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

H. T. STEARNS

PETROGRAPHY OF NIIHAU

G. A. MACDONALD

BULLETIN 12
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TOPOGRAPHIC MAP OF THE ISLAND OF HAWAII, scale 1:125,000, contour interval 250 feet, size 44 x 49 inches, price $1.00, for sale by the Survey Department, Territorial Office Building, Honolulu 2, T. H.

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

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

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

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

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ABSTRACT

Niihau lies 17½ miles southwest of Kauai. Its area is 72 square miles, and its highest point has an altitude of 1,281 feet. The population is about 180, chiefly Hawaiians. The annual rainfall at Kiekie, the ranch headquarters, generally ranges between 18 and 26 inches. The chief industries are the raising of sheep and cattle and production of honey. The island is privately owned.

The main mass of the island is composed of a deeply weathered remnant of a basalt dome of Tertiary age, cut by a dike complex trending NE-SW. These Tertiary rocks are herein named the Paniau volcanic series. The central vent lay about 2 miles out to sea to the east of the present island. The dome, after deep gulches were cut into it by stream erosion and it was cliffed all around by the sea, was partly submerged. During Pleistocene time a broad wave-cut platform on the north, west, and south sides was built above sea level and widened by the eruption of lavas and tuffs, from 9 vents now visible and other vents now buried, to form a low coastal plain. These Pleistocene volcanic rocks are named the Kiekie volcanic series. Ash from Lehua Island, a Pleistocene tuff cone, has been drifted into dunes on the north end of Niihau. Lithified dunes that extend below sea level, and the small outcrops of emerged fossiliferous limestone above sea level, indicate the plus 100-foot, minus 60-foot, plus 25-foot, and plus 5-foot eustatic stands of the sea correlative with changes in the volume of the polar ice caps and concurrent changes in the configuration of ocean basins.

Calcareous dune and beach deposits, short stretches of nullipore reef and beach rock, and playa and alluvial deposits constitute the Recent rocks.

No perennial streams exist on the island but about a dozen playa lakes, fresh or brackish during rainy weather, lie on the plain. The domestic water supply is rain caught from roofs. Only three wells on the island yield water with less than 25 grains of salt per gallon (260 parts per million of chloride). Typically, water holes for stock are about 15 feet across, 5 feet deep, and 8 feet wide. They have been dug in the lowlands where the depth to water is usually less than 5 feet. Forty-six dug wells and water holes exist, the water of some of which has become too salty for stock. Two or three deep wells were drilled 500 to 1,000 feet below sea level, but they encountered salty water. Three wells, not yet used, have been excavated in the Tertiary basalts. One of them has an infiltration tunnel at the bottom. Two seeps perched on vitric tuff beds more than 500 feet above sea level carry large quantities of salt leached from spray that falls on their recharge areas. Several sites are recommended for developing additional water for stock. The island, however, will always be short of domestic water because of aridity, unfavorable geologic structures, continuous deposition of salt spray, and abundant authigenic[1] salts in the lake beds.

[1] Salts deposited concurrently with the sediments as the lakes repeatedly evaporate.

INTRODUCTION

LOCATION AND AREA.—The island of Niihau lies 148 miles northwest of Honolulu on the island of Oahu, and 17.5 miles southwest of Kauai Island. It is part of the County of Kauai. Its north-south length is 18 miles, its maximum width is 6 miles, and its area is 72 square

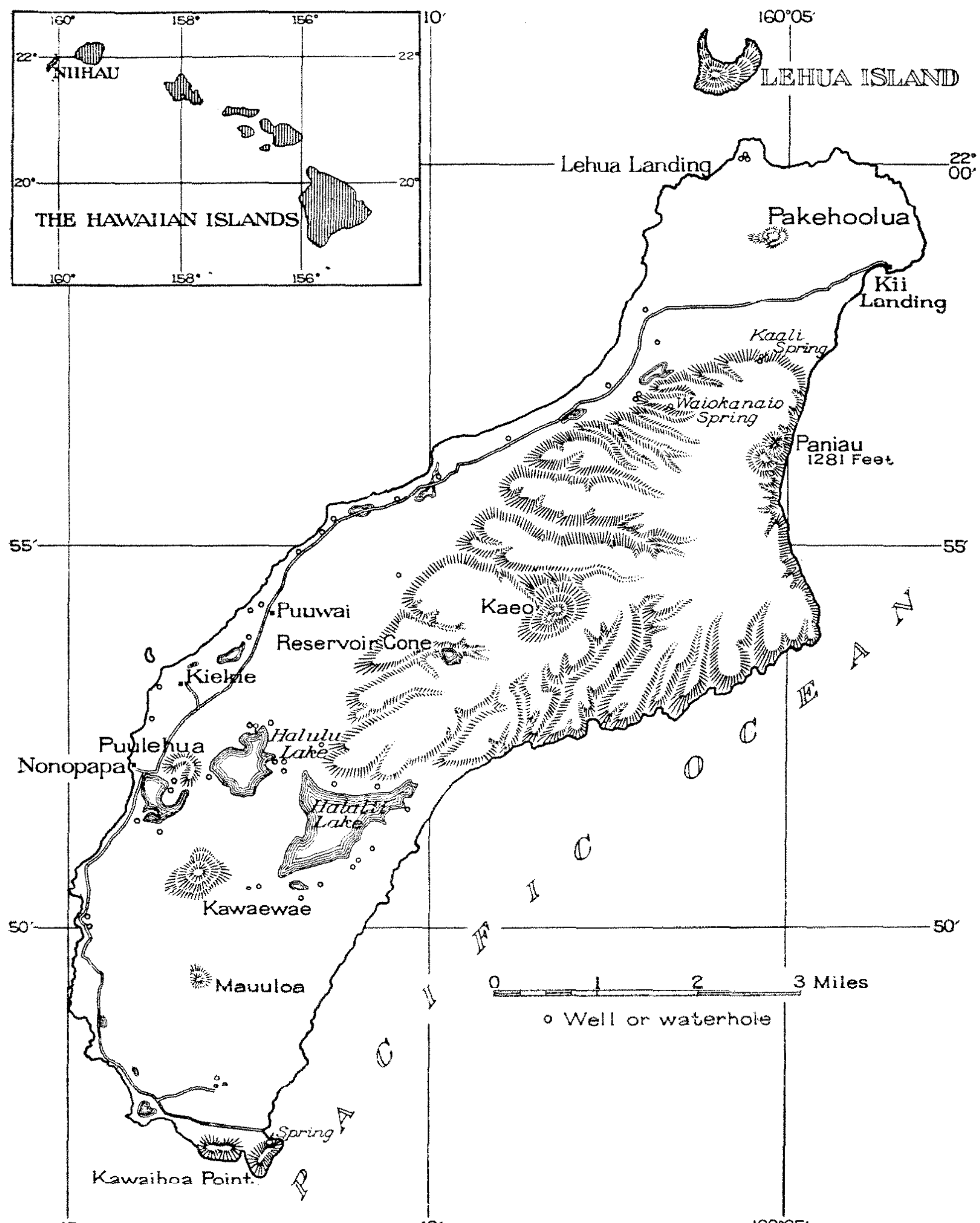

Figure 1. Geographic map of Niihau with inset showing its position in the Hawaiian group.

miles[2] (fig. 1). Of the eight principal islands of the Hawaiian group, only Kahoolawe is smaller. (See insert map, fig. 1.) The highest point, Paniau hill, has an altitude of 1,281 feet. The entire population of about 180[3] Hawaiians and part-Hawaiians lives at Puuwai Village on the western coast. The main ranch house is at Kiekie, and the wool sheds and pier are at Nonopapa. Ships load at Lehua, Kii, and Nono-

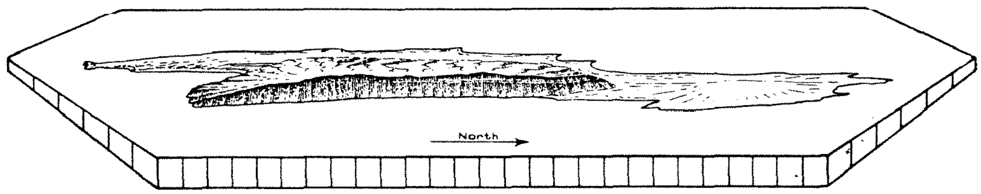

Figure 2. Niihau as seen from the east at an altitude of 10,000 feet.

papa landings. The form of the island is shown in figure 2. The distribution of land with respect to elevation follows:

Distribution of area of Niihau with respect to altitude[1]

Altitude in feet	Area in square miles	Percent of island
0-500	56.3	78.2
500-1000	13.4	18.6
1000-1281	2.3	3.2
	72.0	100.0

[1] Wentworth, C. K., op. cit., p. 15.

HISTORICAL SKETCH.—The island was purchased for a sheep ranch by James and Francis Sinclair from King Kamehameha V in 1864. It is now owned by the estate of Aubrey Robinson, a nephew of the original owners. The island is managed by his son Aylmer Robinson of Makaweli, Kauai. Ever since the island was purchased by the Sinclairs it has been closed to entry except by permission, because the successive owners have tried to maintain the Hawaiian community intact and to keep liquor from the natives. Ancient Hawaiian house sites are common along the beaches. The native population is stated by Hitchcock[4] to have been about 1,000 in 1850, but Robinson[5] believes the number to have been nearer 300.

The impact of World War II was felt immediately on Niihau, as a Japanese plane made a forced landing there after the attack on Pearl Harbor. The pilot was killed by a Hawaiian. The Army patrolled

[2] Wentworth, C. K., Geographic background: in First Progress Rept., Territorial Planning Board, p. 13, 1939.

[3] U. S. census, 1940.

[4] Hitchcock, C. H., Hawaii and its volcanoes, p. 11, Honolulu, 1909.

[5] Robinson, Aylmer, letter of October 13, 1945.

the island for about 3 years but by 1945 all troops had been withdrawn. A Coast Guard unit maintains a radio station on the south end of the island.

INDUSTRIES.—The chief industry of raising sheep has been declining for several years and cattle raising has been on the increase. The 1940 census lists 14,434 sheep, 955 cattle, and 386 horses and mules. Blow flies attack the sheep after wet weather and cause great losses in spite of constant treatment. Many animals died during the drought of 1945 from the lack of feed and because some of the water holes became salty. In 1940 there were reported to be 1,615 hives of bees on the island. The production of algaroba honey is an important industry.

FAUNA AND FLORA.—Domestic goats, introduced to the Hawaiian Islands by Captain Cook in 1788, multiplied rapidly on Niihau and soon ate most of the vegetation. Heavy rains caused rapid soil erosion and large areas of the uplands were stripped to hardpan and bedrock. The red soil, washed down into the lowlands, filled up shallow ponds and bays. More recently, erosion has been slowed down by extermination of the goats and by reforestation of the uplands. The mongoose was not introduced to Niihau; hence, bird life is abundant in spite of rats and feral cats. Peacocks, turkeys, mongolian pheasants, and California quail are abundant. Prairie chickens introduced from the United States mainland in recent years are spreading. Kentucky cardinals recently have found their way to Niihau from Kauai. Migratory birds are common.

Cactus (*Opuntia megacantha*), formerly the chief food for animals during a drought, has been rapidly dying out because of an accidentally introduced disease or insect, not yet identified. The island is too dry for guava (*Pfidium guajava*), a pest on most of the other islands. Lantana (*Lantana camara*), seeded by birds from Kauai, is removed whenever it is found. The chief success in reforestation of the uplands has been accomplished with silk oak (*Grevillea robusta*), haole koa (*Leucaena glauca*), and grevillea (*Grevillea banksii*). Kiawe or algaroba (*Prosopis chilensis*) spread over rocky ledges and the lowland until it became a pest and now has to be cleared. Transpiration by kiawe trees dried up several small but valuable springs and caused several water holes to become brackish. Ironwoods (*Casuarina equisetifolia*) thrive. The native wiliwili tree (*Erythrina sandwicensis*) survived the goats and is now spreading in the upland valleys. Although the wind is strong on Niihau it is not as destructive as it is on Kahoolawe. Numerous grasses have been introduced from abroad, and some have spread widely and greatly improved the range. Small groves of coconuts and date palms thrive in the lowlands, where the water table

Plate 2a. The eastern cliff of Niihau, a sea cliff more than 1,000 feet high cut in lavas of the Paniau volcanic series. In the distance, at the northern end of the island, the low plain consists of lavas of the Kiekie volcanic series. Photo by H. T. Stearns.

Plate 2b. Vertical air view of the southern end of Niihau showing lithified dunes blown inland during the minus 60-foot stand of the sea. Photo by U. S. Army Air Force.

Plate 3a. Kawaihoa tuff cone, Niihau, showing wave-cut bench just above present sea level. Photo by H. T. Stearns.

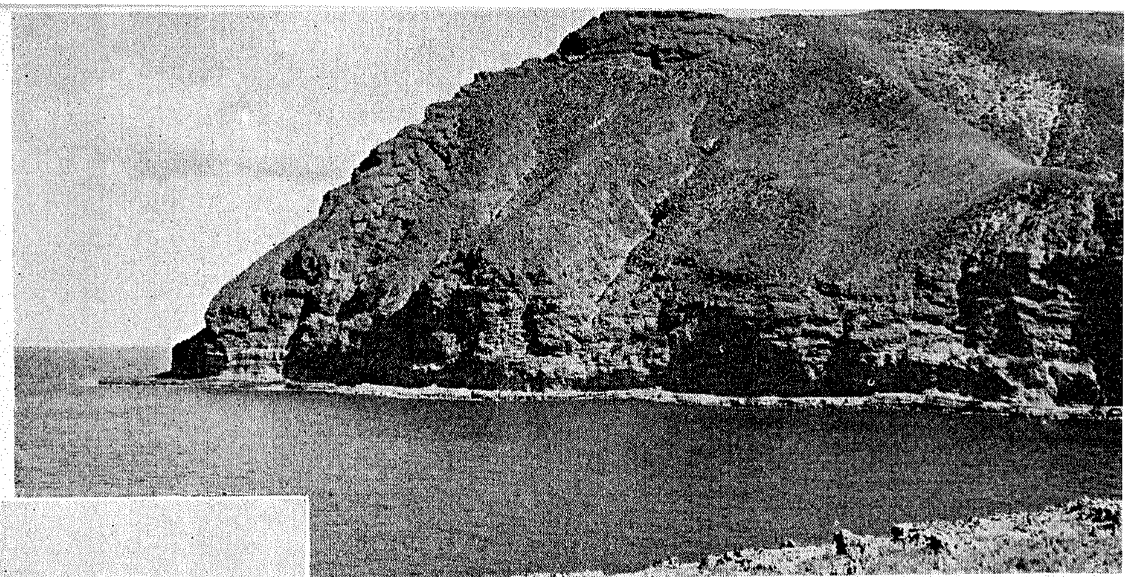

Plate 3b. Marine fossiliferous limestone blocks among basalt boulders along the 25-foot shore line. Note the wave-cut cliff on Kawaewae cone in the background. Photo by H. T. Stearns.

is close to the surface. They have to be watered for about 5 years to establish their roots before they will survive a drought. Many other plants typical of the semiarid areas of the Hawaiian Islands are present.

