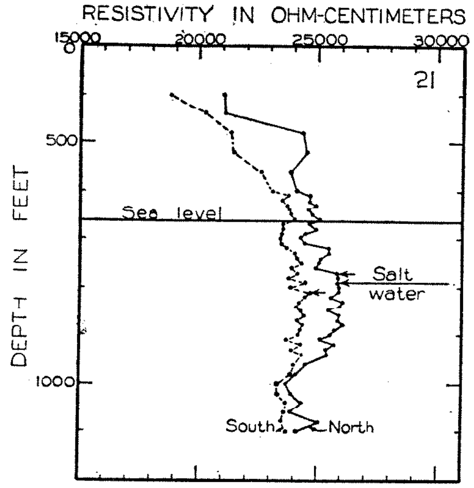

FIG. 24. Resistivity curves obtained at station 21 near lower Maunalei shaft no. 1.

tivity measurements at station 11 and the 1,103-foot elevation of the water in lower Maunalei tunnel. Water was found in shaft 2 at an altitude of 735 feet. (See p. 91.)

CONCLUSION

It has proved possible in the geophysical surveys on both the islands of Lanai and Maui to locate by resistivity measurements the top of salt water of approximate sea-water salinity and thus to determine the depth to salt water below sea level. From these data the elevations of the basal fresh-water table above sea level have been calculated on the basis of the Ghyben-Herzberg principle. Where subsequent tests have been made of such resistivity predictions in drill holes, wells, shafts, et cetera, both on Lanai and Maui, the observed depths to salt water and elevations of the basal fresh-water table have been in close agreement with the values obtained by the resistivity measurements.

It appears feasible to determine in suitable places the depths to salt water where not too deep, the altitude of the basal fresh-water table, and the thickness of the basal fresh-water lens in the Hawaiian Islands by means of resistivity measurements made with the Lee Partitioning Method. It is believed that this method will prove applicable to other areas where fresh water floats on salt water in permeable rocks.

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PART 2

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

PAGE 118

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

By Harold T. Stearns

ABSTRACT

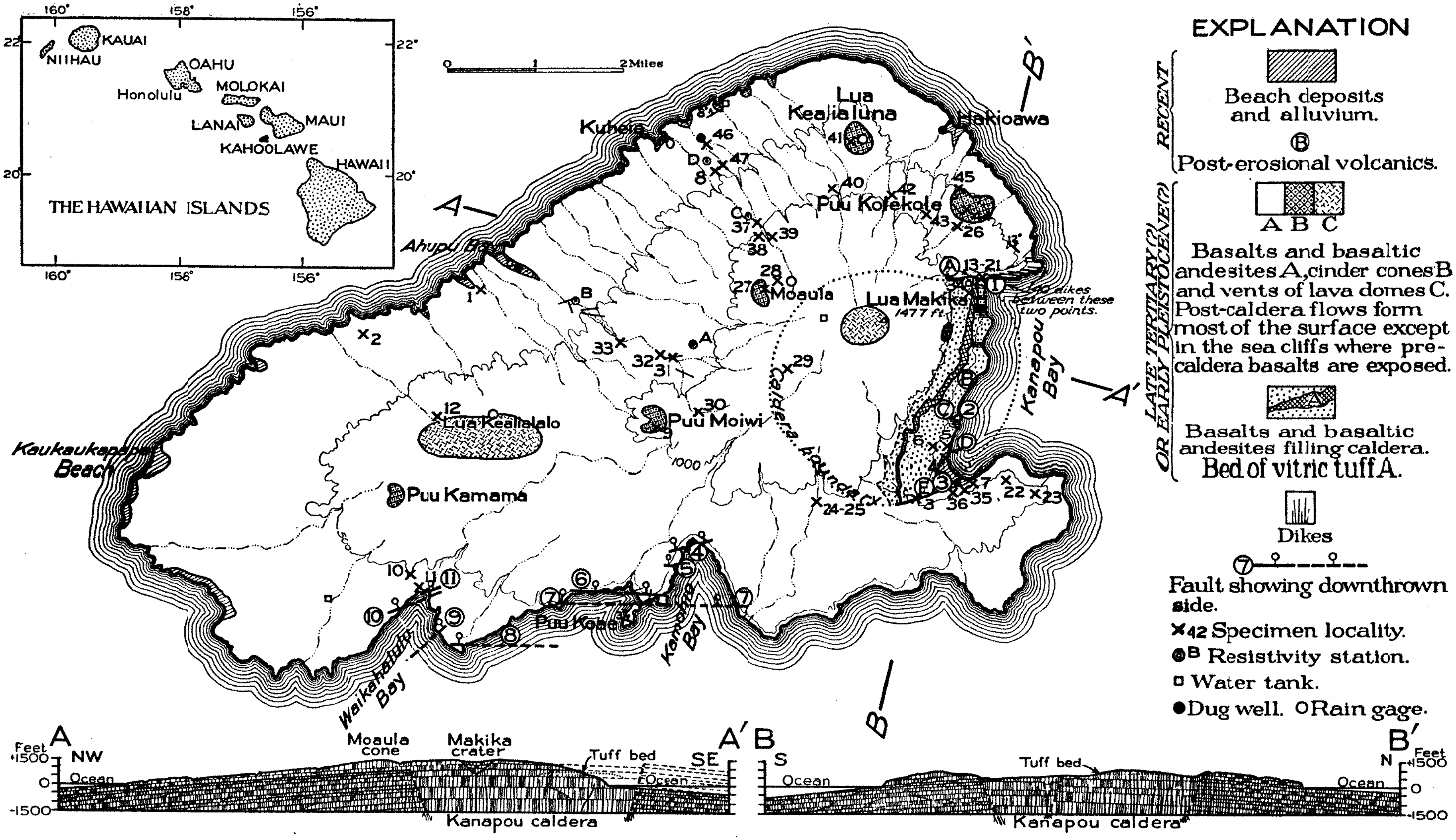
Kahoolawe Island is 11 miles long, 6 miles wide, 1,491 feet high, covers 45 square miles, and lies 94 miles southeast of Honolulu and 6¾ miles southwest of Maui. It is a shield-shaped extinct volcano composed chiefly of thin flows of primitive basalt poured in rapid succession from three rift zones and a vent at their intersection. At one stage the volcano was indented with a caldera about 3 miles across which was later completely filled. A graben led southwestward from it. The rocks are divided into Late Tertiary(?) or early Pleistocene(?) pre-caldera basalts, caldera-filling basalts and basaltic andesites, post-caldera basalts and andesites, and Recent post-erosional basalts. A few thin vitric tuff beds and cinder cones were found. Marine erosion has cut cliffs as high as 800 feet along the east and south shores and exposed a cross section of the caldera. Only shallow ephemeral gulches exist. The entire summit has been eroded to a hard-pan surface by the wind as a result of the vegetation being destroyed by livestock.

The island is semi-arid and well water is needed for stock. The stock is now supplied entirely from storage of rain and flood waters. During droughts water is hauled by boat from the island of Maui. All the wells dug so far yield water that is too brackish for stock except at the fairly inaccessible south side of Kanapou Bay. The resistivity survey indicates a water table 1.5 feet or less above sea level for 2.25 miles inland. A few sites for wells are recommended in the dike complex where small supplies of water suitable for stock might be found.

Petrographic studies by Gordon A. Macdonald indicate that the pre-caldera and caldera-filling lavas are largely normal olivine basalt of the type which forms the bulk of all Hawaiian volcanoes thus far investigated. It represents the undifferentiated magma of the Hawaiian petrographic province. Toward the close of the caldera-filling epoch the vent became less active, and magmatic differentiation produced basaltic andesites, which are interbedded with normal basalts. The post-caldera lavas are largely basaltic andesites and andesites. The much younger lavas, erupted after a period of extensive erosion, are olivine basalts similar in composition to the pre-caldera flows. The mineralogy of the Kahoolawe rocks is described in detail.

INTRODUCTION

Location and area.—Kahoolawe is the smallest of the eight inhabited islands of Hawaii. It is 11 miles long, 6 miles wide, 1,491 feet high, and has an area of 45 square miles. It lies 6¾ miles southwest of Maui at latitude 20° 35′ N. and longitude 156° 35′ W.



Geology by Harold T. Stearns, 1939

FIG. 25. Geologic map of Kahoolawe showing wells, rain gages, reservoirs, and resistivity stations.

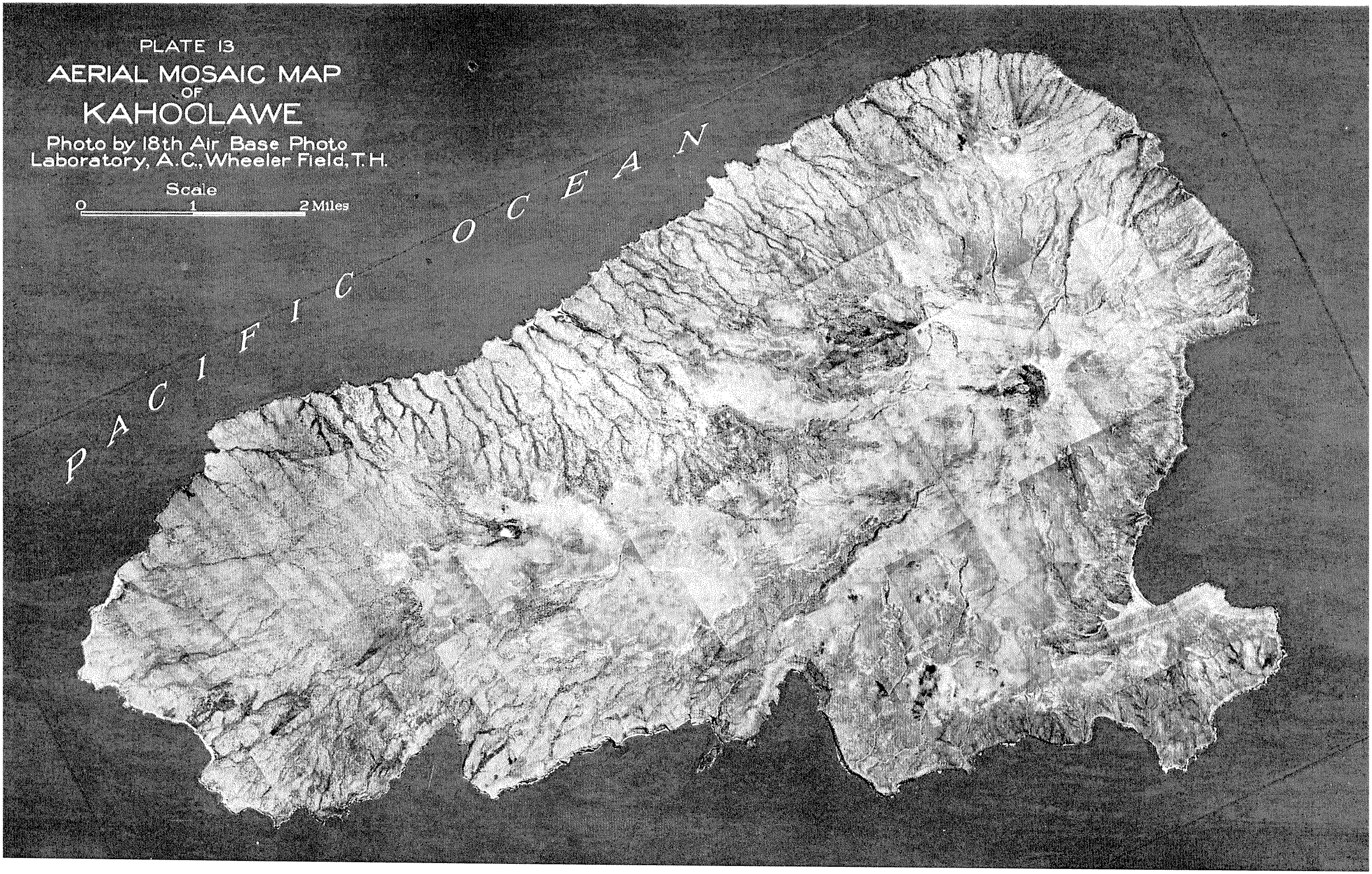
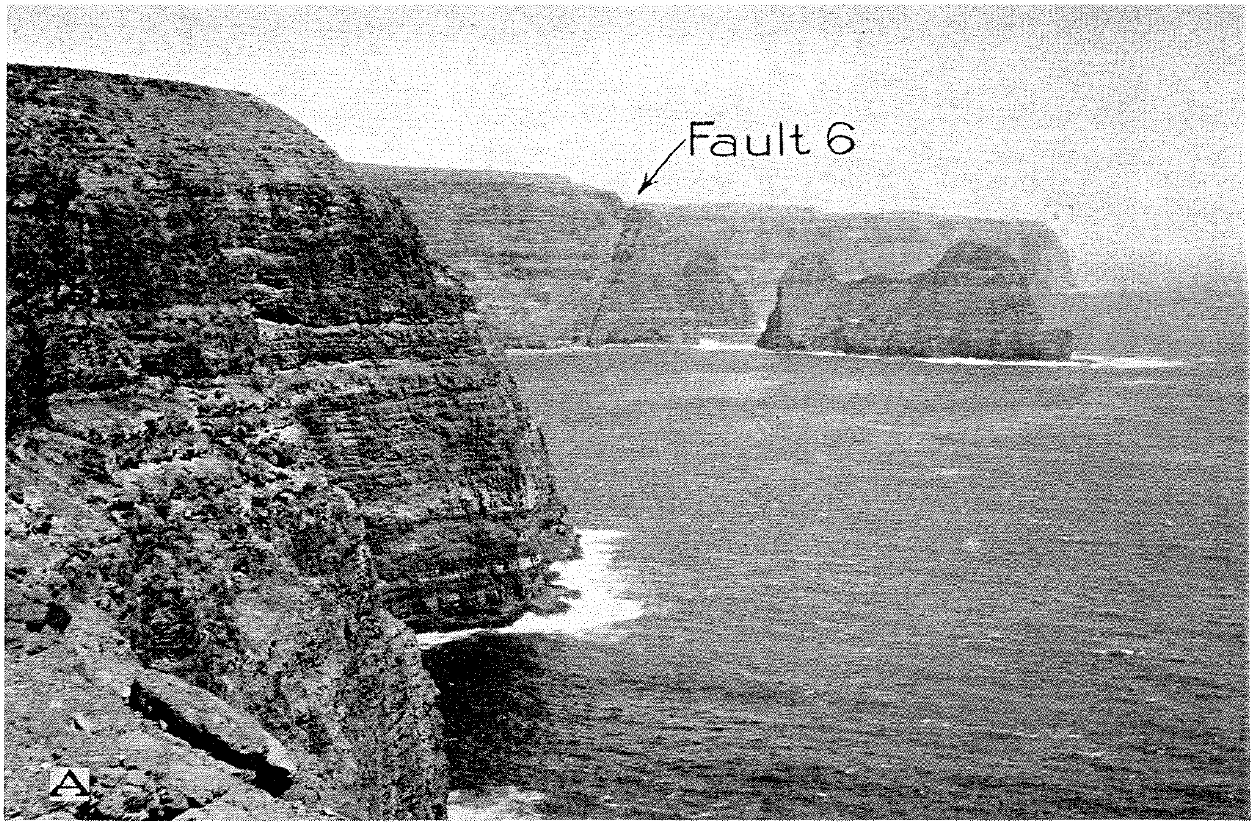
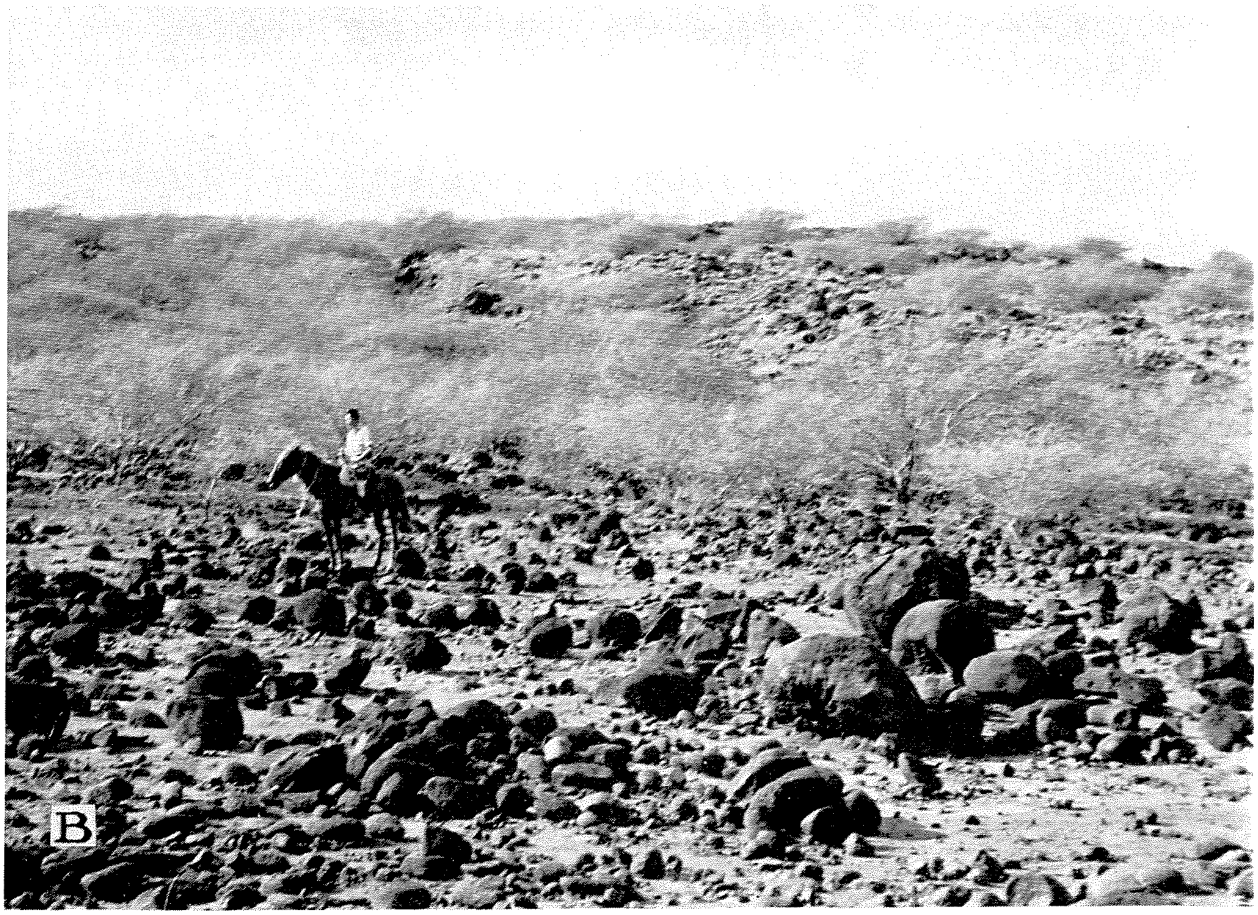


PLATE 13

AERIAL MOSAIC MAP
OF
KAHOOLAWE

Photo by 18th Air Base Photo
Laboratory, A.C., Wheeler Field, T.H.





Pl. 14. *A*, A wave-cut cliff 800 feet high, skirted by a shore platform, forms the south side of Kahoolawe. Fault 6 cuts all the pre-caldera thin-bedded basalts but does not displace the post-caldera lavas; *B*, Surface strewn with boulders 200 feet above sea level near Ahupu Gulch. It was swept bare of soil by a former high stand of the sea.

and 94 miles from Honolulu (fig. 25). The island is reached only by private boat. It is in the Makawao District, County of Maui.

SCOPE AND PURPOSE OF THE WORK.—The writer spent from March 5 to March 13, 1939, in field work on the island of Kahoolawe. Several routes across the island and practically the entire shore line were traversed on horseback. The cliffs on the south and north ends of Kanapou Bay were traversed on foot. The high cliffs bounding the east and south shores were examined from a boat. The purpose of the work was to map the geology, to study the ground-water resources, and to determine whether it is feasible to develop water by means of wells. It is obvious with the rainfall so small that only small supplies of water can be recovered.

An electric resistivity survey was made in December 1939 by G. R. MacCarthy of the Geological Survey, and field work was later done by G. A. Macdonald, also of the Geological Survey, in a study of the petrography of the rocks.

HISTORICAL SKETCH.—Kahoolawe was the place of embarkment in the legendary voyages of the early Hawaiians to Tahiti. The western point of Kahoolawe is still known as Kealaikahiki, or the route to Tahiti. The island figures only once in interisland warfare, when Kalaniopuu invaded it during Kahekili's rule and not finding much booty there steered for Lahaina. It was a place of exile from about 1830 until near the end of the nineteenth century. During these years some of the exiles would occasionally raid Maui for food and supplies.[40]

An investigation of the island for ranching purposes was made by W. F. Allen, and the following is quoted from his report dated March 31, 1851:

"In the center of the northern part is a mound which is the highest land on the island, about this the soil is very good being a sort of loam, here the Natives have some sugar cane growing; melons, potatoes and pumpkins grow well here."[41]

Allen stated that there were many wild goats, dogs, and pigs on the island. In this report no mention was made of bare areas devoid of vegetation such as exist at the present time, making it appear that the entire top of the island has been swept bare by the wind since 1851. However, in 1841 Dana had reported that, "the surface is barren and there is no fresh water, excepting a brackish pool . . ."[42] Although Dana did not visit the island he could see it from Maui.

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[40] McAllister, J. G., Archaeology of Kahoolawe: B. P. Bishop Mus. Bull. 115, p. 6, 1933.

