THE GEOLOGY OF LANAI

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INTRODUCTION

HISTORICAL SKETCH

Lanai is the sixth in size of the eight principal islands of the Hawaiian group. It is exceeded in area by Hawaii, Maui, Oahu, Kauai, and Molokai; Niihau and Kahoolawe are smaller.

From selected view points on Lanai, the near lying islands, Molokai, west Maui, and Kahoolawe are nearly always in sight, and the imposing summit of Haleakala is visible much of the time. In very clear weather, parts of Oahu, 65 miles distant, may be seen. More rarely, Hawaii and the summit peaks of Mauna Kea and Mauna Loa come into view.

Lanai was first settled by the Hawaiians about 1400 A. D.—several hundred years after the first Polynesian migrations to Hawaii.[1] 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 Rev. 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

[1] For an account of the early history and archaeology of Lanai, see The island of Lanai, a survey of native culture, by Kenneth P. Emory: B. P. Bishop Mus. Bull 12, 1924.

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 Company. Between 1838 and 1910 the native population decreased from 1200 to less than 130, partly by removal to other islands.

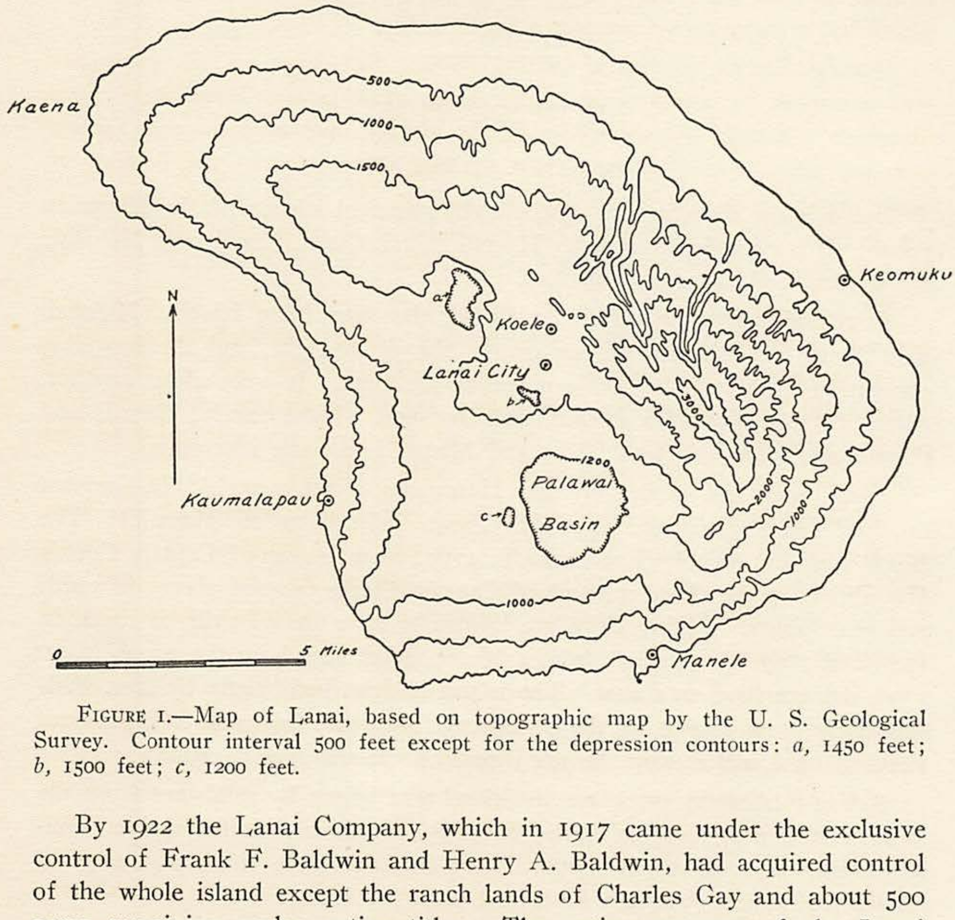

FIGURE 1.—Map of Lanai, based on topographic map by the U. S. Geological Survey. Contour interval 500 feet except for the depression contours: *a*, 1450 feet; *b*, 1500 feet; *c*, 1200 feet.

By 1922 the Lanai Company, 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 Company was purchased in December, 1922, by the Hawaiian Pineapple Company of Honolulu.

There are five centers of population on Lanai. (See fig. 1.) Koele, the headquarters of the Lanai Ranch, has a population of about 80, and was until recently the principal settlement on the island.

Lanai City has a population of about 300. It is the site of the post office established in May, 1924, and the headquarters of the Hawaiian Pineapple Company (Pl. I, *A*), which is constructing office buildings, public buildings, warehouses, dwellings, and shops to provide for about 250 men and their families. An extensive electric power plant and a refrigerating plant with a capacity of 2,000 pounds of ice a day are under construction. The water supply is pumped from a development tunnel in Maunalei Gulch against an 800 foot head, by a 40 horsepower, 2,200 volt motor. The pump has a capacity of 200,000 gallons a day.

Manele Harbor affords a natural shelter for ships. Until the wharf was destroyed by a storm in April, 1924, small power boats were taken alongside. Larger ships anchor in the harbor and cargoes and passengers are taken ashore in boats. A loading chute permits the loading of cattle direct from the shore to the ship on the rocky south margin of the harbor. Until the recent development at Kaumalapau, Manele was the principal port of the island.

At Keomuku, power boats of light draft are anchored off shore and cargoes transferred in skiffs. The landing place, a straight sandy shore, has no protection from storms, but wave action on this side of the island is normally very moderate. Keomuku has a population of about fifty people, principally Hawaiians. Most of the men are employed by the Lanai Company in connection with the cattle industry.

A reentrant in the cliff-bordered west shore at Kaumalapau has been selected by the Hawaiian Pineapple Company as a harbor. By dredging and the construction of a breakwater, vessels of 27 foot draft and 400 feet in length will be conveniently accommodated. Kaumalapau is destined to replace Manele as the chief harbor of the island.

A macadamized road now connects Kaumalapau with Lanai City. Before this highway was built by the Hawaiian Pineapple Company, the principal roads of the island were from Manele to Koele and a road formerly passable for wagons and light automobiles extending from Koele northeast to the coast and thence southeast along the shore to Keomuku (Pl. III, *C*). The Koele-Manele road is kept in repair by the county, but the road from Koele to Keomuku is now hardly passable for vehicles. The Central Plateau and "the Basin" of Lanai may be traversed in any direction by automobile.

Practically all parts of Lanai are accessible by horseback. A number of trails traverse the summit area and extend down the ridges of the northeast and east slopes. The south, west, and north slopes at elevations above about 700 feet also may be crossed in nearly all directions by saddle horses. Below this elevation, travel in some sections is restricted to radial directions and is abruptly terminated at the edge of the coastal pali. The east, northeast, and north shores are easily traversed on horseback. The south and west coast may be skirted on foot with more difficulty. Travel on the coastal bench is interrupted at intervals of a mile or two by sea caves and short reaches of this bench are entirely inaccessible from any direction except by swimming or by ropes from above.

The island is divided at present into ten principal grazing tracts each comprising four thousand to eighteen thousand acres. Many smaller areas are fenced in the plateau and basin area surrounding Koele. The central summit area of forest comprises about five thousand acres.

The traditions of the natives and the presence of dry tree stems and roots in eolian deposits over much of its area make it fairly certain that Lanai was wooded to the sea coast at the time it was first visited by the Hawaiians.

At present about 5,000 cattle and 200 horses owned by the Lanai Company are kept on the island. About 200 sheep and 100 wild goats are at large and a few deer remain in the more inaccessible parts of the upland. Cats, which were once numerous, are now nearly all killed off. The mongoose, common on other Hawaiian islands, has never been introduced. Pheasants and turkeys, introduced many years ago, are present in considerable numbers.

PURPOSE AND SCOPE OF INVESTIGATIONS

The recent purchase of Lanai by the Hawaiian Pineapple Company and the proposed utilization of large parts of its area for the growth of pineapples has led to increased interest in its physical features. As in other islands of Hawaii there is urgent need on Lanai of larger supplies of fresh water.

The present study was undertaken to procure information on the geology of the island with particular reference to available supplies of water, and to supplement my investigations of special geologic features in Hawaii[2] by a study of all the areal and structural features of a single island. For this purpose, Lanai is well adapted; it is small and easily accessible. A recent topographic map of the island was made available for the survey and it was found possible to complete a detailed survey during the time at my disposal.

Field studies were begun on April 9, 1924, and completed on May 21. Most of the central part of the island was reached from Lanai City by automobile and much of the remainder of the island was visited on horse-

[2] Wentworth, Chester K., Pyroclastic geology of Oahu: B. P. Bishop Mus., Bulletin in preparation.

back. Practically all parts of the south and west coasts were traversed on foot, either at the top of the pali or along the coastal bench. A boat trip northward around the shore from Kaumalapau to Keomuku afforded further opportunity to examine the west and north coasts.

Approximately equal attention was given to physiography, structure, and general petrology. Detailed petrographic studies of the specimens of rocks collected is reserved for a later time.

ACKNOWLEDGMENTS

My study of Lanai was made possible by the generosity of the Hawaiian Pineapple Company. A contribution from the Company to Bernice P. Bishop Museum was utilized to supplement my stipend as Bishop Museum Fellow, enabling me not only to complete a survey of Lanai, but also to make comparative studies on other islands. S. T. Hoyt, H. M. Goodale, and Clarence White of the Pineapple Company were of much assistance in making arrangements for field work. In the course of the work, D. E. Root, Engineer in Charge of Construction, and George Munro, Manager of the Lanai Ranch, furnished transportation and guided me to points of especial interest. The long residence of Mr. Munro on Lanai and the variety and accuracy of his observations made his cooperation of exceptional value.

Albert O. Burkland, Topographic Engineer in Charge, United States Geological Survey, Honolulu, first called my attention to certain geological problems on Lanai and has made valuable suggestions regarding the conduct of field work. To Professor H. S. Palmer of the University of Hawaii, who spent four days with me in the field, I am indebted for valuable suggestions and for contributions to the section on ground water.

PHYSIOGRAPHY

SIZE AND FORM OF LANAI

As determined by planimeter measurements on the recently completed Lanai sheet of the United States Geological Survey, Lanai has an area of 140.8 square miles. It is compact in form and departs from rough circularity chiefly by a protruding point at the northwest with a corresponding reentrant to the south. The extreme north-south length is 13¾ miles;

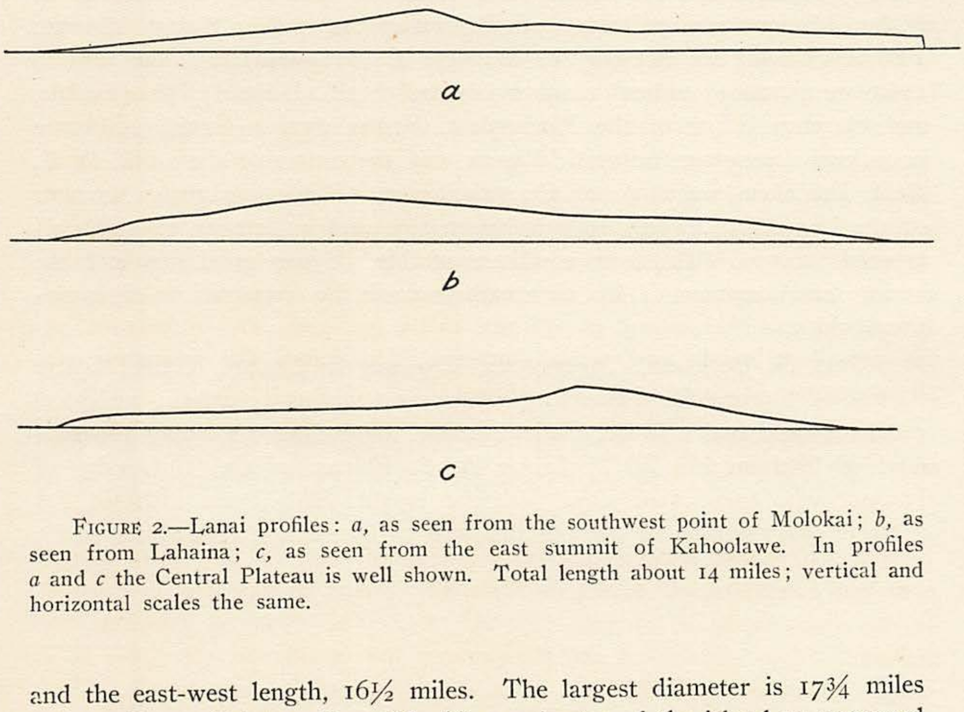

FIGURE 2.—Lanai profiles: *a*, as seen from the southwest point of Molokai; *b*, as seen from Lahaina; *c*, as seen from the east summit of Kahoolawe. In profiles *a* and *c* the Central Plateau is well shown. Total length about 14 miles; vertical and horizontal scales the same.

and the east-west length, 16½ miles. The largest diameter is 17¾ miles —from Kaena Point to Kamaiki. The perimeter of the island as measured from headland to headland across bays less than a half mile wide, is 48.7 miles as compared to 42 miles for a circle of equivalent area. The actual water line perimeter as closely as it may be measured on the map is 55.5 miles.

The highest point on Lanai, 3,370 feet, is somewhat east of the center of the island. Considerable parts of the center of the island lie between 1,000 and 2,000 feet. (See fig. 2 and Table No. 1.)

TABLE NO. I. DISTRIBUTION OF AREA OF LANAI WITH RESPECT TO ELEVATION

ELEVATION	AREA IN SQ. MILES	PER CENT
0- 500	33.9	24.1
500-1000	29.7	21.1
1000-1500	42.7	30.4
1500-2000	26.0	18.4
2000-2500	5.2	3.7
2500-3000	2.7	1.9
3000-3370	.6	.4
	140.8	100.0

PHYSIOGRAPHIC PROVINCES

In most parts of the world physiographic provinces are based primarily on the structure and petrology of the underlying rocks; minor subdivisions are based on process or on stage of development. The entire Hawaiian group of islands may be regarded as a single physiographic province showing remarkable uniformity of topographic forms. Differences exist, however, between islands and between parts of the same island and these warrant further subdivision. While the rocks of the island of Lanai are essentially uniform in resistance to erosion and original structure and furnish no basis for important physiographic distinctions, certain minor divisions may be established on the basis of topographic differences due to faulting, to altitude above sea level, and to relation of the prevailing winds and ocean currents. On Lanai the following six physiographic provinces may be outlined:

Pali Coast, Beach Coast, Flown Margin, Flow Slope, Central Plateau, and High Summit (fig. 3).

Pali Coast

The Pali Coast includes the west and south half of the Lanai coast zone and extends from Kaena to Kamaiki. Inland it may best be limited by the sharp brow of the pali (Pl. III, *B*). Two types of coastline are included: One consists of alternating bays and headlands; the other is a simple sea-facing pali flanked by a very narrow bowlder beach. The pali and beach type has its main development on the southwest point of the island where for three miles it is unbroken and where the pali at the highest point rises more than a thousand feet above sea level (Pl. III, *A*). The bays and headlands type is more irregular and the pali is neither so high nor so continuous. Short bowlder beaches are developed at the heads of the bays into which gulches commonly discharge. On the points and along the sides of the headlands are irregular remnants of an abraded bench which now stands from five to ten feet above sea level (Pl. II, *A*).

Back of this bench rises a cliff which still stands nearly vertical and is from ten to two hundred feet high. The wave attack on the foot of cliffs which are flanked by this bench is relatively feeble and is similarly weak on the bench itself. The irregularity of the surface of the bench is due to differential wave work on the non-uniform basalt of the lava

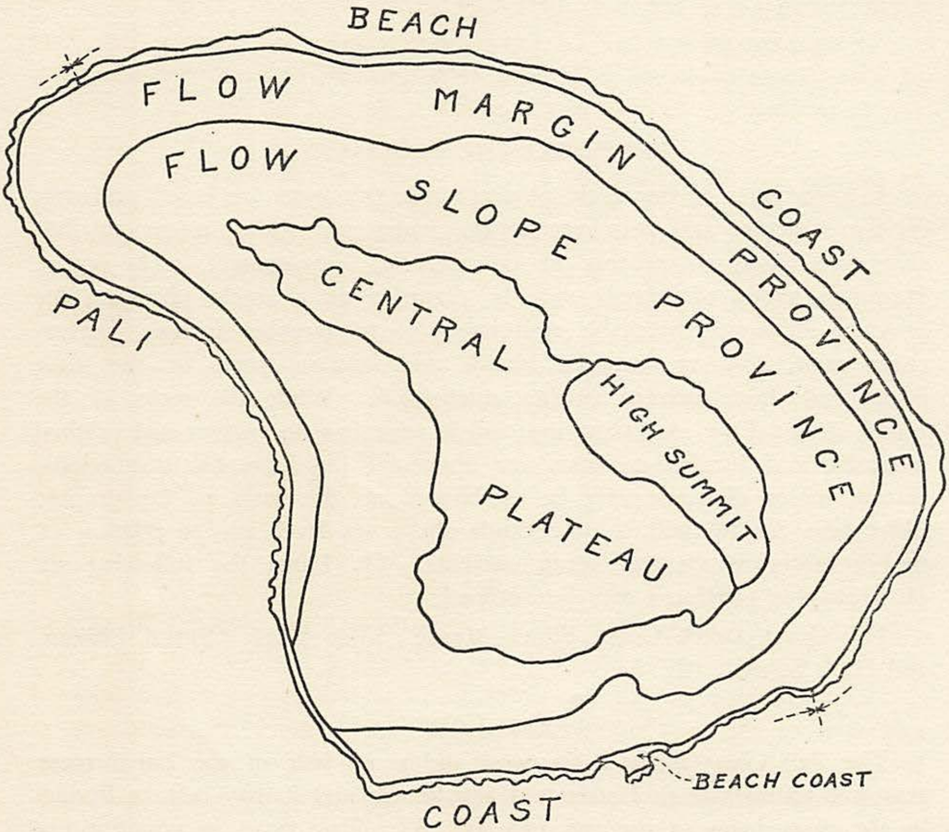

FIGURE 3.—Map showing the physiographic provinces of Lanai.

flows, to the formation of marine potholes by abrasion, and to solution pits, resulting from the action of water. Sea caves, sea arches and stacks are to be seen at a number of places along this coast. The blow holes, which appear at a number of places, and also some of the sea caves are due to slight modification of open lava tubes. All the stacks are very conspicuously surrounded by a marine bench accordant with that of the main shore which points clearly to a stand of the sea some twelve or fifteen feet higher than the present. Though there are exceptions, it may be said in general that the bench remnants remain where the pali is relatively low, and where no coarse debris is delivered to the waves by streams. Near the mouths of streamways, the waves have nearly everywhere cut back to the high cliff as a result in part of the debris made available by the streams. It is believed that the more abundant debris delivered by gravity at the bases of higher cliffs has caused more rapid destruction of the bench here than around the lower points and stacks.

Though the coastal pali on Lanai is steeper on the average than that of some coasts elsewhere in Hawaii, it is nowhere vertical or overhanging for more than 50 or 100 feet and has a general declivity of about 75 degrees. Parts of the southwest Pali Kaholo rise at angles as great as 83 degrees for more than 600 feet above the narrow beach at water line. In general the breaks in the pali face tend to follow joints normal to the surfaces of lava flows, but produce an average slope inclined landward from such planes. For this reason a pali developed in lava flows dipping seaward tends to be steeper than one developed on northeast Molokai, in flows dipping landward; for example, the pali on northeast Molokai.

Beach Coast

The north and east coasts of Lanai are low and flat. At a few places on the north coast, especially toward the west, rock spurs a few feet high reach the coast as low headlands largely buried by sand, but along most of the beach coast no bed rock is exposed at the shore. North of Keomuku is a single low spur of basalt mantled with eolian limestone by cliffs five feet to eight feet high. Southward from Keomuku the coastal belt becomes narrower and terminates inland in low cliffs cut in the basalt of the spurs.

A considerable part of the Beach Coast province represents a seaward extension of the land in recent time—a process going on vigorously at present, as shown by the small deltas at the mouths of principal streams. Along parts of the east coast are low dune ridges which also are commonly present along the north coast (Pl. IV, *A*).