Scope of the work.—The writer was on Niihau from May 23 to May 30, 1945. During this time the island was fairly well covered, on horseback, on foot, and in a buggy, although several of the valleys and the southeastern cliff coast were not traversed. The latter was mapped from air photos. The eastern cliff coast was traversed on foot. Rock exposures are abundant and it is believed that more dikes than have been mapped would be found by a more intensive survey. Samples of water were collected from most of the water holes.

Acknowledgments.—The writer was the guest of Mr. Aylmer Robinson during the Niihau survey. We made the trip from Kauai on the sampan Lehua. Mr. Robinson accompanied the writer during part of the time, and during the rest of the time he supplied competent guides. His familiarity with everything on the island greatly facilitated the work, and he imparted his knowledge freely and did everything possible to make the survey a success. He furnished all horses and other transportation.

Mrs. Ethel U. McAfee edited the report, and James Y. Nitta prepared the illustrations.

Previous investigations.—Dana[6] proposed the hypothesis that Niihau was formerly a part of Kauai and was shifted southward by faulting. However, as generally agreed by later writers, the structure of Niihau clearly disproves this hypothesis. The island is an independent volcano. Hitchcock[7] gives a brief description of Niihau, stating erroneously that the low plain is of coral reef origin. All subsequent writers, including W. A. Bryan,[8] have followed Hitchcock in describing the plain as made of emerged coral reef. Apparently neither Hitchcock nor Dana actually visited Niihau.

Powers[9] landed on Niihau for a few hours, according to Hinds,[10] and collected a few rocks that have been analyzed by Washington and Keyes.[11] Powers disagreed with Dana and stated that Niihau is an independent volcano, composed of thin basaltic lava flows dipping gently westward. He published a map of Niihau made by S. M. Kerns in 1904. Several hills on the lowlands were labelled cones by Powers,

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[6] Dana, J. D., Characteristics of volcanoes: p. 312, 1890.

[7] Hitchcock, C. H., Hawaii and its volcanoes, p. 11, 2nd ed., 1911.

[8] Bryan, W. A., Natural history of Hawaii, p. 101, Honolulu, 1915.

[9] Powers, Sidney, Notes on Hawaiian petrology: Am. Jour. Sci., vol. 50, pp. 257-258, 1920.

[10] Hinds, N.E.A., The geology of Kauai and Niihau: B. P. Bishop Mus., Bull. 71, p. 90, 1930.

[11] Washington, H. S., and Keyes, M. G., Petrology of the Hawaiian Islands; The Leeward Islands: Am. Jour. Sci., vol. 12, pp. 337-340, 1926.

and certain depressions were mapped as craters. However, the present investigation showed that, of the features mapped by Powers as cones and craters, only one of the hills is a cone and none of the depressions are craters. He also stated that four cones are situated on the plateau-like summit of the old island. Presumably these are the four hills in the uplands shown on Kerns' map. Powers probably did not visit them in the short time he was on Niihau. None of them are cones although one of them, named Kaeo, is probably the core of an ancient cone. The other three are erosion remnants composed of the lavas of the dome. Powers believed that the surface of the low plain bordering the higher remnant of the original island is "an elevated coral reef partly covered by flows that have come from about 10 small cones and 3 small pit-craters."[12]

Hinds[13] spent 8 days on the island. His map[14] shows five late tuff cones on the northern part of the plain and Kawaewae Hill as a remnant of the ancient dome. The rest of the plain is mapped as an elevated reef-covered marine platform. In his section[15] he showed the lavas in the plain as part of the ancient dome beveled by marine erosion, although he recognizes in his text that extrusives of a young volcanic episode exist. Hinds followed Powers in considering Niihau to have been an independent volcano. He described the present cliffs of eastern Niihau as a fault line scarp, cut back about 2 miles by marine erosion, and believed that most of the eastern part of the dome had been down-faulted below sea level. It will be shown that the five tuff cones, mapped by Hinds on the northern end of the coastal plain, are actually weakly-cemented dunes of volcanic ash; that the so-called elevated reef-covered marine platform is actually underlain largely by late lavas partly covered by lithified calcareous dunes formed when the sea was lower than at present; that the lavas on the plain are separated from those in the main dome by a profound erosional unconformity; and that Kawaewae is a late cone and not a dome remnant. Hinds lists 30 species of molluscan fossils.[16] Four of the fossil localities are on dunes and lithified dunes. As no marine mollusks are present in situ in the dunes, the shells must have been collected from ancient Hawaiian house sites; hence, they are not fossil. Hinds contributions to petrography are reviewed by Macdonald on page 42.

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[12] Powers, S., op. cit., p. 258.
[13] Hinds, N. E. A., op. cit., pp. 90-101.
[14] Idem, p. 92.
[15] Idem, fig. 16.
[16] Idem, p. 99.

GEOMORPHOLOGY

GENERAL STATEMENT.—Niihau has two major geomorphic provinces—the uplands, a remnant of a shield- or dome-shaped basaltic volcano; and the lowlands, a coastal plain averaging about 75 feet above sea level but containing numerous playa lakes only slightly above sea level. Lehua Island, a tuff cone which lies a mile off the northern tip of Niihau, will be described, as some of its ashes contributed to the coastal plain of Niihau. Kaula Island, 22 miles southwest of Niihau, is a tuff cone crowning an independent submarine volcanic dome.[17] Its ashes were not found on Niihau.

ORIGIN OF THE UPLANDS.—The dome remnant forming the uplands is cut by 10 valleys on the southern slope and 12 valleys on the western slope. Keanauhi Valley, the longest on the island, is 600 feet deep near its mouth and nearly a mile from rim to rim. The interstream divides are slightly-dissected flats parallel to the bedding of the underlying rocks. Many are covered with as much as 5 feet of red lateritic soil underlain by 20 to 50 feet of partly decomposed basalt. All the valleys on the western slope radiate approximately from a point about 1½ miles off the eastern shore, which probably marks approximately the original summit of the dome. The interstream divides are strongly cliffed at the inner edge of the coastal plain. The valleys have been formed by stream erosion, which was probably more active in the past when the whole Hawaiian archipelago stood higher in relation to sea level. The fact that dikes are exposed in the interstream flats indicates that subaerial stripping has proceeded parallel to the bedding and that the surface of the dome remnant has been appreciably worn down, probably about 100 feet below the original dome surface.

Projection of the dips of the lava beds indicates that, prior to stream and marine erosion, the shoreline of the original dome lay about 2 miles farther seaward to the south and west than at present. The problem of reconstructing the eastern part of the dome is more difficult. A typical rift zone, occupied by hundreds of dikes, is exposed in the high eastern cliff. The dikes indicate that the volcanic center lay east of the present island. Hawaiian domes are commonly highly asymmetrical, as illustrated in the form of Kahoolawe Island.[18] In fact, the dome remnant of Niihau closely resembles Kahoolawe, especially as the southwest rift zone is preserved in both islands. It is probable that prior to the great submergence of the Hawaiian Islands (fig. 4), Niihau ex-

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[17] Palmer, H. S., Geology of Lehua and Kaula islands: B. P. Bishop Museum Occ. Papers, vol. 12, no. 13, pp. 1-36, 1936.

[18] Stearns, H. T., Geology and ground-water resources of the islands of Lanai and Kahoolawe, Hawaii: Hawaii Div. of Hydrog., Bull. 6, fig. 31, p. 144, 1940.

tended about 6 miles farther east than it does now (in relation to present sea level). Like the other volcanoes, it probably had a caldera.

It is not probable that Niihau was ever connected to Kauai above water, as the channel between them is now 2,550 feet deep (fig. 3). That depth greatly exceeds the maximum of 1,800 feet of submergence postulated for the deepest recognized (Lualualei) shoreline in the Hawaiian Islands.[19] The 50-fathom submarine shelf, which is 1.5 miles wide off the east cliff coast (pl. 2A), seems to indicate, as Hinds states,[20] a recession of the cliff by that amount resulting from marine erosion. It appears probable that the western wall of the caldera of the original volcano was cut back and modified by marine erosion to form the present eastern cliff, the height and steepness of which is due chiefly to marine erosion. This coast is subject to powerful wave attack at the present time. Hinds' suggestion that the eastern part of Niihau, beyond the eastern edge of the submarine shelf, was depressed below sea level by faulting cannot be disproved, but the present writer can see no evidence for it. It appears at least as probable that a relatively short slope east of the former caldera has been stripped away largely by marine erosion.

ORIGIN OF THE COASTAL PLAIN.—The lowlands have had a complex origin. Surrounding Niihau are a submarine shelf 300 feet below sea level and 1 to 2 miles wide (fig. 3) and a narrower shelf 60 feet below sea level. The 300-foot shelf surrounds all the older Hawaiian Islands and has been termed the Kahipa shore line.[21] It is believed to have resulted from marine abrasion when the sea stood at this level during one or more of the glacial stages of the Pleistocene. The 60-foot shelf, which is known as the Waipio shore line, apparently was formed during the low stand of the sea that accompanied the last glacial stage of the Pleistocene epoch.

Resting on the 300-foot shelf are several tuff and lava cones that have built the shelf above sea level to form the present coastal plain. When the sea lowered to the shore line 60 feet below present sea level, broad sand-covered flats were exposed and the sand drifted inland over the volcanics to form dunes 150 feet high. Most of the sand was blown inland from the southeastern coast, as shown by the pattern of the ancient dunes (pl. 2B). With the rise in sea level concomitant with the partial melting of the polar ice caps, the low seaward part of the sand flats was again covered with water and the dunes became anchored and cemented. Thus the cemented dunes raised the level of parts of

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[19] Stearns, H. T., and Macdonald, G. A., Geology and ground-water resources of the island of Maui, Hawaii: Hawaii Div. of Hydrog., Bull. 7, p. 54, 1942.

[20] Hinds, N. E. A., op. cit., p. 93.

[21] Stearns, H. T., Pleistocene shore lines on the islands of Oahu and Maui, Hawaii: Geol. Soc. America Bull., vol. 46, p. 1934, 1935.

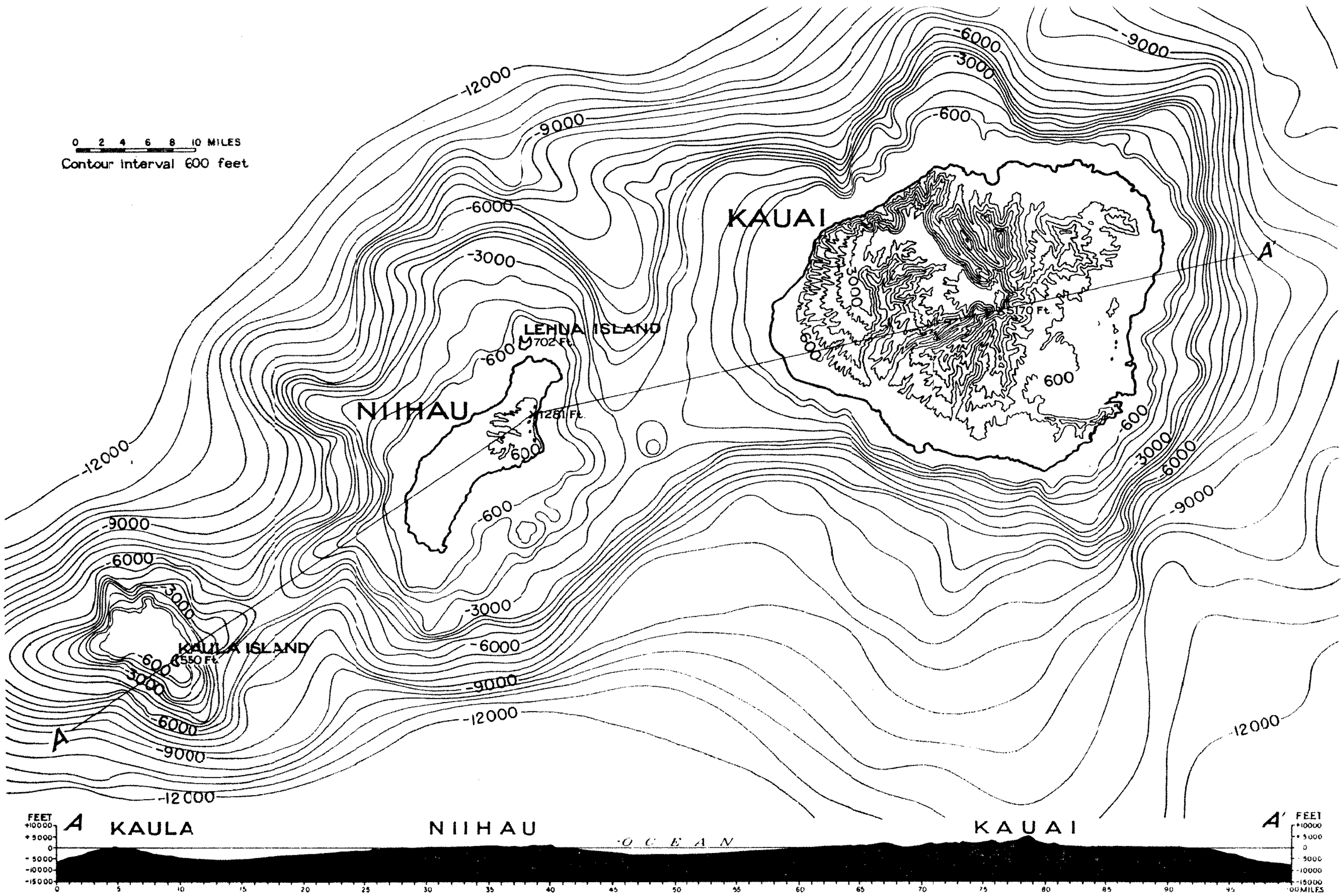

Figure 3. Map of Niihau and Kauai showing submarine contours and profile along the line AA′.

the coastal plain. Depressions on the coastal plain that extended to or nearly to sea level became the sites of ponds and brackish lakes. These are being rapidly filled with red soil washed down from the uplands.