[41] Manuscript rept., Public Archives, Honolulu.

[42] Dana, J. D., Geology, vol. 10, Wilkes expedition: p. 232, 1849.

On December 7, 1857, P. Nahaolelua, Governor of Maui, and Ioane Richardson made a report to King Lot Kamehameha after inspecting the island. The following is quoted from this report:

> There is no fresh water there but the old residents stated that during the rainy times fresh water may be found in small pools, but these waters did not last, when the sunny times came they soon dried up.
>
> There are not many places on this island where brackish water may be found. There is only one brackish water which is accessible seen by us, at Ahupu harbor, this brackish water being on the northwest of said island.
>
> And the old residents informed us, that there is another brackish water on the southeast (southwest) side of said island, it is in a bad place under the cliff at a place called Waikaalulu,[43] another brackish water is at the east side of said island, at Kanapou, the well where Kalaepuni was murdered.
>
> These are the only three places known where brackish water may be found on Kahoolawe.[44]

In this report as in Allen's report, no mention was made of areas devoid of vegetation.

In April 1858 Kahoolawe was leased by the King of Hawaii to Robert C. Wyllie, who, in partnership with Elisha H. Allen, moved several thousand sheep to the island. Kahoolawe was used for ranching until August 26, 1910, when it was set aside as a forest reserve because most of the vegetation had been destroyed by overgrazing. Because of the lack of Territorial funds to reclaim the island from the sheep and goats that overran it, the island was leased in 1918 to the Kahoolawe Ranch Co., which has made great progress in reclaiming it.

According to available records, the island had from 25 to 80 inhabitants between 1823 and 1858 and now it has only one.

ACKNOWLEDGMENTS.—The writer is indebted to Harry Baldwin for transportation to and from Kahoolawe and for other help in conducting the field work, and to Manuel Pedro, the only resident, and to Jack Aina, the guide, who were helpful in many ways and who furnished valuable information regarding the history and water supplies of the island. The writer is indebted also to James Y. Nitta, who assisted in the survey and who, with Harry Täuber, prepared the illustrations for this report. He is indebted to Otto Degener for identifying the plants found on the island.

PREVIOUS INVESTIGATIONS.—No mention of Kahoolawe has been found in the geologic literature except a description of a few rocks from Kuheia Bay by Powers[45] and a statement by Wentworth[46] that the width of the mouths of the gulches suggests submergence.

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[43] Waikahalulu in fig. 25.

[44] Manuscript rept., Public Archives, Honolulu.

[45] Powers, Sidney, Notes on Hawaiian petrology: Am. Jour. Sci., 4th ser., vol. 50, p. 26, 1920.

[46] Wentworth, C. K., The geology of Lanai: B. P. Bishop Mus. Bull. 24, p. 22, 1925.

GEOGRAPHY

Drainage and relief.—The slopes of the island are corrugated with gulches 50 to 200 feet deep, but only during a few days each year do they contain streams. The drainage pattern radiates from Lua Makika, the highest point on the island (pl. 13). The summit area shown in figure 26 as the "dust bowl" is practically undissected and consists of a table land sloping gently seaward in all directions. The north and northwest slope is the roughest terrane because of the close spacing of steep-sided gulches. The island as seen from a distance is a flat dome with a smooth profile interrupted by a single hill, Moaula. Two undrained crater depressions, less than 50 feet deep, indent the Makika and Kealialalo cones. Five hills that are ancient cinder cones, rise from 50 to 250 feet above the slopes of the domes. Spectacular sea cliffs up to 800 feet high form much of the east and south coasts of the island (pl. 14, *A*). Kanapou, Kamohio, and Waikahalulu bays lie in re-entrants in these high cliffs. The cliffed coast line is characterized by hanging valleys; the remaining coast line, by partly drowned valleys.

Climate.—Stiff trade winds blow over the island nearly every

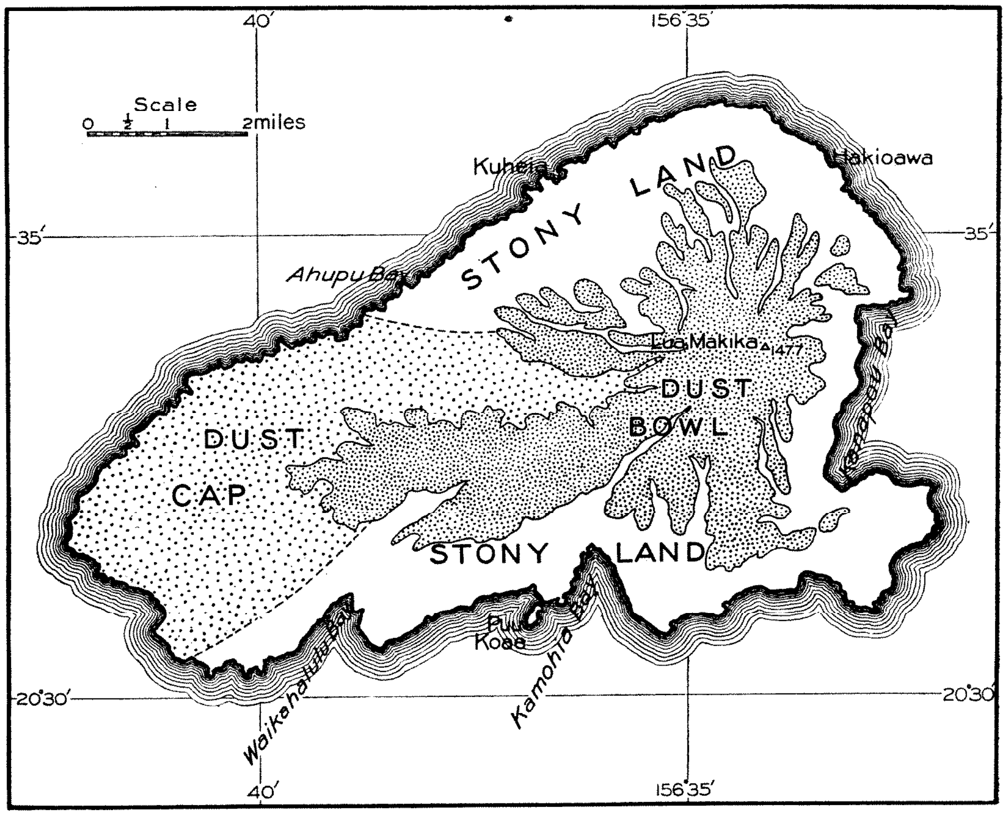

Fig. 26. Map of Kahoolawe showing the character of the surface.

day. They come from the east, however, rather than the northeast, because they are deflected by the bulky Haleakala Volcano, on Maui, which lies in their path.

The "dust bowl" (fig. 26) and the nearly universal wind-pruned form of the trees are mute testimonials to the constant strong east winds. Kahoolawe is probably the windiest island in Hawaii.

Rainfall is recorded at four gages on the island (fig. 25), but the records have not been preserved. According to Manuel Pedro, the maximum rainfall at any gage was 23 inches in 1936, 27.5 inches in 1937, and 24.5 inches in 1938. These figures are only approximate, as the amount of rain in the gage is estimated rather than measured. The gages are visited shortly after substantial rains but not after light showers. Mr. Pedro states that the annual rainfall is almost the same at all stations regardless of the altitude. This may in part be due to the fact that most heavy rains are kona storms which are general. "Naulu" showers occur also.

Most of the rain falls during months of kona or south winds from November to April, but during some years the rainfall is fairly well distributed. Since 1919 the highest observed fall during a single storm was about 4 inches. The lowest annual rainfall since 1919 probably occurred in 1926 and was about 18 inches; the highest occurred in 1937 and was about 27 inches. Kahoolawe is too low to cause the winds to lose much of their moisture; hence its semiarid climate.

VEGETATION AND ANIMAL LIFE.—Prior to the bringing of goats to Hawaii in 1788 by Captain Cook,[47] the island was probably covered with grass, bushes, and scattered trees. The goats ate practically all this vegetation. Of the native trees and shrubs only about 80 wiliwili trees (*Erythrina sandwicensis*) have survived, and less than a half dozen of these are large enough to be called trees. The stump of a native hardwood tree, probably planted by a Hawaiian, remains at an abandoned house site on the cliff bordering Kanapou Bay. At another house site, a ti plant (*Cordyline terminalis*) still struggles against drought and wind, and on the southwest end of the island a single bush of sandalwood (*Santalum ellipticum*?) grows.

Following the destruction of the vegetation the wind blew away the upper 2 to 8 feet of red soil from the entire summit and left nearly 15 square miles of land stripped down in most places to a buff to reddish-tan hardpan consisting of partly decomposed basalt.

With the killing of the goats and most of the sheep in 1918, the

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[47] Thrum's Ann. for 1909, p. 128, Honolulu.

grasses have begun to cover the lower slopes, but they have made no progress on the hardpan surfaces. Australian salt bush (*Atriplex senibaccata*)[48] introduced on Kahoolawe about 1918 has established itself on a considerable part of the wind-swept areas where it is hard to believe that any plant could survive. Particles of rock and soil catch in the plant, partly burying it, but undaunted it pushes up new shoots and slowly but surely spreads over the polished uninviting surface. These plants generally cover about a square foot of area and anchor a dust pile 4 to 10 inches high. Large tracts have been nearly recovered by the salt bush in Makika crater and north of Moaula hill. The former smooth slick surface is now studded with these piles of earth resembling hundreds of stream-lined ant hills. Molasses grass (*Melinsis minutiflora*) introduced about 1934 is beginning to spread also on the bare areas. Kiawe (*Prosopis chilensis*) introduced about 1900 has now spread over all the lower slopes and forms veritable forests on the north and northwest sides. It is slowly invading the summit dust bowl. Only a single dwarfed guava plant (*Psidium guajava*) growing along the main trail to the summit is known on the island. Ironwoods (*Casuarina equisetifolia*) do well in spite of the wind, as shown by the few growing in an experimental plot. A row of planted eucalyptus trees has reached a height of 15 feet, but their tops are wind-killed. Sisal (probably *Agave sisalana*) and cactus (*Opuntia megacantha* and *Nopalea cochenillifera*) were introduced and grow well, but livestock have prevented their spread. Haole koa (*Leucaena glauca*) grows well in gulches where cattle cannot reach it. Lantana (*Lantana camara* var. *aculeata*) grows sparingly. The most prevalent woody plant besides kiawe is tree tobacco (*Nicotiana glauca*). Forbes[49] described 31 ferns and flowering plants occurring on the island in 1913.

Two plots that have been fenced for 5 years have grass and haole koa knee-high in them with all the bare surfaces covered, indicating that much of the island could be reclaimed by vegetation if the livestock were removed.

Mr. Pedro reports that about 500 cattle, 200 wild sheep, 25 wild goats, 17 horses, 3 mules, and 500 wild turkeys live on the island. Rats, mice, and cats (domestic variety gone wild) are plentiful. The common birds include mynahs, doves, sparrows, plover, linnets, and California quail. Mongolian and silver pheasants are reported also.

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[48] Degener, Otto, Flora Hawaiiensis: family 111, Honolulu, 1932.

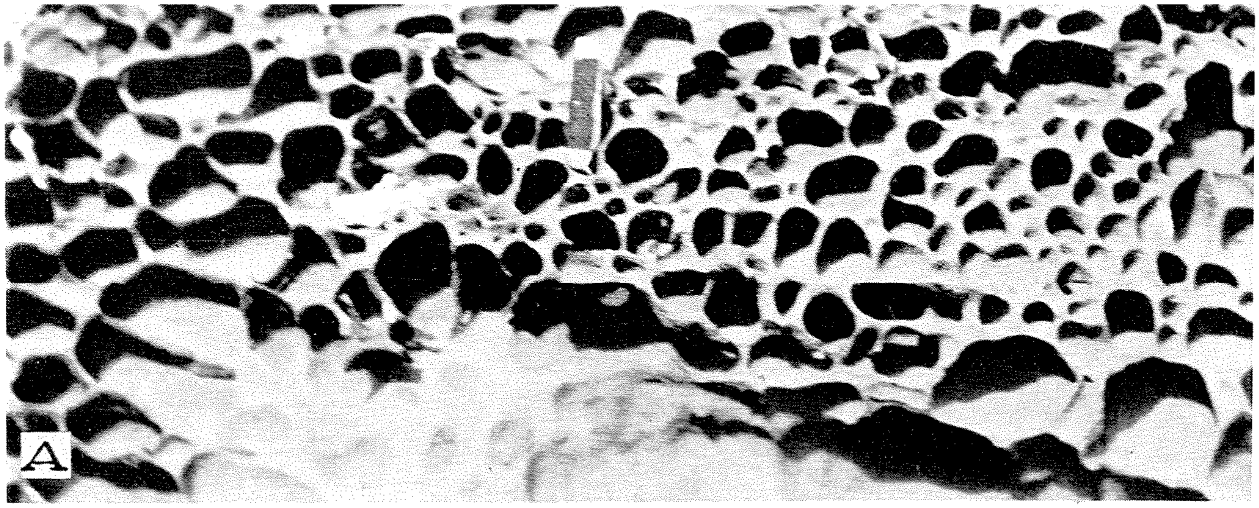
[49] Forbes, C. N., Notes on the flora of Kahoolawe and Molokini: B. P. Bishop Mus. Occasional Papers, vol. 5, no. 3, pp. 1-15, 1913.

GEOMORPHIC FORMS

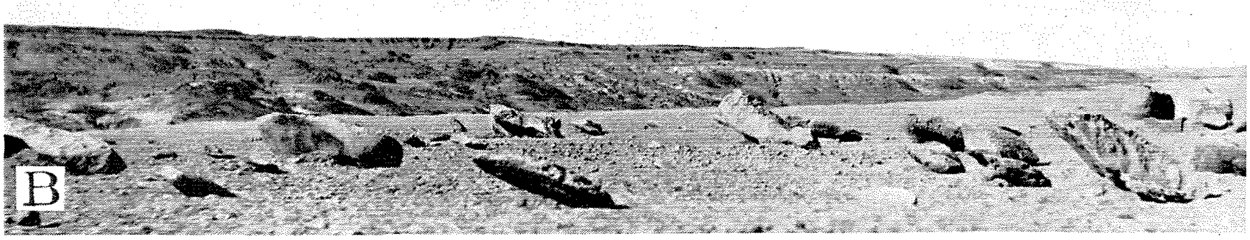
EFFECTS OF WIND EROSION.—The constant strong trade winds blowing across Kahoolawe have caused bizarre and widespread destruction of soil following the introduction of animals and overgrazing. Prior to this time, there was a rocky marginal belt reaching from sea level to an altitude of about 850 feet supporting grass and a few shrubs that had been swept free of soil by erosion, chiefly by the sea, during a former period of submergence (fig. 26). It was covered with residual boulders and lag gravel (pl. 14, *B*), which in low swales form "rock glaciers." Above this area was the flatter top of the island heavily capped with red soil, supporting a thick stand of grass and a few stunted trees and shrubs. Practically all this area, by 1918, had been swept free of soil to hardpan, a surface so hard that the shod hoofs of horses barely mark it. This is the area labelled "dust bowl" in figure 26. Most of the dust bowl is free of rocks, but those that lie on the surface are commonly stream-lined and lie with their light ends pointing upward and to the leeward and their broad heavy ends partly sunk below the land and pointing to the windward (pl. 15, *B*). The rocks reach this position by a series of moves. At first they lie buried, residual remnants of a decomposed lava bed. Gradually the matrix is blown away, leaving them on pedestals of softer material. All this while they are exposed to a sand blast. The wind removes the pedestal and the rock topples with its heavy end down. The rock then sets up eddies which scour at the windward side, sinking it deeper. Meanwhile sand is deposited under the sheltered, leeward side as the rock tilts. Probably the rock rotates slightly during this process if the heavy end has not fallen exactly to the windward at first.

Parallel grooves up to 6 inches deep have been scoured in the hardpan by the wind in some places. Practically no polished rocks or wind-faceted pebbles occur, in spite of the intensity of the wind. This is probably due to the lack of strong abrasives. The partly decomposed basalt soon wears into dust as it moves before the wind.

A few dunes reaching 8 feet in height, composed of earthy particles, are found, but most of the material drifts far away as a red dust banner extending leeward from the island. The former rocky land lying to the leeward of the dust bowl is now covered with 6 inches to 1 foot of red loess. It lies like loosely drifted snow, and during heavy rains, great quantities of it are washed into the lowlands and the sea. Vegetation, especially the kiawe tree, has spread over this area and would soon reclaim it into a soil-covered land,



Pl. 15*A*. Fretwork weathering is present on some basalt boulders along the shore.

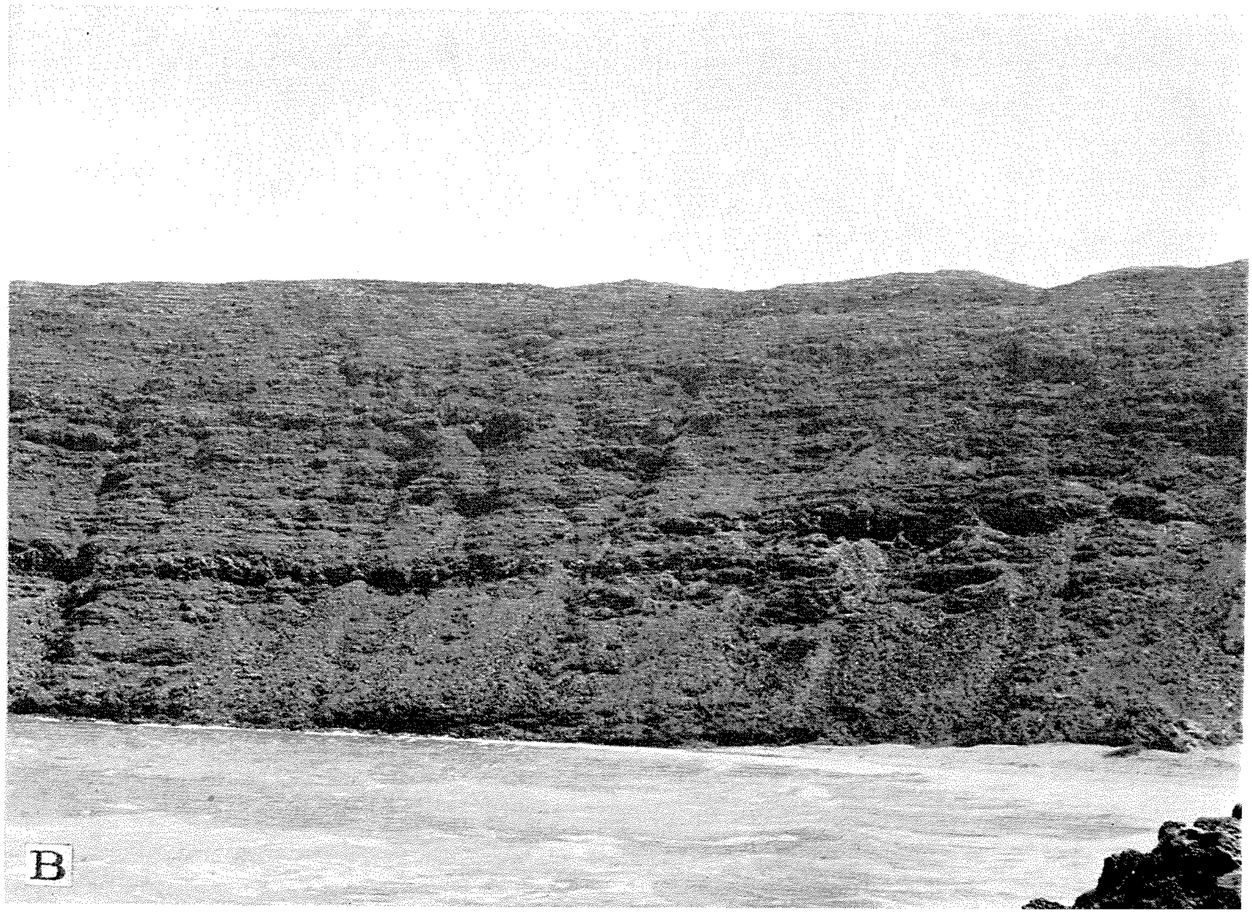


Pl. 15*B*. Residual boulders pointing leeward in the "dust bowl."

Pl. 15*C*. Badland topography produced by water on the northeast side of Puu Kealialuna.

PL. 16*A*. Massive horizontal caldera-filling lavas in Kanapou Bay.

PL. 16*B*. Thin-bedded pre-caldera basalt flows south side of Kanapou Bay.



nearly equal in acreage to the area being destroyed on top. However, many cattle graze there, cropping the weeds and grasses, and their hoofs cut deep gashes in the red dust, causing it to be more susceptible to erosion. It is likely that if cattle were kept off this area for 5 to 10 years, it would be reclaimed and become the most valuable grazing land on the island. It is noteworthy that the rocks are completely covered close to low kiawe trees and replaced by a smooth soil surface supporting grass because the thorny branches prevent the cattle from treading or grazing close to the tree.

At the west end of the island the bays have shores of calcareous sands or lithified beach sand. Inland from them are small areas of calcareous dunes. Similar dunes were seen at the south end of Kanapou Bay. Sand from the shore of the bay has been blown to the top of the adjacent 800-foot cliff.

Over emphasis must not be laid upon the destruction by wind alone on Kahoolawe. The bare surface and loose dust are everywhere the easy prey of running water (pl. 15, *C*). A few times a year heavy rains beat down on Kahoolawe and wash into the sea immense quantities of red soil which has taken centuries to form.