Flow Margin

The Flow Margin province is a belt of indefinite width which lies immediately inland from the pali edge and from the inner margin of the beach zone. It is characterized by a slope somewhat steeper than the dip of the lava flows of which the belt consists. This slope is composed of the treads and risers made by the tops and frayed-out margins of flows. It is commonly strewn with large and small rough blocks of basalt derived from the waste of the flows. The upper margin of the province is at some places well defined but at others rather indefinite. In general, it extends to higher altitudes in those places where the slopes are deeply cut by erosion.

With the exception of a few of the larger gulches on the northeast slope of Lanai and of the coast palis, the Flow Margin province includes the most deeply dissected, rugged and inaccessible parts of the island.

Flow Slope

Within the Flow Slope province are included several different types of topography which show a certain amount of orderly arrangement but which cannot very satisfactorily be treated as subprovinces. The lower part of the Flow Slope, similar to the Flow Margin, is commonly strewn with dark red, rusty, rough lava blocks. Laterally, toward the gulches, the Flow Slope is flanked by true Flow Margin topography. Higher up the slopes the rusty blocks become less numerous and the surface more completely covered with grass. Still higher the slope in many places is swept bare by the wind and the weathered basalt dissected to a topography somewhat resembling clay "badlands." The spheroidal weathering of the basalt controls the form of the separated blocks and extends in incipient form to an unknown depth. Here the coarse detritus consists of large and small spheroidal niggerheads of basalt. Most of them are light red, buff, or drab in contrast to the deep red color of the rough blocks lower down.

In a few places the upper part of the Flow Slope includes a curious topography which consists of black or dark residual piles, spires, and monoliths of slightly weathered rock standing in place above a surface produced by the removal of surrounding rock. In places this lower surface is grass covered and relatively smooth and the ragged rock piles stand out in strong contrast to it. An exceptionally bizarre collection of these erosion remnants is known locally as the "Garden of the Gods."

The upper part of this province where suitably exposed is subject to strong wind erosion and this in turn favors rain wash during heavy storms. In such situations several types of surface are found which have a definite stratigraphic relation to one another. The uppermost of these consists of the low mounds of wind deposited silt which has been drifted over the original soil covered surface. The silt is rarely more than ten feet thick. The mounds vary much in shape, but where erosion is now active they have a pronounced stream-line form with the steepest end toward the wind. Where the surface of the land is not now covered with the eolian mounds, it is commonly dissected by wind and water. The old soil layer usually makes a line of sharp demarkation between the eolian terrane above and the weathered basaltic terrane below (Pls. I, *B*, IV, *B*; fig. 4). Immediately below the soil line the basaltic residuum is deep red in color, becoming lighter with increasing depth and grading to buff and yellow. Still deeper the color is less definitely arranged in zones but is a mottled and graded pattern of yellow, purple and black. The topography immediately below the soil line shows a concave profile which may be vertical or slightly overhanging at the soil line and flattens out in a few feet to a moderate slope. This surface is relatively smooth. Lower down in the yellow and purple part of the basalt residuum are

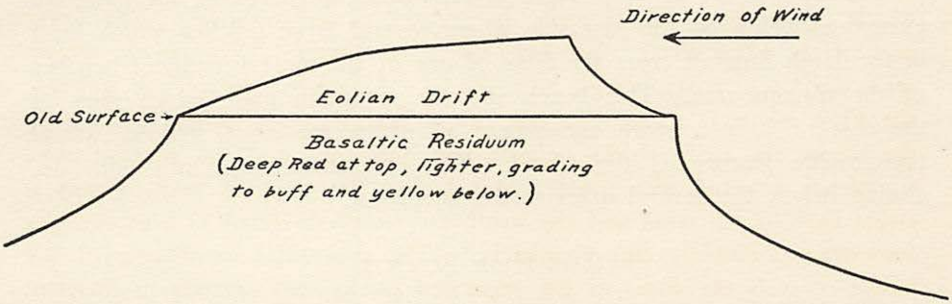

FIGURE 4.—Sketch showing composite profile developed in the Flow Slope province by wind and water.

irregularities of weathering and the surface becomes rougher. This surface in turn gives way commonly to smoother and slightly aggraded surfaces on which vegetation is growing (Pl. IV, *C*).

CENTRAL PLATEAU

The Central Plateau is nearly coextensive with the area of interior drainage. The principal difference is that the dissected southwest slope of the main highland has been included in the High Summit. (See figs. 3 and 6.) This slope drains into the interior basin but stands so high above it that its dissection proceeds at present quite as effectively as though it drained to the sea.

The greater part of this province consists of a gently rolling grass-covered surface. Only a small part of its area is contained in well-defined basins which would be recognized by the casual observer as undrained. The largest of these is Palawai Basin which has a closed area of three to four square miles and a considerably larger area is tributary to it. The depth of Palawai Basin from the lowest point of the rim is about 140 feet.

The most characteristic feature of the Central Plateau, aside from its lack of surface drainage to the sea, is the presence of minor topographic forms not normal to simple dissected volcanic cones. These consist of undrained basins, series of benches, linear scarps not related to drainage, departures of drainage from the radial pattern, linear ridges and somewhat obscure tilted blocks, and linear graben-like troughs. These features show a pronounced primary northwest-southeast alignment with a secondary alignment at right angles and constitute, even without structural data, sufficient evidence of extensive faulting. The most prominent of those tectonic lines are shown in figure 8.

Throughout the province there is very little deep erosion, the principal exceptions being on the east side where several large gulches which head in the High Summit cross the edge of one of the most prominent benches of the plateau area. This bench and the mountain mass which rises to the east of it in a steep escarpment constitute the most striking inland topographic feature of the island. The escarpment continues with declining height for several miles to the northwest.

The High Summit

The High Summit province includes roughly all Lanai which lies more than 2,000 feet above sea level. Its eastern boundary which lies above 2,000 feet is unmarked by natural features, but has been drawn partly on the basis of elevation and partly on the basis of existing vegetation, being the approximate lower limit of the present forest area. On the southwest, the province is rather sharply separated from the Central Plateau by its pronounced dissection. The same distinction serves to define its northwest end.

The High Summit province is about five miles long and two miles wide and consists of a slightly crescentic and narrow ridge extending southeast-northwest and a series of radiating ridges which branch out from it on the northeast side. The northeast side of this province has the normal form of a dissected volcanic cone, on the southwest it is cut off by faulting to form a relatively straight and only moderately dissected escarpment. The entire area is covered with trees and scrubby underbrush and the rocks are deeply weathered. Practically all the gulches which reach the sea along the east coast head in the High Summit province and these include the most important of the island.

CLIMATE

The climate of Lanai is similar to that of the other Hawaiian islands. Its outstanding characteristics are low annual, monthly, and daily temperature range, practical absence of frost, great differences in the mountain and seashore temperatures at the same time, persistence and strength of the northeast trade winds, and moderate to heavy rainfall with striking contrasts in the amounts of rain for adjacent regions at different altitudes or with different exposures to the prevailing Trade Winds. The principal contrast which the climate of Hawaii bears to other parts of the United States is that in Hawaii differences are chiefly geographic rather than seasonal.

For use in this paper data relating to the climate of Lanai were compiled from the records of the Koele station of the United States Weather Bureau (elevation 1780 feet). Some data were taken from recent Weather Bureau publications; other data and particularly those pertaining to stations on Lanai other than Koele were furnished by George C. Munro, who for a number of years has recorded observations.

TEMPERATURE

The temperature record at Koele for the seven year period 1912-1918 inclusive is as follows:

Mean annual	68
High monthly mean (August and September)	71.1
Low monthly mean (February)	64.5
Average maximum, annual	74.8
" " , high month (September)	78.
" " , low month (January)	71.9
Average minimum, annual	61
" " , high month (August)	64.4
" " , low month (February)	56.9
Highest (October)	87
Lowest (January, February, March)	49

The extreme range is seen to be 38 degrees. The average daily range does not exceed 15 degrees and the range from the mean of the coldest to the mean of the warmest month is 6.6 degrees. A comparison of these figures with those for important points in the United States is shown in Table No. 2.

TABLE NO. 2. TEMPERATURE VARIATIONS AT KOELE IN COMPARISON WITH THOSE AT FOUR IMPORTANT MAINLAND CITIES.

	KOELE	NEW YORK	CHICAGO	WASHINGTON	SAN FRANCISCO
Mean annual	68	51.8	48.7	54.7	54.9
High monthly mean	71.1	74.3	72.3	76.8	59.3
Low monthly mean	64.5	30.3	24	32.9	50.9
Highest for year	87	100	103	104	101
Highest for low month	77	67	63	76	72
Lowest for year	49	—6	—23	—15	29
Lowest for high month	59	51	50	52	47
Extreme range	38	106	126	119	72
Range of monthly means	6.6	44	48.3	43.9	8.4

Frost rarely forms in the Hawaiian islands below the 4,000 foot level and probably nowhere below 2,500 feet. There is thus a possibility that frost forms very infrequently in the High Summit province of Lanai above 3,000 feet.

WIND

The wind prevailing on all parts of Lanai is from the northeast. Occasionally during the "kona storms" there is a change to persistent southerly winds. The island is not of sufficient mass to bring about any considerable reversal of the Trade Winds on its southwest side as do Hawaii and east Maui.

RAINFALL

The rainfall of Lanai, so far as it has been recorded, is shown in Tables Nos. 3, 4, 5, and 6. At Koele official records have been kept for a number of years. The data for the other stations is less complete, and probably slightly less accurate (fig. 5). The station at Lanaihale, the summit point of the island elevation, 3,370 feet, has been in operation a few months only. By comparing its record with that of the other stations for the same period and these in turn with their normal records for the same months and for the whole year, it appears that the rainfall at Lanaihale is about 22 inches a year. This is an abnormally low amount for such a situation and it is possible that future records will raise the figure considerably. At the same time it is probable that because of the small area of the island which rises above two thousand feet, and perhaps other unknown factors, the rainfall at Lanaihale will not prove to be greater than 40 to 50 inches.

TABLE NO. 3. RAINFALL AT KOELE FROM MAY 1911 TO APRIL 1924, INCLUSIVE

(Unit equals .01 inch)

	1911	1912	1913	1914	1915	1916	1917	1918	1919	1920	1921	1922	1923	1924
January	......	68	198	517	54	2226	631	477	34	632	578	188	1102	90
February	......	310	172	336	154	381	242	596	20	68	191	200	534	125
March	......	233	534	792	360	570	383	541	200	89	157	202	469	247
April	......	268	16	416	211	261	797	1080	254	232	260	166	941	820
May	177	45	698	594	307	462	694	183	297	243	465	49	99	......
June	89	115	245	104	506	43	136	143	357	92	77	161	289	......
July	143	184	42	185	123	182	188	68	75	188	110	1169	136	......
August	99	153	411	432	70	81	230	274	133	143	63	308	162	......
September	361	72	61	540	223	65	462	140	99	64	181	375	199	......
October	122	81	734	71	160	304	413	43	150	294	420	514	95	......
November	41	38	253	176	195	247	276	403	275	94	306	169	99	......
December	132	61	239	680	742	404	413	184	176	994	749	21	665	......
	1164	1628	3603	4843	3205	5226	4765	4132	2220	3136	3557	2522	4790	1282

TABLE NO. 4. AVERAGE NUMBER OF DAYS WITH .01 INCH OR MORE OF RAIN AT KOELE, LANAI

January	12
February	10
March	12
April	12
May	13
June	9
July	9
August	10
September	9
October	9
November	8
December	12
The year	125

TABLE NO. 5, RAINFALL AT SIX STATIONS ON LANAI, 1913 TO 1918 INCLUSIVE

(Figures in parentheses refer to the map in figure 5)

	1913	1914	1915	1916	1917	1918	Mean
Koele (1)	48.43	32.05	52.26	47.65	41.32	22.20	40.65
Keomuku (2)	5.59	20.14	5.50	12.49	5.83	11.98	10.25
Kanepuu (3)	15.39	29.76	23.46	30.46	29.51	26.66	25.87
Kamoku (4)	16.57	26.78	20.52	40.88	28.06	25.83	26.44
Malauea (6)	13.98	27.86	13.73	35.30	20.05	......	22.16
Palikaholo (7)	13.57	26.70	19.38	30.83	17.63	21.12	21.54
Mean	18.91	27.21	22.47	32.93	23.73	21.56	24.48

TABLE NO. 6. RAINFALL AT SEVEN STATIONS OF LANAI, SEPTEMBER 21, 1923 TO APRIL 28, 1924

(Figures in parentheses refer to the map in figure 5)

Koele	(1)	21.41	(approximate)
Keomuku	(2)	14.52	
Kanepuu	(3)	17.34	
Kamoku	(4)	14.01	
Lanaihale	(5)	13.52	
Malauea	(6)	11.88	
Palikaholo	(7)	11.05	
Mean		14.82	

The stations on the plateau of Lanai show considerable uniformity of rainfall, four stations falling between 20 and 26 inches. Koele, which is

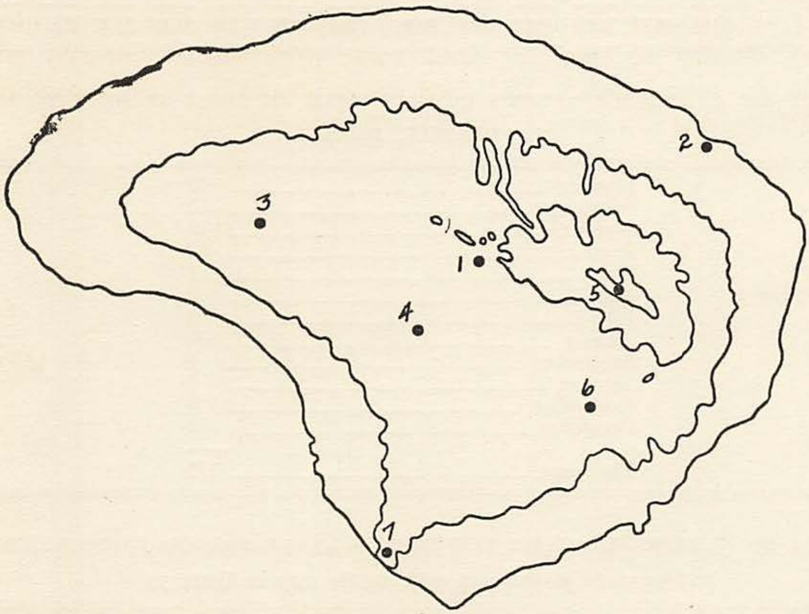

FIGURE 5.—Sketch map of Lanai showing location of rainfall stations. 1, Koele, official U. S. Weather Bureau; 2, Keomuku; 3, Kanepuu; 4, Kamoku; 5, Lanaihale; 6, Malauea; 7, Pali Kaholo. Contour interval 1000 feet.

located closer to the higher parts of the island, has a mean rainfall of about 35 inches. The lowest rainfall is that at Keomuku on the northeast coast where about ten inches is recorded. It is probable that coastal stations along the west pali would show as little and perhaps somewhat less rain than Keomuku. By roughly contouring the map of Lanai on the basis of existing rainfall data and measuring the several areas the following data were obtained:

RAINFALL	AREA
More than 30 inches	7 square miles
20-30 inches	29 square miles
10-20 inches	59 square miles
Less than 10 inches	45 square miles
Total area	140 square miles

Taking the rainfall in the area having less than 10 inches as averaging 8 inches and in the other areas as averaging 15 inches, 25 inches and 35 inches respectively, the total number of mile-inches is 2,215 which gives an average fall of about 16 inches.

In addition to the rainfall, it is probable that a considerable but unknown amount of water is derived by direct condensation of moisture on the vegetation from the heavy clouds of mist which drift over the higher parts of the island. During the month of April, 1924, which was an unusually rainy month, the summit area of the island was enveloped in clouds a large part of each day and to a lesser extent this condition exists the year round.

DRAINAGE

The surface drainage of Lanai is chiefly potential rather than actual. There are no perennial streams which reach the sea and only the few streams which enter the sea along the six or eight miles of coast north and south of Keomuku flow for more than a few hours at a time. I saw water flowing at an estimated rate of two second-feet for several miles in the middle portion of Maunalei Gulch on May 16, 1924. On May 6, 1924, following a heavy shower on the northeast slope of Lanai, streams of water from several of the larger gulches were flowing into the sea north of Keomuku. None of these streams exceeded probably a maximum of five second feet in flow or flowed a total period of more than three or four hours. Both of these observations were made shortly after heavy rains which came at the end of a period of about two months of uncommonly wet weather. Maunalei Gulch is reported by a number of persons to support a small stream of water in its upper course throughout the year. Probably several others of the larger northeast gulches in their upper courses support a small trickle of water during a considerable part of the year, but running water rarely reaches the sea for a period of days.

During April, 1924, many of the gulches on the west and south slopes of Lanai showed evidence of recent torrential flow and contained pools of chocolate-colored water which were gradually drying up. Most of these pools were small and lined with rock and the principal loss was by evaporation. Small areas of the rock are sufficiently impervious to contain such pools though the channels as a whole are subject to large losses by seepage. During the same month on a number of occasions following rains there were pools of standing water a few inches deep and a fraction of an acre in extent at various places in the Central Plateau. None of these persisted for more than a day or two and most of them were still shorter lived. It is probable that in general the deeply weathered basalt residuum of parts of the plateau when saturated with water by heavy rains is more impervious than the unweathered basalt.

The drainage map (fig. 6) shows all definite channels indicated on the United States Geological Survey contour map of the island. Nearly all of them are cut down to bare rock and give evidence of carrying water at intervals depending on the occurrence of heavy rains. The fundamental drainage pattern is radial consisting of the consequent courses of streams down the lava flow slopes of the original basalt cone composing the island.

Variations of the drainage from this simple pattern are chiefly those due to the normal faulting which has affected the island along a northwest-southeast line. The most important result of the faulting is the production of a basin-like area of interior drainage amounting to nearly a fifth of the whole area of Lanai. Along the northeast margin of this basin where it adjoins

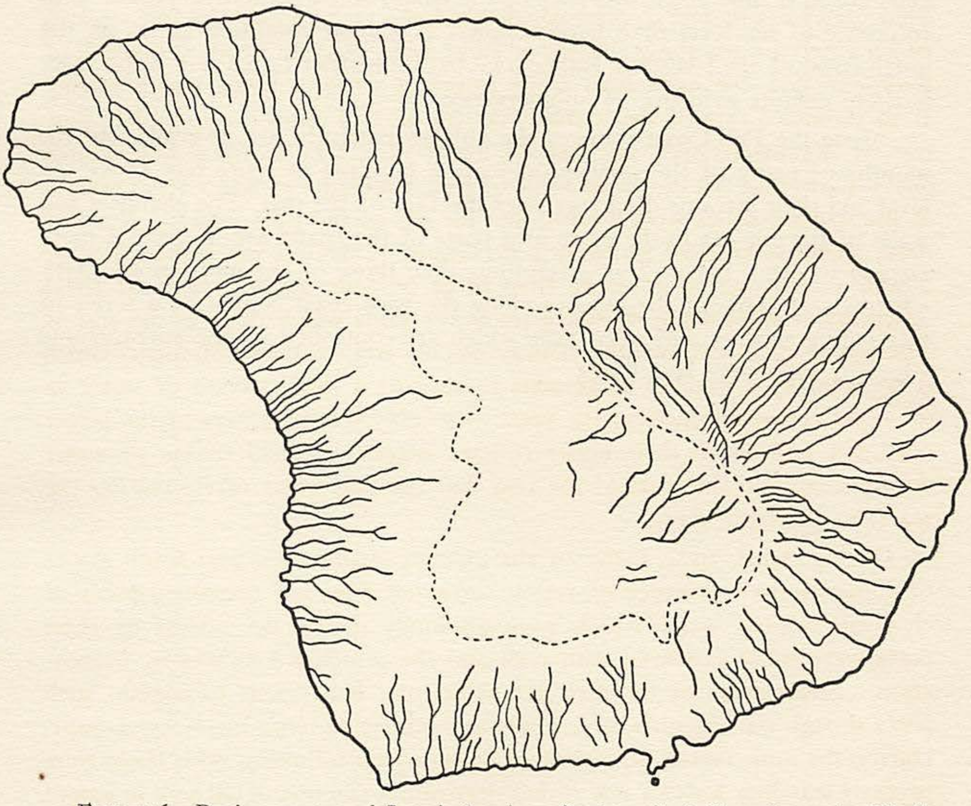

FIGURE 6.—Drainage map of Lanai showing all channels indicated on the U. S. Geological Survey topographic map. The dotted line shows the outlines of the interior basin.

the High Summit province are a number of well marked gulches but much of the area is without definite channels. Northeast of the basin the heads of a number of the gulches which drain down to the Keomuku shore show a marked alignment with the trend of the principal faults and appear to have had their courses determined by these lines of weakness. While a marked similarity between the many gulches of the island, is apparent, they may be arranged in groups which differ from one another in certain features. The channels of the gulches which reach the sea along the shore near Keomuku have variable lower courses; they migrate to and fro over the broad fans which make up large parts of the coastal lowland. The lower parts of some of these gulches are graded to a considerable width and have a flat-bottomed cross profile. The width of the lower parts of a number of the gulches along the east and north shores suggests the possibility that they may have been cut at a time when this part of the island stood somewhat higher with reference to sea level than it does now. A similar condition exists on the north coast of the island of Kahoolawe but on neither Lanai nor Kahoolawe is there definite evidence of submergence.