Hinds' conclusion that the present surface of the coastal plain of Niihau represents an elevated platform of marine abrasion veneered with coral reef is untenable. Much of the plain is underlain by lavas much younger than those of the dome remnant, separated from the older lavas by a profound erosional unconformity and petrographically distinct from them. The surface of the young lavas is little modified by erosion, and the vents from which they were erupted are still easily recognizable. The lava surface is partly overlain by calcareous material, but that material is dune sand exhibiting all the characteristic features of wind-laid deposits. It is further described at a later point.

EMERGED AND SUBMERGED SHORE LINES.—There follows a list of the younger shore lines that have been determined to date in the Hawaiian Islands, with evidence of their existence on Niihau. The oldest is at the bottom.

Pleistocene shore lines on Niihau

Approximate altitude (feet)	Name	Evidence on Niihau
0	....	Present sea level.
+5	Kapapa	Wave-cut benches and emerged beach deposits.
+25	Waimanalo	Wave-cut notches in lithified dunes and emerged beach and reef deposits.
−60±	Waipio	60-foot submarine shelf and lithified dunes extending below sea level.
+45	Waialae	Not identified on Niihau.
+70	Laie	Not identified on Niihau.
+100	Kaena	Emerged fossiliferous reefs and narrow wave-cut benches.
−300±	Kahipa	Broad submarine shelf 300 feet below sea level.

A wave-cut bench of the 5-foot stand of the sea, partly planed down by present storm waves, is a conspicuous feature on Kawaihoa cone at the southern end of the island (pl. 3A). Ancient beach deposits well above storm-wave level lie inland of the present beach south of Kii Landing.

An ancient stack of limestone, 12 feet high, full of coral heads, nullipores, and other marine fossils, stands alongside the road half a mile north of the mouth of Kahunalii Valley. The stack apparently was a reef knoll in the Waimanalo (plus 25-foot) sea. Nearby lithified dunes formed during the earlier Waipio (minus 60-foot) stand of the sea are notched at the 25-foot level. A shore line at the 25-foot level is conspicuous in aerial photographs along the northern side of Kawaewae cone and on the lavas of the cone. On the ground, the ancient strand is identified by blocks of highly fossiliferous limestone scattered among lava boulders (pl. 3B). Coral fragments are common in the limestone.

Lithified calcareous dunes extending below sea level form cliffs along all of the southeastern coast and in numerous places along the western coast. They rise from the 60-foot submarine shelf and are notched in places at the level of the plus 25-foot stand of the sea. They are evidence of a low stand of the sea preceding the plus 25-foot shore line.

A ledge of reef rock containing coral heads and other marine fossils lies unconformably on tuff in a small ravine on the northwestern side of Kawaihoa cone, at an altitude of 100 feet (determined by barometer). A wave-eroded platform covered with black gypsiferous soil is conspicuous at an altitude of 100 feet on the northern side of Puulehua cone near Halulu Lake.

The broad 300-foot submarine shelf surrounding the island is evidence of the Kahipa stand of the sea, 300 feet below present sea level. The valleys draining the uplands are partly drowned at their mouths along the southern cliffed coast and are partly filled with older alluvium, indicating that they were cut originally to a base level well below present sea level. Two deep wells were drilled in the coastal plain, but unfortunately no logs for them are known to exist.

A large part of Kawaewae cone has been removed by marine erosion, and the cone is definitely cliffed considerably above the 100-foot shore line in a place where subaerial erosion could not be responsible for the cliffing (pl. 3B). The cliffs bordering the western side and most of the southern slope of the uplands have been washed bare and rocky, but this stripping cannot be definitely established as the result of marine erosion by stands of the sea higher than the Kaena (plus 100-foot) stand. Subaerial erosion could have removed the soil. The evidence of stands of the sea higher than the Kaena stand is meager. Small outcrops of limestone, if they exist, are obscured by the dense growth of kiawe trees and the heavy veneer of recently-deposited red silt in the valleys traversed. Several of the valleys have not been examined. Evidence of emerged reefs correlative with the 5-, 25-, and 100-foot stands of the sea is extensive on Oahu in comparison with that of the same stands on Niihau.

Niihau is near the present northern margin of the coral seas, where the temperature is too low for vigorous coral growth. The waters surrounding Niihau apparently have always been too cool for extensive reef formation, which is probably the reason evidences of higher stands of the sea have not been found. No living coral reef exists, although a few short stretches of nullipore reef were found on the western and southeastern coasts (pl. 4A). Small coral heads can be seen in the water off Lehua Landing, but the scarcity of coral fragments in the beach sediments indicates that coral is relatively rare offshore.

OTHER SUBMARINE FEATURES.—Five miles southeast of Niihau soundings indicate a subcircular bank rising to 220 feet below sea level (fig 3). Its form suggests a submarine cone, probably belonging to the Kiekie volcanic series of Pleistocene age. It probably lies on the rift from which were erupted the tuff cone of Lehua Island and the small lava dome on the northern end of Niihau. Contours of the ocean floor suggest another cone in the channel between Niihau and Kauai (fig. 3). The great depth (5,260 feet) of the channel between Niihau and Kaula Island indicates that, as postulated by Hinds,[22] Kaula Island rests on an independent volcanic dome (profile AA′, fig. 3). The Niihau dome rises about 13,000 feet above the ocean floor to the north and south.

GEOLOGY

GENERAL CHARACTER AND AGE OF THE ROCKS

The highlands of Niihau, and presumably also the basement of the dome, are built chiefly of thin lava flows poured out rapidly from a dome-shaped shield volcano. The flows are predominantly olivine basalt and basalt. They include both aa and pahoehoe types. No soils, and only a few thin vitric and vitric-lithic tuff beds, are interstratified with the flows in the part of the cone above sea level. Numerous dikes, half a foot to 17 feet thick, cut the dome remnant. Most of them trend northeast-southwest. Cinder cones are absent. Faulting has disturbed the beds in the heart of the dike complex. The name Paniau volcanic series is here proposed for the volcanic rocks composing the remnant of the ancient shield volcano of Niihau, after the type locality on the eastern side of Paniau hill.

In contrast to the thin-bedded lavas in the ancient dome remnant, the later lavas of the coastal plain are massive and nearly horizontal, and consist chiefly of pahoehoe. Except at Kawaewae cone the lavas welled out quietly, forming small secondary lava domes without cinders and with only a little spatter. The Lehua Island and Kawaihoa cones erupted violently, spreading ash far and wide, because sea water entered their vents. The exposed parts of their cones are subaerially-deposited consolidated ash. The name Kiekie volcanic series is here proposed for the volcanic rocks, of probable Pleistocene age, which form the low coastal plain of Niihau. The type locality is at Kiekie, on the coastal plain.

[22] Hinds, N. E. A., op., cit., p. 51.

The cones of the Kiekie volcanic series trend slightly west of north, in contrast to the northeast-trending rifts of the Paniau volcanic series.

The sedimentary rocks are composed of older and younger alluvium, calcareous beach and dune sand, playa deposits, and dunes of cemented ash. Small outcrops of highly fossiliferous emerged reef exist in three places. Recent cemented calcareous beach deposits, commonly called beach rock, lie along some of the coast.

The age of the Kiekie volcanic series is determined by its relation to the shore lines of probable Pleistocene age. All the lavas on the coastal plain are older than the minus 60-foot stand of the sea, which is believed to be correlative with the Wisconsin stage of glaciation. Most of the lithified dunes were formed during the minus 60-foot stand of the sea. Emerged reef of the plus 100-foot stand of the sea lies on Kawaihoa cone, and Kawaewae cone was cliffed by seas higher than the 100-foot stand. The lava forming the northern part of the coastal plain is probably of late Pleistocene age, as there is no evidence on it of the 100-foot stand of the sea and the rocks are only slightly decomposed. In contrast, the rest of the lavas forming the plain are rotted to a depth of several feet. They are all older than the plus 100-foot stand of the sea, which is believed to have occurred during the last Pleistocene interglacial stage. The older lavas on the plain are tentatively assigned to the early(?) and middle Pleistocene.

The dome remnant was deeply eroded prior to the extrusion of the Kiekie volcanic series, and its rocks are now partly decomposed to a depth of 50 feet on the interstream ridges. The 300-foot submarine shelf, which is well developed on the dome remnant, is believed to be of Pleistocene age. The rocks of the Paniau volcanic series in the dome remnant above sea level are tentatively assigned on this basis to the Pliocene epoch. It is probable that building of the dome from the ocean floor began in early middle Tertiary time.

The characteristics of the rocks and their water-bearing properties are summarized in the accompanying table.

Stratigraphic rock units on the island of Niihau

Major geologic unit	Rock assemblage	Thickness (feet)	Symbol on map (pl. 1)	General Character	Water-bearing properties
Recent sedimentary rocks	Unconsolidated calcareous marine beach sand	10±	Rs	Beach sand composed of grains of worn coralline algae, molluscs, and lesser amounts of coral. Skeletons of foraminifera and other marine organisms are locally abundant.	Very permeable and usually contains brackish water at sea level.
	Unconsolidated calcareous dunes	10-120	Rd	Fine-grained cross-bedded cream-colored sand blown inland from the present beaches or derived from older partly lithified dunes.	Very permeable and commonly contain small quantities of potable water.
	Weakly consolidated lacustrine beach sand	8±	Rls	Exceedingly fine-grained calcareous dune sand blown into Halalii Lake from the adjacent sea beaches and subsequently formed into beach ridges by the lake.	Fairly permeable but probably would yield slightly brackish water.
	Unconsolidated earthy deposits	5-50±	Ra	Chiefly younger alluvium consisting of loose, poorly sorted, poorly rounded, stream-laid brown silt, sand, and gravel. Includes talus fans at the foot of cliffs and extensive playa deposits of brown silt and red lateritic transported soil derived from the uplands in historic time.	Poorly permeable but yield small supplies of brackish water near the ephemeral lakes.
Local erosional unconformity					
Late Pleistocene sedimentary rocks	Consolidated emerged marine deposits	1-12	X	Small outcrops of fossiliferous emerged reef and beach limestone.	Too small to carry water.
	Consolidated calcareous dunes (eolianite)	10-150	Pd	Consolidated and partly consolidated calcareous dunes consisting of thin-bedded and cross-bedded eolian limestone composed of pale yellow uniform grains of sand blown inland from beaches during and since the minus 60-foot stand of the sea.	Permeable and yield small quantities of water for stock to dug wells.
	Consolidated dunes of volcanic sand	10-150	Pvd	Consolidated and partly consolidated thin-bedded and cross-bedded dunes of black and brown sand composed chiefly of basalt, basaltic glass, and olivine derived from ash from the Lehua Island vent.	Poorly permeable but might yield small quantities of potable water at sea level to wells far from the coast.

Local erosional unconformity						
Pleistocene volcanic rocks	Kiekie volcanic series	Vitric-lithic tuffs in Lehua and Kawaihoa cones	5-700+	Pt	Gray to brown well-bedded deposits of vitric-lithic tuff and beds of tuffaceous breccia containing angular blocks of older tuffs, lavas, and reef limestone. The beds are generally cemented by calcite and are partly altered to palagonite. They form cones near the vents but are thin elsewhere.	Poorly permeable but supply perched seeps on Kawaihoa cone and potable water to dug wells at sea level near Lehua Landing.
		Lava flows	20-300+	Pb	Dense and vesicular pahoehoe lava flows of olivine basalt that issued from 6 secondary cones. Those on the north and south ends of the island carry little soil; the others carry 2± feet of lateritic soil.	Very permeable and yield small quantities of water for stock to dug wells.
		Cones	300±	Pc	Secondary cones of thin-bedded highly vesicular lava containing a few dense layers, usually with spatter at the summit.	Highly permeable, except one which has a crater filled with soil and alluvium and serves as a reservoir.
Great erosional unconformity						
Tertiary volcanic rocks	Paniau volcanic series	Basaltic lava flows with a few thin ash beds, cut by numerous dikes	1200+	Tb	Lava flows forming a dome of thin-bedded basaltic aa and pahoehoe. The flows are 1 to 50 feet thick and were laid down in rapid succession. The lava issued from hundreds of dikes ½ to 17 feet thick trending SW-NE. A few vitric ash beds generally less than 1 foot thick are interbedded with the basalts.	The basalts are extremely permeable, but they yield only small quantities of water because rainfall is low and they are cut into many small compartments by the dikes. A few seeps issue from the tuff beds.

PANIAU VOLCANIC SERIES

The Paniau volcanic series is exposed only in the dome remnant (pl. 1). The lava flows consist of thin-bedded vesicular olivine basalts, of both aa and pahoehoe types, laid down in rapid succession. They were erupted from fissures 0.5 to 17 feet wide. Rocks containing many large crystals of olivine are abundant.

A few eruptions were accompanied by lava fountains, which locally laid down beds of vitric lapilli ash up to 5 feet thick. The ash beds are well compacted and largely altered to yellow palagonite. The most important ash bed crops out in Kaali Cliff at an altitude of about 500 feet, and it can be traced continuously for more than 2 miles. A lens of vitric ash 3 feet thick is exposed 5 feet above water level in well 13. Another bed of vitric ash crops out just above the well, and formerly a spring issued from it. A 2-foot bed of vitric-lithic ash crops out at Waiokanaio Spring, in the vicinity of which outcrops of thin vitric ash beds are fairly common.

The lavas of the Paniau volcanic series have a total exposed thickness of 1,281 feet at the type locality on the east side of Paniau hill, the highest point on the island. The dome remnant is the southwest rift zone of a shield volcano. All the beds dip away from the axis of the rift zone, at angles ranging from 3° to 10°. The dip is northwestward on the northern side of the rift zone and southwestward on the southern side. The center of the rift zone passes through Kaeo hill, which is composed of dense olivine basalt and is probably the plug of an ancient cone.

The intrusive rocks consist of innumerable basaltic dikes half a foot to 17 feet in thickness, trending NE-SW (pl. 4B). Some are vesicular and platy but most are dense and cross-jointed. The dikes in the eastern cliff are shown diagrammatically on plate 1, as they are too close together in the middle part of the cliff for all of them to be shown on a map of that scale. The heart of the dike complex in the rift zone is a mile wide. The southern edge lies 1 mile north of Pueo Point and the northern edge 2 miles south of Poleho. Some beds in this area have dips ranging from 8° to 12° SE, and they can be seen to form tilted blocks that have dropped between faults which have subsequently been intruded by dikes. Similar dropped blocks, or grabens, are common in the rift zones of Kilauea Volcano, on the island of Hawaii. Two small plugs adjacent to Kaailana Valley occupy eroded vents. Secondary mineralization is common in the vesicles of rocks in the rift zone.