Effects of cones on stream erosion.—The cone of Kealialuna deflects several streams to the north and south of it. This concentration of drainage into two major valleys has caused much larger canyons than the adjacent ones. In time, especially in rainy areas, such streams erode deep canyons that in size are all out of proportion to their neighbors. An unusually wide pie-shaped cone remnant between the mouths of such streams generally indicates the history even after all vestiges of the cone have been eroded away. The four chief stages in the development of such a stream pattern are shown diagrammatically in figure 27. *A* represents a volcanic dome with normal radial drainage, *B,* the secondary cone deflecting the drainage, *C,* an early stage in the formation of amphitheater-headed valleys with those next to the cone eroded farther inland because of greater drainage area, and *D,* the cone eroded away and only an unusually wide pie-shaped remnant of the dome surface and the sharp angles in the streams to indicate the former presence of the cone.

The sea cliff is lower between the two master streams in this figure because the cone erupted after a sea cliff had been cut in the dome. If the cone had erupted before the streams had started on the dome or the sea cliff had formed, the history would be the same

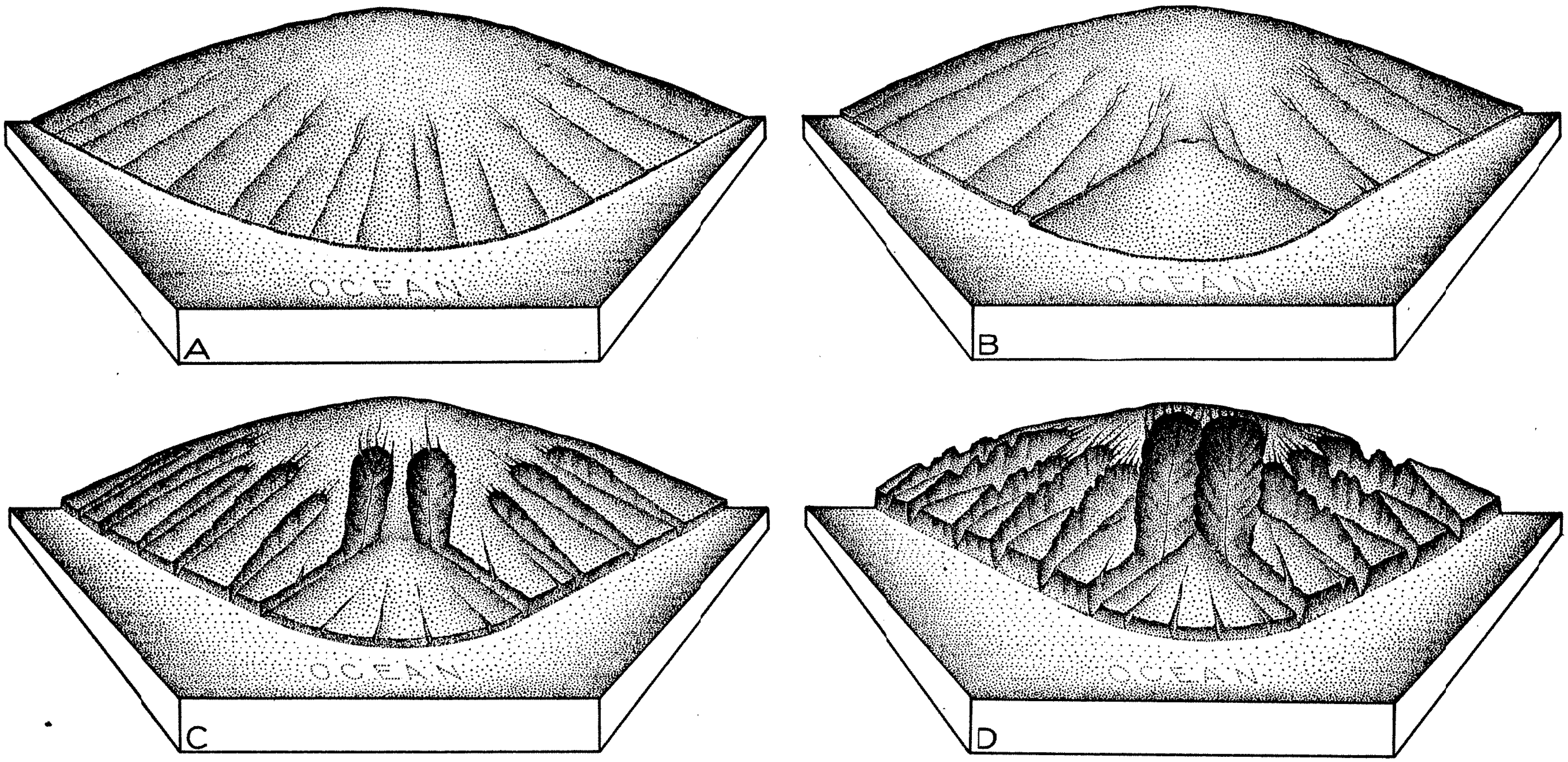


FIG. 27. Diagram showing effect of a late cone on stream erosion. Dome with radial streams, **A**; secondary cone displacing drainage, **B**; two major valleys resulting from concentration of drainage into two streams, **C**; very wide pie-shaped remnant of dome indicating former cone, **D**.

except that the sea cliff would be the same height along the entire coast.

FRETWORK WEATHERING.—Many basaltic boulders along the coast are covered by fretwork (pl. 15, *A*). This type of weathering must be caused by the alternate wetting and drying in the spray and splash zone, for it does not occur on rocks beyond this zone. Bartrum reached the same conclusion for similarly honeycombed rocks along the New Zealand coast.[50] How much of it is mechanical and how much is chemical is not known, but it is probable that both processes operate and the relative effectiveness of one in comparison with the other may depend upon such factors as the composition and texture of the rock. The depressions commonly contain salt. The bottoms of most of the pits slope gently downward and outward. The walls are generally rough and covered with slightly loose crystal grains as though some of the rock had been dissolved, leaving the rest to fall apart by mechanical weathering. Alteration penetrates about one quarter of an inch.

The surface of rocks riddled by sea boring organisms may resemble fretwork weathering, but such rocks are found within tidal range.

SHORE PLATFORM.—Many stretches of the shore are platforms reaching 50 feet in width and extending up to 5 feet above sea level (pl. 14, *A*). Some appear to be relic benches of the 5-foot stand of the sea and others the work of the present sea.[51]

WATER SUPPLIES

The location of the storage tanks, reservoirs, wells, and rain gages on the island is shown in figure 25. At Kuheia storage consists of four 20,000-gallon wooden tanks supplied by flood waters through a flume from Kuheia Gulch, and two small cisterns that catch water from the roofs. At Papakanui beach, half a mile northeast of Kuheia, are two 10,000-gallon wooden tanks which are supplied with water brought in a boat from Maui. These are used only when other supplies are exhausted. In Ahupunui Gulch near the beach there is a 600,000-gallon masonry cistern supplied by a diversion ditch from the gulch when in flood, and in Wiliwilipeapea Gulch, at an altitude of 300 feet, on the southwest side of the island, there is a similar 400,000-gallon cistern, supplied in the same way. On the east slope of Makika cone, at an altitude of 1,450 feet, is a

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[50] Bartrum, J. A., Honeycomb weathering of rocks near the shore-line: New Zealand Jour. Sci. Technology, vol. 18, no. 7, pp. 593-600, 1936.

[51] Stearns, H. T., Shore benches on the island of Oahu, Hawaii: Geol. Soc. America Bull., vol. 46, pp. 1467-1482, 1935; Shore benches of North Pacific islands (in press).

10,000-gallon wooden tank supplied by a rain shed. The tanks supplied by flood waters rapidly fill up with silt owing to the bare areas at their headwaters.

Water a few feet deep stands for part of the year in the craters of Kealialalo and Kealialuna. The latter has a dam a few feet high at the outlet of the depression. Both will hold water for six months or more, according to the frequency of the rains. At one time it was planned to build collection ditches and store additional water in Kealialalo, but the plan was abandoned because the depression would have filled too rapidly with silt.

Seven dug wells once existed on the island, but five of them are now filled (fig. 25). They were all dug in alluvium at the mouths of gulches. The records follow:

Valley	Dug by	Depth (ft.)	Diameter (ft.)	Depth to water (ft.)	Curbing	Remarks
Ahupu[a]	Kynnersley Bros.	33	10	30	None	Remains of troughs still exist.
Do.	Hawaiians	......	......	......	....	Filled up.
Ahupuiki	do.	......	......	......	....	Do.
Kaulana	Von Tempsky	60	6	Dry	Masonry	Formerly equipped with a pump.
Hakioawa	Kynnersley Bros.	18	8	15	..do....	Windmill and troughs in disrepair.
Do.	Hawaiians	......	......	......	....	Filled up.
Kanapou[b]	do.	......	......	......	....	Do.

[a] Mr. J. H. Foss reports that levels indicate that the water in this well stands slightly below low low tide.

[b] Mr. J. H. Foss reports that a test hole was dug 9 feet deep 500 feet from the beach on December 27, 1939, and water was found to stand 0.3 foot above low tide and to contain 26 grains of salt per gallon (270 p.p.m.).

The water of the Ahupu well contained 312 grains of salt per gallon (3,250 p.p.m.) on March 6, 1939, and the water of the Hakioawa well contained 1,210 grains (12,600 p.p.m.) on March 11, 1939, as determined by the writer.

The old Hawaiian wells were located next to the walls of the gulches, where they tapped water from the basalt rather than from the alluvium. The alluvium extends only a short distance up the gulches and narrows, and therefore it has little opportunity for recharge. Moreover, the alluvium consists of boulders imbedded in fine silt that has a low permeability. Water moves more freely from far inland through the basalt, and hence the Hawaiian wells were better located than those sunk more recently by white men.

It would be interesting to determine whether these old wells, if re-excavated, would yield potable water.

The equipment found and reports of visitors to the island seem to indicate that the wells in Ahupu and Hakioawa gulches yielded water suitable for stock until about 1900. E. P. Low states[52] that when he leased the island on December 28, 1906, these wells yielded potable water for stock except during dry months. Angus McPhee reports[53] that he drank potable water from the Ahupu well about 1917. It appears that about 50 Hawaiians obtained drinking water from wells in these gulches during historic time, and that the Kynnersleys likewise pumped water for stock from the wells they dug in the same gulches while they leased the island. Thus, there has been apparently a progressive decrease in the quantity of ground water in the gulches, until by 1919 no water potable for stock remained. Although rainfall records are not available, there is ample evidence from gages on all the other islands, that the rainfall has been abundant everywhere in the Territory from 1937 to 1939, and that there was no progressive dessication prior to 1919. Some cause other than a change in precipitation, therefore, seems to have caused the water from these wells to become salty. The spread of the kiawe tree is coincident with the decrease in the fresh ground-water supply. It may be that they consume by transpiration much of the rain water that formerly percolated to the zone of saturation and supplied these wells. Thick stands of these trees cover the gulch floors and doubtless rob the zone of saturation of most of the fresh water that reaches the water table in the vicinity of the wells. These trees are now green throughout the year by subirrigation. It appears, therefore, that the kiawe tree is not always beneficial for improving water supplies, even though it may be very valuable, as on Kahoolawe, to prevent soil erosion.

Two seeps were found in the cliff at Kanapou Bay on March 7, 1939. One of these seeps, yielding only about a quarter of a pint per minute, was observed just above a dike, at an altitude of about 230 feet, in the gulch north of eruption B, shown in figure 25. The other seep yielding about half a pint per minute, was issuing from the plunge pool 20 feet inland from the dike at eruption E.

ELECTRIC RESISTIVITY SURVEY AND METHODS FOR DEVELOPING WATER

G. R. MacCarthy occupied four resistivity stations on Kahoolawe between November 30 and December 13, 1939 (fig. 25). The data

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[52] Oral communication, Apr. 6, 1939.
[53] Oral report, 1937.

obtained at these four stations are given in the following table. The computed altitudes of the water table shown in the last column are based on the Ghyben-Herzberg principle, with the assumption that at any given point the depth to salt water below sea level is 40 times the height of the water table above sea level.

Station	Altitude (ft. above sea level)	Approximate depth to salt water (ft.)	Computed altitude of water table (ft. above sea level)[a]
A	858.4	900	1.0
B	350.8	370	0.5
C	870.1	930	1.5
D	302.4	320	0.5

[a] There may be an error of 0.25 foot caused by the depth interval that was used.

The exact quality of the water near sea level at these stations is not known, but is probably also fairly high in salt. A dug well of the Maui-type would probably encounter water sufficiently low in salt for stock at stations *A* and *C*. If a drilled well is tried, it should be sunk as far inland as possible and should not extend more than about 10 feet below the water table.

GEOLOGY

GENERAL CHARACTER AND AGE OF THE ROCKS

Kahoolawe is built chiefly of thin-bedded primitive, or Kilauean-type, aa and pahoehoe basalt flows poured out rapidly from a shield- or dome-shaped volcano. No soils and only a few thin pumiceous or vitric tuff beds were found interstratified with the lava flows. These are close to the source cones and mostly between the later flows. A few cinder cones are associated with the closing eruptive phase. The earlier lavas issued quietly or with only small firefountains.

The age of the rocks is uncertain, but to judge from the presence of 30 to 50 feet of soil and partly decomposed rock, it is probable that the volcano ceased activity during late Tertiary or early Pleistocene time. On the basis of the depth of weathering, the island appears to be about the same age as that of Lanai. Evidence of marine erosion extends to an altitude of at least 800 feet, and it is probable that this erosion took place in middle or early Pleistocene time.

Small patches of Recent cinders and lava lie unconformably on the sea cliff bordering Kanapou Bay. Small amounts of unconsolidated earthy sediments and beach sand are found at the mouths of the larger gulches, but no emerged marine limestone was found. The larger gulches are floored with unconsolidated and partly compacted bouldery alluvium for a distance of half a mile or less from the sea (fig. 25).

The alluvium is only slightly permeable, but the basalts transmit water freely through joints, caverns, interstitial spaces between clinkers, and the openings between the successive beds.

STRUCTURE

FAULTS IN KANAPOU BAY

The separation of the lavas into two series is based entirely upon two faults, hence it is essential that the faults be described first. They bound the north and south sides of Kanapou Bay.

Fault 1 (fig. 25) is well exposed on the north end of the bay. The lavas on the north side dip 12° NE. and are strikingly different petrologically from those on the south side, which are horizontal and massive (fig. 28). The fault may be traced from sea level to 800 feet above sea level. It strikes northwestward in the face of the cliff but veers to the west at the top. The dip ranges from 40° SW. to 90°. More than 30 dikes are terminated by it, but one dike fol-

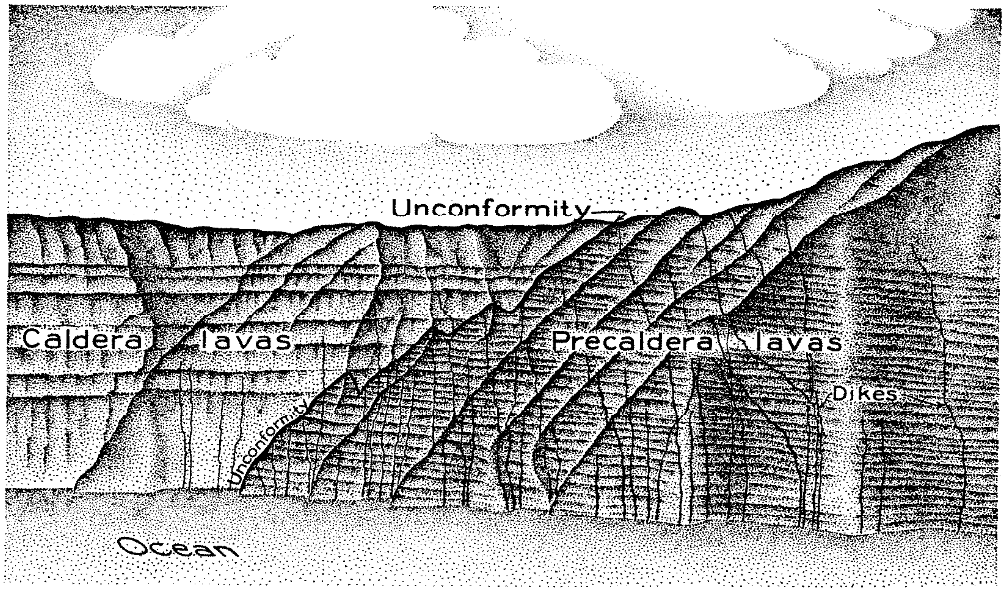

FIG. 28. Unconformity and fault on the north side of Kanapou Bay.

lows it for a short distance and a few cross it, showing that the fault post-dates most of the rifting. None of the beds on the south side match those on the north side, showing that the south side is downthrown more than 800 feet. Prisms of talus breccias exposed between several of the lava beds on the south side of the fault indicate that these lavas accumulated against a fault cliff (pl. 17, *C*).

Fault 3 (fig. 25) trends northeastward and is poorly exposed, because of the heavy mantle of talus and gravel in the gulch that follows it. The evidence for the fault is very clear, however, because the lava beds in the south wall of the gulch do not match those in the north bank. Ordinarily, lack of matching of lava beds in Hawaii is not conspicuous because of their similarity, but at this place they differ greatly. Those on the north side are horizontal and massive (pl. 16, *A*), and those forming the south wall are thin bedded and dip about 5° southeastward (pl. 16, *B*). The drop on the north side of the fault must amount to more than 810 feet, which is the height of the exposure. (See p. 143 for a description of the breccia along it.)

Several beds of fine yellow palagonitized firefountain debris terminate at this ancient fault cliff. Two beds thicken against the cliff either because pumice slid down the face of the cliff during its deposition from the air, or because the wind drifted it against the cliff later. Blocks of basalt that fell from the cliff are embedded in the pumice. Faulting continued after the accumulation of the lavas as shown by the development of friction breccia where the interbedded talus breccia banked against the cliff (pl. 17, *C*).

It is believed on the following evidence that the two faults bounding Kanapou Bay outline a former caldera about 3 miles in diameter and more than 800 feet deep (fig. 25):

1. The rocks on the south and north sides of the bay dip away from a vent that formerly lay between the two faults.
2. The faults definitely curve toward each other as though part of a single curved fault.
3. The lava beds filling the depression between the faults are definitely ponded lavas such as accumulate in a closed basin, as shown by their horizontal attitude and massive character. They resemble closely the lava beds in the floor of Kilauea caldera.
4. The interbedded pumice layers in the ponded lavas indicate proximity to the major eruptive center.
5. The faults are close to the high point of the dome, where a caldera would naturally be located.

For convenience this caldera will be called the Kanapou caldera. Half a mile north of the south corner of Kanapou Bay the caldera lavas are broken by fault 2 (fig. 25) with considerable but unmeasured downthrow on the south side. The fault is well exposed, but a boat landing could not be made for close inspection. Several smaller faults not shown in figure 25 but which are associated with a filled pit crater were seen in this locality.

FAULTS IN KAMOHIO BAY

Four faults are exposed in the cliffs bordering Kamohio Bay (fig. 25). They were all observed from a boat and therefore precise data in regard to them could not be obtained, particularly as to their trends.

Fault 4 is downthrown on the north side and displaces a 3-foot bed of palagonitized pumice. Only the bottom 50 feet of basalt in this 750-foot cliff is displaced. On the opposite side of the bay is exposed a streak of fault breccia at the base of the cliff. Only the lower layers in the cliff are displaced. These two faults are shown as connected in plate 14, but their trends could not be measured.

Fault 5 displaces only the lower 100 feet of basalt in the cliff. The downthrow is on the north side.

Fault 6 is a conspicuous feature in the cliff. It was examined from the rim (pl. 14, *A*). A dense layer appears to have been dropped about 30 feet on the north side of the fault. All except the upper 50 feet of the 550 feet of lava exposed in the cliff is displaced. A prism of talus breccia appears to be on the inland side of the fault, indicating a short time interval before the fault scarp was buried.

Fault 7 appears to have a nearly east-west trend and to have a downthrow of about 40 feet on the north side. It displaces a thin yellow ash layer and appears to be the eastward extension of the fault passing between Puu Koae Islet and the adjacent land. The beds of basalt forming the upper part of the cliff are not broken.

Kalama Point, one and a quarter miles west of Kamohio Bay, is cut by a fault with a large downthrow on the north side. This is shown in figure 25 as the end of fault 7, but it was impossible to land to ascertain the trend.

FAULTS IN WAIKAHALULU BAY

The lava beds in Puu Koae Islet dip 3° N., or in an opposite direction from those on the adjacent land, indicating that this islet is a fault block tilted northward. Rapid marine erosion along the weak plane, induced by the fault between it and the mainland, appears to be responsible for this islet, as the faulting long antidates the present sea cliff. Fault 8 is a prominent fault with a large downthrow on the north side cutting through the point on the east side of Waikahalulu Bay. It may be that this fault bounds the south side of the Koae block, as shown in figure 25.

Fault 9 has a large but unknown displacement, perhaps more than the height of the cliff, which at this place is 250 feet high. Drag dips indicate that the downthrow is on the northwest side. The trend is only approximately shown in figure 25.

Fault 10, on the east side of the bay, has a downthrow of about 40 feet on the northwest side. The upper 50 feet of the 400 feet of basalt exposed in the cliff at this place is not broken.

Possibly a dike occurs along the fault, but this could not be definitely established from the rim of the cliff. The same fault apparently displaces the lower layers in the cliff on the west side of the bay.