Along the Pali Coast some of the gulches reach the sea at grade, but the mouths of many of the smaller ones are a hundred or more feet above sea level and their streams discharge over the face of the pali. The channels and walls of the gulches in the more arid parts of the island are in general more rugged in detail but no less precipitous than those of the more moist parts. Channels of some of the gulches along the west coast consist of a series of alternating reaches and steep falls which are controlled by the surfaces and edges of successive lava flows.

RECENT GEOLOGIC PROCESSES

The geologic processes which result in changes of that part of the earth subject to observation are included under the three headings of vulcanism, diastrophism, and gradation. No volcanic activity occurred on Lanai during historic times, and no other deep-seated igneous activity is known to be taking place. There is no evidence of current diastrophism, such as faulting, folding, or change in the relation between land and sea and although it is probable that a change is taking place with extreme slowness, there is no local evidence of its direction or rate. The modern geologic processes which are operating on Lanai belong in the realm of gradation. This term is here used in its larger sense to include all sedimentary processes—weathering processes, transporting processes, depositing processes, and cementing processes.

It is beyond the scope of the present paper to describe in great detail the processes of erosion and the principles of physiographic development in basaltic rocks under tropical conditions; it will be sufficient to call attention to the most active processes and to point out in a general way the part they have played in the development of the present features of Lanai.

WEATHERING

The most conspicuous weathering process is that which operates most vigorously in the higher and more moist parts of Lanai and has resulted in the decomposition of the basalt to depths of 20 to 40 feet, in places, much more. This process is not understood in detail but it results in the decomposition of the feldspar and pyroxene of the basalt, with the removal of much of the soda, potash, magnesium, and lime, and probably results in extensive hydration of the remaining silica and alumina minerals. As a result of this weathering, considerable parts of the Flow Slope province and higher parts of the island are covered with a dark red soil, which differs in composition from the parent basalt chiefly in its higher content of iron and aluminum and in the loss of part of the soda, potash, magnesium, and lime. Only the upper part of this material is a true soil in the sense of containing organic carbonaceous material, but in places it is several feet thick with essentially the same composition in other respects. Below it are commonly many feet of weathered basalt in which the structure of the rock is largely preserved and many of the minerals still recognizable. In this material may be traced a complete transition from the dark red soil through lighter red or brown to yellow and then to purple or black and only slightly altered basalt. Extending from the soil down to the deepest parts of the weathered zone the basalt residuum shows a remarkable spheroidal structure (Pl. V. *A*). This consists of numerous kernels or nuclear masses of less weathered basalt surrounded by layer on layer of shells which spall off on exposure to the air (Pl. V, *B*). The larger masses in which these spheroidal structures are developed are those bounded by the vertical joints and flow surfaces in the basalt. It has been suggested [3] that the spheroidal structure may be an expression through weathering of a concentric structure developed in the basalt at the time of cooling. It is certain that this explanation does not apply to Hawaiian lavas because similar spheroidal weathering is well developed in some of the deeper parts of the tuff craters as well as in the basalt of Oahu. Exfoliation, which is due to temperature changes, results in the spalling off of surface shells and in the formation of spheroidal masses of granite and other rocks in some regions but this is a surface process and not fundamentally akin to the processes which produce spheroidal structures on Lanai. The daily temperature range is so slight in Hawaii that the spheroidal weathering can hardly be due in the main to temperature changes. In my opinion it is probably due to the volume changes accompanying extensive hydration of the weathered rock. The two factors which appear to be essential to weathering of this sort are burial and the presence of moisture. In most places where the products of weathering are not removed by erosion the entire mass of the basalt is reduced to a soft residuum. At a few localities where the basalt is more resistant or where the partly weathered masses have been uncovered by erosion, are numerous blocks of practically fresh basalt lying about on the surface of the ground. Apparently, once the fairly fresh basalt is exposed to the air and is no longer buried in moisture retaining residuum, spheroidal weathering becomes negligible in amount. If the mass of basalt which is eroded out is affected by incipient spheroidal weathering, the heat of the sun plays a part in scaling off the concentric shells of the top and sides and sometimes leaves the resulting "niggerhead" standing on a pedestal of concentric shells beneath.

Blocks of basalt of any shape which lie on the surface are subject to pitting, forming cavities one to several inches wide and with depths reaching several times their diameter. Initial cavities in the rock doubtless help to determine the locations of the weathering pits but they are in the main due to selective weathering favored by the retention of water. This may be in part simple solution but in the main is probably more complex. The pitting is always very definitely restricted to the top side of the block. In blocks which have been recently overturned the pits remain on the former upper surface. The sides of some such blocks are marked by parallel grooves

[3] Bonney, T. G.: Geol. Soc. Quart. Jour., vol. XXXII, p. 153, 1876.

which run down the slopes and are deepened by continued weathering where the run-off of the rain is localized. Some of the larger pits on low blocks have dust and soil blown into them and retain moisture longer than they otherwise would, thus favoring further decomposition. Though this pit and groove weathering is not altogether simple solution, it nevertheless shows much similarity to the "lapis" type of weathering in limestone regions recently described by Cvijic.[4] Some of the blocks which lie on the surface in the Central Plateau and similar areas show a pronounced lenticular form with a rather definite annular rim or boundary between the upper and lower surfaces of the lens. The upper surface is normally pit-weathered; the lower is smoother, less fresh, the result of wet weathering due to burial. The annular rim represents the soil line at the time the '"niggerhead" lay half buried in the soil. Some of the lenticular blocks have the form of round bi-convex lenses, others are lenticular double pyramids or crude lenticular shapes which show the two types of surface.

On the lower slopes of Lanai in the Flow Margin and Pali Coast provinces weathering consists of sapping and breaking away of the lava block along joints and flow surface partings under the influence of temperature and gravity. Under the less abundant soil the wet type of weathering no doubt takes place but is far less active than in moister parts of the island. This is indicated by the much larger proportion of the basalt which is exposed at the surface as hard, fresh blocks. Pit-weathering is active here and contributes to the very rough, jagged surfaces of the blocks.

In the gulches the principal agent of weathering is gravity. On the dryer slopes gravity reigns nearly supreme and produces the steep, nearly uniform slope of the pali walls. The great porosity of the rock and its relative stability when dry operate to keep the brows of the palis relatively sharp and to restrict the slight curve of transition from the nearly vertical pali wall to the nearly horizontal surface of the Flow Slope above.

Along the coast, erosion dominates over weathering so far as the larger features are concerned. Gravity, operating through the larger jointing system of the basalt mass, serves to determine the slope and form of the coastal pali, following the work of the waves in cutting at its foot. The minuter structure of the mass of thin lava flows is etched out into strong relief by crumbling and wind work, which is probably aided near sea level by spray blown across the pali face.

Pits and pools in the surface of the exposed wave cut bench are in part the result of abrasion as in true potholes and in part due to weathering of rock which is alternately wet and dry. With the exception of those

[4] Cvijic, Jovan, The evolution of Lapies: Geog. Rev., vol. XIV, pp. 26-49, 1924.

surfaces which are clearly smoothed by abrasion, weathering due to alternate wetting and drying, dominates on the higher parts of the old wave cut bench. In the few places where they are exposed, reef rock or detrital limestone show the characteristic jagged, cuspate surfaces due to solution weathering and similar on a small scale to the lapis weathering of Cvijic.[5]

TRANSPORTATION

The most impressive of the modern geologic processes is the incessant attack of the waves on the margin of the land. This is particularly true in regions like Lanai where running water in streams is active only at rare intervals; but to a lesser extent it is true along all coasts, for the persistence of wave work is approached only by the work of the very largest rivers. The direct attack of the sea on the land is confined to a narrow zone extending from a few feet above to a few feet below sea level and the result of this attack is the cutting of a notch against the land. On its lower submarine margin this notch may be deep. Its upper side is prevented from becoming deep by the work of gravity which causes the overlying rock to break down nearly as fast as the notch is carried back.

At present, along most of the Pali Coast province wave abrasion is probably less effective than it has been in times past because most of the pali is flanked by an emerged wave cut bench[6] which ranges from five to thirty feet in width. This bench is not in itself high enough to yield any considerable amount of debris and such debris as falls from the palis strikes the surface of the bench. The waves working on the edges of the bench are therefore largely without tools in the form of rock debris and the edges of the bench prevent any very general or effective attack by the waves at the actual foot of the pali, which is some five to ten feet above sea level.

At the base of parts of the high southwest pali and locally at other places on the coast, the bench is missing. Debris from the pali or discharged from streams is being ground effectively to form well-rounded gravel which lies in narrow steep sloped beaches (Pl. II, *B*). The waves, in their attack on such a beach, vary greatly not only from one day to another, but in the character of successive waves.

The rounding of cobbles and bowlders on a beach is accomplished preponderantly by the few very strong waves rather than by the many weak or average waves. Table No. 17 gives the results of a series of rough

[5] Op. cit.

[6] Wentworth, C. K., and Palmer, H. S., Eustatic bench on islands of the North Pacific: Geol. Soc. Am. Bull., vol. XXXVI, 1925.

estimates of the relative strength and effectiveness of waves at Kaumalapau Harbor on a day when wave action was moderate. The waves were estimated on a scale of ten by visual observation and the relative work done by each size estimated to accord with the number and size of the bowlders which were heard tumbling over the beach with the outgoing water.

TABLE NO. 7—RELATIVE NUMBER AND STRENGTH OF WAVES

STRENGTH	NUMBER	WORK VALUE	TOTAL WORK
1	10	1/10	1
2	12	1	12
3	19	3	57
4	20	10	200
5	8	30	240
6	5	100	500
7	3	300	900
8	1	1000	1000
	78		2910

Such an estimate as that given in Table No. 7 has little quantitative value but serves to indicate the relative importance of the stronger waves. From the figures given it will be seen that over one-third of the total work was accomplished by the single wave of strength 8 which appeared in the series of 78 waves, and that about 80 per cent of the work was done by the 10 per cent of the waves which were of sizes 6, 7 and 8. The importance of this consideration is increased when it is realized that the day the observations were made was one of moderate wave strength and that the same comparison may be made between days as between waves. It is probable that waves on stormy days may perform one hundred or one thousand times as much work as on a day of average wave violence. This is borne out by the effect of waves on artificial structures, which are not uncommonly wrecked by storm waves in a few minutes after having withstood normal wave action for some months or years. It may be pointed out that these structures are built of a certain strength or stability and are quickly destroyed when these resistances were overcome. To a large extent the same is true of the pavement or fabric formed by the bowlders of a beach. The constant action of the waves by elimination of the small or less well placed pieces succeeds in building a relatively stable sloping beach floor. So long as the waves do not exceed the strength of those by which the beach was last worked there will be little change. But a single large wave of the requisite strength to tear out parts of the floor may set much of the beach in motion again and accomplish a relatively enormous amount of transportation and abrasion in a very short time.

In the attack on a beach by a single wave the water is thrown forward and dashed against the sloping surface with a motion which varies from a swelling surge to a strong slap. This variation is not wholly a matter of the total strength of the wave but is largely controlled by the history of approach of the wave and the amount and kind of interference it has suffered from other waves. The function of the wave climax is the dislodgment of the less stable cobbles or bowlders from their positions and is most effective when it is concentrated in a smart slap. After the cobbles have been dislodged by the wave at its climax they are rolled down the beach slope by the backwash until they lodge in some hollow or until the water is largely depleted by draining into the interstices of the beach. After the climax of moderate or strong waves these cobbles may be heard rolling and grinding with a deep chuckling sound under water even when conditions do not permit them to be readily seen. The fact that at any one time the waves are subject to considerable variation and that the cobbles of the beach slope are always approaching but never quite reach full adjustment for stability, points to an incessant milling and grinding of the cobbles of many beaches which is rarely if ever matched by abrasion in streams. Furthermore, in streams the motion of the water is in one direction and when adjustment is complete the resulting bar is fairly stable, but on beaches, the slap of the wave climax may dislodge cobbles which are relatively stable with respect to the backwash or to the more normal surging type of climax.

Many of the cobble beaches of the Lanai coast are formed across the heads of small bays and flank the jutting remnants of the exposed bench on either side. The bedrock is commonly much abraded into potholes, grooves, and channels in the portion which lies under and against the beach. The beach, in turn, is more stable at the ends than elsewhere and in a number of such places "chink-faceted" pebbles and cobbles are being formed. These are rock fragments which are confined but not tightly wedged into crevices, in which they undergo a slight but incessant shuffling motion which wears very distinct and restricted facets on those parts of their surfaces which are in contact with other bowlders or with walls of the crevice.[7]

Among the abrasive processes which take place along the rocky coast is what may be called aqueous sand-blasting. This is the production of sharp crests and random facets on bowlders and pebbles and other rock

[7] Wentworth, C. K., Chink faceting: a new process of pebble shaping: Jour. of Geol., vol. XXXIII, pp. 206-267, 1925.

masses by the action of waves charged with coarse beach sand. To sustain such abrasion the bowlders must remain in one position for long periods. Most commonly abrasion takes place on bowlders and pebbles which are imbedded in calcareous beach sandstone over which the modern beach sand is being swept by the waves. The most common abraded form is that of a sharp crest resultant from the intersection of two facets, the one facing seaward and the other landward. The form and the texture of the abraded surfaces are very similar to those of sand-blasted pebbles though somewhat coarser. It is evident that the abrasion is due to the alternate inshore and offshore action of the water. It is found to be most pronounced where a number of bowlders or masses of basalt operate to concentrate the water in channels in its to and fro motion. Where such channels exist, irregularities in the swirling flow of the water produce crests and facets that are more numerous and more varied in their orientation than those produced by waves parallel to the shore; but even here the definite control of the dominant in and out motion of the water is clearly indicated.

The surfaces of the facets show a slight amount of etching which is more generalized than that produced by sand-blasting under wind action. The most characteristic feature, just as in eolian sand-blasted surfaces, is in the sharp lines by which the slightly undulating facets meet. The angles of these crests vary according to the directions and inclinations of the water currents involved, but some at least of the simple crests in open situations have solid angles of less than 90 degrees.

Differential action of the waves on the strata of aa and pahoehoe, which make up the island of Lanai, has resulted in numerous stacks and sea arches which differ in no essential from those found on rocky coasts in all parts of the world. Sea caves also are not uncommon. Some of them contain small bowlder beaches which further abrasion. Several types of blowing holes and caves are in daily action. In one type the blow hole is in the roof of the cavern and as the waves rush in the spray is blown out at the top with the escaping air. In another type the roof of the cavern is tight and dome shaped and with the inrush of the waves considerable excess air pressure is developed. The air escaping at the top of the constricted entrance just before and just after the wave climax nearly or quite closes the entrance and carries out a strong jet of spray at a low angle. In a third type the roof of the cavern is not at all domed and blowing is only possible as a momentary feature of the rapid surging of water into the cavern.

Running water performs a considerable amount of transportation on the island of Lanai, but the work is very irregularly distributed throughout the year. The presence of large bowlders near the mouths of gulches in the Pali Coast and on the deltas of the streams in the Beach Coast province indicates that coarse materials are carried at certain times in considerable quantities. Finer material, usually in large amounts, is carried when the streams are flowing. There is much evidence to show that erosion of the higher parts of the island and deposition by streams along the Beach Coast have been abnormally rapid during a period of at least 75 years.

The kiawe tree was introduced to Hawaii in 1837 and has since become common on the lower parts of all the islands. Observations on the south coast of Molokai and on the northeast coast of Lanai indicate that a considerable and general filling of the lowlands around the bases of the older kiawe trees has occurred. In some places this fill amounts to two or even three feet and extends for some miles along the coasts.

For that section of the Lanai coast which extends for ten miles southward from the mouth of Maunalei Gulch, my estimates show that the fill during the past fifty years is at least one foot thick and 528 feet wide. An area of 27 square miles drains to this coast and is undoubtedly more actively eroded than most other parts of the island. Disregarding the undrained area, if the remaining 109 square miles of Lanai are assigned an average rate or reduction of one-third as much (which is in rough accord with the relative cross sections of gulches in the two areas), the total area of 136 square miles of the island which lies above 50 feet above sea level will have had removed from it some 2.35 mile-feet[8] in fifty years, or .047 mile-feet per annum. This amounts to .000345 feet from each square mile a year, or a reduction of the area above 50 feet elevation at the rate of one foot in 2900 years. The estimate is conservative and it is believed that the rate of reduction of the island during the past fifty years is somewhat greater than that given.

Erosion of the steeper slopes adjacent to Palawai and other basins on Lanai is sufficiently active to keep them scarred with bare walled gulches and to maintain fans of alluvial material only sparsely covered with vegetation. The channels of the gulches on the north, west, and south slopes of Lanai consist of series of gentle reaches and steeper rapids or falls. At the bottoms of the falls are hollows into which the water falls, carrying its load of sediment. Extending downstream from the deepest parts of the pool are fans of alluvial material which are deposited by the water as it leaves the pool. Only the coarser material is left permanently

[8] A mile-foot is a volume one foot thick and one square mile in area.

in the hollow. This is usually veneered by a layer of finer red-brown alluvial clay deposited during the waning stages of the last flood and during the gradual drying up of the pool which remains.

At many points in these channels the basalt surface, which is frequently slightly weathered, shows numerous small scratches indicating accurately the direction of motion of the water. These, in the main, probably show the flow directions for the higher flood stages and are formed when the water is most strongly charged with rock debris. The scratches are more variable in direction than glacial striae and show more influence of differing hardness of the rock and configuration of the walls. At a few places true potholes are being formed in the basalt but in the main the details of channel configuration are those inherent in such basalt structures as lava tubes and aa and pahoehoe contacts.

At many places small rills flowing over surfaces of clay-like basalt residuum are carving out deep, narrow, and tortuous channels. These contain potholes, spill pools, spiral channel curves and are generally grooved longitudinally. Their form, thus developed in nearly homogeneous soft material, is very suggestive of the dynamic character of the stream of water as it swings from side to side of its crooked channel.

Wind is the third important transporting agent on Lanai; in some places in the north and west parts of the island it is predominant in carving the existing topography. In some places wind erosion has removed ten feet or more of the soil and underlying weathered basalt, exposing material which is unsuitable for the growth of plants and which will remain barren until windbreaks are planted to retain some of the soil material drifting past. In the wind eroded area residual basal "niggerheads" commonly stand on narrow pedestals of the underlying basalt residuum. These are subject to constant wastage on the windward side, with the result that in time the blocks become tilted toward the wind. Many of them have strongly marked pit weathering on the top side and a definite lenticular form which accentuate their definite orientation when they are tipped forward.

The windswept surface of the basalt residuum is often grooved and striated along the northeast-southwest line of the predominant trade winds. Wind formed features similar to those of Lanai are exceptionally well developed on parts of west Molokai and have been described elsewhere.[9]

DEPOSITION

It is apparent that as much rock debris is deposited on or near the island of Lanai as is eroded from it, but the resulting deposits are on the whole

[9] Wentworth, C. K., The desert strip of west Molokai: Univ. of Iowa, studies in Nat. Hist., vol. xi, pp. 17-41, 1925.

less conspicuous than the eroded areas from which they came. Marine gravel deposits are present in the numerous small beaches along the Pali Coast and considerable marine sand is incorporated in the beaches of the Beach Coast province. Much of the material of the shore flat along the beach coast is alluvium deposited by the many ephemeral streams which enter the sea and eolian deposits also are interbedded in the recent sediments. Directly opposite the mouths of the streams are commonly fans of bowlders from which most of the finer material has been washed away by the waves. Beach cusps of gravel slightly coarser than that of the normal beach were noted north of Maunalei.