The lava beds are very permeable where they are not decomposed, but in most places they do not yield water readily because dikes are sufficiently abundant to restrict the movement of water through the lavas. The vitric ash beds are fairly impermeable, and they give rise to two valuable perched seeps and several smaller ones. Most of the dikes are relatively impermeable.

GREAT EROSIONAL UNCONFORMITY

The rocks in the Paniau volcanic series are separated from all other rocks by a profound erosional unconformity. The Tertiary shield volcano underwent a long period of weathering, when streams cut canyons into its carapace and the sea made cliffed headlands of the interstream divides. The Pleistocene basalts in Apana and Haao valleys rest against steep valley walls. All rocks on the coastal plain lie against cliffs or talus fans. The talus fans that extend below sea level are apparently subaerial in origin, and they indicate that the island stood relatively higher at the time they were formed. This greater altitude would have resulted in greater rainfall on the island and an accelerated rate of weathering and stream erosion.

KIEKIE VOLCANIC SERIES

General statement.—The rocks of the Kiekie volcanic series form the surface or underlie most of the coastal plain except for the narrow strip 3½ miles long bordering Keawanui Bay (pl. 1). They consist of both lava flows and tuff. The lava flows are olivine basalt of pahoehoe type, ranging from dense to highly vesicular types, which issued from six secondary lava cones. The tuff is gray to brown well-bedded subaerially deposited vitric-lithic basaltic tuff, containing many angular ejecta of older tuff and coralliferous limestone in a matrix of glass and palagonite, generally cemented by calcite. The lavas welled out quietly and produced only minor amounts of spatter and no cinders. The tuffs were ejected by cataclysmic explosions. The bottom of the Kiekie volcanic series rarely is exposed. It was extruded on the 300-foot submarine bench, but its thickness cannot be determined because the relative amounts of buried volcanics and sediments below sea level are unknown. Above sea level the thickness of the lava flows ranges from 20 to 290 feet. All the lavas carry small phenocrysts of olivine in a black or dark gray matrix.

Lehua Island.—Lehua Island, about 1 mile long, nearly ½ mile wide, and 702 feet high, is composed of subaerially-deposited tuff (pl. 5B). The vent lay in the sea on the north side of the islet and a strong north wind was blowing during the eruption, as shown by the pronounced asymmetry of the cone and deposits of ash as much as 8 miles to the south. The tuff above sea level in Lehua Island is 702 feet thick, and it extends an unknown depth below sea level. It is more than 15 feet thick on the tip of Niihau opposite Lehua Island. Much of the ash from the eruption must have fallen into the sea. The tuff is black and upon weathering turns to a tan powdery soil, which makes it easily differentiated from the red lateritic soils on the basalts. The tuff contains much glass and many fragments of vitreous basalt derived from the exploding magma. Some beds are breccias and contain many large angular fragments. The writer did not land on the island.

Palmer[23] gives a detailed description of Lehua Island. Three series of tuff are described, which he believes were laid down by three different eruptions separated by considerable time. As an alternative explanation the writer suggests that there may have been several vents exploding during the same relatively short eruptive period. The cone has the symmetry of one built during a single explosive eruption in the matter of a few days or weeks. Palmer describes gullies 2 to 5 feet deep between the middle and lower tuff series, but such gullies may develop in loose tuff between explosions a few hours apart. He noted no gullying between the middle and upper tuff series but thought that the presence of blocks of reef limestone only in the upper (latest) tuff indicated a preceding time interval long enough for a reef to develop in the crater of the cone. However, submarine explosions such as made Lehua Island would progressively deepen and widen the vent, and the blocks of reef rock could also be interpreted as indicating that only the last explosions were deep enough to encounter a buried reef. The platform directly under the cone consists of basalt of the Kiekie volcanic series from the cone on the northern end of Niihau, and not until the explosions had excavated the crater to a depth below the basalt capping would appreciable amounts of reef rock be included in the ejecta. Palmer[24] assumed that the presence of xenoliths of dunite and other holocrystalline rocks in the tuff indicated a great depth for the foci of the explosions. However, many lavas in the Hawaiian Islands bring up such xenoliths.[25] They were probably carried up in the magma prior to the explosions and are not indicative of the focal depths of the explosions.

Following the explosions on Lehua Island, ash mantled most of Niihau, as fragments of tuff are found as far south as Puulehua (latitude 21° 52′ N.). The ash is a foot thick on the summit ridge 1 mile northwest of Pueo Point. The few small patches shown on plate 1 are by no means all of the ash-covered areas; many of the grass-covered flats in the upland country are probably covered with a foot or more of ash. Large quantities were carried down the main stream valleys to the

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[23] Palmer, H. S., Geology of Lehua and Kaula islands: B. P. Bishop Museum Occ. Papers, vol. 12, no. 13, pp. 1-36, 1936.

[24] Idem, p. 29.

[25] Macdonald, G. A., Petrography of Maui: Hawaii Div. of Hydrog., Bull. 7, p. 303, 1942; Petrography of Hawaii: Hawaii Div. of Hydrog., Bull. 9, pp. 198-199, 1946.

coastal plain, as shown by 6 feet of ash from Lehua Island near the mouth of Keanauhi Valley, 7 miles southwest of Lehua Island. The whole northern part of the coastal plain now mapped as lava was covered with 5 to 15 feet of the ash. It still remains in most of the low places, but to map the area as ash-covered would obscure the Pleistocene basalt dome. Following the deposition of the ash in this area, the winds piled it into dunes which have since become lithified. Two of these dune ridges were large enough to justify mapping (pl. 1).

The ash dunes extend into the sea at the western coast, where a wide marine bench has been cut into them. This bench is the only clue to the age of the Lehua Island eruption. The dune rock benched by the sea must have formed on the land, as wind-blown sand dunes could not form under water; hence, it is concluded that the eruption occurred during the Waipio (minus 60-foot) stand of the sea in Wisconsin time. The vent must, however, have opened below sea level, as the explosion was the violent hydromagmatic type. There appear to be the remnants of a wave-cut bench at least 30 feet above sea level on the southern shore of Lehua Island, but it was not examined on the ground. The tuff has low permeability but small quantities of water percolate along the bedding planes and through the sandy-textured beds.

PAKEHOOLUA CONE.—The entire northern part of the coastal plain of Niihau Island was built above the ocean by the development of a small dome or shield volcano of olivine basalt pahoehoe, which reached a height of 200 feet above the present sea level. The vent is an inconspicuous depression 25 feet deep bordered by thin beds of scoriaceous lava. No ash was erupted from it. Other small depressions nearby are collapsed roofs of lava tubes that radiate from the vent. The highest point on the dome is a long consolidated dune of ash from the Lehua Island eruption. It was mapped by both Powers[26] and Hinds as a cone. Hinds mapped 5 tuff cones on the northern plain,[27] all of which are small dunes. The basalt dome carries everywhere, except on the tumuli and other original high rocky stretches, a coating of tuff or wind-blown ash from the Lehua Island eruption. The lava has been decomposed only slightly, perhaps because of the ash coating. Deposits of the plus 5-foot stand of the sea are common along the shore south of Kii Landing, but no deposits of the plus 25-foot stand of the sea were found on the lavas of this dome. Yet the dunes of ash from Lehua Island overlie the basalt and extend below sea level. On this evidence the eruption is assigned to the minus 60-foot stand of the sea in Wisconsin time. On the basis of the small amount of decomposition of the lava it is undoubtedly the latest eruption on Niihau. The fact that the magma did

[26] Powers, S., op. cit., fig. 1, p. 258.
[27] Hinds, N. E. A., op. cit., fig. 14b, p. 92.

not explode seems to indicate that it was erupted on land or in very shallow water.

The basalt of Pakehoolua cone is highly permeable. Because of the low rainfall and the extensive exposure of the basalt to the sea, little water can be expected, and it is likely to be too brackish even for stock.

RESERVOIR CONE.—An eruption of olivine basalt occurred in Apana Valley 1.5 miles west-southwest of Kaeo, and the lava flowed down both Apana and Haao valleys. The lava forms a broad delta-shaped mass on the plain below. The crater outlet has been artificially dammed to catch flood waters. A heavy bed of columnar basalt crops out along the lake shore, but higher in the cone the basalt is very scoriaceous. The inland side of the cone is buried by alluvium.

The "Natural Bridge" in Haao Valley is a remnant of a lava tube 15 feet in diameter. It has been blocked with concrete, but the reservoir so formed failed to hold water.

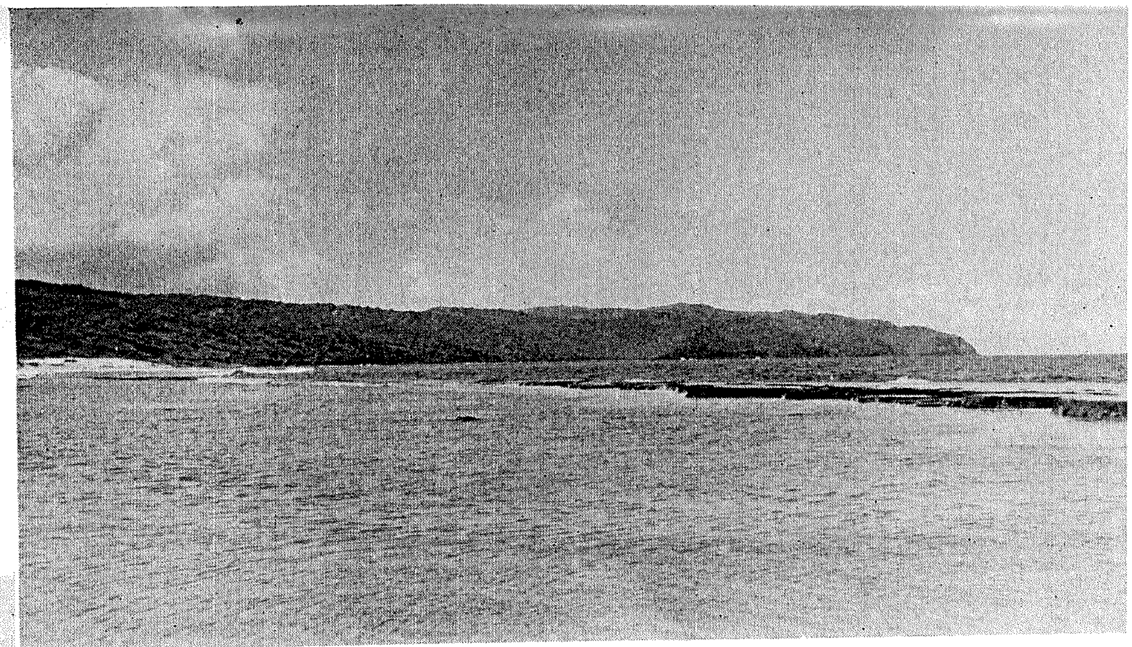
The basalt from Reservoir cone lies unconformably on the lavas of the Paniau volcanic series. It flowed around the ancient sea cliffs which border the dome remnant; hence, it is obviously much later than the lavas of the dome. It in turn is overlain by lithified calcareous dunes formed during the minus 60-foot stand of the sea, and in most places it is covered with 1 to 4 feet of red lateritic soil. Its lavas merge topographically with those from Puulehua cone. The basalt is assigned on this meager evidence to the early(?) or middle Pleistocene.

On the plain the lava flow is indented by several circular depressions 10 to 30 feet deep. Sidney Powers mapped the depressions as pit craters.[28] Apparently the lava pooled to a depth of 60 to 80 feet on the plain and then spilled over the marine shelf to the west. This partly drained the liquid lava from beneath the hardened crust in the pooled area and allowed the crust to collapse in places. The resulting depressions do not have the form of true pit craters. The basalt from Reservoir cone is moderately permeable and yields small quantities of potable water. The reservoir in the crater leaked when the dam was first built, but the visible leaks just downstream from the dam were successfully plugged. The reservoir contains water in wet years. It was formerly used to supply the ranch house at Kiekie but was abandoned because the supply was not dependable.

PUULEHUA CONE.—Puulehua cone, 117 feet high, is crescent-shaped and is composed of dense beds with a few spattery and scoriaceous beds of olivine basalt. The lavas from Puulehua cone are hummocky pahoehoe, in most places fairly well covered with lateritic soil. They crop out over the lowland between Halalii Lake and Kawaewae cone.

[28] Powers, S., op. cit., p. 258.

Plate 4a. Nullipore reef along the eastern coast of Niihau and eroded uplands in the background. Photo by H. T. Stearns.



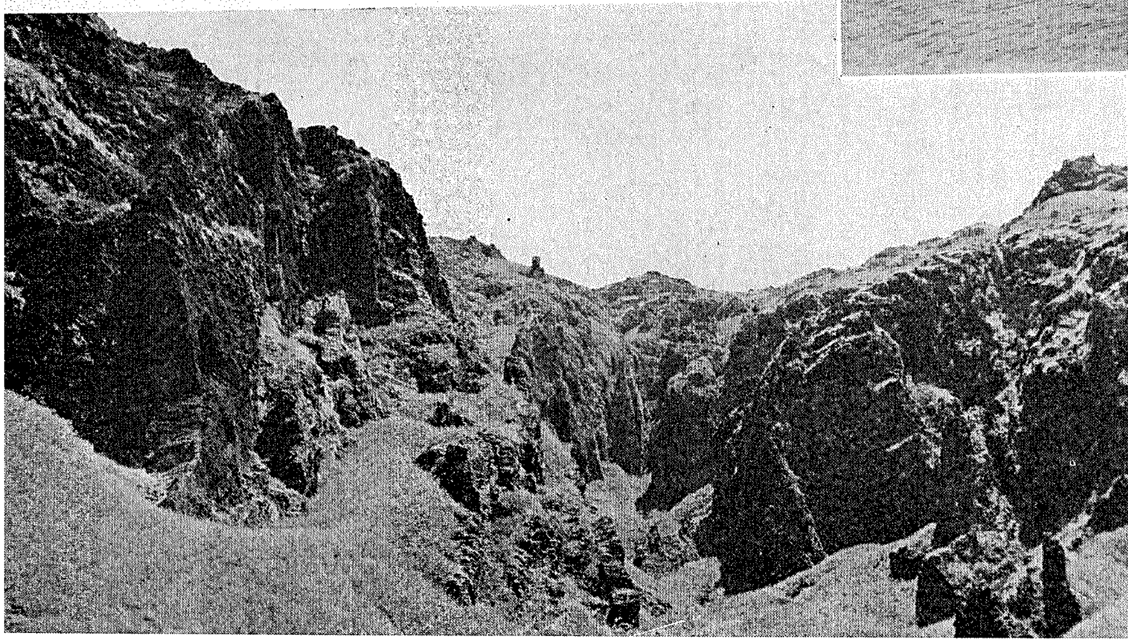


Plate 4b. Closely spaced dikes cutting lavas of the Paniau volcanic series, in the rift zone exposed in the eastern cliff of Niihau. Photo by H. T. Stearns.