Fault 11, on the east side, near the head of the bay, could not be seen clearly from the rim of the cliff on the opposite side, but it appears to be a fault of small displacement with the downthrow on the northwest side.

INTERPRETATION OF THE FAULTING IN KAMOHIO AND WAIKAHALULU BAYS AND THE ORIGIN OF THE BAYS

Kahoolawe passed through a collapse stage before the final lavas were erupted, as faulting cuts only the lower beds of basalt in the cliffs of Kamohio and Waikahalulu bays. The trends of the faults, although not precisely established, are eastward and northeastward, and all the faults bound blocks downthrown toward the north. None of the lava beds thicken noticeably against the fault scarps, indicating that the lava was flowing lengthwise of the downthrown blocks or towards the southwest rather than across them. It is probable that they bound the south side of a rift-zone graben on the long axis of the island, extending away from the summit caldera in the same manner as the southwest rift zone of Kilauea Volcano, Hawaii, extends away from its summit caldera.[54] The lavas that filled the Kanapou caldera likewise buried this rift-zone graben.

The faults crossing these bays are oblique or transverse to the bays and do not appear to have caused them, although they are lines of weakness more easily eroded by the sea. The basalt layers exposed in the cliffs are fairly continuous; hence variations in the strength of the rock do not seem a probable cause.

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[54] Stearns, H. T., and Clark, W. O., Geology and water resources of the Kau District, Hawaii: U. S. Geol. Survey Water-Supply Paper 616, p. 130, 1930.

Waikahalulu Bay has a large gulch draining into it, but the stream is now unable to cut down as rapidly as the sea cuts back the cliff, as shown by its hanging position. Kamohio Bay has practically no drainage emptying into its head, but separated from it by a narrow divide, only about 60 feet high, is Kaneloa Gulch, which drains a large area. This gulch empties into the sea in a small bay west of Kamohio Bay. The gulch may have drained into Kamohio Bay formerly and its water may have been captured by a stream west of the bay in late geologic time, although no proof could be found that this stream has been captured.

Prior to the great submergence of Kahoolawe, referred to on page 146, the rainfall was probably considerably higher than at present. At that time most of the windward drainage probably entered valleys at the sites of Waikahalulu and Kamohio bays. It is likely that these streams with their steep grades, in part induced by rapid wave cutting at their mouths, eroded canyons. It is possible that the bays are former valleys enlarged by wave erosion since submergence, but the evidence for such an explanation is not too convincing.

RIFT ZONES

East rift zone.—A swarm of 40 basaltic dikes averaging about 20 inches in width and trending east-west is exposed in the sea cliff forming the north side of Kanapou Bay. Most of them are terminated by fault 1, but it is obvious that they are part of a dike complex that extended eastward from the former summit vent. Probably this dike complex extended farther south prior to removal of the east rim of the caldera by marine erosion.

Southwest rift zone.—It is assumed that a rift zone extends southwestward (W. 25° S.) along the long axis of the island from analogy with the other volcanoes of Hawaii. No cliff runs transverse to the rift so that only a few dikes in it are exposed. Three cones, Moiwi, Kealialalo, and Kamama, however, are surface manifestation of the rift (fig. 25). It is approximately 1 mile wide, 8 miles long, and nearly but not quite coincident with the extension of the southwest rift zone of Haleakala Volcano.

North rift zone.—The north end of the island extends considerably farther from the east-west axis than the south side. This lack of symmetry has probably been produced by a rift zone running north from the volcanic center. The large cone of Kealialuna is on this rift. Apparently a small amount of lava has erupted from this rift in comparison with the southwest rift.

WATER-BEARING PROPERTIES.—Dike complexes are extremely important in governing the movement of ground water. Dikes are porous and transmit water freely close to the flows they feed, but they become increasingly denser and less permeable with depth, so that several hundred feet below the surface of extrusion they restrict the movement of ground water. This causes the water to accumulate in the permeable basalt compartments between the dikes, in places several hundred feet above sea level. Furthermore, dikes prevent salt water from circulating through the porous lava flows. Thus, they shut out sea water and hold in fresh water. This structure offers the best prospect for developing fresh water on the island.

There are several sites where a drilled well might tap water in the dike complex, but the most promising place at the lowest elevation, is at an altitude of 800 feet in Ahupu Gulch, 1 mile southwest of Moaula cone. A well at this place should encounter the north margin of the southwest rift zone, but the dikes may not be close enough to confine water. A well at an altitude of 1,200 feet half a mile east of this site would penetrate even more certainly the dike complex. The height of the water table at these sites is unknown, but it may not be far above sea level because of the small recharge. Resistivity station A indicated a water table only about 1.0 foot above mean sea level not far away (fig. 25).

TERTIARY AND EARLY PLEISTOCENE(?) VOLCANICS AND THEIR WATER-BEARING PROPERTIES

PRE-CALDERA VOLCANICS

The lavas poured out of the summit crater and fissures prior to the collapse forming Kanapou caldera are typical primitive or Kilauean-type pahoehoe and aa basalt. They are called pre-caldera lavas herein. They range in thickness from 5 to 100 feet and probably average 25 feet. Each flow is generally made of individual layers a few inches to a few feet thick. A detailed petrographic description is given in the chapter "Petrography."

These rocks weather with scraggly outcrops due to the numerous tubular, clinkery, and highly vesicular structures (pl. 16, *B*). They crop out on the north and south sides of Kanapou Bay where they are 800 feet thick. They form most of the high sea cliffs on the south side of the island. Beds of vitric tuff about a foot or less in thickness occur sparingly between the pre-caldera lavas. Some of the rocks along the rest of the shore line may be pre-caldera lavas also.

Water-bearing properties.—Pre-caldera lavas are so permeable that they transmit water freely and are similar to the lavas that yield water copiously to wells along the shores of the larger islands of Hawaii. Nearly everywhere along the coast of Kahoolawe highly permeable lavas crop out and sea water can move readily inland through them (pls. 17, *A* and *B*). The rainfall is so low and infrequent that ground water moving seaward is probably inadequate to supply fresh water to wells anywhere along the coast.

A thin zone of brackish basal water probably exists 2 to 3 miles inland, except near the southwest end, but the land rises so rapidly inland that the cost of a Maui-type well tapping this supply would be prohibitive. It appears that the old Hawaiian wells at Hakioawa and Ahupu gulches obtained brackish water from this zone even near the coast, but they may not have yielded potable water throughout the year.

CALDERA VOLCANICS

All the lava beds that lie between faults 1 and 3 accumulated in the Kanapou caldera (fig. 25). They range in thickness from 10 to 200 feet, and many exhibit dense columnar phases (pl. 16, *A*). The flows, especially near the bottom, owe their unusual thickness to having been ponded in the caldera. They are typical basalts except near the top, where a few basaltic andesites are found. (See chapter "Petrography.") The lavas have an exposed thickness of 1,000 feet, but they extend below sea level an unknown depth in Kanapou Bay, and hence are obviously thicker. They were poured out chiefly from vents in the caldera area, as shown by layers of vitric tuff and a cinder cone interbedded with these lavas in Kanapou Bay. A cross section of a crater pit about 200 feet deep filled by later lavas is exposed half a mile north of the south corner of the bay. A half dozen prominent yellow vitric tuff beds a few inches to a few feet thick are interstratified near the top of the series. In addition is one bed 40 feet thick that dips gently to the north and becomes finer in texture north and south of its mid point. It is shown in figure 25, but the others are too thin and discontinuous to show on this scale map. Due to the low rainfall none of these beds yield any perched springs.

The general structure of the caldera shown in sections A–A′ and B–B′ in figure 25, is doubtless much more complicated in detail than is shown. The structure below sea level is unknown but is probably complicated by pit crater fills, throat breccias, faults, and local cones.

An unusual dike cutting the lower part of the caldera lavas is exposed in the gulch just north of eruption B (fig. 25) at an altitude of 230 feet. It is 2 feet wide and strikes N. 20° W. Next to the country rock, on both sides, is 5 inches of fairly dense platy pahoehoe with zones of vesicles parallel to the walls and with half an inch of glass selvage. Between these pahoehoe margins is 1 foot of aphanitic vesicular aa bordered by clinker. Thus, both massive and clinkery aa may form underground, but, as observed in the Lanai dikes, it follows pahoehoe in order of eruption.

WATER-BEARING PROPERTIES.—These rocks, as a whole, have a very low permeability because of their dense character. They would yield water slowly and in small quantities to wells penetrating them. They help reduce the amount of sea water moving inland from the east side of the island toward the southwest rift.

POST-CALDERA VOLCANICS

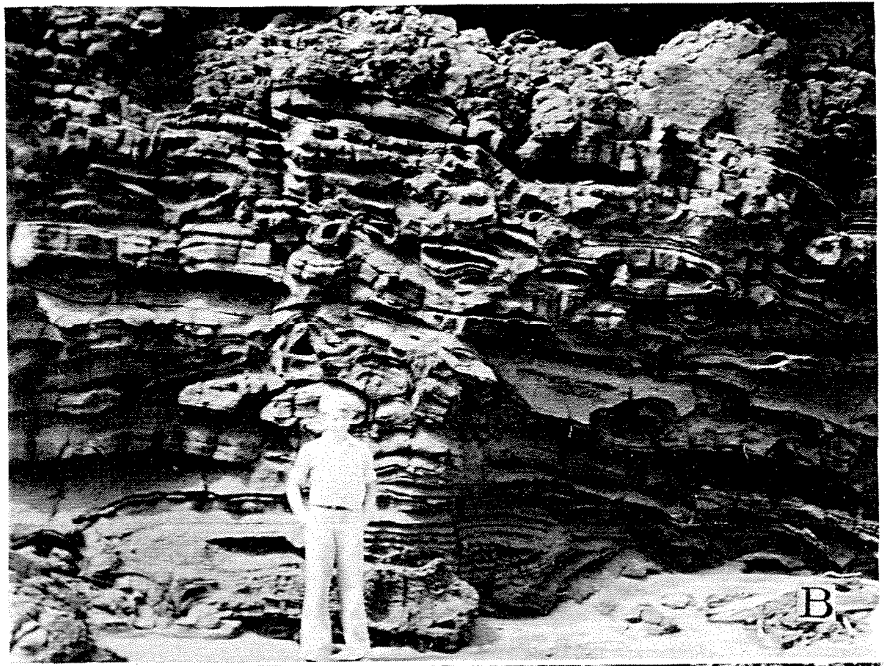
Most of the post-caldera lavas are less vesicular than the older lavas and occur in thicker beds even where they are not ponded, indicating that they were more viscous when poured out. Many carry large olivine crystals, together with feldspar phenocrysts. They commonly contain phenocrysts of pyroxene one-half to 1 cm long, a mineral rare as phenocrysts in the earlier lavas. They consist of both basalts and andesites. (See chapter "Petrography.") Because these lavas finally filled and overflowed the caldera and then spread widely over the island, they constitute a kind of caprock over most of the pre-caldera basalts. They covered the numerous fault scarps of the southwest rift zone also. They form so much of the surface that one gains the impression at first that all the rocks of Kahoolawe are augite, olivine, feldspar aa porphyries.

The greatest producers of post-caldera lavas were Makika and Kealialalo lava domes. Makika dome covers nearly 10 square miles. Both have undrained craters on them. Another low hill, three-quarters of a mile southwest of Moiwi cone, not shown in figure 25, may be a lava dome.

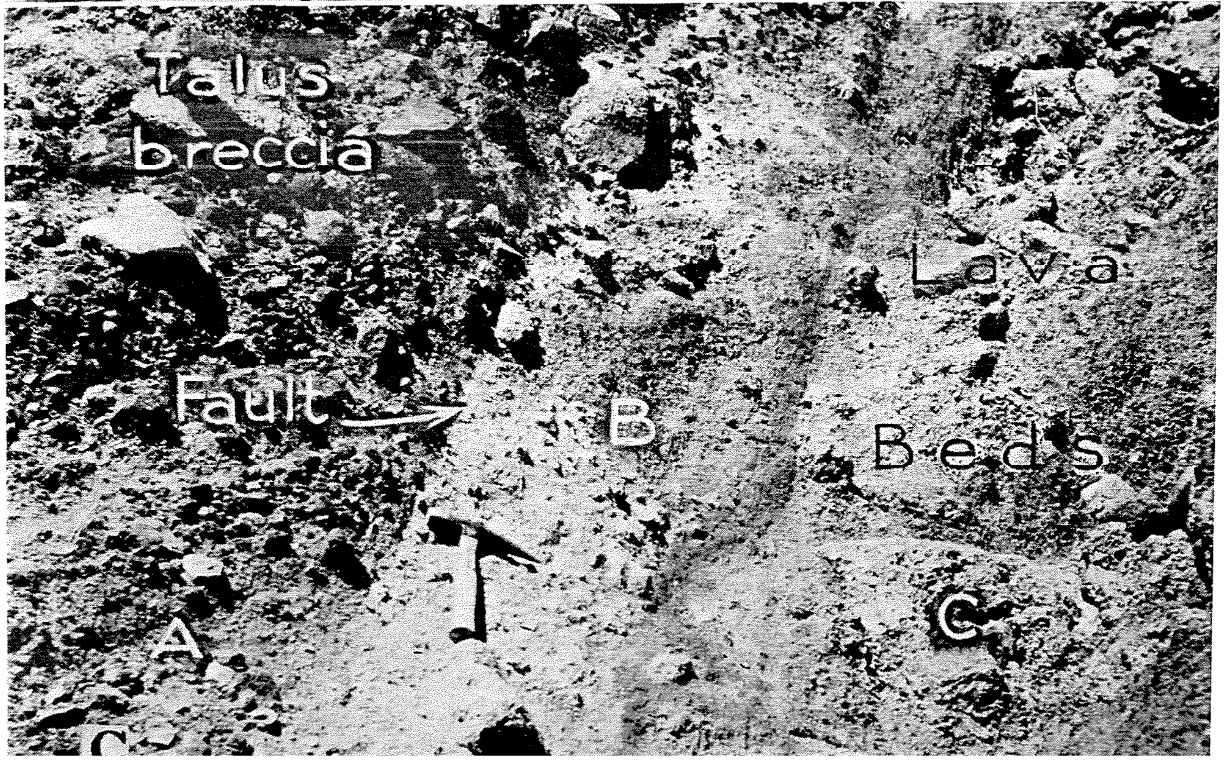
Kealialuna cinder cone, on the north rift zone, is the source of numerous thin scoriaceous flows which spread fanwise from it. A mound of cinders 6 feet high lies under a basalt flow due north of it on the coast. The cinders indicate that another vent lies on this rift.

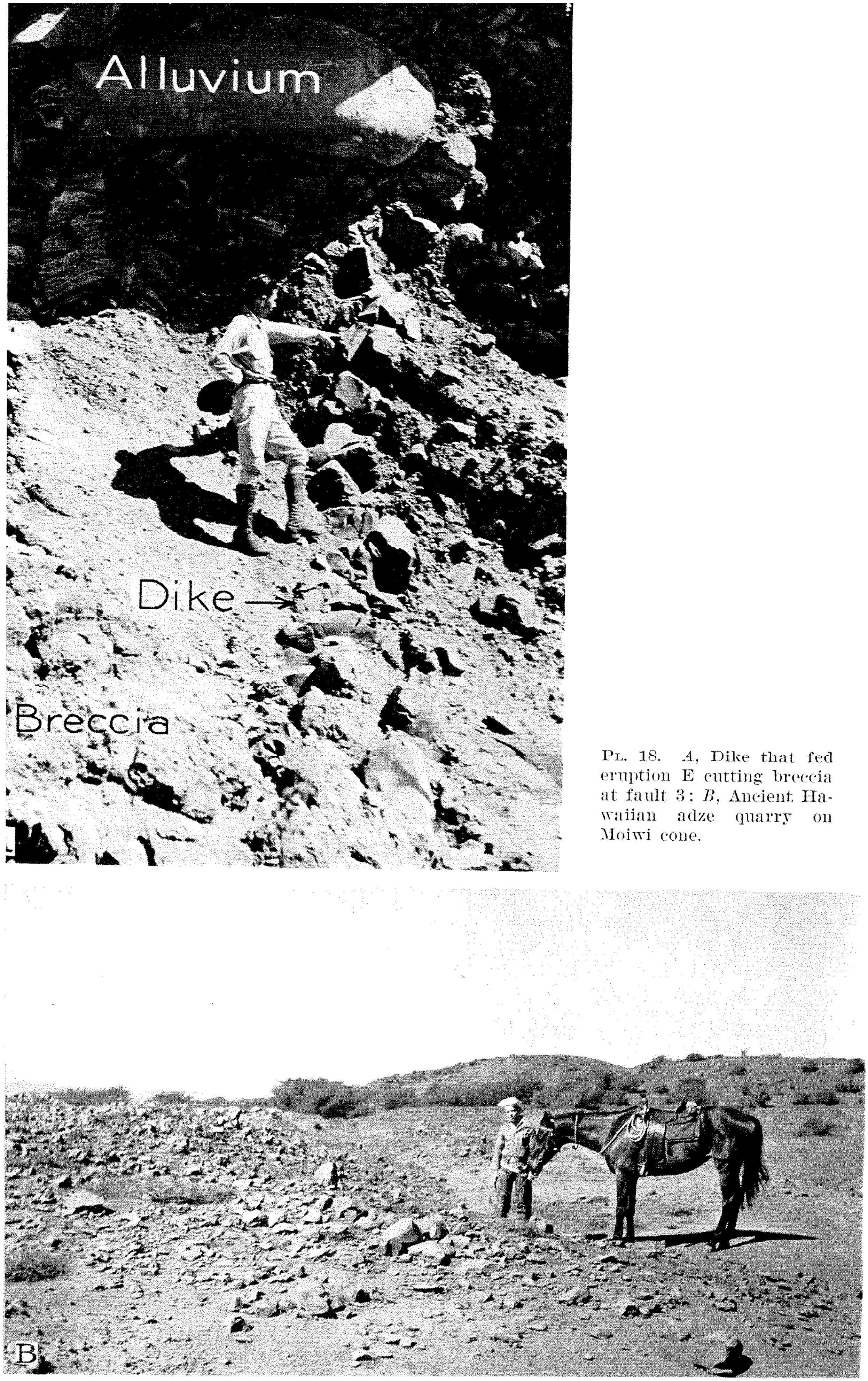
Kolekole cinder cone poured out many thin beds of highly scoriaceous olivine basalt. Its flows at the coast east of the cone are

Pl. 17. *A*, Lava tube in pahoehoe. (Photograph by C. K. Wentworth.) *B*, Typical permeable pahoehoe of the pre-caldera type, Ahupu Bay. Note the filled lava tubes.



Pl. 17*C*. Fault 1 bounding the north side of Kanapou caldera. Talus breccia that interfingers with (A) caldera-filling basalts; (B) friction fault breccia; and (C) pre-caldera basalts.





PL. 18. *A*, Dike that fed eruption E cutting breccia at fault 3; *B*, Ancient Hawaiian adze quarry on Moiwi cone.

underlain by 8 inches of yellow vitric tuff that dips steeply to the north. The flows attain an aggregate thickness northeastward of more than 170 feet. Two dikes, 1 foot and 2 feet wide respectively, striking N. 60° W., are exposed on the west side of the cone. In the gulch nearby, 50 feet of yellow palagonitized cinders belonging to the upper surface of the cone lie under a lava flow 50 feet thick which apparently came from Makika crater.

Moaula cinder cone, 1 mile northwest of the summit, is about 250 feet high and the source of voluminous flows that spread northwestward. The rock on the top of the cone is composed of cemented cinders and thin beds of lava.

Moiwi cone, on the southwest rift, poured out voluminous flows but produced apparently only a small quantity of cinders, although erosion may have removed most of them. Near the summit are layers of very dense blue basalt that were quarried by the Hawaiians for adzes (pl. 18, *B*). Many adze blanks lie among the flakes. The layers dip about 45° away from the vent, hence they are probably flows although they may be dikes.

Kamama cone lies about 1 mile north of Waikahalulu Bay. It poured lava southward and southwestward.

WATER-BEARING PROPERTIES.—The post-caldera lavas are mostly denser and less permeable than the older lavas. They form so much of the surface of the island that they appreciably reduce the amount of the recharge. Few if any lie below the water table; hence they are not important as water bearers.

RECENT VOLCANICS

ERUPTION A.—A dike of fine-grained basalt which cuts ancient breccia and recent talus crops out at fault 1 on the north side of Kanapou Bay at an altitude of about 700 feet (fig. 25). A fan-shaped deposit of cinders extending nearly to sea level and partly covering a small valley filled with gravel and talus lies below the dike but is disconnected from it by erosion.

ERUPTIONS B AND C.—A patch of cinders resting unconformably on the cliff, between altitudes of about 200 and 500 feet, was found about 1.2 miles south of eruption A (eruption B, fig. 25). Two patches of cinders, one above the other, plastering the cliff and therefore of Recent age lie between altitudes of about 250 and 700 feet half a mile south of eruption B (eruption C, fig. 25). Neither of these deposits of cinders were visited, but they are clearly visible from the south rim of the bay.