South of Keomuku for a distance of several miles is a rather definite dune ridge immediately back of the beach and separating it from the shore flat. North of Keomuku is a similar but less continuous ridge. At Manele the mixed gray and white sand from the beach of the harbor is drifted southwest to within a few yards of the beach west of the point. The finer gray eolian sand is here in sharp contrast with the coarse calcareous sand of the beach. Apparently the small quantities of the gray sand which drift beyond the definite dune front are wholly lost in the great mass of the coarse beach sand, for the limit between the two sands is very sharp. On the other hand, occasional northerly winds drive moderate quantities of the gray sand south along the point and over the cliff just west of Puu Pehe to form a sand beach where normally there would be none.

Most of the eolian deposits of Lanai consist of banks of soil and ferruginous basalt detritus which, five to ten feet thick, lie on parts of the northern and western central plateau. Beds a few inches thick may be identified at a number of localities on the west slopes of the island.

At the eastern edge of Palawai Basin are a number of large fans of alluvial material. Some of these are strewn with bowlders three to six feet in diameter. Though many rounded masses of basalt appear in this region which are not true bowlders, it seems clear that many others were transported by streams as parts of alluvial fans and have been exposed at the surface by the removal of much of the fine material which once surrounded them.

CEMENTATION

Processes having to do with the formation of an indurated rock from its detrital constituents are not well understood. On Lanai such processes can be seen to have taken place recently only in a few places, but there is little doubt that extensive lithification is going on within the parts of the rock mass.

Beneath some of the sand and gravel beaches are indurated masses of sandstone or conglomerate which were formed in the same manner as the sediments of the modern beach and which have since been cemented. There is no means of dating these rocks except that some of them appear to be associated with the modern position of sea level and to have been formed since the withdrawal of the sea from the wave cut bench. In some places where the gravel beaches are relatively stable the growing calcareous organisms attached to the bowlders furnish a moderate amount of cementing. In fact, it seems probable that the infiltration of lime cement is going on at the present time wherever the beach is undisturbed for a considerable period and where there is a moderate amount of burial.

In some parts of Lanai where wind transportation is active and calcareous dune sands have accumulated, strongly cemented casts of stems and roots of plants have formed, which are later exposed by the removal of the main mass of sand which probably was indurated slightly if at all. The passage of water down the plant stems and along the roots was probably an important factor in this process though the sap and other constituents of the plants themselves may have reacted to aid deposition of the calcareous cement.

At nearly all elevations wherever the rocks are well exposed there may be deposits of calcium carbonate as joint fillings, as calcareous crusts along the surfaces of lava flows, and as nodular interstitial masses in beds of aa. On Lanai and elsewhere in Hawaii such deposits have been erroneously considered to be coral rocks and an indication of a stand of the sea at an elevation far above its present level. These masses are commonly white and chalky but where less weathered they are hard, banded, travertine-like rocks two to three inches thick. They are devoid of fossils or other organic remains. Coral fragments and shells are found widely spread over the central plateau in association with Hawaiian stone artifacts, but these are clearly of human distribution. In a talus mass at a place northeast of Manele and about 150 feet above sea level shells and coral fragments were found to be so abundant that a natural origin seemed reasonable. Subsequent search in other gulches failed to reveal similar evidences and I have concluded that the deposit must be in part of artificial origin. It is impossible to believe that the sea has stood more than to 10 to 15 feet above its present level at any time since Lanai was formed. Had it done so, it seems certain that there would be clear indications at more than one place and of more than one sort.

AREAL GEOLOGY

In a cursory way it may be said that Lanai has but one rock formation—basaltic lava and its surface residuum. Probably less than 1/500 part of its mass which lies above sea level is composed of other rocks. With the exception of the marine organic rocks, all of the sediments which make up even this small fraction are derived directly from the basalt, the weathering of which yields to the sea more calcium carbonate than is used by reef building organisms around the shores of the island. However, in describing the areal geology of Lanai, it is not sufficient to give attention only to the preponderant basalt; it is useful to recognize that the island has commenced that long series of changes under the influences of weathering and erosion which have led to such topographic and petrographic diversity in all the great continental masses. Because of the slight progress made by the rocks in the rock cycle and the continued activity of all the agents involved, the local sedimentary rocks are of especial interest to the student of geologic processes. They include detrital marine rocks, organic marine rocks, detrital derivatives of organic marine rocks, alluvial sediments, eolian sediments, talus deposits, and terrestrial chemical sediments.

Detailed microscopic and other laboratory examinations of the rocks collected in the course of the present study have not yet been made. The descriptions given below are based on field observations and on megascopic examinations of the specimens and are preliminary to more exhaustive studies to be made at a later time.

LANAI BASALT

Basalt is the only thick rock formation on Lanai. With the exception of the rock comprising the Manele headland the basalt has not been subdivided and is considered as one series of lava flows. There are indications of local unconformity between flows in the coastal pali east of Manele and in the south part of Pali Kaholo, but study of these areas showed no definite separation into an old and a new series of lavas and I believe that the principal mass of the island was built up in a single, more or less continuous episode of basaltic extrusion.

The Lanai basalt is exposed at the surface in the broken blocks and jointed margins of the successive flows in the entire Flow Margin and Pali Coast provinces and in smaller areas at numerous other localities.

Over much of the Central Plateau and High Summit and a considerable part of the Flow Slope the basalt is covered to depths of ten or twenty feet by the residuum which results from its weathering. Probably in many places weathering extends much deeper than this, perhaps even to one hundred or two hundred feet. The principal area of surficial rocks is along the northeast coast where a series of alluvial, marine, and eolian

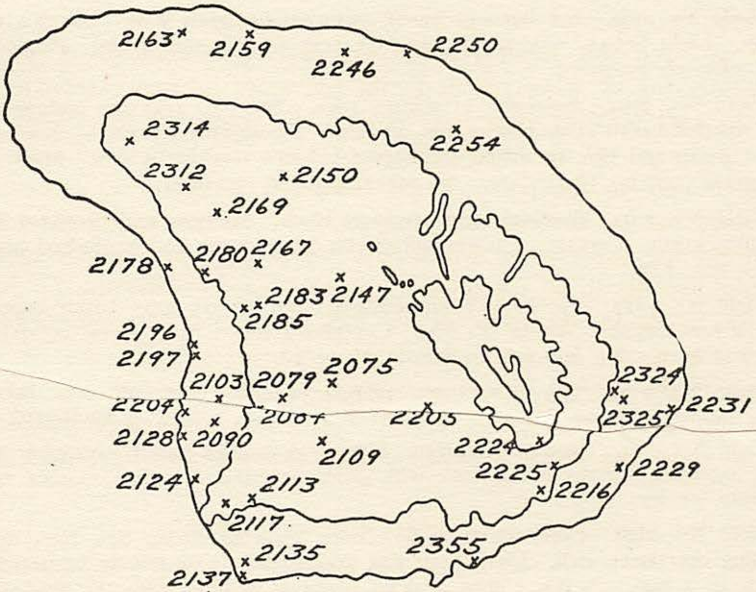

FIGURE 7.—Key map showing localities from which rock specimens were obtained.

sediments covers the basalt to a depth of a few tens of feet over a width of a third of a mile or less. Thicknesses of these surficial rocks are so variable and the boundaries so vague that it has not proved practicable to map them.

Megascopic Petrology

The outstanding megascopic features of the specimens collected on Lanai are given in the descriptions below. The locations of the specimens are shown in figure 7. The term basalt is used in its general sense of basic aphanite.

Field No. 2075. Specimen from residual basalt blocks lying on surface of ground. Compact, medium gray basalt containing augite, plagioclase, and olivine. General grain 1/10 mm., augites up to 2 mm., olivines to 1 mm. Plagioclase partially altered to kaolin.

Field No. 2079. Specimen from residual block. Medium steel gray basalt containing irregular vesicles to 1/2 mm. Olivine crystals reach 2 mm.; matrix is made up of augite and plagioclase of 1/4 mm. grain. Plagioclase somewhat kaolinized.

Field No. 2084. Specimen from residual block. Medium gray basalt of 1/4 mm. grain containing globular vesicles to 1 mm. No olivine observed, matrix of plagioclase slightly kaolinized, and augite.

Field No. 2090. Specimen in place in road cut. Light gray, compact basalt containing a few 1/2 mm. globular vesicles. Grain 1/10 mm. No minerals identified.

Field No. 2103. Specimen of basalt inclusion in basalt flow. See No. 2104 for matrix. Light brown, moderately vesicular rock of 1/4 mm. grain. Plagioclase, no other minerals identified.

Field No. 2104. Specimen of matrix rock. See No. 2103 for inclusion. Dark gray, mottled basalt containing 2 mm. vesicles. Porphyritic texture containing bright purple, green and blue tarnished, irridescent olivines reaching 5 mm. Matrix of 1/2 mm. grain contains plagioclase. No other minerals identified.

Field No. 2109. Specimen from residual block. Medium gray speckled basalt of 1/10 mm. grain. Contains a few small olivine phenocrysts and kaolinized plagioclase laths 2 mm. long.

Field No. 2113. Specimen from residual block. Dark gray basalt containing a few 1/2 mm. vesicles. Grain 1/4 mm. Contains a few 1 mm. olivine crystals and is fresh and hard. No minerals of matrix identified.

Field No. 2117. Specimen from residual block. Light buff gray basalt containing numerous 5 mm. vesicles. Plagioclase to 2 mm. somewhat kaolinized.

Field No. 2134. Specimen in place. Slate gray mottled basalt containing irregular 3 mm. vesicles. Porphyritic texture with olivine crystals to 5 mm. Grain very fine. 1/20 mm. or less.

Field No. 2128. Specimen from flow mass showing strong flow lines developed in falling over steep wall. Light gray, fine grained basalt containing scattered olivine crystals to 3 mm. A few 1 mm. vesicles oriented in lines with the gneissoid flow structure.

Field No. 2135. Specimen in place. Medium gray basalt of 1/4 mm. grain. Contains a moderate number of strongly oriented elongate 12 mm. vesicles. No minerals identified in the matrix.

Field No. 2137. Specimen in place. Buff gray basalt of 3/4 mm. grain, somewhat weathered. Contains a few scattered 2 mm. olivine crystals.

Field No. 2147. Specimen from residual block. Dark gray, speckled basalt, of porphyritic texture and 1/3 mm. grain in the matrix. Olivines to 3 mm. fairly numerous. A few plagioclase laths reach 2 mm. Moderate number of 1 mm. vesicles of which some are filled with secondary calcium carbonate, probably aragonite.

Field No. 2150. Specimen from residual block. Medium gray basalt of 1/2 mm. grain containing a moderate number of 5 mm. globular vesicles and a few small irridescent olivine crystals.

Field No. 2159. Specimen in place. Slate gray basalt showing flow structure with elongate vesicles incrusted with aragonite(?) and of 1/10 mm. grain. No minerals identified in the matrix.

Field No. 2163. Specimen from residual block. Slate gray basalt of 1/10 mm. grain and conchoidal feature. Very hard and contains scattered 2 mm. olivines and a few 1 mm. vesicles. No minerals identified in the matrix.

Field No. 2167. Specimen from residual block. Slate gray basalt of 1/10 mm. grain and a few strongly oriented 20 mm. vesicles. Contains 1 mm. plagioclase laths partially kaolinized.

Field No. 2169. Specimen from residual block. Dark gray basalt of 1/4 mm. grain containing a few 2 mm. globular vesicles. No olivine identified; 1 mm. plagioclase laths partially altered to kaolin.

Field No. 2178. Specimen in place. Slate gray basalt of 1/20 mm. grain with a few 1/2 mm. vesicles. Plagioclase partially altered to kaolin; no olivine identified.

Field No. 2180. Specimen in place. Medium gray basalt of 1/10 mm. grain and practically no vesicles. A few 2 mm. olivine crystals; no other minerals identified.

Field No. 2183. Specimen in place. Medium gray, very cellular basalt with 5 mm. vesicles and 1/20 mm. grain. No minerals identified.

Field No. 2185. Specimen in place. Medium gray basalt of 1/10 mm. grain containing a few 5 mm. vesicles. No minerals identified.

Field No. 2196. Specimen in place. Dark gray basalt containing irregular vesicles and a few olivine crystals up to 2 mm. No other minerals identified.

Field No. 2197. Specimen in place. Slate gray basalt of 1/20 mm. grain containing a few 1 mm. vesicles and scattered 1 mm. olivine crystals.

Field No. 2204. Specimen in place. Gray basalt with prominent flow structure and elongate vesicles. Has 1/20 mm. grain. No minerals identified.

Field No. 2205. Specimen from residual block. Light gray basalt of 1/4 mm. grain and containing irregular 1 mm. vesicles. Olivine crystals reaching 3 mm. are numerous. Plagioclase considerably altered.

Field No. 2216. Specimen in place. Slate gray, very porous basalt with 1 mm. vesicles. No minerals identified.

Field No. 2224. Specimen from residual block. Gray black basalt containing a few 1/2 mm. vesicles and of 1/4 mm. grain. Contains 1 mm. plagioclase partially altered to kaolin.

Field No. 2225. Specimen in place. Medium gray basalt of 1/4 mm. grain and containing 1 mm. plagioclase partially altered to kaolin.

Field No. 2229. Specimen in place. Gray black, very cellular basalt containing 3 mm. vesicles of slightly irregular form. 1/10 mm. grain; no minerals identified.

Field No. 2231. Specimen in place. Green gray basalt of 1/3 mm. grain containing 2 mm. vesicles and numerous olivine crystals of 1 mm. diameter.

Field No. 2246. Specimen in place. Gray black basalt containing slightly oriented 5 mm. vesicles and of 1/10 mm. grain. Contains 3 mm. olivines; no other minerals identified.

Field No. 2250. Specimen in place. Dark gray basalt of 1/4 mm. grain containing a few 5 mm. vesicles. Contains a moderate number of 2 mm. olivine crystals and 1/2 mm. plagioclase partially altered to kaolin.

Field No. 2312. Specimen from residual block. Medium gray basalt of 1/4 mm. grain containing a few vesicles and few 1 mm. olivine crystals. 1 mm. plagioclase laths are partially altered to kaolin.

Field No. 2314. Specimen from residual block. Medium gray basalt containing a few 3 mm. vesicles and of 1/4 mm. grain. Plagioclase up to 1 mm. partially altered to kaolin.

Field No. 2324. Specimen in place. Dark speckled basalt containing a moderate number of vesicles reaching 1 mm. Plagioclase crystals 1 mm. in diameter are extensively altered to kaolin.

Field No. 2325. Specimen from dike. Slate gray compact basalt without vesicles and of 1/20 mm. grain. A very few olivines reaching 1 mm. are present. No other minerals identified.

Field No. 2355. Specimen in place. Gray black basalt of 1/10 mm. grain containing irregular 2 mm. vesicles, some of which are filled with aragonite. A few 2 mm. olivine crystals are present.

Until the specimens have been studied microscopically little can be added to the megascopic descriptions of individual rocks except to state some general facts concerning the rocks of other Hawaiian islands. These are based chiefly on the studies by Cross[10] and Washington.[11]

The bulk of the rock which makes up the Hawaiian islands is basalt. Special types such as bronzite, picrite, nephelite, and nephelite-melinite basalts are found on some of the islands. Washington finds several types of andesite abundant on the island of Hawaii. Of the constituent minerals plagioclase, augite, olivine, and magnetite are of most importance in the order named; many of the lavas contain practically no other minerals. Neither quartz nor any other form of free silica have been found in Hawaiian lavas except very rarely, though the silica content is sufficiently high to make this lack seem rather anomalous. No chemical analyses have yet been made of any Lanai rocks. As an example of the general composition of basaltic rocks of the type found in the group, the following average of 56 analyses, compiled and largely made by Washington[12] for basalts from the island of Hawaii, will be instructive.

SiO_2	49.73
Al_2O_3	13.71
Fe_2O_3	2.92
FeO	8.64
MgO	8.27
CaO	9.10
Na_2O	3.16
K_2O	1.02
TiO_2	2.84
P_2O_5	0.48
MnO	0.13
	100.00
Specific gravity	2.940

[10] Cross, Whitman, The lavas of Hawaii and their relations: U. S. Geol. Survey Prof. paper 88.

[11] Washington, H. S., The petrology of the Hawaiian islands: Am. Jour. Sc., 5th ser., vol. V, pp. 465-502; vol. VI, pp. 100-126, 338-367, 409-423, 1923.

[12] Washington, H. S., Average composition of Hawaii lavas: Am. Journ. Sc., 5th ser., vol. VI, p. 361, 1923.

MANELE BASALT

The only recognizable crater remnant on Lanai is that which forms the headland south and west of Manele Harbor. From the rock island Puu Pehe eastward round the curving shore of the headland the structural rim of the crater is clearly shown by the lava flows. For a part of the distance the layers which once dipped toward the center of the crater are removed by erosion, but at other places the crest is preserved and layers dipping both in and out radially may be clearly seen. The greater part of the crater, including the south and east sides, has been eroded away by the sea.

All the basalt which lies to the south of the sandy neck of land at Manele probably came from this crater. The higher parts of the headland are built of a large number of thin flows which contain less aa material and are generally more regular in the bedding than much of the Lanai basalt. Petrographically, the rock appears to differ in no essential from that of the main mass of the island.

BASALTIC RESIDUUM

No sharp line can be drawn between the unweathered basalt and its thoroughly weathered residual products. In the lower parts of Flow Margin province much of the basalt which lies about in blocks is fresh and unweathered except for a few inches at the surface. Higher up, weathering is more pronounced and practically no fresh basalt is exposed. Even the basalt of the steep walls of gulches such as Maunalei is much weathered. Tunnels which penetrate the ridges southwest of Maunalei Gulch and which in places go under at least three hundred feet of cover are excavated in rock which is far from being fresh and unaltered.

No detailed studies have been made of the weathering of basalt in Hawaii. The weathering of similar rocks under conditions that are somewhat the same has been studied by others and certain general facts appear. Of the minerals which compose the basalt the plagioclase feldspar is most easily weathered and in many specimens otherwise quite fresh the plagioclase is found to be partially altered to kaolin. Augite and olivine are next in the rapidity of their weathering. The general course of the weathering from the chemical standpoint is shown in the following table:

TABLE NO. 8—COMPARATIVE ANALYSES OF HAWAIIAN BASALTS AND SOILS WITH OTHER TERRESTRIAL MATERIALS

	A	B	C	D	E
Silica	59.77	47.90	27.54	10.11	21.1%
Alumina	14.89	18.23	22.64	8.31	45.6%
Ferric iron	2.69	13.36	36.45	13.36	100.0%
Ferrous iron	3.39				
Lime	4.86	8.99	0.46	.17	1.9%
Magnesia	3.74	6.05	1.07	.39	6.4%
Soda	3.25	2.20	1.19	.44	20.0%
Potash	2.98	1.50	0.62	.23	15.3%
Water	2.02	....	....		
All others	2.41	1.77*a*	10.03*a*		
	100.00	100.00	100.00		

a These figures are not given by Maxwell; it seems probable from the large value of the remainder in analysis of C that much of the amount unaccounted for is water.

A. Average composition of the lithosphere: Clarke, F. W.: U. S. Geog. Survey Bull. 695, p. 33, 1920.

B. Hawaiian lavas and C., Hawaiian soils: Maxwell, W., lavas and soils of the Hawaiian islands, p. 61, Honolulu, 1898.

D. Analysis C has been recalculated making the iron constant so as to show the actual loss of the other constituents.

E. Percentage of each constituent saved in the soil, assuming iron to remain constant.

Comparison of column B with column A will show that the Hawaiian lavas as compared to the average of all the known rock materials of the earth are low in silica, potash, and soda, and high in alumina, iron, lime, and magnesia. In the alteration which attends weathering and results in soils there is an enormous reduction of the lime and magnesia, a large reduction of the silica, soda and potash, and a moderate reduction of alumina in relation to the iron. Possibly in some of the materials represented by these analyses there has been an actual secondary increase of iron; if so the reduction of the alumina would be less than appears. The effect of this factor on the proportionate reduction of the other constituents is negligible and the essential relative positions would remain the same. The popular belief in Hawaii that calcareous crusts and joint fillings at high elevations indicate marine coral formations finds a partial basis in the erroneous idea that the lime must in some way have largely come from the ocean. It should be pointed out in this connection that all the lime and other mineral salts of the sea have been derived from land masses by the weathering of igneous rocks and that among the rocks of the earth those of Hawaii are high in their lime content, yielding to the sea proportionately more than their share of the total amount. The reef rocks which fringe the shores of the Hawaiian islands certainly represent but a tiny fraction of the calcium carbonate which has been delivered to the sea since the islands were first exposed to the agents of weathering, and the basaltic rocks, rather than the sea, must be regarded as the ultimate source of lime.