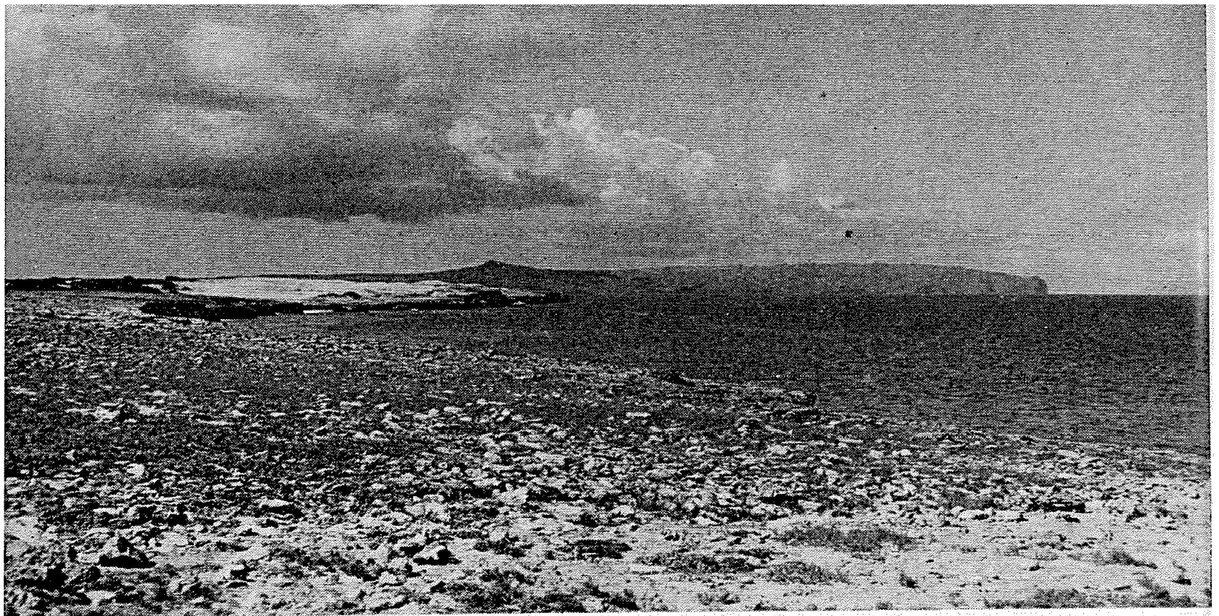
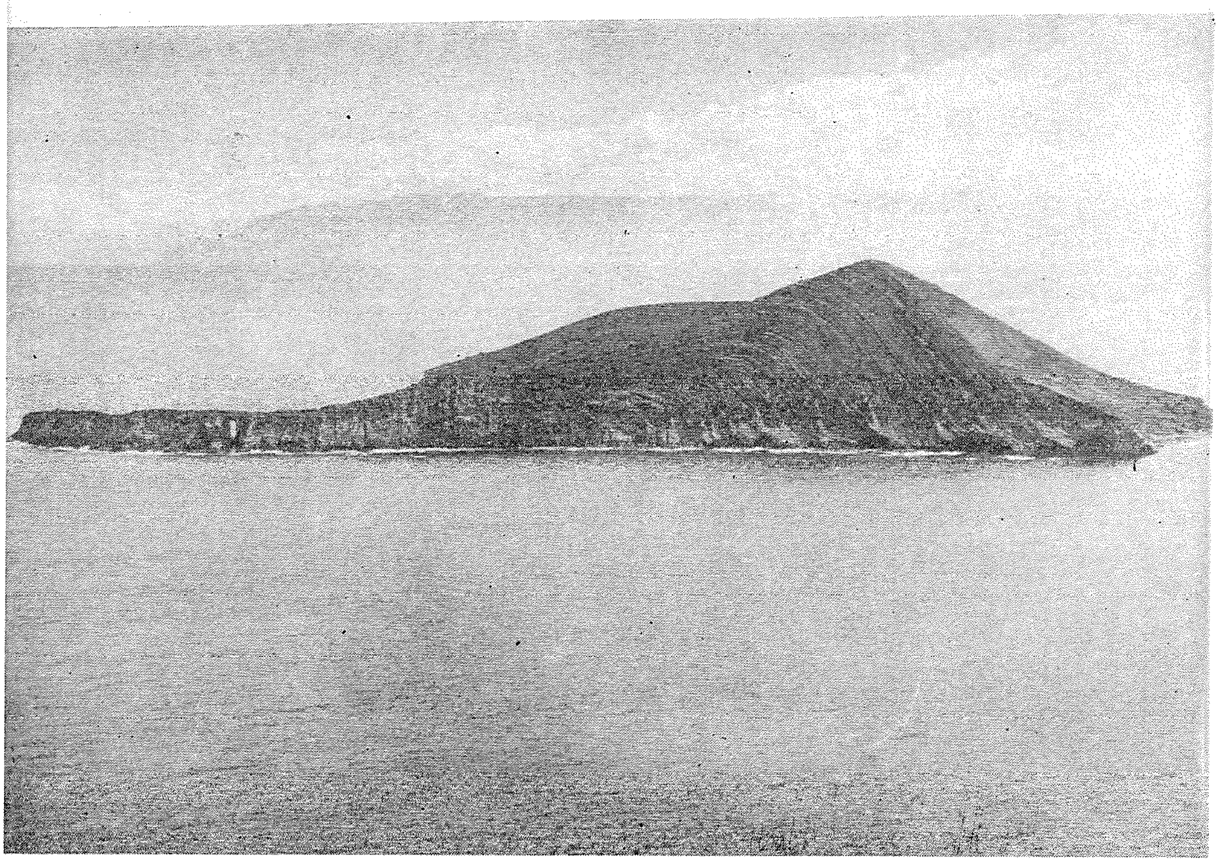


Plate 5a. The eastern coast of Niihau from the southern end of the island. The rock in the foreground, including that in the low sea cliffs, is eolianite. The peak in the uplands is Kaeo. Photo by H. T. Stearns.

Plate 5b. Air view of Lehua Island, north of Niihau. Photo by U. S. Army Air Force.



Lithified calcareous dunes formed during the minus 60-foot stand of the sea lie on the southwestern side of the cone. Black muds, apparently of marine origin, partly fill the crater. Erosion of the southern slope of the cone about 50 feet above sea level suggests a shore line. On the northwestern side of the cone, at an altitude of 100 feet, is a ledge of rock which has apparently been swept bare by the sea, and below the ledge is a bank of black soil that contrasts with the usual red lateritic soil. Such black soils generally are a good indication of marine invasion, especially if they are gypsiferous. It is believed that Puulehua cone erupted on dry land during the Kahipa (minus 300-foot) stand of the sea, as the eruption was not of the violently explosive subaqueous type.

The lavas from Puulehua are fairly permeable and yield small quantities of brackish water fit only for stock.

UNNAMED CONE NORTH OF PUULEHUA.—Half a mile north of Puulehua the road crosses a broad, gently-sloping hill, rising to about 110 feet above sea level, which appears to be a small lava dome that erupted probably a little later than Puulehua. Its lavas merge with those of Puulehua and Reservoir cones.

KAWAEWAE CONE.—Kawaewae cone, the highest secondary cone on Niihau, reaches 320 feet above sea level. The cone has been partly eroded during higher stands of the sea, and it formerly contained more cinders than it does now. A bed of yellow altered lava fountain debris about 50 feet thick, and also what appears to be a dike, lie on its southern side. The cone is capped with dense massive rock. The flows from Kawaewae cone are olivine basalt and cannot be separated in the field from those of adjacent vents.

Kawaewae hill was regarded by Hinds as an erosion remnant of the Tertiary lava dome, but its structure is obviously that of a cone. Furthermore, its lava resembles petrographically that of the other Pleistocene vents and differs from the Tertiary lavas of the dome remnants (see the section on petrography).

Much of the surface of Kawaewae cone is deeply weathered to red laterite. A well-preserved 25-foot shore line marked with fossiliferous limestone can be traced around the northwestern slope. Lithified dunes formed during the Waipio (minus 60-foot) stand of the sea lie on its southern slope. A large part of the cone has been eroded away. As no streams could have done the work, the erosion must be the result of higher seas. The cliff on the northwestern side appears to have been formed when the sea was perhaps 200 feet above its present level. Kawaewae cone is probably the oldest vent of the Kiekie volcanic series.

MAUULOA CONE.—Mauuloa cone, 2 miles south of Kawaewae cone, rises 198 feet above sea level. It is a small lava dome. Only a faint suggestion of a crater exists. The lava from this cone extends for several miles in all directions and underlies large areas of lithified calcareous dunes. The cone is older than the dunes, which are of late Pleistocene age. Its lavas are considerably decomposed and may be contemporaneous in age with those of Puulehua. Mauuloa cone is tentatively assigned to the middle Pleistocene.

The lavas are fairly permeable but have not been explored for water except near the coast, where the water is brackish.

KAUMUHONU CONE.—A cone of olivine basalt 178 feet high, composed of dense and scoriaceous beds typical of the vent of a secondary lava cone, lies on the southern coast of Niihau near Kaumuhonu Bay. A large part of the cone has been eroded away by the sea. The eastern slope of the cone is overlain by tuff from Kawaihoa cone, which is known to be older than the plus 100-foot stand of the sea, and the cone is assigned tentatively to the early or middle Pleistocene. Its lavas probably carry only salt water because they are open to the sea.

KAWAIHOA CONE.—Forming the southeastern tip of Niihau is the western segment of a basaltic tuff cone, the vent of which lies in the sea to the east. It is 548 feet high and is composed of well-bedded subaerial vitric-lithic tuff and breccia typical of cataclysmic explosions (pl. 3A). Presumably the magma exploded on contact with sea water. Fragments of older vitric-lithic tuff, olivine basalt, and coralliferous limestone are numerous in the beds of the cone, indicating that the explosions blasted their way through reef rock and older tuff and lava.

An ancient valley on the northwestern side of Kawaihoa cone, about 40 feet deep, is filled with eolianite formed during the Waipio stand of the sea. In a small gully on the northern shore is a ledge of reef limestone 100 feet above sea level (measurement by aneroid barometer). The Kawaihoa cone apparently was formed during the low stand of the sea preceding the plus 100-foot stand.

The tuff has low permeability, but it supplies two perennial seeps on the northern slope of the cone.

LATE PLEISTOCENE SEDIMENTARY ROCKS

CONSOLIDATED DUNES OF VOLCANIC SAND.—Two prominent tan-colored hummocky dune ridges, trending northeast and southwest, lie on the northern part of the coastal plain of Niihau. They rise 20 to 90 feet above the adjacent plain. A few cuts show that they consist entirely of grains of volcanic sand, composed chiefly of glass and olivine crystals, with distinct cross-bedding. Some of the glass is altered. Lower dunes lie scattered over the whole northern end of the island. Only the largest patch of these lower dunes, 1 mile northwest of Kii Landing, is mapped on plate 1. The dunes were built by the trade winds, which reworked the ash that fell during the Lehua Island eruption. They extend into the sea at Puukoae, on the western coast, indicating that they were laid down in late Wisconsin time, when the sea level was lower than now. The five "tuff cones" indicated in the northern part of the costal plain on Hinds' map[29] are actually formed of this dune sand. They show the structural and textural features characteristic of sand dunes but none of the features of true tuff cones.

The dunes of volcanic sand are fairly permeable but lie mostly above the water table; hence they carry little or no water.

CONSOLIDATED CALCAREOUS DUNES.—Eolianite, limestone formed by the cementation of dunes composed of fine-grained calcareous sand, covers nearly half of the southern part of the coastal plain of Niihau. It forms long, narrow ridges, reaching a height of 144 feet and dying out from east to west (pl. 2B). Three other ridges of eolianite lie at Nonopapa, near Kiekie, and south of Keawanui Bay on the western coast. These three latter ridges run parallel to the coast and to the modern dunes. The dune structure is commonly hidden under a veneer of caliche-like material. Some dunes apparently have weathered away, leaving behind only blocks of dense limestone, which ring when struck by a hammer, scattered in many places over the southern plain. In others, weathering and erosion have developed a miniature karst topography. Most of the southern and southeastern coast is a sea cliff 10 to 50 feet high cut in eolianite (pl. 5A). Some of the dunes are not firmly cemented below the caliche-like crust and have supplied part of the sand in the modern dunes. The eolianite rests on lateritic soil of the early(?) and middle Pleistocene lavas, indicating that much of the weathering of the lavas antedates the dune building.

The dunes accumulated during the minus 60-foot stand of the sea, as nowhere on them are there shore lines higher than that of the plus 25-foot stand. A few dunes at low altitude may have accumulated during the plus 5- and 25-foot stands, but no attempt was made to differentiate them on plate 1 from the older dunes. Examples are the patch mapped on the northern shore of Halulu Lake and some of those near Kiekie and Nonopapa. The distribution of the dunes indicates that the same wind directions prevailed in the late Pleistocene as today.

The eolianite is exceedingly permeable and has no surface runoff. Dug wells penetrating it some distance from the coast obtain water suitable for stock at sea level. Much of the eolianite is underlain at sea level by basalt, and care should be taken in selecting the site for a well to avoid encountering basalt, which requires blasting.

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[29] Hinds, N. E. A., op. cit., fig. 14b, p. 92.

CONSOLIDATED REEF AND BEACH LIMESTONE.—Patches of emerged fossiliferous marine limestone lie on the northwestern slopes of Kawaihoa and Kawaewae cones. They are too small to show on plate 1, except by a cross. Those on Kawaihoa cone lie about 100 feet above sea level and those on Kawaewae about 25 feet. A former marine stack of coralline limestone about 12 feet high lies 1½ miles northeast of Kaununui. The bodies of marine limestone are too small to carry water.

RECENT SEDIMENTARY ROCKS

UNCONSOLIDATED EARTHY DEPOSITS.—The unconsolidated earthy deposits are chiefly loose, poorly-sorted, poorly-rounded, stream-laid bouldery alluvium in the valleys, and silt and clay in the lowlands. They include talus at the foot of cliffs, and clay and silt deposits, commonly full of salts, laid down in the intermittent lakes (playas) of the coastal plain. Most deposits carry a veneer of red lateritic soil washed from the uplands in historic time. In a few places in the valleys there are terraces of older alluvium too small to show on plate 1. The older alluvium resembles the younger alluvium but is partly consolidated. Most of the alluvium and talus contains black interstitial material that is a gumbo when wet but is not a ceramic clay. The alluvium ranges from a thin veneer to deposits of unknown thickness at the valley mouths. Projections of the walls of Keanauhi Valley, 1½ miles from the coast, meet 100 feet below sea level, indicating that the alluvium may be about 150 feet thick there. Drilling would probably reveal deposits of older alluvium considerably below sea level under the Pleistocene lavas of the coastal plain. The sediments shown in section AA′, plate 1, probably are chiefly earthy marine and land sediments with intercalated lenses of reef, dune, and beach deposits.