ERUPTION D.—An 18-inch dike striking N. 40° E. and cutting older alluvium deposited by the intermittent stream occupying this gulch, crops out about 600 feet north of the north end of the sand beach in Kanapou Bay at an altitude of about 50 feet (eruption D, fig. 25). The alluvium contains boulders up to 4 feet in diameter in a dirt matrix. In one place the dike encloses dirty alluvium and is bordered by palagonitized pumice (fig. 29). This dike is the feeder of a post-alluvium eruption. If a flow poured out here, it has been eroded away or lies under the sea. Evidently the lava at

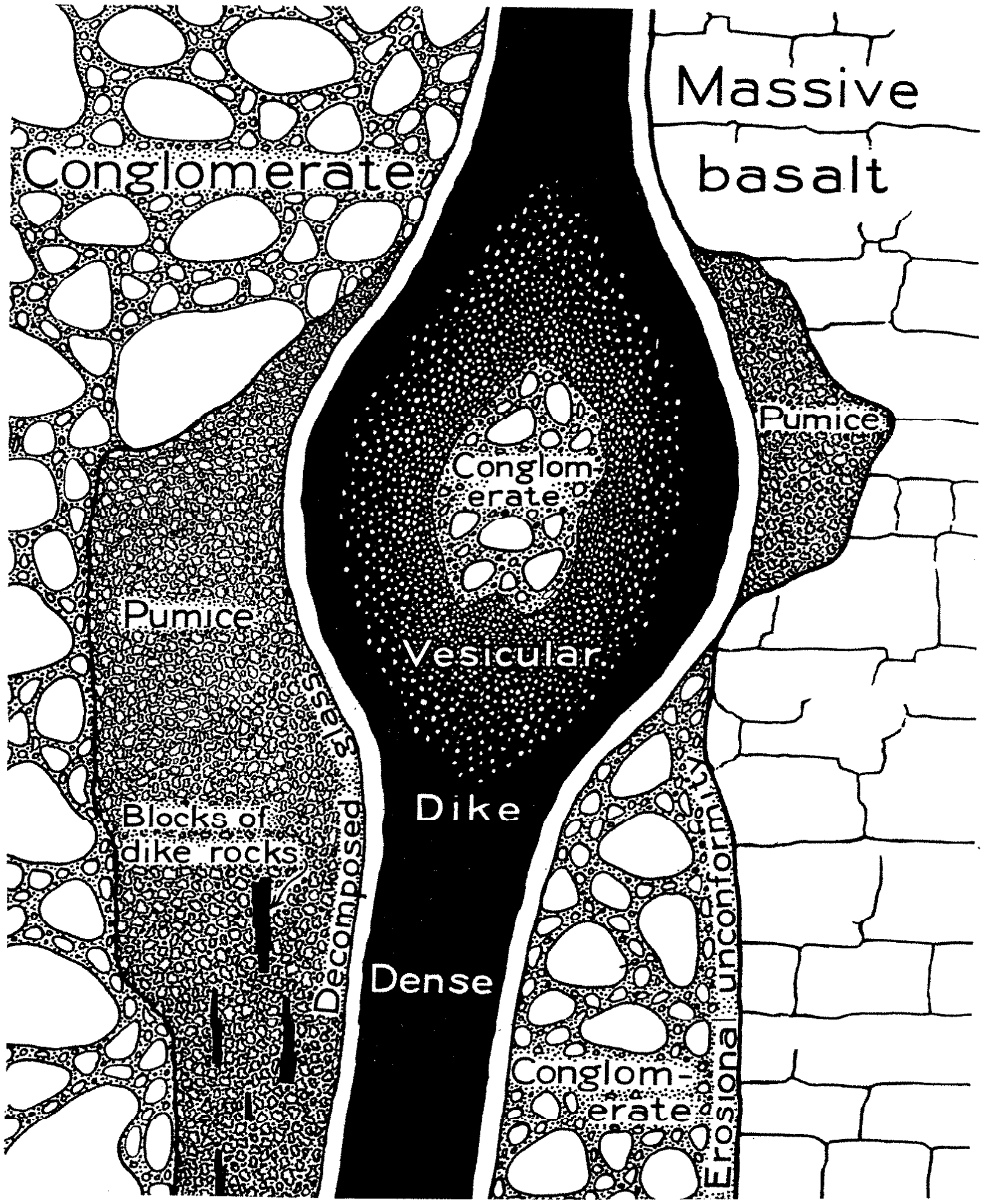


FIG. 29. Intrusive pumice cut by a dike that encloses alluvium, both intruded into recent alluvium, Kanapou Bay. Scale: 1 inch = 1 foot.

the start of the eruption disrupted into pumice before actually reaching the surface, and the dike was emplaced subsequently when the less gas-charged lava arrived. It is the first pumice dike so far observed in Hawaii.

Eruption E.—Fault 3 is exposed with 20 feet of firmly cemented talus breccia adjacent to it at an altitude of about 380 feet in the north fork of the gulch draining into the south side of Kanapou Bay. The breccia next to the fault is made up of fine debris that becomes coarser 15 feet away where it contains blocks up to 6 feet across. The bedding strikes N. 40° E. and dips 30° SE. An aphanitic dike 1 foot wide has been injected along cracks in the breccia parallel to the fault plane (pl. 18, *A*). The dike pinches out in three places but reaches the top of the talus where lava was erupted from it in the form of cinders that now lie unconformably upon the breccia. The cinders are 35 feet thick and are overlain by recent talus and alluvium. At the forks just below this outcrop the cinders rest on weathered basalt with a contact striking N. 65° E. and dipping 55° NW.

It is significant that all the Recent eruptions are confined to the ancient caldera area, and that lava found its way up the ancient faults bounding the north and south sides. The cinders are easily eroded and lie on such a steep cliff that they obviously could not persist long. The Recent volcanics cover too small an area to act as water bearers.

GEOLOGIC HISTORY

It appears from the geologic structure that during the first very active phase of volcanism on Kahoolawe, an egg-shaped cone was built with a summit vent near the large east end (fig. 30). It may have reached a height of about 3,000 feet in relation to present sea level. Lavas poured out quietly with only short periods of quiescence from the east, north, and southwest rift zones, as well as from a small summit crater. Sufficient lavas were extruded from the southwest or main rift to give the island a definite elongate form. Small firefountains played at rare intervals during eruptions, laying down thin deposits of pumice nearby.

Then came the usual stage of collapse that follows the rapid youthful cone-building phase of a Hawaiian volcano.[55] This mature stage ended with a caldera about 3 miles across and more than 800 feet deep, as the whole summit area collapsed (fig. 31). The southwest rift likewise collapsed, forming a trough about a mile wide

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[55] Stearns, H. T., Four-phase volcanism in Hawaii (abstract): Proc. Geol. Soc. America for 1940, vol. 51, p. 1947, 1940.

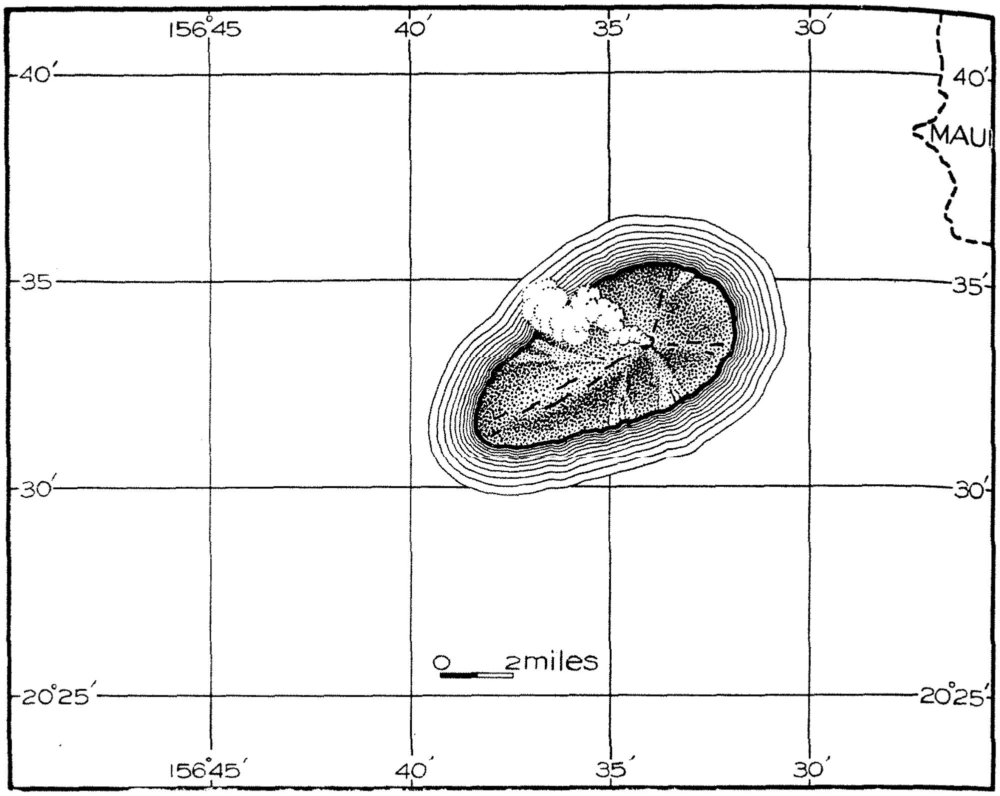

Fig. 30. Kahoolawe during its early stage of rapid extrusion of thin basalt flows from three rifts and a small summit crater.

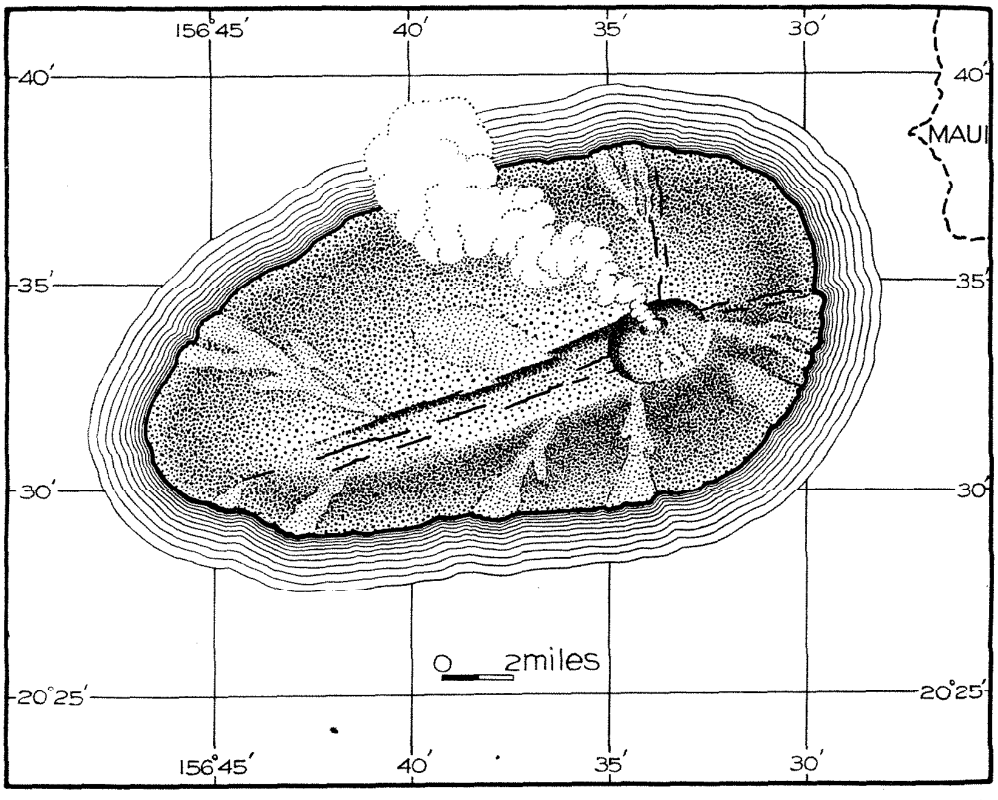

Fig. 31. Kahoolawe during its collapse phase with a summit caldera about 3 miles across and a graben along the southwest rift zone.

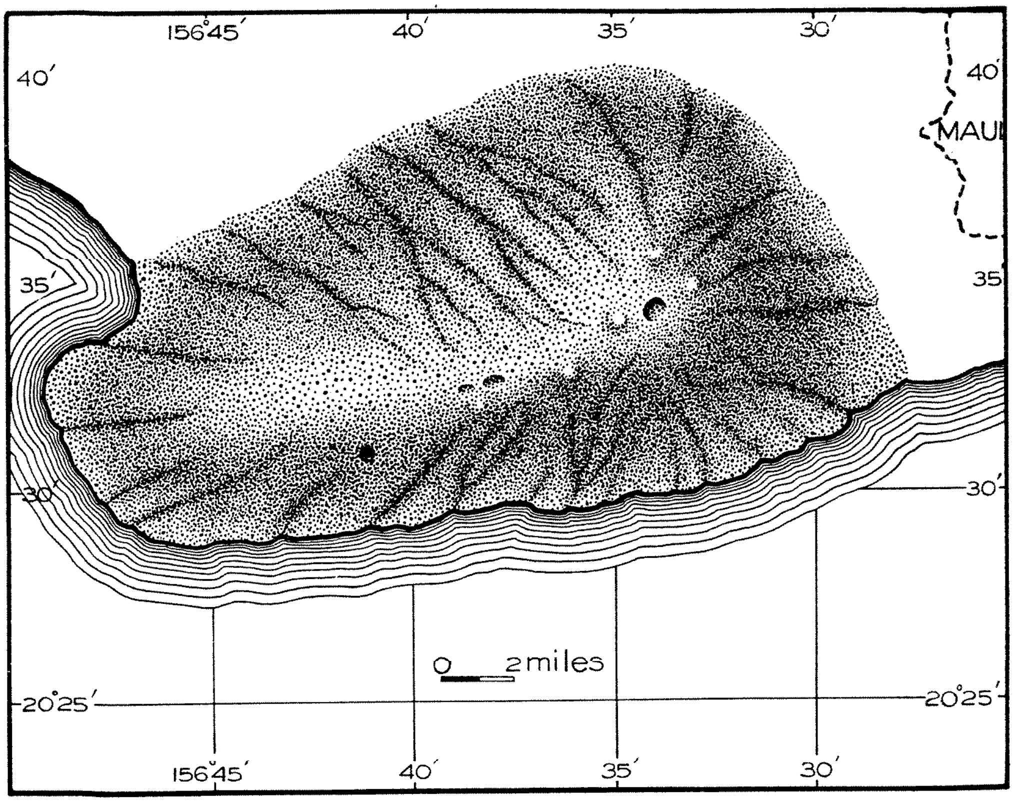

FIG. 32. Kahoolawe at the close of volcanic activity and before the great submergence. It was at this time connected to Maui, Lanai, and Molokai.

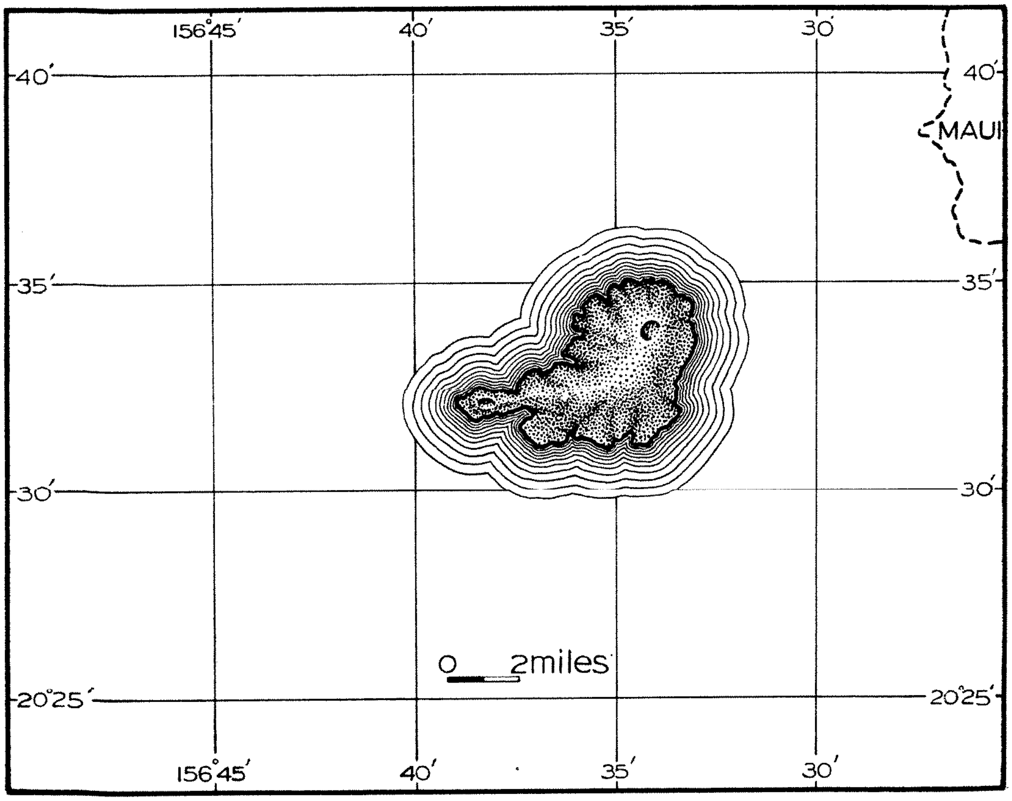

FIG. 33. Kahoolawe at the time it was submerged to a level of 800 feet above the present shore.

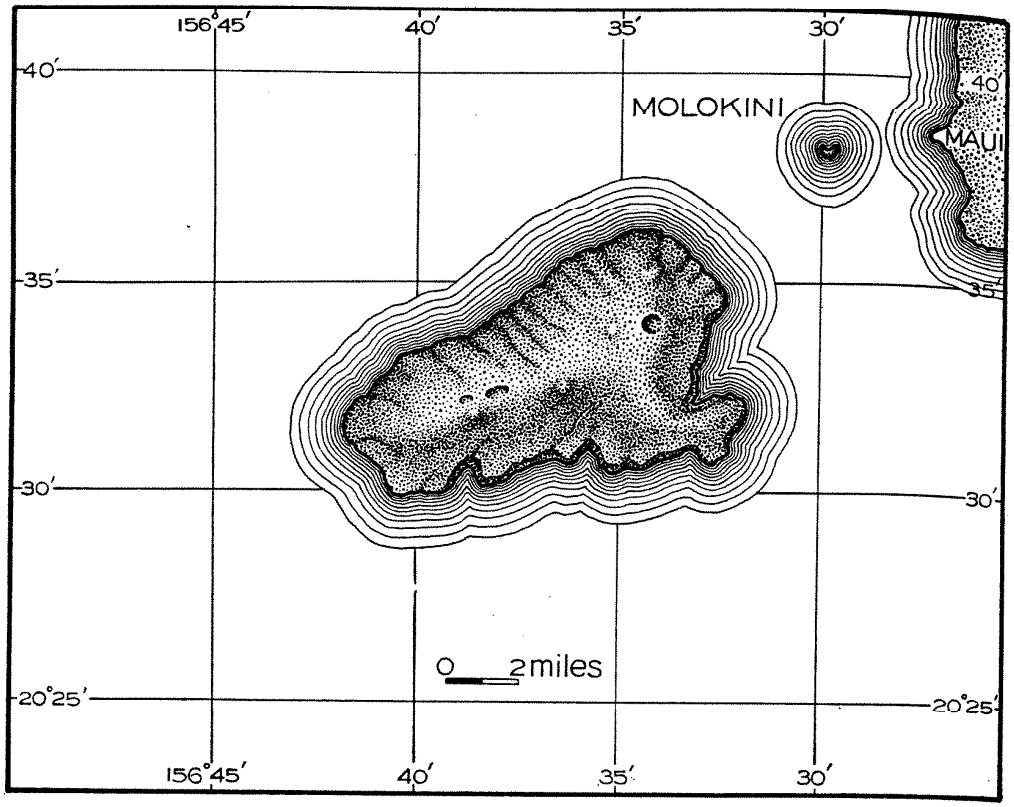

FIG. 34. Present-day Kahoolawe after re-emerging 800 feet.

bounded by échelon fault scarps 50 or more feet high. Lavas continued to erupt during this period, and hence the total amount of movement indicated by the various faults does not mean that fault scarps of the equivalent height existed. Kahoolawe at that time closely resembled the present Kilauea Volcano.

This stage was followed by the old-age or cinder-cone stage when a few bulky cinder cones were formed and the lavas differentiated into rocks less basic. Collapse progressively ceased and the lavas buried the scarps and completely filled and obliterated the caldera (fig. 32). Kahoolawe was then apparently connected with Lanai, Maui, and Molokai as one large island.

Quiet reigned, soils began to form and plants gained a foothold. Rivers slowly etched the surface as the soils reduced the porosity of the dome. The trade winds reaching Kahoolawe were robbed of most of their moisture as the island lies to the leeward of the great bulky dome of Haleakala. Consequently, erosion was slow with the result that a thick mantle of soil accumulated during this epoch.

The present shore line is about 2,000 feet above the shore line of early glacial time, as the entire Hawaiian archipelago has been submerged about this amount. Thus the mouths of the valleys were deeply drowned, but the gulches were so small, except possibly Waikahalulu and Kamohio, that the effect is not so noticeable as on the other more eroded islands.

Wet periods concomitant with glacial times probably allowed forests to thrive, but during the warm interglacial stages the rainfall probably decreased to such an extent that the forests were replaced by open stands of trees, brush, or grass.

The sea was not idle during this long period, but rapidly cut into the east and south sides of the island. Occasional kona storms battered the west and north shores producing low cliffs. The partial drowning of the island gave the sea opportunity for fresh attacks at various levels, but apparently the longest halt was at some depth below present sea level, as all cliffs now extend well below the ocean.