In the gradual chemical transformation which results in the formation of the dark brown and red soils from basalt are accompanying physical changes, one of which is the development of a spheroidal structure, prominent in the whole mass of partially weathered basalt. In a way not clearly understood this results from the gradual extension inward of decomposition toward the nuclei of the spheroids, these being the last to become altered. The initial blocking out of the rock into polyhedral masses which constitute the spheroidal units follows the lines of vertical and inclined joints and the assumption of the spheroidal from the polyhedral form is only an additional illustration of the superior stability of the spheroidal form whether the attack be by solution, abrasion, surface heating or other non-directive force. I believe, though the hypothesis has not been tested and may not be original, that the spheroidal structure itself is the result of volume changes accompanying the weathering which proceeds from the outside toward the inside. That all rocks increase in volume as they become weathered is well established. Therefore an increase in volume which takes place differentially—the outside subject successively to more change than the inside—will result in shearing and tensional stresses between the outer and inner parts, just as occurs in the better known process of exfoliation under the heat of the sun.

BEACH ROCKS

At various places on the coast of Lanai small masses of calcareous conglomerate and sandstone lie embedded in the sediments of the present beach or cemented in and around the eroded and carved remnants of the wave-cut bench. Conspicuous examples are found at Manele, in various of the bays near Kaumalapau and near Honuaula Point on the north coast. Everywhere these rocks show structures and attitudes identical with the sediments of the modern beach and like them are sandy in the quieter coves and contain pebbles and become conglomerates near the adjacent cliffs of basalt and near the mouths of streams which carry coarse debris during their brief periods of activity. The petrographic character of these beach rocks is shown in the following descriptions:

Field No. 2059. Specimen of beach conglomerate from beach at head of Kaumalapau Harbor. Specimen is itself a bowlder 50 cm. by 25 cm. by 15 cm. The conglomerate shows practically no bedding of small enough scale to show in the specimen. One side is smooth and concave, representing the cast of the larger bowlder or convex surface of bedrock on which the gravel was originally deposited. The rock is made up in about equal proportions of cobbles of 10 cm. to 15 cm. diameter, pebbles ranging from 1 cm. to 4 cm. and of granule gravel ranging from 2 mm. to 5 mm. Each of these classes serves as a matrix to the next coarser material but the classes are not sharply separated. The larger cobbles are mainly of basalt and show much variety in color, texture and mineral composition. One cobble of coral quite reaches the larger of the basalt cobbles in size. Shapes range from subangular to fairly well rounded. The proportion of coral fragments is greater in the smaller pebble grades and only slightly broken; shells of several species of mollusks are incorporated in the mass. The finer granule grades of the matrix are composed of calcareous and basaltic fragments in about equal proportions and these in general are poorly rounded. A still finer matrix, buff brown, surrounds the granules. This appears to be a mixture of calcareous cement and red-brown terrigenous debris washed in by streams.

The whole rock is cemented with a calcareous cement and is a compact, rather durable rock, though it could not be considered hard. The larger constituents are mostly in contact with one another and show very little general orientation though in places a local orientation of the longer diameters of the finer debris in relation to the surfaces of the larger constituents appears.

Field No. 2355. Specimen of pebbly beach sandstone from beach outcrop east of Manele. This rock is a well cemented sandstone of which the grain varies from 1/10 mm. to 2 mm. with the bulk of the grains about 1 mm. in diameter. There are two basalt pebbles 4 cm. long in the specimen, but practically no fragments between these and the size of about 4 mm. Ninety to ninety-five per cent of the matrix is composed of coral and other organic calcium carbonate fragments. It is very noticeable that in the fairly uniform matrix the calcareous fragments are mainly 1 mm. or more in diameter and the basalt fragments are mainly ¼ mm. to ½ mm. in diameter as a result of the differing density of the two materials and a rather effective sorting by the waves. The only additional constituent seen in a megascopic examination is a small amount of olivine in somewhat abraded grains which are rather smaller on the whole than the basalt grains.

Field No. 2355B. Specimen of basaltic sandstone from beach outcrop east of Manele. This is a compact well cemented sandstone of dark gray color and a grain ranging from 1/10 mm. to 1½ mm. The bedding is well marked and there is a considerable variation in the material of different layers. About 70 to 80 per cent of the rock is made up of basaltic fragments, which so dominate its appearance that the rock is in places almost indistinguishable megascopically from a medium grained basalt though close scrutiny under the hand lens shows its sedimentary origin. As in specimen No. 2355 a few small grains of olivine are present. The rock is cemented with calcium carbonate.

RECENT SEDIMENTS

Along the entire Beach Coast province of Lanai are moderate quantities of marine sand which for the most part is a mixture of reef-rock debris and land-derived rock particles. In places the calcareous element predominates, notably on the beach immediately west of the Manele headland. At numerous bayheads and in pockets in the emerged bench in the Pali Coast are small deposits of marine gravel. The most continuous of these is the narrow bowlder beach which is more or less continuous at the foot of Pali Kaholo.

The gravel is mainly composed of basalt with only minor parts of reef rock fragments. The calcareous elements of the sand are in part fragments of coral, algae, and molluscan shells but appear to include also large quantities of the shells of Foraminifera.

Alluvial sediments on Lanai consist of poorly assorted fan and channel deposits closely associated with the modern streams. Along the coast the alluvial sediments meet and mingle with the marine sediments, but differ from them in being less well sorted, more heterogeneous lithologically and mineralogically, and less rounded. Inland, the alluvial deposits merge into colluvial deposits which in turn merge into talus deposits with no sharp line at any part of the series. Much of the Palawai Basin and of other basins in the Central Plateau is covered with such material which serves to round the contour of the depression and to soften the outlines of the original fault topography.

To indicate the locations of all talus materials is hardly possible since they are found in small quantities nearly everywhere except on the flattest of undissected plains. Many talus deposits are now so mantled with vegetation and so merged with slopes of colluvium and alluvium below as to be inconspicuous. In Maunalei Gulch and other large gulches on the east side of the island the lower lateral walls are flanked by talus slopes in such a way as to raise a doubt whether stream action is as active as it has been at some time in the past. That the sapping of the lower part of the lateral pali depends on the somewhat effective removal of debris by the stream seems certain and at present the stream is held near the middle of the channel by large talus accumulations along a considerable part of its course.

Very little talus appears at the foot of the cliff, along most of the Pali Coast, testifying to the generally effective removal by the sea. Several very large talus cones, however, flank the southern part of Pali Kaholo and extend several hundred feet out into the sea.

Along most of the east and north coast of Lanai modern wind blown sand is abundant. Along the north coast where the beach is in many places very close to the margin of the rocky lava slopes, sand forms a thick mantle, reaching a maximum of about 150 feet above sea level on its landward edge. For the most part the sand lies in elongate ridges rather than in dunes of the crescentic type. Along the east coast the eolian sand is more intimately mingled with fluviatile and marine deposits in the coastal zone though thin sand deposits extend farther inland.

On the northeast and north parts of the Flow Slope and across the north part of the Central Plateau eolian sediments lie in small eroded patches and as drifts on the lee slopes of some of the higher elevations. This material can hardly be called sand. It probably contains a large percentage of fine material and consists of small fragments from the soil and basaltic residuum which is being eroded from the upland.

A low point which projects slightly from the shore line one mile southeast of the mouth of Maunalei stream is covered with cemented eolian calcareous sand. The point itself is composed of lava which has been veneered by the sandstone. Associated with the sandstone, which is weathered into a jagged, cuspate surface, is a calcareous crust formed by the leaching of the sand. No large coral fragments or any other material indicating marine action higher than at present were seen on this point.

STRUCTURAL GEOLOGY

MAJOR STRUCTURE

As nearly as can be learned at the present time, the original form of Lanai was that of a single, simple cone built of many thin lava flows. Probably the outlines of the base of the original cone were essentially those of the present island on the northwest, north, east, and southeast coasts; on the south and west sides the original coast line was somewhat outside the present one. The original slopes of the flows which make up the cone ranged from 5 to 15 degrees, being in general somewhat steeper on the east and southeast sides of the cone. The vent from which the flows came and which once occupied the apex of the cone was probably situated one or two miles southeast of Lanai City and had an elevation of nearly if not quite 5,000 feet. The dips of lava flows composing the present high summit mass are to the northeast and east and it is clear that the original crater summit must have been somewhat to the west and high above what is now the Palawai Basin. Contrary to popular opinion, Palawai Basin is not a volcanic crater but owes its origin to faulting which produced a number of similar basins in the Central Plateau.

FAULTING

Perhaps the most interesting single geologic feature of the island of Lanai is the extensive faulting which has played so prominent a part in producing its present surface configuration. Because of the deep cover of deeply weathered material which lies over the basalt in most of the region affected by faulting and the present impossibility of identifying individual lava flows, it has not been possible to map the fault traces nor to determine the amounts of throw as might be done in a region underlain by fossiliferous sedimentary rocks. The principal evidences of faulting are the anomalous topographic features which are so prominent in the Central Plateau and the remarkable regularity these show when traced on a map. (See fig. 8.) The interpretation of faulting on the basis of topographic features is strengthened by the fact that in a few places along these topographic lines indubitable evidences of displacement are to be found. In the middle portion of Kawaiu Gulch, which reaches the coast about three miles east of Manele, is a poorly exposed section of a fault trending about N. 30° W. in which the southwest side is downthrown to an unknown amount. In the same gulch were noted several exposures of a dike which trends in a similar direction. Throughout considerable of the length of this gulch are large quantities of brecciated rock, and at a good many points narrow defiles and low sags cross spurs. They are not related to the dominant drainage and appear to have been developed along the same line of faulting. It is also significant that there is an abrupt jog in the coast at the mouth

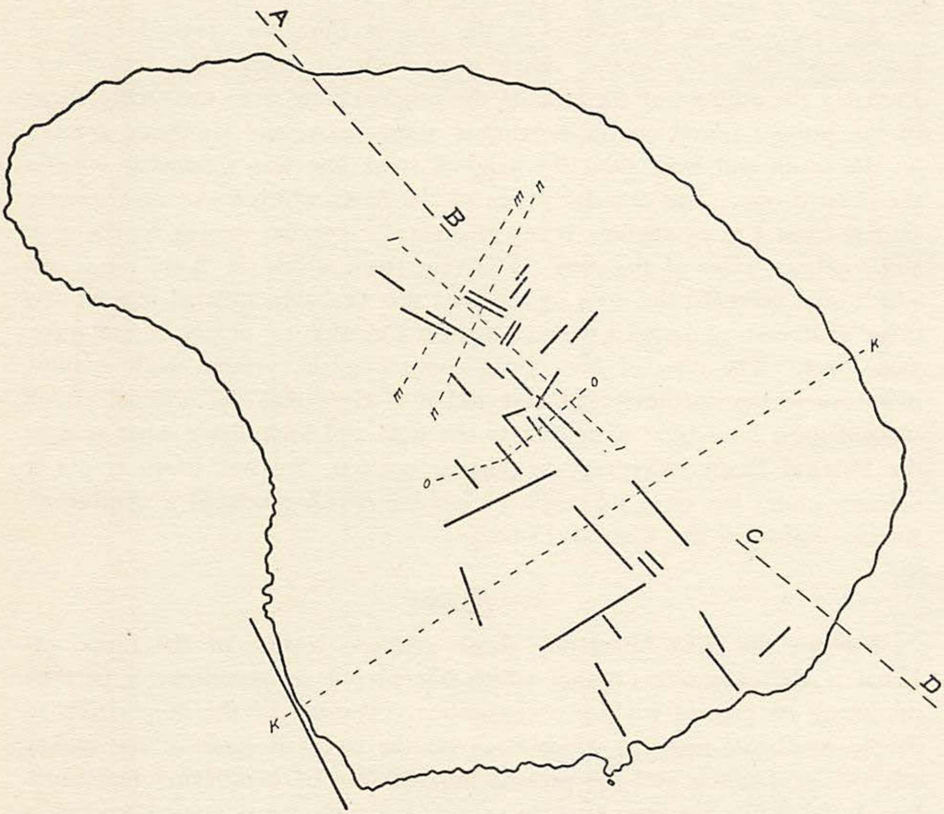

FIGURE 8.—Map of tectonic lines. The heavy lines are drawn mainly from topographic anomalies which constitute the usual evidence of faulting. Lines kk, ii, mm, nn and oo show locations of sections in figures 7 and 8. AB is a portion of the line connecting the west Molokai summit, Mauna Loa, with the summit point of Lanai. CD is a portion of a similar line from the summit point of Kahoolawe.

of this gulch and a number of lesser ones farther west, several of them associated with valleys having notably steep east walls, and like Kawaiu containing much brecciated rock debris. All these features point to normal block faulting with the displacement taking place along a number of planes and downthrowing of the blocks progressively to the southwest. The traces of at least three of these fault planes were seen in the face of the coastal pali east of Manele. The only one examined closely trends N. 20° and dips 60° to the southwest. There is clear evidence of movement, but the amount of the throw, which seems to have been large, is indeterminable. The series of steps which are clearly shown in the present topography at many places along the northeast margin of the Central Plateau are similarly the result of block faulting. The principal faults trend in a southeast-northwest direction and are associated with a subordinate set of cross faults which trend nearly at right angles to them. (See fig. 8.) Thus the main

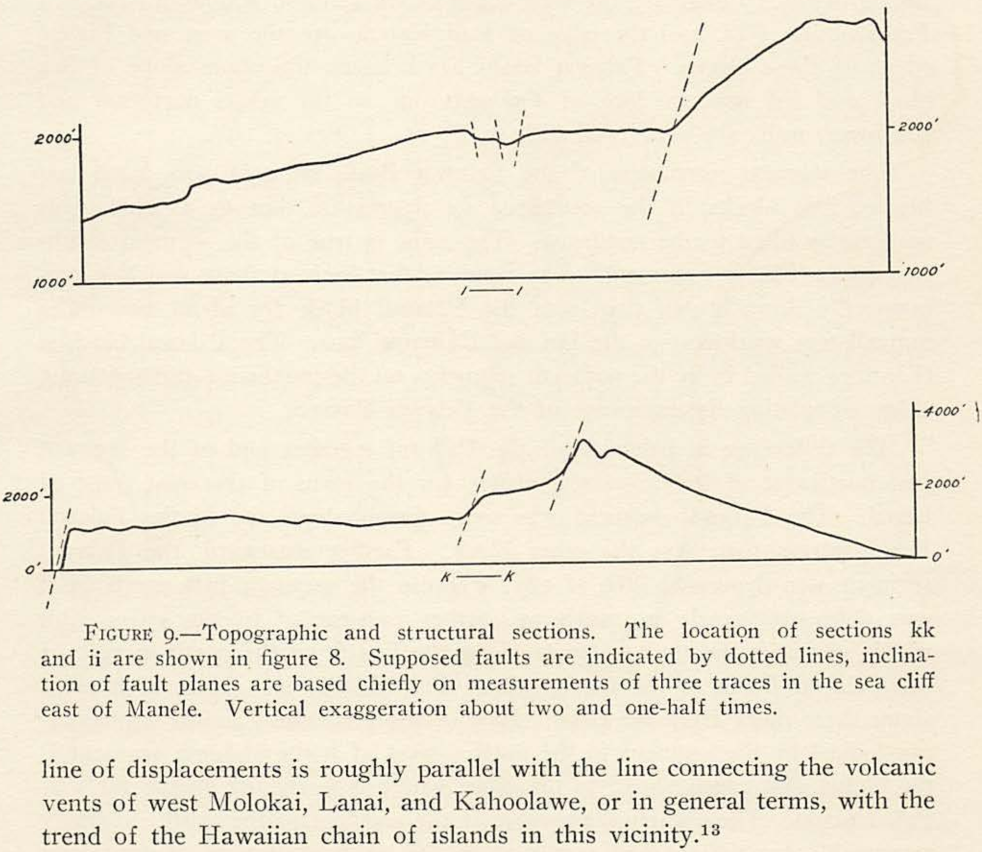

FIGURE 9.—Topographic and structural sections. The location of sections kk and ii are shown in figure 8. Supposed faults are indicated by dotted lines, inclination of fault planes are based chiefly on measurements of three traces in the sea cliff east of Manele. Vertical exaggeration about two and one-half times.

line of displacements is roughly parallel with the line connecting the volcanic vents of west Molokai, Lanai, and Kahoolawe, or in general terms, with the trend of the Hawaiian chain of islands in this vicinity.[13]

Since the extrusive vents are arranged mainly along a northwest-southeast line and have built up their volcanic piles to merge in a linear submarine ridge having its chief declivities on the northeast and southwest sides, it is but natural that structural failure by which parts of these piles have slumped away toward the deep sea should take place along fault lines

[13] Powers, S., Tectonic lines in the Hawaiian islands: Geol. Soc. Am. Bull., vol. 28, pp. 501-514, 1917.

parallel to the main axis of the ridge. The westernmost of the faults on Lanai is represented by the straight southwest pali which rises at its highest point a thousand feet above the ocean. The Palawai Basin owes its origin to the fact that the segment which runs between it and Pali Kaholo in a northeast-southwest direction behaved in a different way from those to the north and south. This segment apparently was downthrown in such a manner that the northeast edge of each block stood much higher than the southwest edge, as a result of strong tilting to the northeast. The west facing brow of Lanaihale, the west edges of the Hii and Kaluanui flats, and Pepeiaohuhu Hill, and the edge of Pali Kaholo are the west and higher edges of these blocks. Palawai Basin lies between the upper slope of one block and the western face of the next one so far as its northeast and southwest walls are concerned (Pls. v, *C*, vi, *A;* figs. 9, 10).

The segment northwest of the Palawai Basin segment was much less broken into blocks in the course of its depression, but as a whole was moderately tilted to the northeast. The same is true of the segment southeast of the Palawai segment. The result is that each of these was less pronouncedly downthrown than was the Palawai block for about two miles immediately southwest of the Hii and Kaluanui flats. The Palawai block is therefore walled in by the adjacent segments on the northwest and southeast sides, completing the enclosure of the Palawai Basin.

The difference in behavior of the Palawai segment and of the segment just northwest of it is also responsible for the form of the west coast of Lanai. The Palawai segment was more deeply depressed in the Palawai Basin section than was the other block. Farther westward, the Palawai segment was depressed little if any, whereas the segment just north of it was depressed nearly as much as farther eastward. In the cross fault which separates the two segments along the line from the north margin of the Palawai Basin to the north end of Pali Kaholo is a pivot at a point about three miles from the coast. East of the pivot the Palawai segment is overlooked by the segment to the north; west of it the Palawai segment is the higher and continues so to the place where it is cut off by the fault of Pali Kaholo. The greater depression of the segment to the north is largely responsible for the marked reentrant in the west coast from Kaumalapau northward.