The alluvium has low permeability but carries small quantities of water at sea level. However, many of the wells in it yield bitter water because of the salts deposited by evaporation of the playa lakes.

UNCONSOLIDATED CALCAREOUS DUNES.—Shifting dunes of so-called "coral sand" blown from present beaches and from poorly lithified Pleistocene dunes reach heights of 110 feet (pl. 1). They are slowly becoming anchored by the spreading of kiawe trees and other introduced plants. They are highly permeable, and well 48, which is in dune sand, yields the best water in the island.

LACUSTRINE BEACH DEPOSITS.—Ridges of weakly-consolidated, very fine calcareous sand 1½ miles long, ¼ mile wide, and less than 10 feet high lie on the west side of Halalii Lake (pl. 1). They are interpreted as beach ridges thrown up by the waves of the lake in prehistoric time. The lake is now full of red mud. One ridge on the eastern side of the deposit is composed of brown silt and may indicate a very late change in the character of the beach deposits. The calcareous sand apparently was blown by the wind into Halalii Lake from the beaches and dunes to the east and then worked westward by the waves of the lake. The ridges are now fairly well covered with vegetation. The sand is permeable but the quality of the water in the ridges has not been determined by wells. It is probably bitter.

Unconsolidated beach sand.—Most of the shore of the coastal plain is bordered by beaches of "coral" sand. Actually coral particles are scarce in the sand, the major part of which consists of grains of waterworn shells and skeletons of foraminifera, nullipores, and other marine organisms. The deposits rarely exceed 20 feet in thickness and are highly permeable. They generally yield water too salty for stock.

Consolidated beach deposits.—Well-bedded calcareous beach rock is found along some of the coast, especially seaward of lakes. It dips seaward 5°-10° and forms outcrops too small to show on plate 1, and too small to carry water.

Living reefs.—Living nullipore reefs fringe the coast east of Halalii Lake (pl. 4A) and form small strips off a few other sandy beaches. Some appear to be growing on planed-off beach rock. Apparently conditions are not favorable for reef development.

GEOLOGIC HISTORY

1. Building of a dome-shaped island about 2,500 feet above present sea level and about 13,000 feet above the adjacent ocean floor, by the outpouring of basalt flows from a shield volcano with its eruptive center about 2 miles east of Niihau and from a strongly developed rift zone extending southwestward from the center (fig. 4). By analogy with other Hawaiian domes, a caldera probably indented the submit as shown in figure 4. The eastern rim of the caldera may have been lower than the western, as the eastern side was destroyed by subsequent erosion more rapidly than the western side.

2. Cessation of volcanism and establishment of a stream pattern.

3. Long period during which high marine cliffs were formed on the eastern and southeastern coasts and lower ones on all other coasts. Streams cut canyons in the dome. Weathering formed deep lateritic soil on the inter-stream divides.

4. Gradual submergence of the island by a large but unknown amount, in common with the other islands of the archipelago (fig. 5). The island probably reached stability by the end of the Pliocene or during the early Pleistocene.

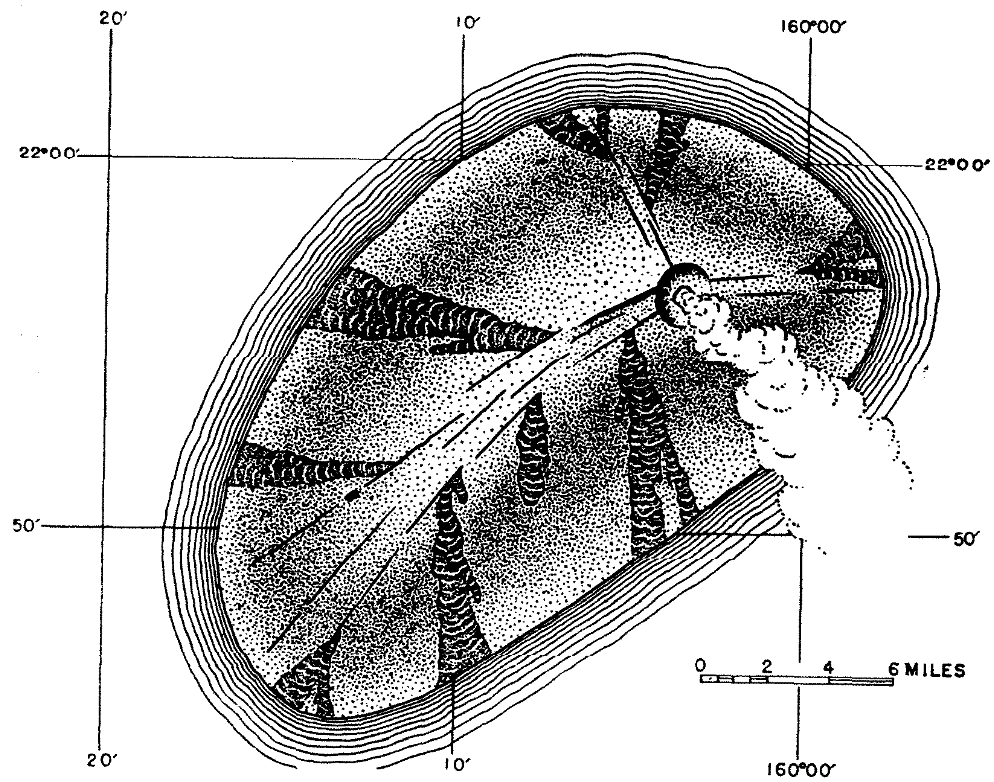

Figure 4. Niihau after completion of the primitive basalt dome and formation of the caldera.

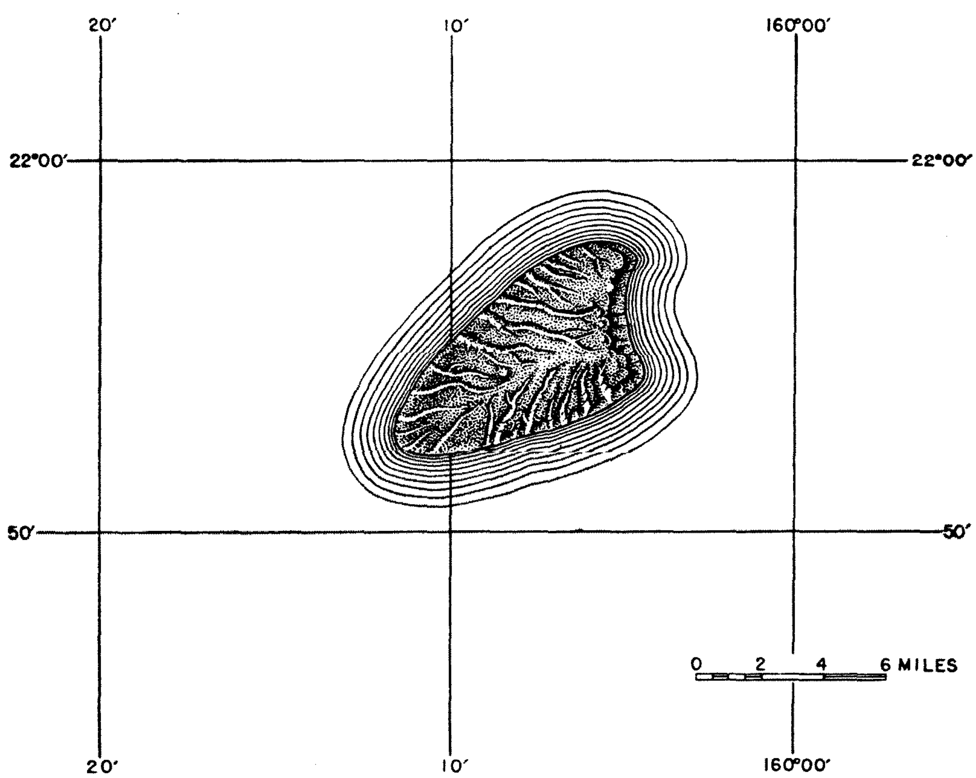

Figure 5. Niihau after a period of erosion and the partial submergence of the primitive basalt dome.

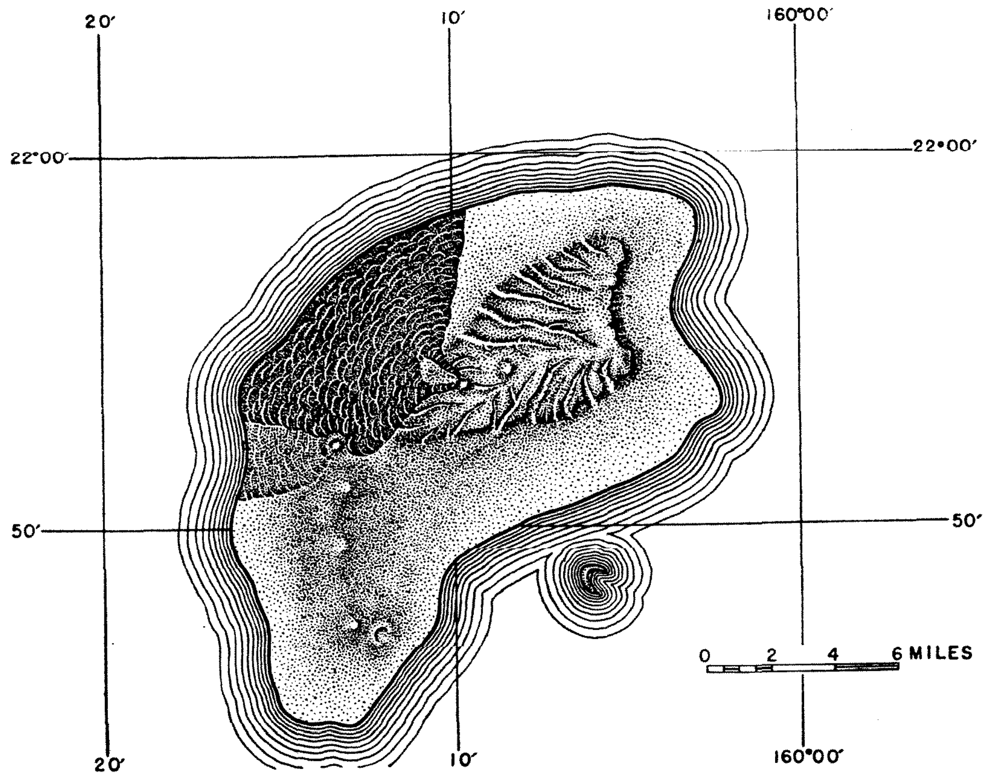

Figure 6. Niihau during the middle Pleistocene, when the sea was lowered by the removal of water to form the continental glaciers. Several secondary volcanic eruptions have occurred.

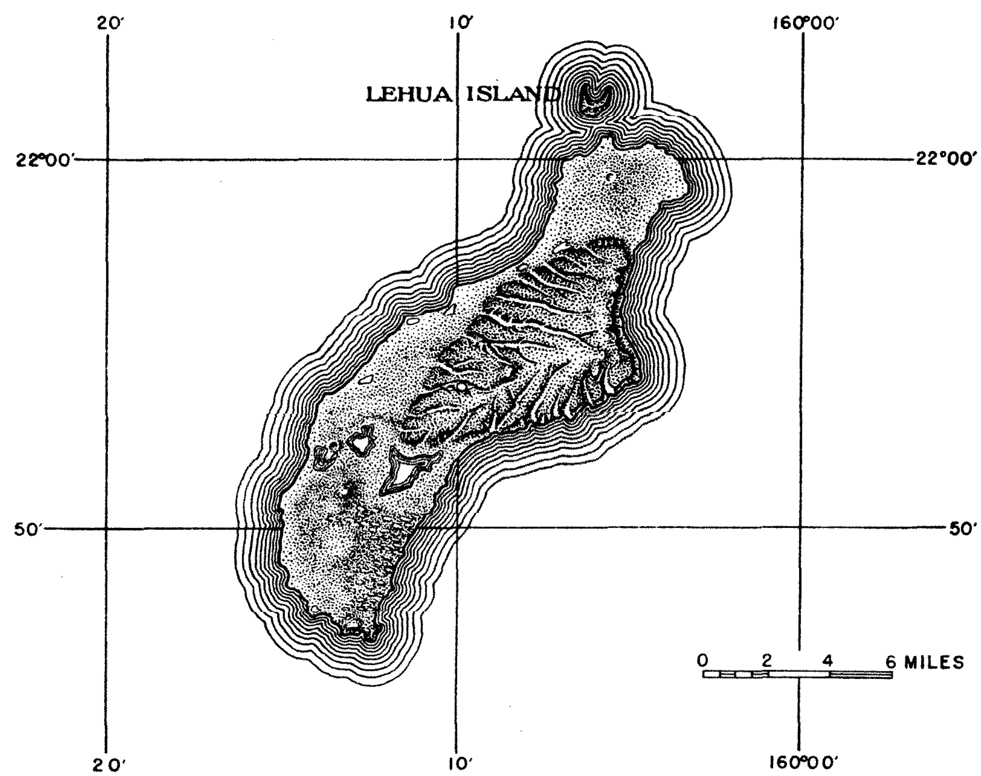

Figure 7. Present form of Niihau.

5. During the Pleistocene there occurred many shifts in sea level, from about 250 feet above to 300 feet below present level. A shelf 0.5 to 1.5 miles wide was cut 300 feet below present sea level, indicating long halts of the sea at that level. Reefs grew during rising seas.

6. Concurrent with the shifting seas of the Pleistocene, volcanism was renewed and lava and tuff built the submarine shelf above sea level. Buried cones are known to lie below sea level (fig. 6).

7. During the plus 100-foot stand of the sea the northern part of the coastal plain was still under water and Lehua Island had not yet erupted.

8. During the minus 60-foot stand of the sea sand blowing inland built extensive calcareous dunes, and a narrow shelf was formed around the island. A lava dome built the northern part of the coastal plain above sea level and Lehua Island was formed by a submarine explosion. Ash from Lehua Island fell over most of Niihau and soon thereafter was blown into dunes on the northern plain.