The great change of the land in relation to present sea level was not submergence only. The slopes of Kahoolawe have been stripped of soil up to an altitude of about 800 feet and the flats were left with wave-rounded boulders (fig. 33). The lack of coral deposits makes it difficult to interpret the marine history, but judging from its neighbor, Lanai, there were probably many ups and downs before the sea reached its present level.

During this long erosional epoch the sea cut back into the buried caldera and eroded Kanapou Bay along the weak fault lines.

When the sea cliff at the head of this bay had reached its present form apparently after the sea had attained its present level, lava found its way up the old faults in the caldera and burst out on the cliff face in five places. These Recent eruptions appear to have been related to the late volcanism in Haleakala Crater and the Ulupalakua rift on nearby Maui.

Goats were brought to the island about 1788, and in a few years the cover of vegetation was nearly destroyed and Kahoolawe was transformed into a great desert of drifting red dust. Here in the short span of 152 years the soil accumulation of a million or more years was blown away forever and the former green little island became a bare bald forbidding land (fig. 34).

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PETROGRAPHY OF KAHOOLAWE

By Gordon A. Macdonald

INTRODUCTION

The geology of Kahoolawe was mapped by Stearns in March 1939, and from the several specimens collected by him it was thought that the rock units might be mapped on the basis of petrographic studies. Accordingly, the writer spent four days on Kahoolawe in December 1939 collecting additional material. The following report is based largely on microscopic studies of 47 specimens. Thanks are due H. T. Stearns, C. S. Ross, Horace Winchell, and H. A. Powers, who read and criticized the manuscript of this paper.

The lavas of the Hawaiian Islands vary greatly in their permeability according to their composition and structure, and detailed petrographic studies are now being made of the rocks of all the islands with a view to determining these relationships. Petrographic work is useful also in determining the geologic relations of certain lavas. Thus, on Oahu, the nepheline basalts usually fill valleys, and carry water in their basal parts, and merely the determination of a rock as a nepheline basalt yields a clue to its geologic relations and water-bearing properties. Petrographic studies of valley-filling lavas in East Maui have been of aid in working out the complicated geologic structure of that region.

The optical properties of the minerals have in all cases been determined in thin section. The composition of the feldspars has been determined by various extinction angle methods. The size of the optic axial angle of pyroxenes has been estimated from the appearance of optic axis or acute bisectrix interference figures. The percentages of various constituents have been estimated. Although it is realized that these methods are less precise than immersion and universal stage methods, it is believed that the results obtained are of sufficient value to be recorded.

GENERAL FEATURES

The rocks of Kahoolawe fall conveniently into four broad groups, based on the geologic history and structure of the island. Throughout its early stages the volcano built a broad dome, composed of innumerable thin flows of olivine basalt. These are conveniently described as the *pre-caldera lavas.* At a later period the top of the mountain collapsed, and there was formed a large summit caldera, and a complex graben leading southwestward from it. Further eruptions gradually filled the caldera, and the lavas which accumulated within it are referred to as the *caldera-filling lavas.* Finally the flows overtopped the rim of the caldera, first at the lowest and gradually at higher and higher points, and coursed down the sides of the mountain. A broad lava dome was built over the site of the old caldera. These flows which followed the filling of the caldera, and which now form a thin cap over most of the island, are called the *post-caldera lavas.*

Following the cessation of post-caldera volcanism, the island long lay subject to erosion, and a high sea cliff was developed around much of the island. Following this long interval of quiet, volcanic activity once more burst forth, and several small flows and cinder eruptions took place along the cliffs bordering Kanapou Bay. These most recent volcanic rocks are called the *post erosional lavas.*

MINERALS

FELDSPAR

Plagioclase.—Lavas containing phenocrysts of soda-lime feldspar are widespread. The crystals are more or less tabular in habit, and in the hand specimen are white or colorless and have a glassy lustre. They are generally small, few exceeding 8 mm. Every gradation in size can be found between the large phenocrysts and the feldspars of the groundmass. Under the microscope, the phenocrysts are euhedral to subhedral in outline, and nearly all show Carlsbad and albite twinning. Pericline twinning is comparatively rare. Most show normal zoning, and oscillatory zoning is not uncommon. Typically, the zoned crystal is made up largely of a core of calcic feldspar, either labradorite or bytownite, which commonly shows oscillatory or slight normal zoning. The most calcic feldspar observed is a calcic bytownite, about An_{85}, but the innermost zone is generally a calcic to intermediate labradorite. The core is surrounded by a rim of strongly zoned feldspar progressing through a narrow band to the outermost zone, which corresponds in composition to the feldspar of the groundmass. The core is commonly much rounded by resorption before deposition of the outer zones. In a few crystals a row of inclusions of pyroxene marks the contact of the central core with the outer, strongly zoned part. The outer zones of several contain numerous tiny inclusions of very pale brown glass, but the core is relatively or completely free from such inclusions.

In an olivine basalt (12)[56] collected on the northwest side of Lua Kealialalo, abundant phenocrysts of colorless, glassy plagioclase reach a length of 8 mm. They contain cores of calcic bytownite, notably rounded by resorption, and surrounded by shells showing normal and oscillatory zoning ranging from sodic bytownite along the inner edge to calcic labradorite at the outside. Sharply separated from these are the outermost rims of calcic andesine, corresponding in composition with the plagioclase of the groundmass.

Reversed zoning was seen in only two specimens. One is an olivine basalt (38), probably post-caldera in age, in which the phenocrysts are made up of a core of calcic andesine (An_{45}), strongly rounded by resorption, and surrounded by a thin outer shell of sodic labradorite (An_{55}) of the same composition as the groundmass feldspar. The transition from the core to the rim is gradual, but takes place through a very narrow zone. The second is a basaltic andesite (10) exposed near the head of Waikahalulu Bay, containing plagioclase phenocrysts many of which show cores of sodic bytownite (An_{73}), rounded by resorption, and surrounded by a shell of intermediate bytownite (An_{78}) which passes outward through intermediate zones into sodic andesine.

The soda-lime feldspar of the groundmass typically forms subhedral to anhedral, lath-shaped microlites, which in some rocks are entirely untwinned, but in most show Carlsbad and often albite twinning. Pericline twinning is very rare. Normal zoning is frequently observed, but the range of composition represented is in most cases small. The composition of the groundmass plagioclase ranges from labradorite to oligoclase, and is of primary importance in the naming of the rocks, since groundmass feldspar generally far exceeds in amount the feldspar of the phenocrysts. Albite has been recognized in only one specimen, a coarse-grained gabbroic rock (21) collected near the top of the small gulch which enters the northwest corner of Kanapou Bay. In this rock the plagioclase grains show normal zoning from sodic labradorite to oligoclase-andesine, and many are surrounded by a narrow rim of albite (An_6).

Many rocks contain interstitial anhedral grains of feldspar with undulatory or irregular extinction and a refractive index slightly lower than that of the other plagioclase, usually lying within the range of oligoclase but sometimes in that of andesine. In some it forms rims about the more calcic plagioclase. The birefringence is low, $\gamma - \alpha =$ generally about .008. Most grains are untwinned, although some show Carlsbad twinning and a very few show albite

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[56] The location of the specimens is shown in fig. 25.

twinning. The optic sign is positive, and the optic angle frequently appears abnormally small. In a few thin sections the mineral appears nearly uniaxial. In a number of grains in a lava from Molokai examined by C. S. Ross the measured axial angle varied between 68° and 90°, and on one of these the refractive indices were close to 1.550 and 1.557.[57] This mineral is present in lavas of all ages on Kahoolawe, but it is especially widespread and abundant in the post-caldera lavas, particularly in those of andesitic composition.

The mineral described above is identical with that found by Barth in lavas from a number of Pacific volcanoes, and identified by him as probably anemousite,[58] a feldspar containing more or less nepheline or carnegieite. This conclusion was based on its occurrence in rocks containing considerable amounts of normative but no modal nepheline, and on calculations which indicated that it was probably composed of a mixture of carnegieite with albite, orthoclase, and anorthite. There are reasons, however, to doubt the accuracy of this conclusion. Professor A. N. Winchell has pointed out to the writer[59] that it is difficult to understand how the nepheline molecule can be fitted into the structure of the alkali feldspar. Moreover, the mineral has recently been positively identified by the writer in several rocks which contain notable amounts of normative quartz. It is present in the 1887 lava flow from Mauna Loa, Hawaii, which contains 9.96 percent normative quartz; in the 1859 flow, which contains 7.74 percent normative quartz; and in the trachyte from Puu Anahulu, which contains 1.8 percent normative quartz.[60] It is also present in several rocks from the Waianae Range, on Oahu, which contain normative quartz.[61] The presence of this mineral in rocks containing such notable amounts of normative quartz and only a moderate to small amount of modal olivine makes it appear doubtful whether the nepheline molecule is actually an essential constituent, and therefore whether the mineral is appropriately termed anemousite.

Many of the lavas in which this peculiar feldspar is found contain several percent of normative orthoclase which cannot be identified in the mode. It may be that the abnormally small optic axial angle

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[57] Mr. C. S. Ross has kindly examined several thin sections of Hawaiian lavas containing this mineral. He is of the opinion that its observed characters are not such as to warrant a more definite conclusion than that it represents a somewhat anomalous feldspar. Unpublished memorandum, Sept. 9, 1940.

[58] Barth, T. F. W., Pacificite, an anemousite basalt: Wash. Acad. Sci. Jour., vol. 20, pp. 60-68, 1930; Mineralogical petrography of Pacific lavas: Am. Jour. Sci., 5th ser., vol. 21, pp. 401–402, 1931.

[59] Oral communication, July 1939.

[60] Washington, H. S., Petrology of the Hawaiian Islands, II. Hualalai and Mauna Loa: Am. Jour. Sci., 5th ser., vol. 6, p. 113, 1923.

[61] Macdonald, G. A., Petrography of the Waianae Range, Oahu, in Stearns, H. T., Supplement to the geology and ground-water resources of the island of Oahu, Hawaii: Hawaii Div. of Hydrography Bull. 5 (in press).

is due to the presence of more or less potash in the soda-lime feldspar. This has not been demonstrated, however.

Another possible explanation of the abnormally small axial angle of the interstitial feldspar is suggested by its irregular extinction, in some grains patchy but more commonly undulatory, resembling that shown by the interstitial quartz grains in many granitic rocks. This undulatory extinction is probably the result of internal strains and distortion of the crystal structure arising as a result of the crystal being forced to accommodate itself to the residual openings between the earlier-crystallized minerals. Just as in the interstitial quartz, the undulatory extinction may be accompanied by a distortion of the other optical properties, resulting in an apparent optic angle of smaller size than normally would occur. In a very few rocks, such as the one from Molokai examined by Ross, the small apparent axial angle is found in feldspar grains which are not interstitial. But here also it is accompanied by undulatory extinction, and may be the result of strains set up during flowage. In this paper the mineral is referred to as interstitial oligoclase or interstitial andesine according to its refractive index.

ALKALIC FELDSPAR.—In the gabbro (21) from the northwest corner of Kanapou Bay the interstices are filled with anhedral feldspar showing a peculiar mottled extinction faintly suggestive of microperthite, a negative 2V close to 75°, and $\beta = 1.525$ (± .003). This is regarded as orthoclase, possibly containing more or less albite. Similar material is found occupying the interstices in diabasic intrusives near the southwest corner of Kanapou Bay (4, 35, 36). The optic angle is always negative and variable, ranges from near 0° to about 70°. The birefringence is low, the refractive index distinctly less than that of balsam, and the extinction is commonly undulatory. Minute inclusions of highly acicular apatite are very abundant. Material with apparently identical characteristics has been observed in other coarse-grained intrusive rocks, notably those from the West Maui volcano, and from the Palolo boss in the Koolau Range on Oahu. An olivine basalt (47) collected in Kaulana Gulch about 1½ miles N. 28° W. of the top of Moaula cone contains a mineral of similar characteristics except that the optic axial angle is small, ranging from 0° to 30°, with a negative sign. This is probably sanidine.

OLIVINE

Olivine is a very common constituent of the rocks of Kahoolawe. It is present as phenocrysts and in the groundmass, although its occurrence as phenocrysts is much more general. It is rich in the forsterite molecule, as is indicated by the large size of the optic axial angle.

Olivine phenocrysts reach a maximum diameter of 8.0 mm. They constitute less than 5 percent of most rocks but may amount to 15 percent. Groundmass olivine, although a common constituent of Kahoolawe lavas, is never present in great quantity. Rocks rich in olivine, such as are fairly common elsewhere in Hawaii, have not been found on Kahoolawe. When fresh, the olivine in the Kahoolawe lavas is nearly colorless under the microscope, but many grains, particularly those of the groundmass, show a very pale green tinge which appears to be the result of slight alteration. The phenocrysts are commonly in part, or even entirely, altered to iddingsite.

The olivine phenocrysts are euhedral to subhedral in outline, and many are highly tabular parallel to the side pinacoid, sections in the zone normal to (010) appearing very acicular, with a length commonly ten times their width. Rounding and embayment by magmatic resorption are almost ubiquitous. In some slides resorption has eaten entirely through the tabular crystals, and in sections cut nearly normal to the side pinacoid this results in a train of rounded remnants of olivine having identical optic orientation, separated by straits of groundmass. All of these features were recognized many years ago in the rocks of Mauna Loa and Kilauea, Hawaii, by E. S. Dana.[62] A few rocks were found in which the phenocrysts are sharply euhedral, showing no signs of resolution. No zoning has been detected, but the methods employed might easily fail to reveal the small changes in composition, probably of a zonal nature, which are reasonably to be expected. Wherever it has been possible to detect any difference in the optical properties of phenocrysts and groundmass olivines the change appears to be toward a more iron-rich olivine in the groundmass. This is in agreement with the results obtained by Barth for Pacific lavas in general.[63]

The olivine phenocrysts are commonly altered in part, or even wholly to iddingsite. In most this forms a thin coating over the entire outer surface and penetrates irregularly along fractures in the olivine. In others the olivine may be entirely replaced by pseudomorphs of iddingsite. Under the microscope the latter is reddish-brown in color, and distinctly fibrous in appearance. The pseudomorph is composed of a single crystal of iddingsite, which

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[62] Dana, E. S., Petrography of the Hawaiian Islands: in Dana, J. D., Characteristics of volcanoes, pp. 324-325, 343, 1890.

[63] Barth, T. F. W., Mineralogical petrography of Pacific lavas: Am. Jour. Sci., 5th ser., vol. 21, p. 380, 1931.

shows a crystallographic orientation parallel to that of the original olivine, the lamellar basal cleavage of the iddingsite lying normal to the *c* axis of the olivine. In many the olivine was rounded and embayed by resorption previous to the formation of the iddingsite, and in these the rim of iddingsite follows exactly the embayed outlines of the olivine.

In a few rocks, iddingsite pseudomorphs after olivine, and olivine crystals surrounded by a rim of iddingsite are enclosed in an outer shell of fresh olivine.[64] The olivine of this rim is crystallographically parallel with that of the core, and tends to restore the euhedral outlines lost by resorption. The contact of the iddingsite with the olivine of the rim is sharp, whereas that with the olivine core is feathery and irregular.

Iddingsitization of groundmass olivines is very rare, and where it does occur it is only found in a few grains, the rest of the groundmass olivine remaining fresh or only stained slightly greenish by incipient serpentinization. It seems probable that these few iddingsitized grains in the groundmass are actually of intratelluric formation, and should be considered with the phenocrysts.

The occurrence of crystals of olivine altered to iddingsite and surrounded by rims of unaltered olivine has previously been discussed by Ross and Shannon[65] and by Edwards.[66] Ross and Shannon have conclusively demonstrated the deuteric origin of the iddingsite. Both these authors and Edwards have also noted the presence of associated unaltered groundmass olivine. Ross and Shannon concluded that the phenomenon was due to the preferential alteration to iddingsite, in zoned crystals, of zones of olivine of a certain limited composition. Edwards has pointed out, however, that the iddingsite rims, far from following any regular zone, are often highly irregular in shape, following the outlines of what are clearly crystals of olivine much rounded and embayed by magmatic resorption. He also regards the feathery inner contact of the iddingsite as due to replacement, in contrast to the sharp outer contact, "pointing to a sudden cessation of reaction and a reversal to olivine precipitation."[67] He attributes the formation of the iddingsite to the

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[64] These phenomena were clearly described and illustrated from Hawaiian lavas by F. Möhle (Beitrag zür Petrographie der Sandwich- und Samoa-Inseln: Neues Jahrb., Beilage-Band 15, p. 84, fig. 2, 1902), although his interpretation of their origin was somewhat different, and his identification of the iddingsite as iron hydroxide was in error.

[65] Ross, C. S., and Shannon, E. V., The origin, occurrence, composition and physical properties of the mineral iddingsite: U. S. Nat. Mus. Proc., vol. 67, pp. 1-19, 1925.

[66] Edwards, A. B., Three olivine basalt-trachyte provinces and some theories of petrogenesis: Royal Soc. Victoria Proc., vol. 48, pp. 23–24, 1935; The formation of iddingsite: Am. Mineralogist, vol. 23, pp. 277-281, 1938.

[67] Edwards, A. B., The formation of iddingsite: Am. Mineralogist, vol. 23, p. 279, 1938.

unusual concentration of water vapor in the magma in the vent during and just preceding extrusion, while the outer rim of olivine has developed following extrusion.

In consideration of the evidence presented by Edwards, together with the fact that in the Kahoolawe rocks the outer rim of olivine is never found except where unaltered olivine of the same composition is also present in the groundmass, it seems safe to conclude that the olivine of the core was developed by intratelluric crystallization, often followed by extensive resorption and alteration to iddingsite, probably during the time in which the enclosing magma occupied the apex of a cupola, or even the feeding channel of the volcano. During this period the concentration of the volatile constituents might be expected to reach a maximum. The amount of volatiles present in the magma will usually decrease rapidly following extrusion, and it is then that the formation of the outer rims of olivine and crystallization of the olivine of the groundmass take place.

PYROXENE

ORTHORHOMBIC PYROXENE.—Hypersthene has been found in seven specimens, of which six are of andesitic composition. Four are porphyritic and in these the hypersthene occurs as phenocrysts. In two the hypersthene, much rounded by resorption, is enclosed in a shell of monoclinic pyroxene with crystallographic orientation parallel to that of the core. The two nonporphyritic rocks are shallow intrusive types with an even grained, diabasic texture. In these, also, the hypersthene is enclosed in a rim of clinopyroxene, indicating that it was an early mineral to crystallize. Orthorhombic pyroxene is never abundant, making up from 1 percent to 5 percent of the enclosing rock. It is nearly colorless in thin section, showing only extremely weak pleochroism.

Orthorhombic pyroxene, although never abundant, is fairly widely distributed in the lavas of Hawaii. It was first recognized from Oahu by Dana, in 1889,[68] and was later described by Cross.[69] It has since been recognized in lavas from Kilauea and Mauna Loa,[70] and

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[68] Dana, E. S., Contributions to the petrography of the Sandwich Islands: Am. Jour. Sci., 3rd ser., vol. 37, pp. 441-467, 1889.

[69] Cross, W., Lavas of Hawaii and their relations: U. S. Geol. Survey Prof. Paper 88, pp. 19-20, 1915.

[70] Washington, H. S., Petrology of the Hawaiian Islands; II. Hualalai and Mauna Loa: Am. Jour. Sci., 5th ser., vol. 6, p. 112, 1923.

Stone, J. B., The products and structure of Kilauea: B. P. Bishop Mus. Bull. 33, p. 21, 1926.

Stearns, H. T., and Clark, W. O., Geology and water resources of the Kau District, Hawaii: U. S. Geol. Survey Water-Supply Paper 616, p. 160, 1930; the petrographic description is by Cross.

from West Maui,[71] and the writer has found it in several lavas from Lanai (pp. 61–62).

MONOCLINIC PYROXENE.—Clinopyroxene is present in the groundmass of every specimen from Kahoolawe which has been studied. In contrast, phenocrysts are much less frequent in their occurrence, and indeed in the restricted sense of the term they are totally absent. A gradual transition in size from the larger crystals to the small pyroxene granules of the groundmass was found in all specimens. However, in many it is obvious that the larger crystals represent intratelluric crystallization and are distinctly earlier than the groundmass pyroxenes. They are consequently regarded as phenocrysts and are so referred to herein.

Phenocrysts of pyroxene do not attain the size or abundance of those of olivine and feldspar. They seldom exceed 1 mm in length, and none exceed 2 mm. In hand specimen they are black, and have the glassy lustre and blocky fracture characteristic of the mineral. In thin section they are very pale brown to colorless, and euhedral to subhedral in outline. Twinning parallel to (100) and to (001) was seen in some slides. The pyroxene phenocrysts range in composition from diopsides to pigeonites. Glomerophenocrysts, composed of aggregates of small, subhedral pyroxenes, were found in a few rocks.

The groundmass pyroxene invariably appears to be of pigeonitic composition. In most rocks the groundmass is a fine-grained, intergranular aggregate of plagioclase laths with subhedral to anhedral, nearly colorless clinopyroxenes. The fineness of grain often makes difficult the determination of the optical properties of the pyroxene.

In several specimens interference figures in both phenocrysts and groundmass pyroxenes have been examined, and in all except one the groundmass pyroxene shows an optic axial angle of distinctly smaller aspect than that of the phenocrysts. The general trend of pyroxene differentiation thus appears to be away from diopside toward pigeonitic pyroxenes richer in iron. This trend is in agreement with that found by Barth[72] and by Wager and Deer.[73]

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[71] Powers, H. A., Differentiation of Hawaiian lavas: Am. Jour. Sci., 5th ser., vol. 30, p. 64, 1935.