MINOR STRUCTURE

The great mass of Lanai basalt is essentially homogeneous and within any area of a few square miles shows the same variety of features as is shown on the entire island. There are probably certain differences between different parts of the island in such features as the average thickness of flows or the proportion of aa in the lava mass but these are not suffi-

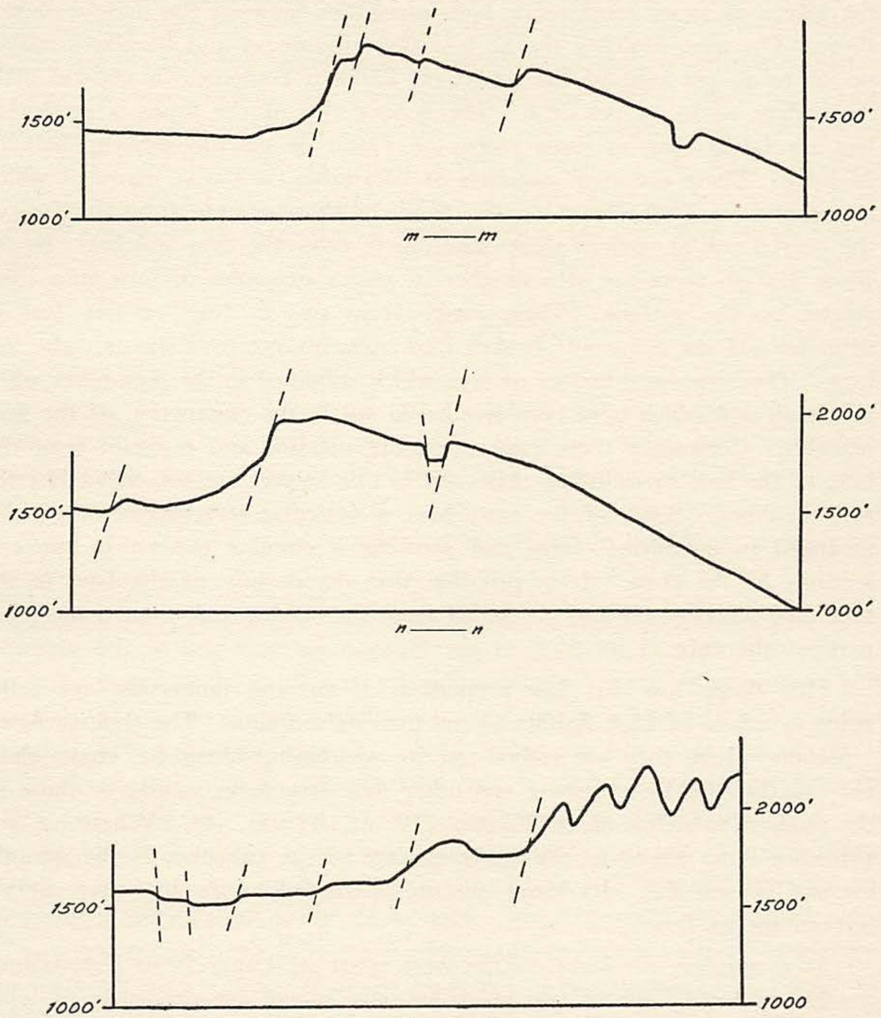

FIGURE 10.—Topographic and structural sections. The location of sections mm, nn and oo are shown in figure 8. Supposed faults indicated by dotted lines. Vertical exaggeration about six times.

ciently prominent to be detected in the course of a general areal study. The most conspicuous characteristic of the Lanai basalt as compared with the basalt of Oahu and Molokai, with which I am most familiar, is the relative thinness of the Lanai flows. These are very rarely over five or six feet thick and in many places are considerably thinner. Another feature is the somewhat smaller proportion of the whole series which is contained in the layers of aa or scoriaceous lava which lies between the more compact flows. On west Molokai the aa is rather prominent and in places makes up 30 to 40 per cent of the mass; on Lanai it composes in general little more than 10 to 15 per cent. The general dip of the flows is somewhat less on Lanai than at most places on Oahu or on the western half of Molokai. There are great numbers of lava tubes on Lanai, many of which are several hundred feet in length. Some of these emerge from the face of the coastal pali at various places and others enter the deep gulches. In the Flow Margin there are at a number of places examples of lava tube casts strewn on the surface. These range from two to four or five feet in diameter and are commonly broken into segments not over six or eight feet long. They represent masses of lava which solidified in the lava tubes while in transit and which have been weathered out in the destruction of the flow margins. Commonly these casts are more massive and resistant than the bulk of the lava surrounding them and in this respect are somewhat like the rock in dikes. Some of the casts have a vesicular structure with vesicles arranged in cylindrical form and showing a circular pattern in the end sections of the casts. It is probable that the cooling of the lava in the tube took place slowly and proceeded from the outside wall toward the inner part of the tube.

Thin flows, low dip, low proportion of aa, and numerous lava tubes point to a lava of high fluidity at the time of eruption. The thinner flows, especially where they are etched out by weathering along the coast, show very marked bubble structure and other flow structures similar to those of the modern pahoehoe about Kilauea (Pl. VI, *B*; VII, *A*). Where aa and pahoehoe flows alternate, the upper surface of the pahoehoe is the smoothest and nearest flat. Its lower surface is molded to the irregular surface left on the aa flow.

At a number of places on the west coast of Lanai from Kaumalapau northward and in one or two gulch bottoms inland, are exposures of what is either old aa in thick masses or volcanic agglomerate. These are more or less mingled with flow lava and are of a very irregular structure which is not clearly a part of a definite cone. If these are parts of secondary cones, they are much older than the lava in the upper part of most of the west coast pali. It may be that they are merely thick accumulations of aa lava, perhaps formed at the foot of a low sea cliff or that they are the result of secondary pyroclastic action induced by the contact of flows with sea water. It is probable that during the formation of Lanai interruptions occurred during which some erosion took place and perhaps some changes in the type of volcanic action. However, data is lacking for making clear correlations or any definite chronological subdivisions.

At one or two places the lava which overlies the margin of the agglomerate has flow lines which stand essentially vertical and indicate that the mass was extremely viscous at the time it flowed down over the steep edge of the agglomerate mass. At one point near the west coast (specimen No. 2103b—) there is a mass of basalt containing angular inclusions of an older lava. These are of various sizes from one to twenty centimeters across and are oriented in the direction of flow.

There are very few dikes on Lanai. About a half dozen are exposed in the wall of Maunalei Gulch near the old pumping station. A dike was found in Kawaiu Gulch, running parallel to the principal tectonic lines, and another small dike near the forks of Awehi Gulch. An intrusive mass 75 feet to 100 feet in each dimension having a dike as its source, is located near the head of Lopa Gulch and is exposed in a nearly vertical wall.

GEOLOGIC HISTORY

EMERGENCE OF VOLCANIC PILE

Maui, Molokai, Lanai, and Kahoolawe islands constitute a single volcanic unit; in only a few places does the depth of water between them exceed 100 fathoms. These four islands are separated from Oahu by Kaiwi Channel, about 350 fathoms deep, and from Hawaii by the Alenuihaha Channel, more than 700 fathoms deep. The entire chain of islands rests on the ocean floor at a general depth of 2,500 fathoms; 50 miles east of Maui, the depth of water is 3,000 fathoms. Considered as a unit, therefore, the four islands make up a huge mass of basalt 2,000 square miles in area, which has built up to within 100 fathoms of sea level. Although the area of the combined four islands is less than one-third that of the islands of Hawaii and their total mass above sea level even less, it is probable that the entire mass measured from the ocean floor is not more than a third less than that of Hawaii.

Of this great pile of volcanic rock, Lanai is a relatively small part. Its subaerial portion is but the smaller and summit portion of a very much larger mass which lies beneath the sea. The total volume of the subaerial part is 148 thousand mile-feet, or 116 billion cubic meters. The volume of the submarine portion of Lanai is not known and depends largely on the extent to which Lanai rises from the deep sea as an independent cone or is built subordinately on the side of a greater cone. Rough computations based on both these assumptions indicate that the volume cannot be much less than 20 times nor much more than 80 times the volume of the subaerial part. This volume may be compared with that of some of the greatest lava flows of historic time. The 1865 flow of Etna was estimated to amount to 92 millions of cubic meters, those of 1852 and 1869, at 420 and 980 millions respectively and a prehistoric flow near Randazzo at more than one billion cubic meters. From descriptions given by Geikie [14] it is probable that some of the great fissure flows of Iceland and of other regions may have had volumes several times as great. It is probable that the basalt flows which built up the various islands of Hawaii more often than not covered but a part of the cone on which they were erupted. A lava flow six feet thick and covering one-fourth of the land area of Lanai would have a volume of about 170 million cubic meters. A six foot flow covering the whole island of Lanai would have a volume of about 680 million cubic

[14] Geikie, A., Textbook of geology, 4th ed., vol. I, p. 300, 1903.

meters. It is apparent that these volumes are closely in accord in order of magnitude with those given by Geikie. If broad submarine areas were covered with lava, the amounts would be enormously greater.

Taking 200 million cubic meters as a liberal figure for the average volume of the basaltic flows of Lanai, it follows that in the formation of the subaerial part alone the equivalent of 580 flows is needed. Judging from what is known of volcanic action in Hawaii and in other places it is very unlikely that these flows would follow one another at lesser intervals than perhaps ten years. On the other hand, they certainly came with considerable regularity and frequently enough to prevent extensive deep erosion during the intervals. According to my estimate the total amount of material removed from Lanai by erosion is equivalent to approximately 25 feet over the whole area and represents something like 100 to 150 thousand years. During the course of this erosion some gulches have been cut to depths of a thousand feet or more and very many to depths of 100 feet. Certainly less than a hundredth part of this erosion took place between successive lava flows and the average amount must have been not more than a thousandth part. On this basis, crude though it is, it may be said that the flows probably succeeded one another at an average interval of not less than ten or more than 100 years. On the assumptions stated the time required for the building of the subaerial part of Lanai is not less than about 6,000 and not more than about 60,000 years. How much longer time was required for the building of the submarine base on which Lanai now stands is unknown, nor is it known whether this base was built primarily by the same series of volcanic eruptions or is merely a much older part of the great series of submarine elevations which extend from Hawaii to Kauai.

RELATIVE AGE OF LANAI

There is little fossil evidence to guide in making age comparisons of the several Hawaiian islands. The meager physiographic and diastrophic evidences at hand leave little doubt that Lanai is younger than Oahu and Kauai. All parts of these two islands have suffered vastly more erosion than similar parts of Lanai and have experienced a much more complicated series of diastrophic events. There is no evidence on Lanai of a wave cut bench at 35 feet above sea level corresponding to that on Oahu. It cannot, of course, be assumed that three islands situated along a 200 mile line will have the same diastrophic history, especially when they are volcanic masses showing considerable local instability. On the other hand, it seems entirely unlikely that such an island as Lanai would stand unaffected by emergence and submergence due to any cause during a period when larger islands such as Kauai and Oahu were subject to a number of changes relative to sea level. Furthermore, if shifts of sea level be admitted as causes of emergence and submergence, the islands would be affected alike.

The island of Hawaii is the site of volcanic action which continues to the present time; but at least two of the centers of eruption, Kohala and Mauna Kea, have shown no activity in recent times and are of considerably greater age than the craters in the southern part of the island. The common assumption that Hawaii is the youngest of the Hawaiian islands is certainly true of the great mass of the island as we know it today. It is possible, however, that the northern parts of Hawaii may be older than some parts of Maui, such as the Haleakala, or than eastern Molokai, but it is unlikely that the Kohala cones will be found to antedate the older parts of Maui, Molokai, Kahoolawe, or Lanai.

There are good reasons for believing that eastern Molokai is younger than western Molokai and that eastern Maui is younger than western Maui. My brief study of Molokai suggests that the basalt cone of eastern Molokai extending westward over central Molokai at a very low angle is piled against the eroded east margin of the Mauna Loa cone on the western part of the island. The common belief that western Maui is older than eastern Maui seems reasonable in view of the deep erosion of the cone of western Maui and the obvious freshness of the features of Haleakala.[15] Furthermore, there are some traditions indicating that an eruption may have taken place at Le Perouse Bay near the southwest coast of East Maui about the middle of the 18th century.

The fact that eastern Oahu and eastern Molokai are respectively younger than western Oahu and western Molokai suggests some sort of rhythm in the order of eruptions and tempts a student to finish the series by making western Maui and eastern Maui respectively younger than Lanai and Kahoolawe, a scheme which takes into account the arrangement of these craters in two lines with the assumed older crater of each pair in the southwest line. If this geometrical suggestion were applied in the other direction, it might be said with much assurance that western Oahu is older than western Molokai, Lanai, or Kahoolawe and that eastern Oahu is older than eastern Molokai or any part of Maui. On the basis of the degree of erosion there is some reason for considering eastern Molokai older and eastern Maui younger than western Maui. Concerning the order of western Molokai, Lanai, and Kahoolawe, there is less basis for judgment. Western Molokai appears to have suffered some windward marine erosion before it became protected by east Molokai. Lanai shows no similar features.

[15] Thurston, Lorin A., The last lava flow on Maui: Honolulu Advertiser, February 24, p. 9, 1924.

Kahoolawe has a number of great bights along the south and east coasts but the form and locations of these suggest faulting much more than erosion.

If Lanai and Kahoolawe are older respectively than western Maui and eastern Maui as western Oahu and western Molokai are almost certainly older than eastern Oahu and eastern Molokai, then the interval between the west and east components of each pair became successively much less toward the southeast. Specifically it may be believed that Lanai is not much, if any, older than western Maui. Some observers would consider it much younger, on the basis of the deep dissection of western Maui. Another consideration, however, which suggests greater age for Lanai is the very large amount of coastal erosion on the west coast. Even if the impressive Pali Kaholo, which cuts off the southwest part of the island with a drop of a thousand feet, is disregarded because of its probable fault origin, there is a considerable coast line north of Kaumalapau on which cliffs of 100 to 400 feet high have been developed by the undoubted action of the waves. The marine abrasion of this coast is considerably more pronounced than that of the similarly situated coast of western Molokai. This fact taken alone would suggest a greater age for Lanai but the effect of the somewhat different trend of the Molokai coast should be considered as operating against this conclusion. Furthermore the lack of any considerable abrasion of the north coast of Lanai seems to point conclusively to the protection afforded by the island of Molokai from the very first exposure of Lanai to the waves. In this connection there is the possibility that Lanai is not to be taken as a unit and that its western part is older than its northern and eastern parts in spite of the fact that no clear evidences of great differences in age were found in the field. Kahoolawe is much less eroded on its western coast than is Lanai and may be considered younger so far as present knowledge exists.

From the various lines of reasoning presented above it is believed that Lanai is younger than any part of Molokai and is older than either eastern Maui or Kahoolawe. Lanai and western Maui may be of nearly simultaneous origin with the probability that if a difference of age exists western Maui is the older.

No means is at hand to date with accuracy the formation of Lanai. On the basis of an erosional period of some 100,000 to 150,000 years and a volcanic formative period of perhaps 50,000 years, the first appearance of Lanai above sea level dates from a time well back of the Wisconsin stage of the Pleistocene but not so far back as the early Pleistocene if recent estimates of the duration of that subdivision of geologic time are correct. Moreover, if the terrace building epoch indicated by certain features of Oahu be correlated with one of the more pronounced advances of glacial ice in North America, Lanai, which, according to the foregoing discussion postdates these features, will be at least somewhat younger than early Pleistocene.

DATE OF FAULTING

At some time following the formative stage on Lanai the newly made volcanic mass suffered extensive normal faulting by which the southwest part of the island including the summit peak was downthrown in successive blocks. The actual displacement in any one of the several fault planes has not been measured, but apparently the total amount of downthrow involved was not less than three thousand feet.

The present topography of the island appears to have been developed under the existing conditions and no evidence was detected of topographic features antedating the period of faulting. It is therefore probable that the faulting took place relatively soon after the building of the island. Associated with the faulting were a small number of dike intrusions which like faults follow a northwest-southeast trend. It is probable also that the eruption which formed the Manele crater and headland took place at this time.

DEVELOPMENT OF PRESENT TOPOGRAPHY

Following the faulting which created the Central Plateau, stream erosion continued with no known interruption to the present day. The south, west, and northwest coasts have been extensively eroded by the sea and parts of the northern end of the plateau have suffered from considerable wind erosion, of which the greater part is believed to have taken place in very recent times. A rough estimate based on the area of contour indentation indicates that an average of 25 feet has been removed from the entire island by stream erosion, an amount equal to 3,520 mile-feet. A similar estimate of marine erosion on the west and south coasts (excluding Pali Kaholo) shows that an area of about 2.75 square miles has been cut away to an average depth of about 80 feet. Thus marine erosion amounts to about 220 mile-feet or about one-seventeenth of stream erosion. If Pali Kaholo is the result of marine erosion, which I very much doubt, something like 1,000 mile-feet more would be added.

The estimated rate of erosion on Lanai during the past fifty years—of one foot in 2,900 years—applies to a somewhat accelerated rate under the modern conditions of generally restricted vegetation. The average rate during the entire history of the island is doubtless somewhat less although the aggradation of some of the larger gulches suggests a more vigorous erosion at some period in the past. One foot in 5,000 years is perhaps the average rate of erosion. At this rate the erosion of an average 25 feet of rock from the surface of Lanai would require about 125,000 years. It should be remembered that this estimate is based on very rough visual estimates of the amount of fill around the bases of kiawe trees and on very general applications of this data to other parts of the island. On the other hand, as compared with parts of North America or other continental area where such estimates have been made, the erosive history of Lanai is extremely simple. There are here fewer sources of very large errors due to unknown fluctuations in conditions.

SHIFT OF SEA LEVEL

The last geologically remote event on the island of Lanai was the withdrawal of the sea from the shores in such a way as to expose the prominent wave cut bench which extends for miles along the Pali Coast province. This bench stands five to ten feet above mean sea level at its inner margin and varies in width from zero to 30 or 40 feet. Considering the depth at which it must have been formed, the bench indicates change of relation between land and sea of twelve to fifteen feet. It is thought to be the result of a shift in sea level and to be, together with the occurrence of a similar bench on all the other islands of Hawaii, additional evidence indicating a general world-wide shift of the level of the sea as suggested by Daly.[16] It is apparent from the very small amount of marine abrasion which has taken place subsequently that the emergence of this bench is of very recent date.[17] On Oahu it took place later than the very last of the pyroclastic eruptions at Koko Head. Similar evidence of recency is found in other places.

The emergence of the bench has served to greatly retard coastal abrasion because the zone of abrasion has been carried out some feet or yards farther seaward and because the margin of the low bench against which waves are now cutting furnishes very little debris. Such debris as now falls from the old sea cliff lands on the bench. When especially high waves are able to clear off this bench, the debris is concentrated in the reentrants, resulting in the bench being more largely cut away than the points. On the points and around some of the fine marine stacks of the

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[16] Daly, R. A., A general sinking of sea level in recent time: Nat. Acad. Sc. Trans. pp. 246-250, 1920.

[17] Wentworth, C. K., and Palmer, H. S., Eustatic bench on islands of the North Pacific: Geol. Soc. Am. Bull., vol. 36, 1925.

west coast abrasion of the emerged bench is relatively feeble at the present time.

The lowering of sea level relative to the land has had essentially no effect on inland erosion. The gradients of most of the gulches are so high and many of them were formerly so slightly adjusted to sea level that the emergence of the land by twelve or fifteen feet was of slight importance in this connection.

HUMAN INFLUENCES

It is probable that the first Hawaiian immigrants found nearly all parts of Lanai wooded or otherwise covered with vegetation. Since the island was settled, house and boat building, wearing of trails, and harvesting of plant products have led here as elsewhere to considerable destruction of the forest cover. As a result, erosion by streams and by winds has been greatly increased. An even greater change was initiated when cattle, sheep, and goats were introduced. Within the past sixty or seventy years considerable areas at the north and northwest have been reduced to barren windswept wastelands, whose margins are deeply trenched by torrential rains vastly more destructive on bare areas than on lands that are well mantled with vegetation.

Within the past decade considerable progress has been made toward checking erosion by the wind and by unrestrained runoff. With the substitution of pineapple culture for cattle raising over large parts of the Central Plateau, the area of forest and grasslands may be increased and the destruction of the soil cover largely eliminated.

GROUND WATER[18]

GENERAL RELATIONS

In all regions, the ultimate source of ground water is atmospheric precipitation in the forms of snow, rain, or dew. Of the water which falls on the land, a part runs off the surface immediately and reaches the channels of streams, another part is evaporated into the air, and a third sinks into the ground. Of that part which runs off the surface, some may later evaporate or sink into the ground. The part which is evaporated ultimately falls again as rain or snow, though perhaps not in the same region. The portion which sinks into the ground may be retained in the upper few feet as soil water and be drawn to the surface again by plants and discharged into the air by transpiration. It may penetrate much deeper. Of the deeper portion, a part will remain more or less permanently in the ground water zone but other parts will emerge as springs and seeps and serve as a source of further runoff. Thus the water which falls on the land is involved in a great cycle of exchanges between atmospheric water, running water, and ground water and, depending on local conditions, water at any given place or time may be moving in nearly any direction in this cycle. Ultimately all ground water which does not reach the atmosphere by a shorter route reaches the sea by underground circulation and thence in time is evaporated but the length of time involved in such complete circulation is quite unknown.