9. The sea rose about 85 feet, drowning the seaward parts of the dunes. Vegetation spread over the rest and cementation occurred. Playa lakes formed in depressions in the lowlands.

10. The sea fell 20 feet and formed benches and beaches 5 feet above present sea level.

11. The sea fell 5 feet to the present level and modern beaches and dunes formed (fig. 7).

12. Feral goats in historic time ate so much of the vegetation that much of the deep red soil on the uplands, formed during the million years or more since the cessation of volcanism there, was washed into the lowlands, filling up Hawaiian fish ponds and many of the playas. Extinction of the goats and the introduction of kiawe, haole koa, and other desert plants are slowly reclaiming the eroded areas of the island.

CLIMATE

Niihau is subtropical and semiarid. No climatological data are available except rainfall records. The island lies in the tradewind belt and these winds are dominant, as shown by the distribution of sand dunes. Strong northerly and southerly winds occur and many of the trees are bent, indicating that strong winds blow frequently. Droughts occur frequently, one having terminated in March 1945. At such times the feed becomes powdery and little nutrition is left in it and some of the waterholes go salty. As a result large numbers of animals are lost.

According to Mr. Aylmer Robinson, the middle part of the lowlands between Nonopapa and Puuwai Village receives more summer showers than the remainder of the island. Southerly winds bring heavy downpours, which are usually general. Naulu[30] showers bring relief to some parts of the island during hot weather.

Following is a table showing the monthly rainfall for 7 years at Kiekie. Mr. Robinson believes that a longer record would lower the annual average of 26 inches. Records have been kept longer but have not been compiled. Two years since 1941 have been exceptionally wet, when 45 to 50 inches of rain fell. Eight inches fell in April 1945.

Monthly rainfall at Kiekie, Niihau, 1919-1925[1]
(Data furnished by Aylmer Robinson)

Month	1919	1920	1921	1922	1923	1924	1925	Average
January	0.65	7.30	7.19	0.62	7.00	0.06	0.30	5.62
February	0.08	1.16	0.75	0.58	4.11	2.34	2.40	1.63
March	0.87	1.69	0.65	0.98	5.44	0.26	2.61	1.79
April	1.76	2.10	0.53	0.86	1.92	6.45	0.58	2.03
May	1.63	1.16	2.29	1.39	0.32	0.78	2.73	1.47
June	1.26	2.43	0.97	0.98	1.13	0.56	0.71	1.15
July	2.50	2.90	1.64	0.90	2.51	1.78	4.58	2.40
August	1.29	1.82	0.85	1.47	2.97	0.89	1.44	1.53
September	2.81	2.23	1.05	3.77	1.15	1.08	1.38	1.92
October	4.96	0.47	0.41	1.32	2.69	0.91	5.24	2.29
November	1.77	2.60	0.45	5.90	0.50	3.40	0.74	2.19
December	8.16	3.33	4.84	0.22	6.59	4.44	4.35	4.56
Annual	27.74	29.19	21.62	18.99	36.33	22.95	27.06	26.27

[1] The period is regarded by Mr. Robinson as probably somewhat wetter than normal.

WATER RESOURCES

SURFACE WATER

Niihau has no perennial streams but it has about a dozen lakes. During May 1945 nearly every lake bed was covered with fresh water. Most of the lakes are typical playas and soon evaporate, leaving salts behind. The others, such as Halulu Lake and the lake southwest of Puulehua, are greatly decreased in area by evaporation. Most of the lakes are filled intermittently with fresh flood water from the uplands. Those that do not receive runoff are always brackish. All are within a few feet of sea level. Unlike the others, Halulu Lake receives about 10 gallons per minute from Kaluaolohe Spring, which issues from a small outcrop of eolianite. The spring water flows through a small solution cavern at the contact of the eolianite and underlying red soil, as re-

[30] Naulu showers are caused by clouds that form off the leeward coasts and then move inland, dropping their moisture apparently as the result of local convection currents. They fall during times when neither the northeasterly trade winds nor southerly winds blow, and they are reported to occur chiefly in the afternoon during hot weather.

vealed in an excavation. The water of the spring is evidently basal water but is too salty for stock.

The largest perennial spring, called Waiokanaio, issues from crevices in basalt at an altitude of about 500 feet in the northern wall of Waiokanaio Gulch. A trench about 15 feet deep has been excavated to intercept the water, but recent test holes downslope indicate that some of the water is escaping. Just inland of the trench a 2-foot bed of vitric-lithic tuff is exposed. The entire flow of the spring could probably be intercepted by tunnelling about 50 feet along the surface of the tuff bed. The tuff bed is cut by several dikes, hence a long tunnel is inadvisable. According to Mr. Robinson, the flow of the spring has decreased from 2½ to 1½ gallons per minute, as a result of the growth and transpiration of kiawe trees nearby. Water is pumped from a collection tank at 570 feet to an altitude of about 1,100 feet to supply stock. Other vitric tuff beds in this same area yield no water. The salt content, like that of Kaali Spring, is unusually high for a perched spring, owing to salt spray.

The second largest high-level spring is Kaali, which issues about 500 feet above sea level in the high cliff on the northern side of the dome remnant (pl. 1). It discharges from a conspicuous bed of tuff, probably vitric. The flow is about one gallon a minute and the water is piped to masonry tanks in the pasture below and to a wooden tank at Kii Landing. The salt content is 36 grains per gallon[31] (378 parts per million of chloride). The chlorides, primarily derived from ocean spray carried inland by the wind, are undoubtedly leached from the soil by the percolating water. The tuff bed is a good perching structure, but so many dikes cut through it that its recharge area is small.

Two seeps called Waiakaulili Spring issue from fractures in tuff in a small gully on the northern side of Kawaihoa cone. The combined flow is about a pint a minute. The salt content on May 26, 1945, was 45 grains per gallon (467 parts per million of chloride).

Two watersheds have been built recently to catch water for stock. One is at the coast near Kiekie and the other is southwest of Kawaewae cone. Sites were selected where eolianite is covered by a sloping veneer of uncracked caliche. The caliche is coated with asphalt, and the water is stored in masonry tanks. Some loss by seepage has resulted from the widening of cracks in the asphalt by weeds.

BASAL GROUND WATER

Basal water occurs in all formations that extend below sea level and is the chief supply of water on the island. All wells yielding basal

[31] All water was titrated for chloride (Cl); hence the figures in parts per million in parentheses are the result of direct determination. They were divided by 10.39 to give grains of hypothetical NaCl per gallon. Fractions of grains are omitted.

water are listed in the accompanying table, and their locations are shown on plate 1. The salt content of the well water given in the table is much lower than it usually is in those wells, as the samples were collected after a very wet period.

WATER IN BEACH SAND.—Beach sand yields water freely to dug wells but the water is usually of poor quality. The sand beaches are so narrow that recharge depends almost entirely on formations inland; hence, the success of wells in the beach sand is variable. Wells too near the coast may be unfit for use by stock when heavy surf is running. Others are salty all the time. No wells in beach sand yield water fit for human consumption throughout the year, although possibly in very rainy months a small quantity of suitable water could be obtained. Most wells are sweeter if they are dug in beach sand inland of strips of beach rock, as the capping of beach rock prevents heavy surf from causing excessive mixing.

WATER IN CALCAREOUS DUNES.—Dune sand is very permeable and where it is extensive it yields water of good quality. Well 48, which is in dune sand, yields the best water in the island. The salt content is only 8 grains per gallon (81 parts per million of chloride). The well formerly supplied a U. S. Army camp. The draft is reported to have been about 100 gallons per day. Wells 14, 45, and 49 all contain water that is exceptionally low in salt for Niihau. These wells are all newly dug, and heavy draft would probably cause them to become salty. Evidently diffusion and mixing is less rapid in the dunes than in the other formations. Also, more salt spray probably is deposited on the highlands than on the lowlands. It is surprising to find the salt content of wells 48 and 49 less than that of Kaali and Waiokanaio springs, which are perched about 500 feet above sea level.

WATER IN ALLUVIUM.—The permeability of alluvium differs greatly according to texture. The quality of the water depends on (1) nearness to a body of surface water, (2) quantity of salt crystals in the alluvium, (3) nearness of the well to other saturated formations, and (4) permeability of the alluvium. Near the lakes the wells penetrate brown and black playa silts and red silt recently washed from the uplands, and along the border of the uplands they penetrate alluvium. Well 29 was dug into black silt and was abandoned because the water was bitter. The well is filled now, but the bitterness indicates that salts other than sodium chloride caused its unpotability. The salts doubtless were deposited concurrently with the alluvium, probably along the shore of an ancient playa.

Well 46 probably derives its excessive salt from Halalii Lake bed, as wells 44 and 45, closer to the sea, are sweeter. Well 42 is fairly low in salt, probably because water is percolating to it from the Ter-

Wells and water holes[a] on Niihau

(All samples titrated by Sam Wong, U. S. Geol. Survey, Honolulu)

Number (Pl. 1)	Type of well	Approximate depth (feet)	Diameter (feet)	Aquifer	Salt (NaCl)[b] (gr. per gal.)	Chloride (Cl)[b] (p.p.m.)	Date, in May 1945	Remarks
1	Water hole	6	....	Tuff from Lehua Island vent	14	142	30	Always sweet.
2	Do.	6	15	Do.	....	....	....	Do.
3	Dug well	10	6	Do.	....	....	....	Do.
4	Water hole	4	15	Silt	....	....	....	Sometimes bitter.
5	Do.	4	15	Do.	....	....	....	Good water hole.
6	Do.	3	15	Red silt	30	313	30	Do.
7	Dug well	17½	6	Basalt of Paniau volcanic series	96	1,000	30	Abandoned in 1931 because of sulfurous odor.
8	Water hole	5	15	Silt(?)	....	....	....	Good water hole.
9	Dug well	27	8	Basalt of Paniau volcanic series	60	626	30	30 feet of tunnel at bottom, N. 50° E., dug about 1931.
10	Water hole	5	15	Dune sand	....	....	....	Good water hole, new.
11	Do.	6	15	Beach sand	318	3,300	30	New.
12	Do.	6	15	Brown soil	....	....	....	
13	Dug well	50	8	Basalt of Paniau volcanic series	137	1,420	29	Dug about 1931. 6 inches of water in bottom.
14	Water hole	8	15	Alluvium	199	2,070	30	Strong supply.
15	Do.	5	15	Eolianite	....	....	....	Good water hole.
16	Do.	5	15	Beach sand	....	....	....	Not good if surf is heavy.
17	Do.	6	15	Basalt of Kiekie volcanic series	80	828	30	Red soil at top. Fair water hole.
18	Do.	5	15	Beach sand	....	....	....	Salty.
19	Drilled well	....	....	....	....	....	....	No record. Drilled about 1905.
20	Water hole	4	15	Beach sand	326	3,390	30	Fairly good.
21	Do.[c]	4	15	Brown silt	[c]52	540	30	Too salty for animals in dry weather.
22	Dug well	8	10	Beach sand	....	....	....	Not very good.
23	Do.	15	10	Basalt of Kiekie volcanic series	230	2,390	....	Supplies village; 4 feet of beach rock at top.
24	Water hole	5	15	Do.(?)	....	....	....	Salty.
25	Do.	5	15	Algal limestone	....	....	....	5 inches interbedded red soil. Too salty for animals.
26	Do.	....	5	Silt	....	....	....	Salty.
27	Do.	5	10	Eolianite	553	5,740	26	Kaluaolohe Spring passes through it.
28	Do.	5	15	Basalt of Kiekie volcanic series	198	2,060	26	Two 3-foot wells nearby.
29	Dug well	30	6	Alluvium	....	....	....	Filled; too bitter for stock.
30	Water hole	5	15	Laterite	522	5,420	26	....

Wells and water holes[a] on Niihau (Continued)

31	Do.	5	15	Silt	452	4,700	26	....
32	Do.	8	10	Basalt of Kiekie volcanic series	116	1,200	26	Being dug in 1945.
33	Do.	5	15	....	111	1,150	26	....
34	Do.	....	5	....	....	....	....	Too salty for stock, formerly usable.
35	Do.	....	5	....	247	2,570	25	Do.
36	Do.	5	15	Laterite	260	2,700	25	....
37	Do.	....	4	Silt	....	....	....	Too salty for stock.
38	Do.	....	....	....	....	....	....	Too salty for stock except in wet weather.
39	Do.	....	5	....	....	....	....	Do.
40	Cistern	8	20	....	....	....	....	Catches run-off; potable water.
41	Water hole	....	....	Basalt of Kiekie volcanic series	....	....	....	Always too salty.
42	Do.	5	15	Alluvium	174	1,810	26	Good all the time.
43	Drilled well	....	....	....	....	....	....	Brackish. Formerly flowed. Drilled about 1905.
44	Water hole	7	15	Dune sand	97	1,010	26	Dug 1944.
45	Dug well	7	15	Do.	....	....	....	Do.
46	Water hole	5	15	....	1,570	16,300	26	At edge of alluvium.
47	Do.	4	15	Laterite	87	902	26	1 foot of eolianite at top.
48	Dug well	8	4	Dune sand	8	81	26	Supplied domestic water for U. S. Army for a short period. Draft was 100 gal/day.
49	Do.	8	5	Do.	20	206	26	Supplied U. S. Army laundry for a short period.
50	Water hole	4	15	Eolianite	155	1,610	26	Always good.
51	Do.	4	15	Do.	260	2,700	26	Do.
52	Do.	....	....	Do.(?)	....[c]	....	....	Good water hole.
53	Do.	....	....	Do.(?)	....	....	....	Do.
54	Do.	....	....	Basalt of Kiekie volcanic series	....	....	....	Do.
55	Do.	....	....	Eolianite	....	....	....	Salty except in wet weather.
56	Do.	....	....	Do.	....	....	....	Do.
57	Do.	....	....	Do.	....	....	....	Do.

[a] All water holes are dug so that stock can enter them, and differ in this respect from the dug wells, which are curbed.
[b] All water was titrated for chloride (Cl). The figures for chloride in parts per million are those actually determined. They were divided by 10.39 to give grains of hypothetical NaCl per gallon. Fractions of grains are omitted.
[c] Sample from small dug well nearby, which is kept covered for human use.

tiary basalts nearby. Well 14 has a fairly low salt content and is reported to yield a good supply at all times. The largest valley in the uplands drains into the sea past this well.

WATER IN EOLIANITE.—Eolianite yields water freely to wells, and wells 50-53 obtain good stock supplies from it. However, wells 55-57 commonly become too salty for stock in dry weather. Wells dug in eolianite near playa lakes yield water of better quality than those dug in silt, as the eolianite does not contain residual salts.