[72] Barth, T. F. W., Crystallization of pyroxenes from basalts: Am. Mineralogist, vol. 16, p. 199, fig. 1, 1931; The crystallization process of basalt: Am. Jour. Sci., 5th ser., vol. 31, pp. 325-328, 1936.

[73] Wager, L. T., and Deer, W. A., Geological investigations in East Greenland, III. The petrology of the Skaergaard intrusion, Kangerdlugssuaq, East Greenland, Med. om Grønland, Komm. for Videnskabelige undersøgelser i Grønland, Bd. 105, Nr. 4, pp. 240-261, 1939.

BIOTITE

Biotite has been identified in only specimen 27 from the northeast side of Moaula cone. The biotite appears uniaxial, with a negative sign. It is distinctly pleochroic, with the formula X = very pale yellow, Y and Z = reddish-brown, and occurs as anhedral flakes, up to 0.2 mm across, occupying the interstices and projecting into vesicles. It is clearly of late magmatic origin.

Biotite is only rarely reported from any of the Pacific volcanoes,[74] and is generally believed to be rare in the rocks of Hawaii. It has, however, been recognized from scattered localities by a number of writers. It was first reported by Möhle from lavas of Molokai.[75] Cross noted its occurrence in the groundmass of one rock from Kauai,[76] and of another from the Waianae Range, Oahu.[77] Sidney Powers recorded its presence in oligoclase andesite from the West Maui volcano,[78] Stearns[79] reported a hornblende-biotite trachyte from the Waianae Range, Oahu, and Howard Powers noted biotite from Haleakala.[80] Biotite has recently been recognized by the writer as a late mineral in many of the younger lavas of the Waianae volcano.

MINOR ACCESSORY MINERALS

Apatite.—Minute prismatic grains of apatite are present in almost every rock. They are highly acicular in habit, and are characteristically enclosed in interstitial feldspar. The abundance of apatite in the interstitial material points to the concentration of PO_4 in the final residual fluid just previous to final consolidation.

Iron ore.—Both magnetite and ilmenite are common in the groundmass of the Kahoolawe lavas, making up generally from 10 percent to 15 percent of the rock. The grains range from euhedral to anhedral, but anhedral grains, formed late in the period of groundmass crystallization, are nearly always found to be in much greater abundance than are euhedral or subhedral grains. The patches of interstitial glass, and in some slides the interstitial feldspars, are commonly seen to be clouded with a very fine dust of iron

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[74] Barth, T. F. W., Mineralogical petrography of Pacific lavas: Am. Jour. Sci., 5th ser., vol. 31, p. 392, 1931.

[75] Möhle, F., Beitrag zür Petrographie der Sandwich- und Samoa-Inseln: Neues Jahrb., Beilage-Band 15, p. 74, 1902. Although first definitely recognized in Hawaiian basalts by Möhle, biotite had previously been recognized in trachyte from West Maui, and doubtfully in a lava from Haleakala by E. S. Dana, op. cit., pp. 463–465.

[76] Cross, W., op. cit., p. 45.

[77] Idem, p. 19.

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

[79] 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. 181 and 189, 1935.

[80] Powers, H. A., Hawaiian adz materials in the Haleakala section of Hawaii National Park: Hawaiian Acad. Sci. Proc. for 1938-1939, B. P. Bishop Mus. Special Pub. 34, p. 24, 1939.

ore, which in some is so dense as to render the material nearly opaque. Microphenocrysts of magnetite, euhedral to subhedral in outline, are rare. They reach a maximum diameter of 0.25 mm.

The abundance of iron ore dust in the interstitial glass, and of tiny anhedral granules of ore which separated late in the period of groundmass crystallization, appears to support the contention of Fenner that there is a relative concentration of iron in the final residues of crystallizing basalts,[81] although it should be noted that in those rocks which have least interstitial glass, it has a lighter color and lower refractive index than that of the more effectively quenched rocks in which glass is more abundant. In the thoroughly crystallized rocks there has been an extensive separation of ores at or near the very end of the period of crystallization, leaving the small amount of residual glass relatively free of iron oxides.

Both magnetite and ilmenite are present, judging from the outlines of the euhedral grains, magnetite showing square or diamond-shaped cross sections, while ilmenite is frequently lath-shaped. In anhedral grains it has not been possible to distinguish between them. Magnetite is usually more abundant than ilmenite, although in a few rocks this relationship is reversed.

A few tiny flakes of blood-red hematite, associated with the interstitial feldspar, were found in one specimen, a basaltic andesite (1) from a point near the coast north of Lua Kealialalo.

GLASS

Glass is not abundant. It is present in many rocks as minute patches occupying the interstices between the minerals of the groundmass. This interstitial glass is very pale brown to colorless, with a refractive index distinctly below that of balsam. In many specimens it is rendered cloudy, and in some nearly opaque, by a finely dispersed dust of iron ore. Where more abundant, it is darker brown in color, with a refractive index approaching or even exceeding that of balsam. In completely glassy firefountain ejecta it is deep-brown, with a refractive index of about 1.60, corresponding to a silica content of about 47 percent.[82]

TERTIARY AND QUATERNARY VOLCANICS

PRE-CALDERA LAVAS

Lavas of pre-caldera age may be identified with certainty only in the sea cliffs along the north and south sides of Kanapou Bay (pl.

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[81] Fenner, C. N., Crystallization of basalts: Am. Jour. Sci., 5th ser., vol. 18, pp. 225-253, 1929.

[82] George, W. O., The relation of the physical properties of natural glasses to their chemical composition: Jour. Geology, vol. 32, pp. 353-372, 1924.

16, *B*), and for a short distance in each direction from the bay mouth. Along the southern coast thin-bedded lavas (pl. 14, *A*) are cut by faults belonging to the rift zone which extended southwestward from the main caldera. These lavas are probably the correlative in age of the pre-caldera or earlier caldera-filling lavas at Kanapou Bay, but a definite correlation is not possible. Pre-caldera lavas may also be exposed in places along the lower slopes of the northern part of the island, but they cannot be certainly differentiated from post-caldera lavas.

The pre-caldera lavas, as exposed in the sea cliffs at Kanapou Bay, are thin flows of olivine basalt. The thickness of individual flows ranges from about 5 feet to 100 feet, an average thickness being in the order of 25 feet. Both aa and pahoehoe forms are represented, but the former are the more abundant. In hand specimen they are medium- to dark-gray, and range from nearly nonvesicular to highly vesicular and scoriaceous. Olivine phenocrysts are widespread, but not abundant. The same is true of phenocrysts of feldspar. Phenocrysts of pyroxene are rare in the hand specimens, although microphenocrysts of both rhombic pyroxene and pigeonite are occasionally encountered in thin sections. A few flows are nonporphyritic.

Specimen 13 is an olivine basalt from a point about 480 feet above sea level at the northwest corner of Kanapou Bay. It is a moderately vesicular, medium-gray rock with scattered phenocrysts of olivine reaching a diameter of 4 mm, enclosed in a thin shell of reddish-brown iddingsite, and tiny laths of plagioclase set in a microcrystalline groundmass. The vesicles range from a fraction of a millimeter to a centimeter in major diameter, and exhibit the irregular shapes characteristic of aa. Under the microscope the olivine phenocrysts show extensive rounding and embayment by resorption, and are encased in a thin armor of iddingsite which follows the embayed outlines of the olivine. The microphenocrysts of plagioclase show Carlsbad and albite twinning and slight normal zoning, averaging in composition about intermediate labradorite (An_{55}).

The groundmass is intersertal in texture, with a grain size averaging about 0.02 mm. It is made up principally of plagioclase, pigeonite, and iron ore. The former occurs as tiny lath-shaped, subhedral to anhedral grains, most of which are twinned on the Carlsbad law and some on the albite law. Extinction angles indicate a sodic labradorite (An_{53}). The pigeonite has a small $+2V$, and $Z \wedge c = 44°$. About 5 percent of interstitial feldspar with a small apparent optic angle is present, as well as a few percent of pale-brown interstitial glass, with a refractive index close to that of balsam. Many of the vesicles are lined with a thin layer of glass.

Number 16, collected 120 feet higher in the section, is very similar in mineralogical composition except that olivine phenocrysts are rare, and small in size. The structure is transitional between pahoehoe and aa. For the most part, the vesicles have the subspherical outlines characteristic of pahoehoe, but locally there are streaks of clinkery aa.

Specimen 19 from an altitude of 740 feet in the same gulch is rich in feldspar phenocrysts. The rock is medium-gray, with moderately abundant small vesicles of pahoehoe type. Lath-shaped white phenocrysts of plagioclase make up about 15 percent of the rock and reach a length of 5 mm. A few smaller phenocrysts of olivine and pyroxene are also present. Under the microscope the plagioclase phenocrysts show Carlsbad and albite twinning, and normal zoning from sodic bytownite to sodic labradorite. Many olivine grains are highly tabular parallel to (010), and are rounded and embayed by resorption. Most are surrounded by thin shells of iddingsite, and some of the smaller grains are completely altered to this mineral. The pyroxene is a pigeonite, with $+2V$ about $45°\pm$. It forms subhedral grains, the crystal faces of the prismatic zone being fairly well developed, but the base absent. The groundmass is intersertal, consisting of tiny laths of sodic labradorite, granules of pigeonite, and abundant magnetite in a matrix of colorless glass with a refractive index distinctly below that of balsam. Glass is unusually abundant, making up about 10 percent of the groundmass.

Specimen 14 is a completely nonporphyritic type lying about 60 feet stratigraphically above number 13. It is a dark gray, moderately vesicular aa. A few of the vesicles are partly filled with a white zeolite. Under the microscope a few small microphenocrysts of hypersthene and plagioclase lie in a groundmass which varies in texture from intergranular to intersertal, with an average grain size of about 0.03 mm. The plagioclase phenocrysts consist for the most part of a core of intermediate bytownite, with a narrow, strongly zoned rim passing rapidly into sodic labradorite (An_{51}). The hypersthene crystals show a large negative optic angle. Some grains are surrounded by a narrow shell of monoclinic pyroxene, and others are intergrown with monoclinic pyroxene, the *c* axes lying in parallel position. The groundmass consists of subhedral to anhedral grains of sodic labradorite (An_{51}), and pigeonite with $+2V = 25°\pm$ and $Z \wedge c = 41°$. Plagioclase constitutes about 40 percent, and pigeonite about 45 percent of the groundmass. Anhedral grains of feldspar and patches of pale-brown glass occupy the interstices. Subhedral to anhedral granules of iron ore form about 10 percent of the groundmass, and tiny acicular crystals of apatite are enclosed in the interstitial feldspar.

CALDERA-FILLING LAVAS

In contrast to the thin-bedded flows of pre-caldera age, exposed along the north and south shores of Kanapou Bay, the high sea cliff along the western shore of the bay is composed of massive, very thick flows (pl. 16, *A*) which were poured out on the floor of the old caldera, and ponded there to form lava lakes. These flows reach a maximum thickness of about 200 feet. As would be expected in view of their much greater thickness and resultant slower rate of cooling, these lavas are in general much coarser grained than are those of either the pre-caldera or post-caldera series. Throughout much of their thickness they are dense, and show well-developed columnar jointing. Several layers of yellow vitric tuff are interbedded with the lavas near the top.

Most of the earlier caldera-filling lavas are normal basalts, usually carrying a little olivine. They resemble in mineral composition the pre-caldera lavas. Interbedded with these, and becoming more abundant in the upper part of the section, are andesitic lavas similar to those of the post-caldera series. There is, in fact, no real break between the caldera-filling and post-caldera lavas. The rim of the caldera appears to have been lower on the south side than it was on the north,[83] and consequently lavas escaped from the caldera and flowed out over the slopes to the south, forming "post caldera" flows, while other flows or even parts of the same flows were still being impounded on the north by the walls of the caldera.

Typical of the caldera-filling lavas is a coarse-grained basalt (4) from a 50-foot flow near the southwest corner of Kanapou Bay. It is a medium-gray rock, nearly nonvesicular, equigranular, and with a diabasic texture. The average grain size is about 0.25 mm. In thin section the texture is seen to range from diabasic to intergranular and intersertal. It is made up largely of subhedral, lath-shaped crystals of plagioclase (40%) and subhedral to anhedral grains of pigeonite (45%). The plagioclase shows Carlsbad and albite twinning, and is slightly zoned from sodic labradorite in the center to calcic andesine on the outside. Many crystals contain abundant inclusions of glass. The pigeonite has a +2V ranging from very small to about 40°. A few grains are twinned on (001). Olivine is represented by a few scattered grains, rounded and embayed by resorption and largely altered to iddingsite, which are generally found as inclusions in the pyroxene. Iron ore makes up about 5 percent of the rock, the grains ranging from subhedral to anhedral in outline. Both magnetite and ilmenite are probably present. Apatite forms tiny, highly acicular crystals enclosed in interstitial feldspar and glass. Associated with colorless interstitial glass is a very feebly birefringent substance, with a refractive index notably less than that of balsam. Apparently identical material in other rocks has yielded interference figures with a small negative optic axial angle, and is regarded as probably sanidine. While classified as a basalt, this rock shows affinities with the basaltic andesites of the post-caldera lavas.

Specimen 20, from the uppermost part of the caldera-filling series, near the head of the gulch which empties into the northwest corner of Kanapou Bay, contains more phenocrysts of olivine than any other found on Kahoolawe. It is an olivine basalt, light-gray and moderately vesicular, with spherical vesicles of pahoehoe type reaching a diameter of 8 mm. Phenocrysts of fresh, glassy olivine reach a maximum size of 5 mm, and constitute about 15 percent of the rock. Many grains are surrounded by a narrow rim of iddingsite.

The groundmass has an average grain size of about 0.1 mm, and ranges in texture from intergranular to intersertal. Plagioclase makes up about 35 percent of the rock. It shows both oscillatory and normal zoning, and ranges in

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[83] Stearns, H. T., personal communication.

composition from labradorite-bytownite to sodic labradorite. Pigeonite composes another 40 percent of the rock. Iron ore ranges from subhedral to anhedral. Rod-shaped crystals of ilmenite are most abundant, but equant grains of magnetite are also abundant. The total amount of iron ore is about 5 percent. A few minute, needle-like grains of apatite are present. Colorless to very pale brown glass, with a refractive index distinctly lower than that of Canada balsam, fills interstices between the mineral grains.

A block of coarse-grained, gabbroic rock (21) was found in the fault breccia, near the head of the same gulch as specimen 20 at the northwest corner of Kanapou Bay. Its source is unknown, but it is probably of caldera-filling age. It is medium- to light-gray, with an even granular, granitic texture, and an average grain size of about 0.5 mm. It appears to be related in mineral composition to the oligoclase gabbro described by Cross from Waialae Canyon, on Kauai,[84] but it differs in the lack of olivine, a few grains of which are present in the Kauai rock, and also in the absence of aegirine and the apparent nontitaniferous character of its pyroxene. It more closely resembles coarsely granular intrusive rocks studied by the writer from the West Maui volcano.

Microscopically, this rock is found to consist of plagioclase (45%), pyroxene (20%), and alkalic feldspar (25%), with about 5 percent each of iron ore and interstitial glass. The plagioclase shows albite and Carlsbad twinning, and normal zoning from sodic labradorite to oligoclase-andesine. Many grains are surrounded by a narrow rim of albite (An_6). The pyroxene is a pigeonite with +2V about 40°, and $Z \wedge c = 41_c$. Many grains are twinned on (100). Between these lies anhedral alkalic feldspar, with a peculiar mottled extinction suggestive of microperthite, a large negative optic angle, and refractive index distinctly below that of balsam. Euhedral crystals of apatite as much as 0.2 mm long and 0.05 mm wide are fairly common, and more acicular, smaller crystals are abundantly distributed through the interstitial feldspar.

LAVAS OF CONES IN THE NORTH RIFT ZONE

Puu Kolekole and Lua Kealialuna are small lava domes, capped by cinder cones, lying on the north rift zone. Their age is uncertain, but because they are partly buried by post-caldera lavas, which are thin in this area, and because they are composed of normal olivine basalt, they are probably contemporaneous with either the early caldera-filling lavas or the uppermost pre-caldera lavas.

Specimen 44, from the top of Puu Kolekole, is a dark gray olivine basalt, sparingly vesicular, with the pahoehoe type of vesicle, and with moderately abundant phenocrysts of olivine reaching 2.5 mm across. In thin section the olivine phenocrysts are euhedral to subhedral and colorless. The larger crystals are surrounded by narrow rims of iddingsite, and many of the smaller ones are completely altered to that mineral. The groundmass is intergranular, with an average grain size of about 0.02 mm. It is composed of subhedral to anhedral laths of sodic labradorite (45%), pale-brown granules of monoclinic pyroxene (25%), and interstitial grains of oligoclase (10%), with about 15 percent iron ore, both magnetite and ilmenite being present.

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[84] Cross, W., Lavas of Hawaii and their relations: U. S. Geol. Survey Prof. Paper 88, pp. 14-15, 1915.

The lava from the Kealialuna dome is similar to that from Puu Kolekole. Specimen 41, from the west rim of Lua Kealialuna, is an olivine basalt unusually rich in pyroxene. It is a light-gray, very fine grained lava, containing a few olivine phenocrysts up to 3 mm across. Streaks of dense lava alternate with others containing moderately abundant, tiny vesicles, a fraction of a millimeter across, of the irregular aa type.

In thin section the olivine phenocrysts are colorless when fresh, but often stained pale-green by incipient alteration. They show a very large 2V, indicating the mineral to be rich in the forsterite molecule. Formerly euhedral grains have been altered around their edges to granular aggregates of pyroxene and iron ore, in which the shape of the original grain is still clearly outlined. Phenocrystic olivine makes up about 5 percent of the rock.

The groundmass is abnormally rich in pyroxene. It consists of nearly equidimensional grains of pigeonite, subhedral to anhedral in outline, with a small positive optic angle, lying so close together that they touch or nearly touch each other, with the interstices filled with anhedral feldspar. Pyroxene constitutes about 55 percent of the rock; sodic labradorite, about 25 percent; interstitial oligoclase, 7 percent; and iron ore, 8 percent. Large irregular grains and granular aggregates of iron ore, up to 0.3 mm across, are scattered throughout the slide, as well as smaller subhedral and euhedral grains of both magnetite and ilmenite.

POST-CALDERA LAVAS

Continued eruptions finally completed the filling of the Kanapou caldera, and thin flows from the summit vents moved unobstructed down the outer slopes of the mountain. Over the site of the caldera there was built a broad, gentle dome culminating at Lua Makika, the highest point on the island. Other lower domes were built along the principal rift zone to the west-southwest, constituting Puu Moiwi and the hill east of Lua Kealialalo. Firefountains built cinder and spatter cones at Moaula, Puu Moiwi, and Puu Kamama. Rocks of post-caldera age form the entire top of the present island, extending to, or nearly to the sea cliffs along the southern coast, and an unknown distance down the northern slope where they are for the most part inseparable in the field from the earlier lavas.

The post-caldera lavas range in composition from olivine basalts to andesites. The most abundant are those here classified as basaltic andesites. These are rocks of basaltic habit, close to basalt in composition, but in which the average composition of the feldspar falls within the range of andesine. Iddings has proposed the name *hawaiite* for these rocks.[85] They show every gradation into the true basalts.

The andesites form medium- to light-gray, massive flows, averaging about 40 feet in thickness. In texture they are both porphyritic

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[85] Iddings, J. P., Igneous rocks: vol. 2, p. 198, New York, 1913.

and nonporphyritic. Phenocrysts of olivine and plagioclase are abundant, and augite is much more common as phenocrysts than in the older lavas. Platy jointing is moderately well developed, and some specimens show a definite silvery sheen on these joint surfaces due to the parallel orientation of the cleavage surfaces of large numbers of minute feldspar crystals. Although less abundant on Kahoolawe, this trachytic texture is typical of many of the andesitic rocks of the Hawaiian volcanoes. It is present in those from the Waianae Range, Oahu, and from Haleakala, but it is best developed in the oligoclase andesites of the West Maui volcano.[86]

Specimen 11 is fairly typical of the andesites. It was collected from the basal post-caldera flow at the northern end of Waikahalulu Bay. It is light-gray and dense, with moderately well developed platy jointing parallel to the flow planes. A few small phenocrysts of feldspar and pyroxene and of brownish-green olivine altered around the edges to iddingsite are present. The joint surfaces show a distinct sheen due to the parallel arrangement of innumerable tiny cleavage faces of feldspar. Under the microscope the groundmass is pilotaxitic to trachytic. Fluidal texture is in most places pronounced. The olivine phenocrysts are rounded and embayed by resorption, and altered around the edges to iddingsite. In a few the iddingsite is surrounded by a narrow rim of finely granular pigeonite. The pyroxene phenocrysts show a +2V of about 60°. Some grains are twinned parallel to (001). Plagioclase phenocrysts show Carlsbad and albite twinning, and normal and oscillatory zoning. The core is zoned from sodic bytownite to intermediate labradorite, and is corroded and embayed by resorption. It is sharply separated from the rim of sodic andesine, a row of tiny crystals of pyroxene marking the contact. The average grain size of the groundmass is about 0.05 mm. It is made up of lath-shaped crystals of sodic andesine, oriented by flowage, and small granules of pigeonite, together forming about 75 percent of the rock. Iron ore, both magnetite and ilmenite, constitutes about 15 percent. A small amount of oligoclase and colorless glass are interstitial.