The more important factors affecting the primary and secondary disposition of water as runoff, evaporation, and water absorbed are the following:

(1) Configuration of the surface. Run-off will be most rapid and absorption and evaporation less rapid where slopes are steep and where the surface is cut by an extensive and direct network of drainage channels. Absorption is favored by the opposite condition of levelness and lack of channels.

(2) Vegetal cover. The presence of a forest cover reduces evaporation by maintaining a higher relative humidity in and around the trees and by protecting the damp surface beneath from heating by the sun. Likewise the underlying cover of leaves and twigs helps to retain moisture

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[18] In the preparation of this report on ground water, I have received valuable advice and suggestions from Professor H. S. Palmer of the University of Hawaii, who spent four days with me in a field examination of parts of the Lanai coast and of the features of upper Maunalei Gulch. Many of the conclusions and views presented in this paper are substantially those given by Professor Palmer in a preliminary report on the ground waters of Lanai, transmitted to the Hawaiian Pineapple Company.

by temporary absorption and by protecting the surface from the sun. By retaining moisture and by binding the soil together all vegetation, both trees and grasses, operates to retard the formation of drainage channels through retarding run-off and favoring absorption.

(3) Pervious soil and rock. A pervious soil favors absorption and reduces both evaporation and run-off. The more readily water enters the soil and penetrates underlying rock, the larger proportion of the total water reaching the surface by precipitation will be absorbed.

(4) Precipitation. The increase of precipitation will, in general, similarly affect all three modes of disposal but not all equally. With a very low rainfall very little water runs off the surface, but when the rainfall increases run-off becomes more important. Probably increase in rainfall means increase in all three methods of disposal, but relatively to the others run-off increases and evaporation decreases with absorption remaining nearer the normal proportion to the rainfall. Uniform distribution of rain throughout the year favors the maximum absorption. Though under certain conditions the reverse might be true, in general precipitation in the form of snow leads on the melting of the snow to excessive run-off and to the retention of a smaller part of the water in the ground.

(5) Humidity. Any factors which affect humidity, such as temperature, prevailing winds, and configuration of surrounding country, will affect evaporation and thus affect the amounts of water which run-off and which are absorbed.

THEORETICAL CASE OF A CIRCULAR ISLAND

In figure 11 is shown the result of an attempt to deduce the form of the water body in a circular conical island under certain conditions. Curves 1 to 5 represent successive approximations in the computation. The assumptions used were as follows:

(*a*) That rainfall is uniform over the entire island.

(*b*) The island is composed of homogeneous material.

(*c*) That flow through any tangential section of a radial segment is proportional to the slope of the upper surface at this place, and to the area of the section.

(*d*) That the flow of (*c*) in equilibrium condition must equal the total rainfall on the segment inland from the section in question.

Assumptions (*a*) and (*b*) are not realized in the case of any actual island but do as well as any other conditions for the purposes of the computation. Assumptions (*c*) and (*d*) are probably not in strict accord with the principles of hydraulics but have an approximate value in indicating the general form of the water body as shown in curve 5 of figure 11.

ANALYSIS OF GROUND WATER FACTORS

Rainfall and Run-Off

Lanai has an average rainfall of about 16 inches. This amounts to about 106 millions gallons daily, about one-half of which falls on the higher one-fourth of the island. Of this amount, a considerable part is absorbed and added to the ground water supply. The distribution of rainfall throughout the year is fairly uniform, though a few severe storms with very heavy rainfall are experienced, which operate to reduce the amount of water absorbed.

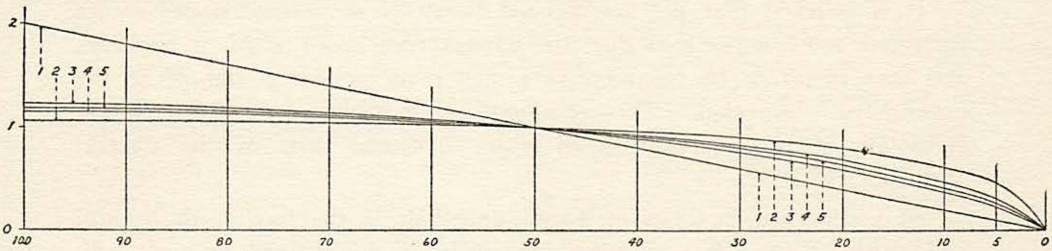


Figure 11.—Diagram showing the form assumed by a water body in porous sand under the conditions assumed and described in the text. Lines numbered 1 to 5 are approximations 1 to 5. Vertical scale exaggerated ten times.

With reference to run-off, Professor Palmer has classified parts of Lanai as follows:

Enclosed basins, no run-off to the sea	23 square miles,	16 per cent
Forested areas and gently sloping areas, moderate run-off	11 " "	8 "
Steep, barren or rather barren areas, high run-off to the sea	106 " "	76 "

Permeability of Rocks

The rocks of the Hawaiian islands are highly permeable. To quote Professor Palmer:

> The rocks of Lanai, like the basalts of the other Hawaiian islands, are extremely pervious. I know of no extensive body of rock through which water can move more readily.
>
> Three types of voids are made in lavas during their formation. First, release of dissolved gases during eruption makes many bubbles, many of which connect with one another. Second, while cooling the rock shrinks and shrinkage causes tensional stresses to which the rock yields by fracturing. The resulting cracks or "joints" are roughly perpendicular to the surface of the lava flow. Third, chilling of the upper and lower surfaces of a live flow makes a brittle and hard crust. Movement of the still fluid interior shatters the crust, making the extremely jagged aa surface. Or if the crust is slightly plastic it forms the irregular, ropey pahoehoe surface. When

a later flow covers the first it is unable to make perfect contact, so that many sizable, inter-connecting openings are found between successive flows.

Jarring of the rock by subsidence, by earthquake waves, or other stresses may produce other voids by fracture. Voids of any origin may be further enlarged by the solvent action of water moving through them.

Due to the abundance of openings of these various classes the rocks of Lanai, with very few exceptions, are highly pervious.

To this statement I have little to add. Lava tubes are abundant on Lanai and add to the permeability of the whole rock mass. My field studies confirm Professor Palmer's estimate of the highly pervious character of the Lanai rocks.

It is believed that the decomposed basalt is at certain stages of its formation more impervious than the unweathered basalt which it underlies and may therefore be regarded as a factor in increasing run-off at the expense of absorption. This residuum is probably responsible for the formation of temporary pools of water in some parts of the Central Plateau.

At a very few localities on Lanai, especially in the face of the coastal pali north of the "Five Needles" are beds of decomposed volcanic ash, one or two feet in thickness and covering an area of two or three acres. They are similar to the much thicker and more extensive beds of ash in the Kau district, Hawaii, where small bodies of perched ground water have been obtained by driving tunnels along their upper surfaces. On Lanai beds of this kind are too small to be of value in preventing the downward percolation of water.

Differential movement of two parts of the earth's crust with respect to one another along a fault plane sometimes crushes a considerable quantity of the rock and produces debris of varying fineness known as "fault gouge." If this material is a fine powder it is relatively impervious; if coarser debris is mixed with finer, the entire mass may be somewhat less pervious than the original rock. If the faulting of the rock is such that pervious layers abut against impervious ones in the fault plane the impervious layer may constitute a considerable interruption to the movement of ground water. Also a break produced in a transverse direction by the faulting may constitute an important route for the movement of ground waters.

Lanai consists almost exclusively of "extrusive rocks," volcanic rocks which have been erupted at the surface. "Intrusive rocks" are represented by a few dikes formed by injection of liquid lava into pre-existing rocks. They stand vertically or at a high angle, have a considerable extent, and cut across the lava flows. Because they have usually cooled under pressure, they are of finer grain and more nearly free of gas bubbles than the flow lavas and therefore lack the variations in permeability which

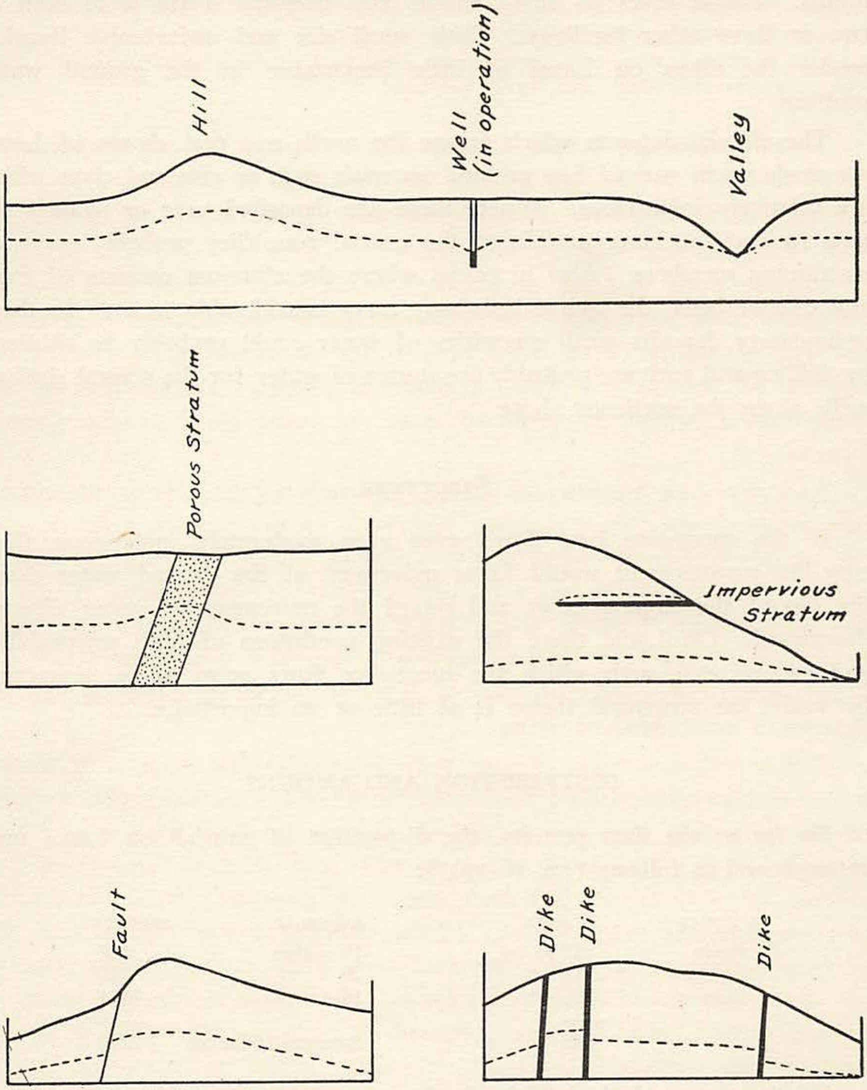


FIGURE 12.—Diagrams showing the effect of various structures on the water table.

obtain in and between successive flows. In general dikes are important restraining members and in some parts of Hawaii they are controlling factors in the movement of ground water.

Six or eight dikes with bearings ranging from N 10° E to N 45° E cut the walls of Maunalei Gulch just downstream from the development tunnel. Single dikes of small extent and irregular form were seen at two or three other localities. Their small size and unfavorable location render the dikes on Lanai of little importance in the ground water problem.

The alluvial deposits which fringe the north and east shores of Lanai are made up in part of fine grained materials such as silts and clays which are relatively impervious. Where these are deposited over or against the lava rock at the inner margin of the coastal zone they probably serve as restraining members. Also in places where the alluvium consists of finer and coarser beds, the coarse beds may carry considerable water. In these sedimentary deposits small quantities of water could probably be obtained by drilling and such are probably the source of water for the several shallow wells along the northeast shore.

Structure

If the successive lava flows were even moderately impervious their cone-like arrangement would favor movement of the ground water down the dip of the sloping flows and retard the movement of water directly downward. On Lanai there the existing conditions of high permeability and general ease with which the successive flows seem to be penetrated by water, the structural factor is of little or no importance.

DISTRIBUTION AND AMOUNT

So far as the data permits, the disposition of rainfall on Lanai may be expressed as follows (pp. 16-19)[19]:

DISTRICT	AREA	RAINFALL	PRODUCT
Basin	23 sq. mi.	19 inches	437
Forest	11 "	29 "	319
Barren	106 "	14 "	1484
	140	Average 16 inches	2240

Of the water which falls in the basin area, none runs to the sea. A small part is evaporated, perhaps 80 per cent is absorbed. This amounts to 15.6 per cent for the entire island.

Of the area classified as forest, about four square miles is also included in the interior drainage area. Eighty per cent of the rainfall of this part will amount approximately to 4.1 per cent of the island total. The water

[19] Palmer, H. S., Unpublished report, May, 1924.

which falls on the remaining seven square miles of the forest area is divided between run-off, evaporation and absorption. From an inspection of the rainfall distribution and from such information as I have been able to obtain I believe that at least half the rainfall of the year comes at a time when there is no run-off to the sea. If it be assumed that 40 per cent of this half is absorbed and if the other half be distributed as run-off, 30 per cent absorbed and 30 per cent evaporated, the total amount absorbed within the forest part of the area equals 3.1 per cent of that for the entire island.

The part of the rainfall absorbed in the barren area is conservatively estimated at 25 per cent. This amounts to 16.6 per cent of the whole. Adding these partial percentages, the total absorption for the island is shown to be 29.4 per cent of the total rainfall—an amount equal to approximately 42 million gallons daily. The corresponding figure obtained by Palmer is 40 million gallons.

The form and position of the main body of ground water on Lanai may be approximately determined. It everywhere lies at relatively low levels because of the extreme porosity of the rocks. It deviates from the approximate theoretical form deduced in figure 11 by virtue of topographic irregularities of the surface, including those due to erosion and by virtue of variations in the permeability of the rock. Figure 13 shows a somewhat generalized topographic section of Lanai from Kaumalapau to the mouth of Hauola Gulch north of Keomuku. On to it are projected profiles of Maunalei and Kaumalapau gulches. The light broken line indicates the form of water table deduced in figure 11 and plotted to a height of 250 feet in the center. This form obviously is not correct. If it were, water would be running in lower Maunalei Gulch throughout the year. Furthermore, the facts concerning Maunalei Gulch indicate that the upper parts are fed during wet seasons sooner and to a greater extent than are the lower parts. These facts suggest that the form must be modified somewhat as shown in the heavy dotted line in figure 13. From another point of view there is justification for such a change because the shore parts of Lanai, particularly the northeast shore, are more completely dissected by drainage channels and the water table would there be lower and have a lower gradient than farther inland. It is believed that much effective drainage may occur through porous alluvium in this zone which operates to lower the water table without show of surface flow. It seems unlikely that upper Maunalei Gulch is ever fed by seepage directly from the main water body of the island, and the assumption that the gulch is fed by local water bodies or by underground streams of water on its way down to the main water body constitutes in itself evidence for interpretating the water table as somewhat raised in this vicinity. As shown in figure 13, the modified hypothetical water table is 650 feet above sea level at its highest point. This is almost certainly too high. From the conditions found on other islands and from known characteristics of the rock it seems improbable that the water table is over 200 feet above sea level at its highest point and may be much lower, perhaps not more than 50 or 75 feet.

No general ground water body exists in any of the ridges immediately southwest of Maunalei Gulch to depths some 300 feet below their crests. The pipe line tunnels which were being driven through those ridges at the time of my visit were substantially dry throughout. They showed only a trifling seepage in a few places relatively near the surface. These facts

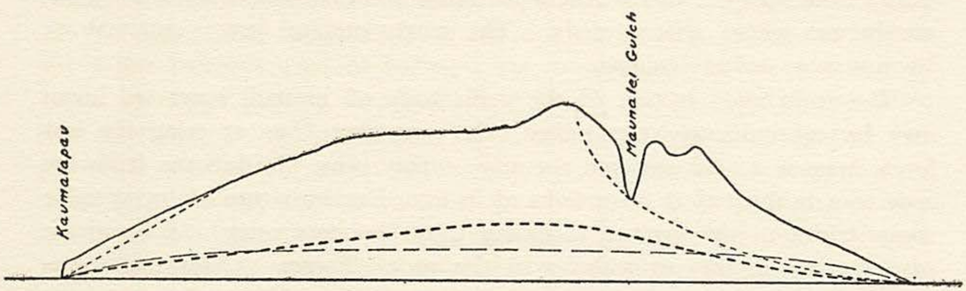


FIGURE 13.—Section across Lanai from Kaumalapau to mouth of Hauola Gulch. Light dotted lines indicate channel profiles of Maunalei and Kaumalapau gulches; the light broken line is the theoretical form of the water table plotted from data from figure 11; the heavy dotted line is modified to indicate the probable actual form of water table. Section exaggerated six times vertically and the water table profiles much more.

and the general absence of springs and permanent flowing streams indicate that the water table does not follow in a generalized way the details of surface configuration as it does in many parts of North America and elsewhere but that it subsides to a very great depth below the surface and is only in the broadest outlines related to the surface details. (See Pls. VII, *B*, VIII, *C*.)

MODE OF OCCURRENCE

The present supply of water used at Koele and at Lanai City comes from a development tunnel which enters the east side of Maunalei Gulch about a half mile above the old pump house and at the level of the stream, 1103 feet. A maxmium daily flow of approximately 400,000 gallons has been recorded from this tunnel and the amount rarely if ever falls below

200,000 gallons. The principal source of the water is a highly pervious zone of aa lava above a bed of denser lava. It is probable that this zone is only a small part of the route by which the water is reaching lower levels and that most of the passages and pervious rock masses are more nearly vertical.

Since the driving of the tunnel a number of years ago the water has been pumped over the intervening ridges to Koele and Lanai City but a series of tunnels is being driven to carry a pipe line at a lower level, which will reduce the lift to 800 feet.

Emory[20] has described the Hawaiian method of obtaining water for household use. One of these is the collecting of dew from the shrubbery and on oiled tapas spread out for the purpose, principally on the upland part of the island. On the north, northeast and east shores were a number of brackish wells. The west shore was poorly supplied with water. Wells at Kaunolu and at Kaumalapau are reported to have supplied water for about one hundred horses. That at Kaumalapau in 1922 contained about two feet of brackish water. Sea water was kept from entering the well by a straw and mud seal and the main supply came in from the landward side at a rate of 25 to 50 gallons an hour. Mountain springs in Waiakeakua, Kawaiu, Kaiholena and Maunalei gulches were used by the natives; also the small pools of water which form after rains. Nine days after heavy showers in 1922 Emory observed in gulches on the south coast pools of water containing from 20 to 100 gallons of water. In 1924 I saw similar pools containing even larger amounts of water.

DEVELOPMENT PROJECTS

From an unpublished report by Palmer[21] the following has been taken:

The questions which should be asked concerning a project for developing water on Lanai are as follows:

(1) Are there any water bodies which can be made to yield 250,000 to 500,000 gallons a day, either individually or in the aggregate?

(2) Where do such water bodies lie?

(3) How may they be tapped?

(4) Will the quality of water be satisfactory?

(5) What will the development cost and the operating cost be?

THE MAIN GROUND WATER BODY

It is undoubtedly true that wells could be sunk anywhere in the central part of Lanai about to sea level and reach abundant supplies of water. Judging from the

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

[21] Palmer, H. S., A preliminary report on the ground waters of Lanai, unpublished manuscript submitted to the Hawaiian Pineapple Company, May, 1924.

capacities of wells in similar rocks on Oahu, such a well would probably yield hundreds of thousands of gallons a day. The limit of yield of such a development would be set by the capacity of the pump that could be fitted into the well and not by the possible inflow into the well. If the well were large enough to contain a single-acting pump of 24-inch stroke and 10-inch bore, and the pump were operated at 15 strokes per minute, and there were no slippage or other loss, the yield would be about 160,000 gallons a day.

A well in Palawai Basin would have a lift of 1100 feet, one at Lanai City a lift of nearly 1600 feet. A well might be sunk conveniently close to the new road and about two miles in a straight line from Kaumalapau Bay, and would have a lift of 1000 feet. This would probably be far enough inland to avoid serious contamination by sea water.

To pump a million gallons through a lift of 1000 feet, would require 8.3 billion foot pounds of work, which would cost $313.00 with electricity at 10 cents per K. W. H., making no allowance for friction, slippage, or other losses. Such a development is geologically possible, but should be thoroughly studied by an engineer before being undertaken.