Olivine basalts are present throughout the section of post-caldera lavas, but are relatively unimportant in total volume. They are indistinguishable from the more massive pre-caldera flows. Specimen 29, collected about one mile S. 60° W. of Makika crater, is typical. It is a dark-gray, moderately vesicular pahoehoe, with abundant phenocrysts of olivine and plagioclase reaching a length of 7 mm. Microphenocrysts of pyroxene are present in thin section. The texture of the groundmass is intergranular, and locally diabasic, some feldspar laths being partly or completely surrounded by pyroxene. The plagioclase phenocrysts show minor normal zoning, from intermediate to sodic bytownite. The olivine phenocrysts are much rounded and embayed by resorption, and are surrounded by a narrow rim of reddish-brown iddingsite. The pyroxene microphenocrysts are pale-brown in color, with +2V about 50°, and weak dispersion of the bisectrices. Twinning parallel to (001) is present in

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[86] Cross, W., Lavas of Hawaii and their relations: U. S. Geol. Survey Prof. Paper 88, pp. 26-27, 1915.
Washington, H. S., and Keyes, M. G., Petrology of the Hawaiian Islands: VI. Maui: Am. Jour. Sci., 5th ser., vol. 15, p. 206, 1928.

a few grains. Many of the phenocrysts are compound grains, made up of several variously oriented, smaller grains of pyroxene. The pyroxene of the groundmass appears to be very similar to that of the microphenocrysts. The groundmass plagioclase ranges from intermediate to sodic labradorite. It shows normal zoning, and albite, pericline, and Carlsbad twinning. Iron ore includes both magnetite and ilmenite. To a small extent, the interstices are filled with pale-brown glass, and with very finely crystalline material, made cloudy by a finely dispersed dust of iron ore.

Typical of the basaltic andesites is specimen 30, collected about ½ mile east of Puu Moiwi. It is a moderately vesicular rock containing a few small phenocrysts of plagioclase set in a light-gray, microcrystalline groundmass. It was collected from an aa flow about half a mile N. 70° E. of Puu Moiwi, in the south fork of Ahupu Gulch. The phenocrysts make up about 5 percent of the rock. Under the microscope, they show normal zoning from sodic bytownite to intermediate andesine, with no evidence of magmatic resorption. They are set in an intergranular groundmass composed of intermediate andesine and pigeonite, with a small amount of interstitial oligoclase. Both magnetite and ilmenite are present, but the former seems to be somewhat the more abundant. Apatite forms minute, highly acicular crystals enclosed in the oligoclase. A small amount of very pale brown glass, with refractive index distinctly lower than that of balsam, occupies interstices between the minerals. It is clouded with fine, dusty iron ore.

Specimen 32, collected in Ahupu Gulch nearly a mile north of Puu Moiwi, is perhaps more typical of this group of rocks. It is a dense, medium-gray rock with moderately abundant phenocrysts of olivine, reaching 5 mm in diameter, and less abundant, smaller phenocrysts of plagioclase. The olivine has a large 2V, and is surrounded by reddish-brown iddingsite. The plagioclase phenocrysts show normal zoning from calcic to sodic labradorite and constitute about 5 percent of the rock. The groundmass is intergranular, with an average grain size of about 0.05 mm. It is made up of lath-shaped grains of calcic andesine (35%); subhedral to anhedral grains of pigeonite (25%); olivine, showing no signs of alteration (10%); interstitial oligoclase (10%); and euhedral to anhedral grains of magnetite (10%).

Specimen 26, collected on the southwest side of Puu Kolekole, is very similar to specimen 32, except for the absence of olivine in the groundmass, and the more sodic composition of the groundmass plagioclase, which is an intermediate andesine.

A similar rock was collected by Sidney Powers close to the northern coast, near the house at Kuheia Bay, and has been analyzed chemically by Washington.[87] The analysis is given in the accompanying table, together with that of the only analyzed rock from the neighboring island of Lanai. The locality given is so vague that it has not proven possible to duplicate the specimen. The rock is described by Washington as an andesine basalt, ophitic in texture, consisting of tabular andesine and granular augite, with a few grains of olivine, and some very dusty, interstitial glass. It is compared to similar rocks from Mauna Kea and Kohala, Hawaii.

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[87] Washington, H. S., Petrology of the Hawaiian Islands; I. Kohala and Mauna Kea, Hawaii: Am. Jour. Sci., 5th ser., vol. 5, pp. 493-494, 1923.

Chemical analyses and norms of rocks from Kahoolawe and Lanai

	(1)	(2)
SiO_2	51.12	51.35
Al_2O_3	12.91	15.60
Fe_2O_3	1.75	1.34
FeO	9.71	8.50
MgO	7.88	6.70
CaO	10.56	10.40
Na_2O	3.94	2.43
K_2O	0.21	0.64
H_2O+	0.19	0.44
H_2O-	0.12	0.09
TiO_2	1.91	1.89
P_2O_5	0.27	0.28
MnO	0.09	n.d.
	100.66	99.66
Sp. gr.	3.039	2.878
at	22°	21°

Norms

	(1)	(2)
Q	.....	2.04
Or	1.11	3.89
Ab	33.64	20.96
An	16.68	29.47
Di	27.69	16.57
Hy	0.90	20.18
Ol	13.55	.....
Mt	2.55	1.86
Il	3.65	3.65
Ap	0.67	0.67

(1) Basaltic andesite ("ophitic andesine basalt"): "lowest flow, near house, Kahoolawe Island." Washington analyst; Washington, H. S., op. cit., p. 493.
(2) "Aphyric basalt . . . Elevation 1,360 feet, Lanai Island." Washington analyst; Washington, H. S., op. cit., p. 487.

On the northeast side of Moaula cone a thin flow, ranging from a few inches to two feet in thickness, is plastered over the cinders. It apparently represents a burst of spatter from the firefountain, of great enough volume to coalesce and form a small, local flow down the side of the cinder cone. This rock (27) is dense, medium- to dark-gray, with moderately abundant phenocrysts of olivine partly altered to iddingsite that range up to 8 mm across, and a few phenocrysts of pyroxene and plagioclase, in a microcrystalline groundmass. The plagioclase phenocrysts are composed of a core of intermediate labradorite, much rounded by resorption, and surrounded by a narrow rim of normally zoned feldspar passing to intermediate andesine at the outer edge. Inclusions of pale-brown glass are abundant in the outer zones. A few colorless, subhedral phenocrysts of augite, with $+2V = 55° \pm$ and weak dispersion of the optic axes and bisectrices, are present. Hypersthene, in colorless to very faintly pleochroic subhedral grains, forms about 2 percent of the rock.

The groundmass is intergranular to intersertal, with an average grain size of about 0.02 mm. It consists of intermediate andesine, clinopyroxene, olivine, and iron ore. Feldspar and femic minerals are present in about equal quantities, and pyroxene is notably more abundant than olivine. Large flakes of biotite, reaching 0.2 mm across, occur interstitially and projecting into vesicles. The biotite appears uniaxial, with $X =$ very pale yellow, and Y and $Z =$ reddish-brown. It makes up about 4 percent of the thin section. Biotite is completely absent from specimen 28 collected from the same flow a little to the south and down the slope of the cone.

Lava flows, a few inches to two feet thick, are intercalated in the cinders of Moiwi cone. These flows supplied the ancient Hawaiians with materials for the manufacture of stone adzes (pl. 18, *B*). They are as dense as the dike rocks, but free from the platy jointing, detrimental to the manufacture of stone artifacts, which is characteristic of the dikes. A partly finished adze collected at this quarry by Stearns, has been studied in thin section. It (specimen 9) is a very dense, dark-gray rock, with a few, small phenocrysts of white feldspar. The chipped surface is covered by a very thin reddish-brown patine. In thin section, the rock is seen to consist of scattered small laths of plagioclase and granules of pyroxene and iron ore in an extremely fine-grained groundmass resembling in appearance "salt and pepper" devitrification of volcanic glass. The plagioclase phenocrysts are intermediate labradorite; the pyroxene is pigeonitic, with +2V about 45°. The groundmass is a very fine grained, allotriomorphic aggregate of feldspar and pyroxene, with an average grain size of about 0.003 mm.

INTRUSIVE ROCKS

Dikes, ranging from a few inches to a few feet in thickness, and standing nearly vertical, cut both pre-caldera and caldera-filling lavas in great number along the northwestern shore of Kanapou Bay. This swarm of dikes represents a cross section of one of the rift zones of the volcano, and shows the same range in composition as the lavas. They are mostly dense, although a few with vesicular centers were noted. Thin glassy selvages are usually present, and many show well-developed columnar cross jointing. A few dikes are exposed along the southern coast, and a few in Ahupu Gulch north of Puu Moiwi.

Specimen 6, from a dike near the southwestern corner of Kanapou Bay, is a moderately to highly vesicular, dark-gray nonporphyritic basaltic andesite with the irregular aa type of vesicle. The texture is intergranular to intersertal. The rock is made up of plagioclase, zoned from calcic to sodic andesine, pigeonite, iron ore, tiny acicular grains of apatite, and a small amount of colorless, interstitial glass. A few small, rounded grains of iddingsite are present.

Specimen 31, which is similar in composition to specimen 6, is from a 1.5-foot dike cutting thin-bedded lavas at an altitude of 700 feet in Ahupu Gulch north of Puu Moiwi. It is medium- to light-gray, and moderately vesicular with the aa type of vesicles. A few phenocrysts of olivine up to 1 mm across, and of hypersthene up to 0.5 mm across, are set in an intersertal groundmass with an average grain size of 0.1 mm. The olivine phenocrysts (3%) are somewhat rounded by resorption, and are enclosed in a narrow rim of iddingsite. The hypersthene (5%) occurs in colorless subhedral grains, showing no definite evidence of resorption, although a few are encased in a thin armor of clinopyroxene. The groundmass consists of small laths of calcic andesine (28%); interstitial oligoclase (7%); pigeonite, with a very small positive optic angle (35%); olivine, largely altered to iddingsite (2%); and iron ore (15%). The interstices are filled with pale-brown glass (5%), clouded with pulverulent iron ore.

A pod-shaped mass of coarse-grained intrusive diabase is enclosed in the pre-caldera lavas near the southwest corner of Kanapou Bay. Its age is unknown. It may be pre-caldera or younger. It is a medium-gray, equigranular rock, with an average grain size of about 0.7 mm. The texture ranges from diabasic to intersertal. The rock is composed of about equal quantities of pigeonite and plagioclase, the latter showing normal zoning from sodic labradorite to calcic andesine. Interstitial pale-brown glass, clouded with a fine dust of iron ore, is fairly abundant, and has a refractive index distinctly below that of balsam. A few pseudomorphs of iddingsite after olivine are present. They show evidence of extensive corrosion by the magma, and are usually found imbedded in grains of pyroxene. A few small, acicular crystals of apatite are included in the feldspar. Subhedral to anhedral grains of iron ore, a few slightly altered to limonite, form about 5 percent of the rock.

PYROCLASTIC ROCKS

Pyroclastics are not abundant on Kahoolawe. The pre-caldera (?) lava domes of Puu Kolekole and Lua Kealialuna are topped by small cones composed of cinder and spatter. Moaula, Puu Moiwi, and Puu Kamama are similar features formed at post-caldera vents. Except that they are finer grained and more glassy, the cinders are microscopically similar to the associated flows.

A vitric lapilli-tuff crops out along the northern base of the Kolekole cinder cone. It is composed of dark-brown glassy ribbon lapilli and other firefountain debris, from a fraction of an inch to an inch and a half in diameter, set in a fine, powdery ocherous matrix. Under the microscope the matrix is seen to be palagonite with a refractive index distinctly below that of balsam. Both isotropic and fibrous, faintly polarizing forms are present. The glass of the lapilli is dark-brown, with a refractive index close to 1.60.

Several beds of friable brownish-yellow tuff, 1 or 2 feet thick, are intercalated with upper caldera-filling lavas along the west side of Kanapou Bay (p. 139). Granularity generally ranges between 0.05 and 1.0 mm. For an inch or two beneath overlying lava flows they are baked to a hard, dark brownish-red material resembling brick. The upper bed is thicker than the others, reaching a maximum of about 30 feet in the central part of the cliff, and thinning rapidly both northward and southward. Where it is thickest it contains abundant lapilli of dark-brown glass, from 0.1 inch to an inch or a little more in diameter. In this part it resembles the lapilli tuff from Puu Kolekole described above. The fine tuffs, and the matrices of the coarser ones, are composed microscopically of very fine grained, weakly polarizing, fibrous yellowish-brown palagonite similar to that in many other Hawaiian tuffs.[88] It should be noted, however, that the refractive index is greater than that of balsam and therefore considerably higher than that of the typical Iceland palagonites.[89]

The tuffs and lapilli-tuffs interbedded with the lavas at Kanapou Bay were originally completely vitric. They were formed by material drifting from firefountains which erupted in the floor of the caldera during its filling.

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[88] Wentworth, C. K., Ash formations of the island Hawaii: Hawaiian Volcano Observatory, Special Rept. No. 3, pp. 126-134, 1938; Pyroclastic geology of Oahu: B. P. Bishop Mus. Bull. 30, pp. 101-110, 1926.

[89] Peacock, M. A., Petrology of Iceland, the basic tuffs: Royal Soc. Edinburgh Trans., vol. 55, pp. 51–76, 1926.

Sidney Powers has recorded the presence of probable melilite in a pebble of altered tuff collected on the beach near Kuheia Cove. The specimen was examined for him by C. H. Warren.[90] Nothing resembling melilite has been seen by the present writer in rocks from Kahoolawe.

POST-EROSIONAL BASALTS

At five points along the cliff in Kanapou Bay, small eruptions took place long after other volcanic activity on the island had ceased. These produced small flows and masses of cinder which mantle the sea cliff and in places overlie talus. Dikes cutting the talus are attributed to the same eruptive period (pl. 18, *A*).

Kahoolawe lies directly on the continuation of the southwest rift zone of Haleakala volcano, and it is probable that these post-erosional eruptions are the result of activity along this rift. The composition of the rocks unfortunately resembles too closely that of many Haleakala lavas, as well as earlier lavas of Kahoolawe, to permit their assignment on this basis to either volcano.

All these post-erosional lavas are olivine basalts. Specimen 18 is a gray, dense, nonporphyritic lava from a fissure flow erupted through talus and fault breccia at an elevation of about 730 feet at the northwest corner of Kanapou Bay. It has an intergranular texture with an average grain size of about 0.07 mm, and microphenocrysts of olivine and pyroxene only a little larger than the minerals of the groundmass. Olivine forms about 5 percent of the rock. The olivine phenocrysts are partly or completely altered to iddingsite, and in many grains the iddingsite is surrounded by an outer rim of second generation olivine. The groundmass pyroxene (40%) is a pigeonite. The plagioclase laths show Carlsbad and albite twinning, and normal and oscillatory zoning from intermediate labradorite to andesine-labradorite (30%). About 10 percent of interstitial oligoclase is present, and about 15 percent of iron ore, apparently largely ilmenite. Minute acicular crystals of apatite are enclosed in the feldspar and are especially abundant in the interstitial oligoclase.

A finely vesicular, dark gray, very fine grained basalt (3) associated with cinders about 500 feet above sea level in the gulch entering the southwest corner of Kanapou Bay, is quite similar to the rock just described. Former olivine microphenocrysts have been completely altered to iddingsite. A few microphenocrysts of pyroxene have a +2V of about 60°. In contrast, the groundmass pyroxene is a pigeonite with +2V about 30°. The plagioclase is an intermediate labradorite. Dark-brown glass, with a refractive index distinctly higher than that of balsam, and heavily clouded with a fine dust of iron ore, constitutes about 45 percent of the rock.

About 0.3 mile north of the southwest corner of Kanapou Bay, a short distance above sea level, a narrow dike cuts recent talus (pl. 18, *A*). Specimen 5 from this dike is a slightly vesicular, dark-gray rock with small phenocrysts of olivine and plagioclase in a very fine grained groundmass. Under the micro-

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[90] Powers, S., Notes on Hawaiian petrology: Am. Jour. Sci., 4th ser., vol. 50, p. 261, 1920.

scope the olivine was found to be largely altered to iddingsite. The crystal outlines are sharp, showing little or no evidence of resorption. In a few grains the iddingsite shows slight zonal structure, a narrow outer rim extinguishing at a slightly different position from the core. The core is a single massive crystal of iddingsite; the rim is less regular in structure, and is formed of many tiny fibers, showing slight variations in orientation, but nearly normal to the *c* axis of the olivine. The plagioclase phenocrysts are zoned from calcic to sodic labradorite. The microlites are of sodic labradorite. Pigeonite is the most abundant mineral of the groundmass. A small amount of interstitial oligoclase is present and often includes minute needles of apatite. Iron ore forms about 15 percent of the rock. Lath-shaped euhedral grains are ilmenite, and many of them are coated and surrounded by cloudy leucoxene.

MAGMATIC DIFFERENTIATION

The general trend of differentiation at Hawaiian volcanoes has been set forth by Daly, [91] Cross,[92] and Powers.[93] More recently, the subject has been discussed by Barth[94] for Pacific volcanoes in general, and by Howard Powers[95] specifically in regard to Hawaiian volcanoes.

The course of the differentiation from olivine basalts toward more salic, and in some toward more femic types, has been recognized by all of these writers, but there has been less unanimity as to the details of the changes, and the processes which brought them about. Most writers have considered crystal settling in a fluid magma to be the principal factor in the differentiation process.

The pre-caldera lavas of Kahoolawe are closely similar petrographically to the early lavas of all the other Hawaiian volcanoes. The universal similarity of these "primitive" olivine basalts, even though some volcanoes are much older than others, was cited by Cross[96] as evidence that there has been little or no differentiation in the main magma reservoir beneath the Hawaiian islands throughout the history of the visible volcanoes. Moreover, as was also pointed out by Cross, the small amount of variation in composition of these lavas throughout the early history of the building of the cone indicates that differentiation was ineffective at each vent during all of this period. This is the epoch of frequent eruption of voluminous flows of highly fluid basalt. The magma column at no

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[91] Daly, R. A., Magmatic differentiation in Hawaii: Jour. Geology, vol. 19, pp. 289-316, 1911.

[92] Cross, W., Lavas of Hawaii and their relations: U. S. Geol. Survey Prof. Paper 88, pp. 86-93, 1915.

[93] Powers, S., Notes on Hawaiian petrology: Am. Jour. Sci., 4th ser., vol. 50, pp. 278-280, 1920.

[94] Barth, T. F. W., Mineralogical petrography of Pacific lavas: Am. Jour. Sci., 5th ser., vol. 21, pp. 526-529, 1931.

[95] Powers, H. A., Differentiation of Hawaiian lavas: Am. Jour. Sci., 5th ser., vol. 30, pp. 68-71, 1935.

[96] Op. cit., p. 93.

time remains closed and quiescent for a long enough period to allow any notable differentiation of any kind to take place. It seems certain that these early olivine basalts are to be regarded, as they were by Howard Powers,[97] as the primary magma from which the other varieties have been derived.

The trend of differentiation is suggested by the apparent changes in composition of the minerals crystallizing in these rocks. Later olivine is probably more iron-rich than earlier olivine. The same is true of the pyroxenes. The feldspars show a trend from those rich in lime toward members richer in soda. The crystallization history of the olivine basalts thus shows a change in the composition of the liquid residuum toward a magma richer in alkalies and iron, poorer in lime and magnesia, than was the parent magma. This is precisely the trend found by Fenner as a result of a general study of crystallization in basalts.[98] It is also the trend found by Wager and Deer in their study of the crystallization history of the Skaergaard intrusion in East Greenland.[99]

Differentiation on Kahoolawe has progressed to a much smaller extent than in several of the other Hawaiian volcanoes. Oligoclase andesites are widespread on West Maui, and on Kohala, Hawaii. Soda trachytes are known from West Maui, Hualalai, and Waianae volcano on Oahu. Nephelite basalts are present on the Koolau volcano, Oahu, and on Kauai. In contrast, the most salic type found on Kahoolawe is an andesine andesite, and by far the most abundant salic types are basaltic andesites, close to basalt in composition. Nephelite rocks have not been found on Kahoolawe.

In summary, differentiation showed little or no effect on the Kahoolawe lavas in the early period of frequent eruptions during which the major part of the cone was built. The lavas remained olivine basalts, and show little variation among themselves. It was not until after the summit caldera had been formed by collapse and partially refilled, that the lavas start to deviate appreciably from their primitive composition. Eventually, eruptions probably became less frequent, and the magma chamber and conduit remained closed and quiescent for longer periods. This permitted the development of more salic types, and the post-caldera lavas of Kahoolawe are largely basaltic andesites, with occasional layers of olivine basalt like that of the earlier lavas, and a few flows of andesite.

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

[98] Fenner, C. N., The crystallization of basalts: Am. Jour. Sci., 5th ser., vol. 18, pp. 225-253, 1929.

[99] Wager, L. R., and Deer, W. A., op. cit., pp. 240-261.

The late, post-erosional lavas are olivine basalts, and may represent a return of the eruptive magma of Kahoolawe to a composition similar to that of the lavas which initiated the growth of the volcano. However, in view of their position on the prolongation of the Ulupalakua rift zone of Haleakala, together with the long intervening period of inactivity when the volcanic hearth of Kahoolawe was apparently extinct while the Ulupalakua rift has remained active until historic times,[100] it appears more probable that the post-erosional lavas at Kanapou Bay are genetically allied with Haleakala rather than with Kahoolawe.

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[100] The last eruption of Haleakala occurred near Makena, Maui, about the year 1750: cf. Powers, S., op. cit., p. 265.

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