The pumping cost might be decreased by decreasing the lift by placing the well closer to the sea. The 500 foot contour line crosses the axis of the gulch east of Kaumalapau Bay at a distance of 4000 feet from the sea. The quality of water at such a site might or might not be satisfactory, which could be determined only by drilling. Moreover, the first tests might be made with only a light draft on the well and be satisfactory, whereas the heavier draft of actual use might cause a serious deterioration of the quality of the water.

In such a well it would be impossible to use an air lift, because the amount of submergence would be so great as to bring the bottom of the well into the salt water zone that underlies the rather thin body of fresh water.

Sinking a shaft at any convenient point on the island would undoubtedly enable one to develop large supplies of ground water near to the sea level. This has been done on Oahu Plantation and by the H. C. & S. Co. on the Island of Maui. At the latter some twenty millions of gallons of water are pumped in a day during dry times. The advantages of a shaft over a drilled well are (1) that one can make cross-cut tunnels to increase the supply, and (2) one can excavate chambers large enough to accommodate pumps of any capacity. Such an installation is, of course, very expensive.

It seems probable that drilling or shaft sinking would obtain an adequate amount of water from the main ground water body, and that the quality of the water would be satisfactory if the development were well in from the shore. Cost of installation and operation are not in the province of this report.

Perched water bodies: Inasmuch as no horizontal restraining members were seen on Lanai, it is impossible to make recommendations for this type of project. If such perched water bodies, held up by horizontal restraining members, could be identified it would be possible to tap them by tunnels.

The dikes, since they are approximately vertical, do not hold up bodies of perched water; they merely restrain the ground water and perhaps help to concentrate its downward movement into trunk channels.

Water in transit. The tunnel in Maunalei Gulch appears to intersect a trunk channel in which is concentrated some of the general downward movement of water. It is probable that supplies of comparable size would be developed by driving similar tunnels elsewhere in Maunalei Gulch or in the upper part of Hauola Gulch. It would be entirely a gamble as to whether water would be struck or not. It might well be necessary to drive several long and expensive tunnels before meeting with success.

A few general propositions may be given as to choice of site and direction for tunneling.

(1) The tunnel should go under a ridge or mountain-mass which is covered with a good growth of rain forest rather than under a bare ridge. The forest indicates (a) good rainfall on the body of rocks to be tapped, and (b) that run-off and evaporation are not excessive so that absorption is fairly high.

(2) The tunnel should go into a mountain-mass or into a ridge of great bulk rather than into a narrow ridge.

(3) A single tunnel 500 feet long is more than twice as apt to be successful as a tunnel 250 feet long. If there is already a 500-foot tunnel, it will be more advantageous to drive a 250-foot branch than to drive a new 250-foot tunnel. All these propositions result from the fact that there is more chance of lateral escape of water near the surface than in the interior of a ridge.

(4) Although there is no evidence that dikes do control the movement of ground water on Lanai, it is probably the case as this is generally true elsewhere in the Hawaiian Islands. Therefore it is desirable to drive tunnels in such a direction as to intersect the dikes instead of running parallel to them. Thus in figure 6, which is a diagrammatic sketch map of the conditions in Maunalei Gulch, tunnels AC and MO are so oriented that they might tap water behind dikes which could not be done by tunnels AB and ML. Also, tunnels AB and AC are better situated than tunnels ML and MO since they are headed into the larger and better forested mountain mass.

Tapping the water in this way has the advantage that it would save a good deal of pumping lift and would permit the convenient installation of adequate pumps.

It is possible that tunnels driven from Palawai Basin in a northeasterly direction would tap water behind impervious gouge along the fault surface. This possibility was suggested by Dr. Wentworth.

My suggestion that a tunnel might profitably be driven northeast from the northeast margin of Palawai Basin is based on two considerations; first, the tunnel would tap the largest high land mass of the island and have a probability of reaching either considerable water in transit from the surface downward or the highest part of the main ground water body, and second, that by penetrating the several fault planes between the basin and the main mountain mass water bodies might be encountered at somewhat higher levels than those of the surrounding areas. (See fig. 12.) Among the several methods by which this mass could be penetrated is that of an inclined drift at an angle of about 30 degrees. Such a drift would approach closer and closer to sea level and at the same time penetrate the mountain mass in the search for possible underground trunk drainage lines. If these trunk lines were successfully reached at a considerable elevation above sea level, pumping costs in operation would be less for water used on the plateau than if the main body were tapped at or near sea level by a well or shaft either in the basin or near the coast. Also if it were necessary to go all the way to the main water body it would be reached at slightly higher elevations in the section reached by an inclined drift than by a shaft or well in the lowest part of the basin. The distances of the 2,000-, 1,500-, and 1,200-foot contours from the summit ridge are approximately 3,500, 7,500, and 10,500 feet, respectively. An incline from the 2000-foot line to reach sea level under the summit ridge would have an angle of about 30 degrees; one from the 1200-foot line about 6½ degrees. Assuming the fault which cuts off the face of the summit ridge to have an angle of 70 degrees, a drift at an angle of 20 degrees would reach it in the shortest distance from any selected elevation. At this angle only an incline driven from the 2,000-foot line would reach the fault above sea level. Inclines driven at lower angles from lower positions would intersect other fault planes of the system and with the prospect of reaching water sooner.

The principal advantage of the suggested inclined drift is that it combines the chance of striking an elevated supply of water with the practical certainty of striking abundant water at or near sea level. These two elements would enter in different proportions according to site of entry and angle of the inclined tunnel. The initial cost of this development would be greater than several of the exploratory projects mentioned by Palmer, but it seems to carry greater total potentiality than any other one plan.

The expense of driving inclined tunnels as compared with either horizontal tunnels or shafts and the scarcity of contractors competent to undertake this sort of work are factors which must be considered.

SUMMARY

Ground water to the amount of at least a half million gallons daily in addition to present supplies can be developed on the island of Lanai. No especially favorable local structures exist in the rocks of the island to indicate a definite choice of several possible development projects. The amount and quality of water to be obtained in any of these projects is unknown but so far as they may be estimated depend roughly on the initial and operating costs. Those projects carrying greater assurance of ultimate success will cost more in the initial development and perhaps also in the operating costs. A careful study of initial and operating costs, together with estimates of the amounts of water needed and the site of utilization of the water should be made by the engineer in charge for several of the projects mentioned above before any are selected for trial.

SOIL

The soil of Lanai is almost wholly residual and results from the weathering of the basalt into a lateritic residuum. Alluvial soils on the northeast shore flats are composed of similar products of weathering assorted and worked over by streams.

So far as known, no chemical analyses of Lanai soils have been made. It is probable that the soils do not differ greatly as a whole from those of other parts of the Hawaiian islands, of which an average analysis is given on page 40.

Most of the Central Plateau province is covered with a mantle of thick soil and a similar cover lies on the upper parts of the Flow Slope province at the southwest, west, north, and northeast sides. The lower parts of this province and the Flow Margin province carry soil in places but are in general not suitable for any sort of planting. Of all the Hawaiian islands Lanai has probably the largest proportion of arable land. This is due to the extensive block faulting which has produced the Central Plateau.

The soil has been swept from considerable parts of northern Lanai by the erosive action of the trade winds. At other places trenching by running water within recent times has rendered considerable areas unsuitable for agriculture. Both of these processes have been greatly augmented by the destruction of the forest and grass cover by sheep, goats and cattle. At the present time the number of these animals is greatly reduced and considerable progress has been made in stabilizing the soil cover. Much attention has been given by George C. Munro to methods of preserving and restoring the soil cover by the planting of windbreaks and careful rotation of grazing areas. Under his skilful management the condition of the island has been much improved in the past few years.

STONE

Small dimension stone can readily be obtained at many places on Lanai. Many of the basalt residual blocks lying on the surface along the road from Kaumalapau to Lanai City have been roughed out into blocks for paving and culverts along the road. Stones larger than 12 in. by 12 in. by 24 in. are less readily obtained than smaller sizes owing to the thinness of the flows on Lanai but can be had in large quantities from ledges exposed in various gulches on the west coast or other parts of the pali zone.

Breakwater stones of ten tons in weight are being obtained from the hillside quarries operated by the Hawaiian Dredging Company at Kaumalapau. Here, as elsewhere in Lanai, a considerable amount of smaller rock is necessarily produced in getting out the large stones. The rock is all basalt, weighs about 180 pounds a cubic foot and is suitable for breakwaters and harbor work of all sorts.

For concrete aggregate and other purposes for which crushed rock is used, the basalt of Lanai is excellently adapted. A crusher has been installed by the Hawaiian Pineapple Company near Kaumalapau and a quarry opened from which rock is to be taken for the new macadam road.

SAND AND GRAVEL

An abundant supply of clean and rather coarse coral sand is available on the beach west of Manele. At other points on the coast considerable quantities of mixed coral and basalt sand may be had but at none of these is the sand so clean, uniform in quality or abundant. This sand is believed to be fairly satisfactory for ordinary concrete work and similar sand is extensively used in other parts of Hawaii. For concrete which requires the utmost strength this sand is unsuitable and quartz sand from some mainland source will be needed since there are no supplies of such sand in Hawaii.

There are numerous gravel beaches along the Pali Coast from which gravel of various sizes could be obtained. The grains are firm and all rather well rounded but there is a wide range of sizes in any one deposit. To produce any considerable quantity of gravel of a given grade would require extensive screening.

A

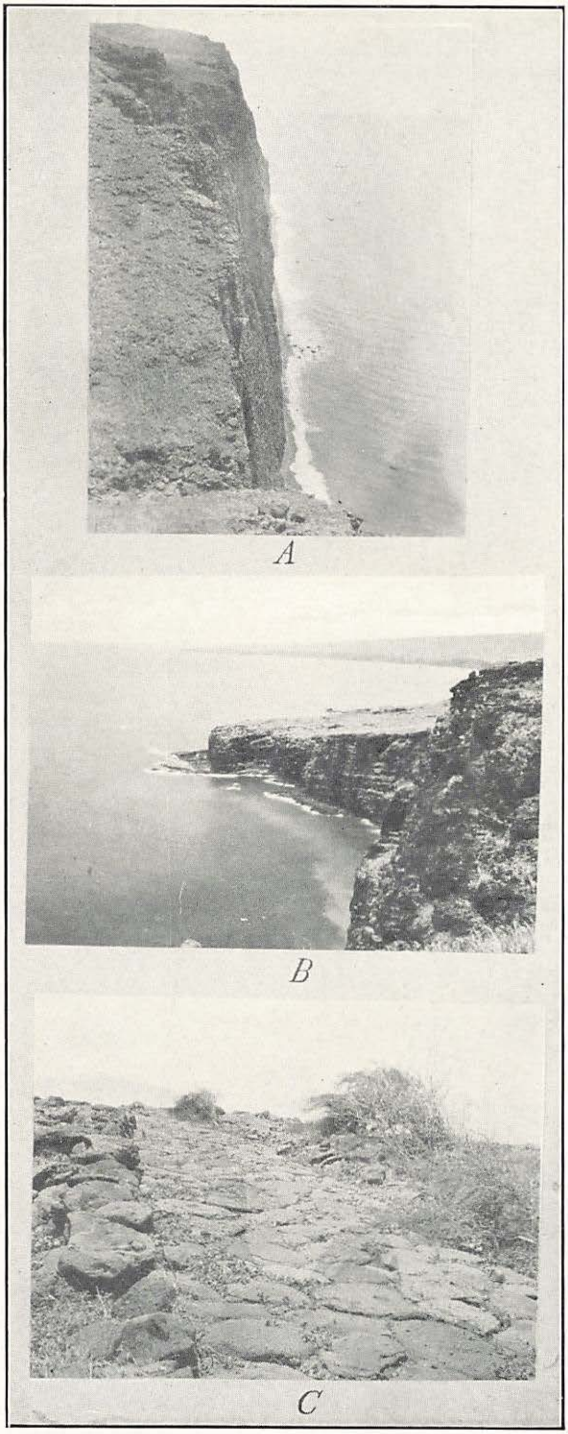
B

VIEWS ON LANAI: *A*, LOOKING SOUTHWEST FROM AN ELEVATION BACK OF KOELE, SHOWING GENTLY ROLLING TOPOGRAPHY OF THE CENTRAL PLATEAU PROVINCE; *B*, MAUNALEI GULCH FROM THE TRAIL LEADING TO THE OLD PUMPHOUSE. NOTE THE STEEP VALLEY WALLS AND SLIGHT ROUNDING OF THE BROWS OF THE CLIFFS.

A

B

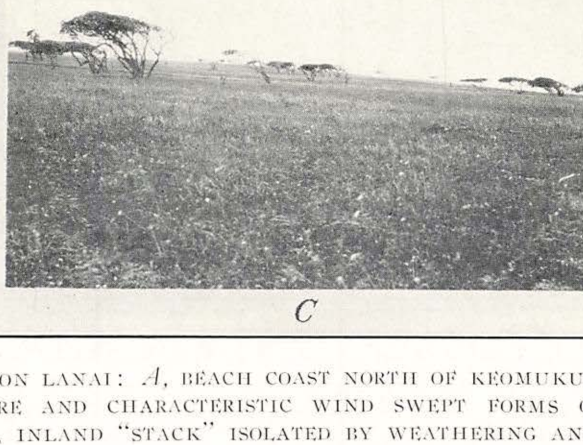
VIEWS ON LANAI: *A*, LOW CLIFF AND WAVE CUT BENCH SOUTHWEST OF MANELE, COMPOSED OF MANELE BASALT; *B*, BOWLDER BEACH AT THE FOOT OF THE PALI EAST OF MANELE.



VIEWS ON LANAI: *A*, LOOKING SOUTHWARD FROM THE TOP OF PALI KAHOLO, WHERE THE PALI FACE IS ABOUT 600 FEET HIGH; *B*, PALI ON THE WEST COAST; *C*, OLD HAWAIIAN TRAIL NORTH OF MAUNALEI GULCH.

A

B



C

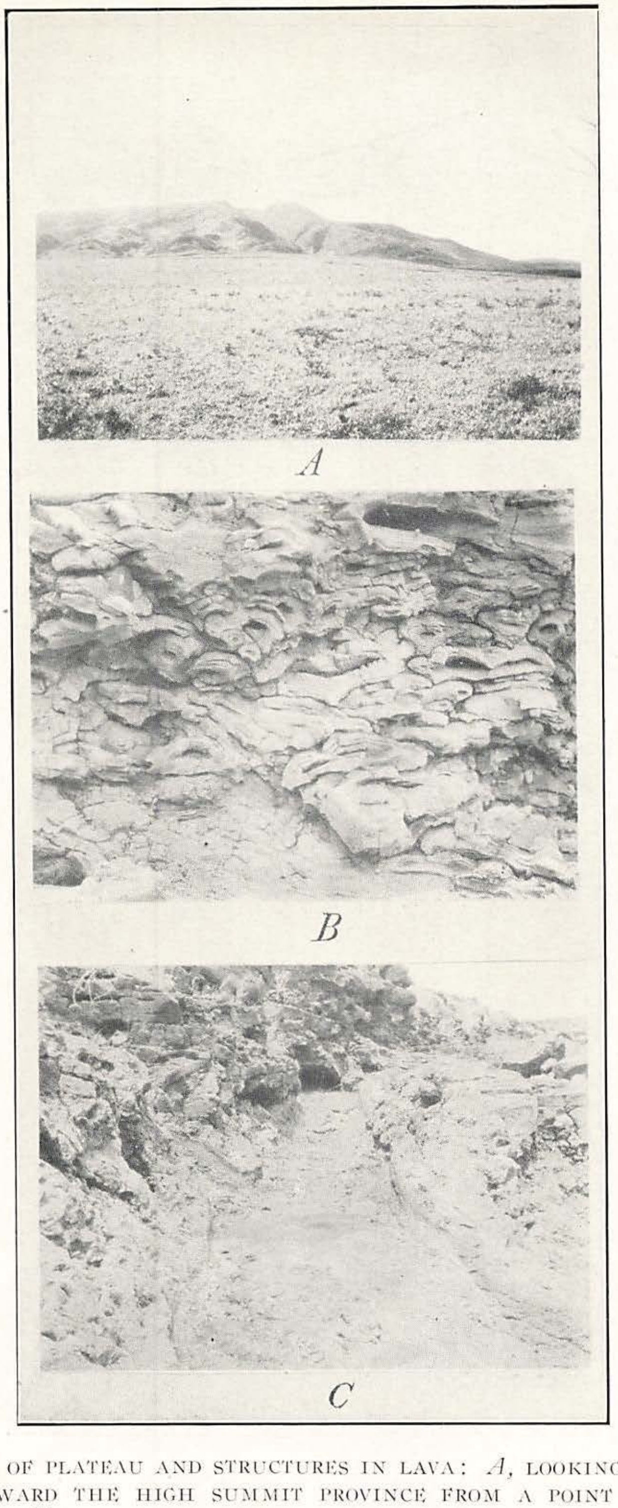
VIEWS ON LANAI: *A*, BEACH COAST NORTH OF KEOMUKU SHOWING FLAT SHORE AND CHARACTERISTIC WIND SWEPT FORMS OF KIAWE TREES; *B*, INLAND "STACK" ISOLATED BY WEATHERING AND EROSION IN THE FLOW SLOPE PROVINCE; *C*, THE KOELE-KEOMUKU TRAIL, UPPER FLOW SLOPE PROVINCE, SHOWING WIND-SWEPT TREES. LOOKING NORTHWEST.

A

B

C

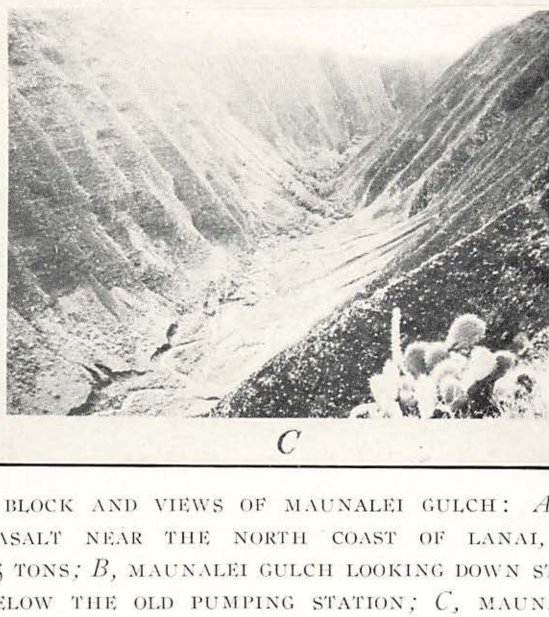
RESIDUAL SPHEROIDS OF BASALT AND VIEW OF CENTRAL PLATEAU: *A*, SPHEROIDS IN THE FLOW SLOPE PROVINCE OF NORTHWEST LANAI; *B*, SPHEROID SHOWING UNDERLYING CONCENTRIC SHELLS; *C*, CENTRAL PLATEAU PROVINCE SOUTH OF LANAI CITY, LOOKING TOWARD THE HIGH SUMMIT. PALAWAI BASIN IS JUST BEYOND THE RIGHT MARGIN. NOTE THE ABRUPT SCARP BY WHICH THE SUMMIT MASS OVERLOOKS THE PLATEAU.



VIEW OF PLATEAU AND STRUCTURES IN LAVA: *A*, LOOKING NORTHEAST TOWARD THE HIGH SUMMIT PROVINCE FROM A POINT ON THE PLATEAU; *B*, DETAIL STRUCTURE OF LANAI BASALT IN SEA CLIFF AT KAUMALAPAU; *C*, LAVA TUBES NEAR SOUTH COAST OF LANAI. NOTE THE SMALL TUBE AT THE LEFT WHICH JOINS THE LARGER ONE.

A

B



C

BASALT BLOCK AND VIEWS OF MAUNALEI GULCH: *A*, BLOCK OF MASSIVE BASALT NEAR THE NORTH COAST OF LANAI, ESTIMATED WEIGHT 125 TONS; *B*, MAUNALEI GULCH LOOKING DOWN STREAM FROM A POINT BELOW THE OLD PUMPING STATION; *C*, MAUNALEI GULCH LOOKING UP STREAM FROM A POINT ON THE PUMPING STATION TRAIL. CLOUDS OVERHANG THE HEAD WALLS.