WATER IN THE KIEKIE VOLCANIC SERIES.—All but two of the wells that enter basalt of the Kiekie volcanic series yield good supplies of stock water. Well 30 is close to playa deposits, and well 41 was dug so close to the coast that sea water rushes into it through crevices. Well 32, which was dug in May 1945, is an improvement over other water holes in basalt because it was dug far enough from Lake Halulu to avoid playa salts. Such wells are more expensive because the ground rises 10 to 20 feet within short distances from the playas, and some of the rock requires blasting.

Wells 30, 36, and 47 obtain water from lateritic soil on the basalts of the Kiekie volcanic series. Well 47 penetrated lateritic soil at the base of the eolianite, and it yields water with 87 grains of salt per gallon (902 parts per million of chloride).

The tuff from Lehua cone near Lehua Landing yields small quantities of water to wells 1-3. The salt content is lower in those wells than in any other except well 48, which is in dune sand. Although the wells are close to the coast the tuff, being fine-grained, is sufficiently impermeable to prevent agitation of the ground-water body by the surf. The yield of the wells is small, as it is reported that they can be bailed dry quickly.

WATER IN THE PANIAU VOLCANIC SERIES.—The dense beds of basalt in the Paniau volcanic series yield water slowly, but the clinkery, vesicular, and highly-jointed beds yield water freely. Wells 7, 9, and 13 were sunk to tap the basal water in the upland spurs. Well 7 was abandoned because of the bad odor of the water, probably caused by decaying vegetation in the adjacent alluvium, as the basalt does not contain materials that would yield sulfurous water.

Well 9 contained 60 grains per gallon of salt (626 parts per million of chloride) when sampled. It is not used. It is a Maui-type well[32] 27 feet deep, with 30 feet of skimming tunnel at the bottom. Unfortunately it is shut off from the water under the major part of the uplands by several massive dikes (pl. 1), and hence it is unfavorably located for developing a large supply even with additional tunnelling.

[32] A Maui-type well consists of a shaft dug to a level a few feet below the basal water table, with one or more horizontal tunnels driven outward from the bottom of the shaft to skim fresh water from the upper part of the basal zone of saturation.

Well 13 was blasted through 50 feet of basalt containing an intercalated 3-foot lens of vitric tuff. The well was pumped for 3 days with a hand pump but was abandoned when it was found to be yielding water with more than 100 grains of salt per gallon. It lies just inland of a dense 5-foot dike. If no other dikes are found nearby a tunnel at the bottom of this well might increase its yield, but the rather high initial salt content seems to indicate that it is cut off structurally from the main supply under the uplands.

QUANTITY AND QUALITY OF THE BASAL WATER

The only basal water sufficiently low in salt for drinking, according to U. S. Public Health standards, is in wells 1, 48, and 49. These wells have small yields; hence the prospects are poor for developing drinking-water supplies. Numerous wells yield water fit for cooking, washing, and stock, and by proper development and light draft considerable additional quantities of such water could be developed. However, the total quantity of recoverable ground water is small and amounts to thousands of gallons per day. This results from low rainfall, adverse geologic structures, large quantities of salt carried inland by spray, and deposits of authigenic salts in some of the earthy formations. There is no possibility of developing supplies of millions of gallons of water per day, such as are common in the larger Hawaiian islands.

UNDEVELOPED SUPPLIES

The largest undeveloped supply of ground water probably lies between the dikes in the basalt of the Paniau volcanic series underlying the axis of the uplands. A shaft to sea level and tunnels crosscutting the dikes (Oahu-type well)[33] in upper Keanauhi Valley or in the Puu Kaeo area would develop such water, but the well would probably be too expensive in relation to its yield to justify the cost. Exploratory drilling in that area might reveal small quantities of water considerably above sea level. Drilled wells near the heads of valleys in the uplands should generally recover stock water, but some of them might be unsuccessful if they happened to penetrate a small compartment between two dense dikes.

Most of the dikes in the basalt strike southwestward, and this should cause the ground water to move in that direction. The most economical way to develop ground water moving from under the uplands is to sink a well in each interdike compartment at the southwestern end of the uplands. The wells could be dug in the alluvium at the contact with

[33] Stearns, H. T., Supplement to the geology and ground-water resources of the island of Oahu, Hawaii: Hawaii Div. of Hydrog., Bull, 5, p. 10, 1940.

the basalt to save excavating in hard rock. The water would probably carry too much salt to be fit for human consumption. Drilled wells in the lava plain near the mouth of Apana Valley at the word "line" on plate 1 should develop stock water. The wells should be drilled no more than 5 to 10 feet below the water table, and care should be taken to avoid overpumpage.

PART 2

PETROGRAPHY OF NIIHAU

By Gordon A. Macdonald

PETROGRAPHY OF NIIHAU

By Gordon A. Macdonald

ABSTRACT

Among the lavas of the Paniau volcanic series, of Tertiary age, olivine basalts probably predominate but ordinary basalts are abundant. Picrite-basalt of the primitive type, containing abundant olivine phenocrysts, also occurs. Andesites are probably present but are rare. Most of the lavas of the Kiekie volcanic series, of Pleistocene age, are olivine basalt, but one is transitional between olivine basalt and picrite-basalt. In many of the Pleistocene lavas the late-crystallized augite is titanian. A single occurrence of melilite-nepheline basalt has been reported. Chemical analyses of five rocks are listed.

INTRODUCTION

Thirty-three specimens of the lavas and tuffs of Niihau, collected by H. T. Stearns, have been studied. The lavas and some of the tuffs have been examined in thin section; the rest of the tuffs have been examined in immersion liquids. The compositions of the feldspars have been determined from their refractive indices. The sizes of optic axial angles have been estimated from the appearance of optic axis and acute bisectrix interference figures.

PREVIOUS WORK

Niihau was visited briefly by Sidney Powers, who described the Tertiary lavas of the island as basalt, the flows ranging from 5 to 30 feet thick, generally nonporphyritic but some showing small olivine phenocrysts. The younger lavas on the western side of the island he recognized as olivine basalt. Several pieces of white pumice, drifted from some distant eruption, were noted.[1]

Specimens collected by Powers were studied by Washington and Keyes, and five of them were analyzed.[2] The analyses are listed on a later page. The lavas of Niihau are stated to be "basaltic, most of them labradorite basalt with very notable amounts of olivine. A few are andesine basalt, with comparatively small amounts of olivine, and one specimen is of a limburgitic basalt." No distinction was made of lavas belonging to the pre-erosional (Tertiary) and post-erosional (Pleis-

[1] Powers, Sidney, Notes on Hawaiian petrology: Am. Jour. Sci., 4th ser., vol. 50, pp. 257-259, 1920.

[2] Washington, H. S., and Keyes, M. G., Petrology of the Hawaiian Islands; V. The Leeward Islands: Am. Jour. Sci., 5th ser., vol. 12, pp. 337-340, 1926.

tocene) groups. No nepheline basalt was reported in the Powers collection.

Hinds spent 8 days on Niihau, and he clearly recognized the division of the igneous rocks into two groups, composing respectively the remnant of the original shield volcano and a later series of volcanics. The lavas of the island as a whole were stated to be olivine basalts, the dominant type containing large olivine phenocrysts and, in general, feldspar phenocrysts. Dikes of augite andesite are mentioned. One specimen of melilite-nepheline basalt also was reported.[3]

Three specimens of tuff from Lehua Island, and five specimens of tuff from Kaula Island (22 miles southwest of the southern end of Niihau) were studied in thin section and carefully described by Palmer.[4]

PANIAU VOLCANIC SERIES

General statement.—The volcanic rocks of the Paniau volcanic series, of Tertiary age, constitute the remnant of the original Niihau shield volcano. The flows are generally thin-bedded and moderately to highly vesicular. Both aa and pahoehoe varieties are represented. Olivine basalts and basalts (containing less than 5 percent olivine) appear to be nearly equally abundant. Picrite-basalts of the primitive type, containing numerous phenocrysts of olivine, are common but less numerous than the other two types. Of the 15 specimens of lava of the Paniau volcanic series collected by Stearns, 5 are olivine basalt, 7 are basalt, and 3 are picrite-basalt. According to Stearns (oral statement), rocks containing moderately abundant megascopic olivine phenocrysts are actually considerably more numerous in the field than those with few or no phenocrysts, and olivine basalt is therefore probably predominant over basalt in the structure of the shield. Innumerable dikes cut the lava flows in the rift zone of the volcano. They include the same rock types found among the flows.

All specimens of lava flows and dikes of the Paniau volcanic series were stained by Shand's method,[5] but none contain nepheline.

Olivine basalts.—Most of the specimens of olivine basalt contain moderately abundant phenocrysts of olivine, from 1 to 5 mm long. Two of the specimens contain a few phenocrysts of augite, up to 4 mm long, and one contains abundant tabular phenocrysts of plagioclase, up to 1 cm long. Only one specimen is nonporphyritic. The groundmass of the lavas is intergranular or intersertal.

[3] Hinds, N. E. A., The geology of Kauai and Niihau: B. P. Bishop Mus., Bull. 71, pp. 97-98, 1930; Melilite and nephelite basalt in Hawaii: Jour. Geology, vol. 33, p. 534-535, 1925.

[4] Palmer, H. S., Geology of Lehua and Kaula islands: B. P. Bishop Mus., Occasional Papers, vol. 12, no. 13, pp. 24-26, 1936.

[5] Shand, S. J., On the staining of feldspathoids, and on zonal structure in nepheline: Am. Mineralogist, vol. 24, pp. 508-510, 1939.

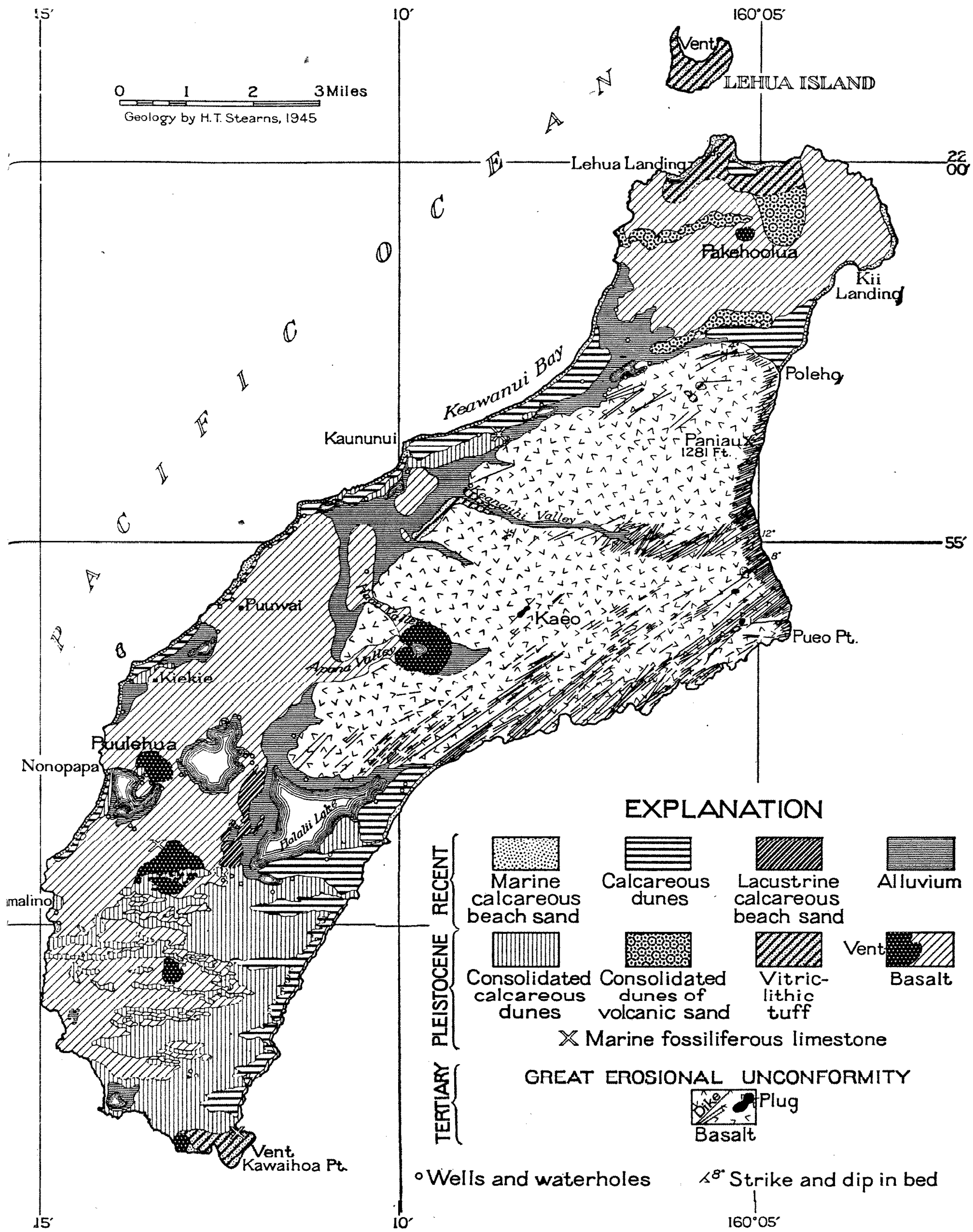

Figure 8. Geologic map of the island of Niihau (after H. T. Stearns, Hawaii Div. of Hydrography Bull. 8, fig. 24, 1946). The Pleistocene basalt flows and their vents comprise the Kiekie volcanic series; the Tertiary basalts form the Paniau volcanic series.

The olivine phenocrysts have a 2V close to 90°, corresponding to a forsterite content of about 85 percent. In some specimens they are partly resorbed, and in all they are partly altered to iddingsite. The augite phenocrysts have a +2V of about 55° to 60°. In one specimen they are glomerocrysts, formed of several small grains with varying orientation. The feldspar phenocrysts are sodic bytownite (β=1.569). All three types of phenocrysts grade in size through microphenocrysts into the groundmass.

The groundmass of the olivine basalts is composed principally of calcic to medium labradorite (Ab_{31-40}), monoclinic pyroxene, olivine, magnetite, ilmenite, and in some specimens a little interstitial glass. Minute acicular crystals of apatite are enclosed in the feldspar. The specimen containing feldspar phenocrysts has an abundant matrix of opaque black glass. In two of the specimens the groundmass pyroxene is pigeonite, in one it is pigeonitic augite (+2V=40°), in one (the nonporphyritic specimen) it is augite (+2V=55°), and in the last it is undeterminable. One specimen contains a small amount of interstitial calcic andesine, probably potassic, with a small positive optic angle.

In these rocks, and also in the basalts, groundmass olivine commonly is largely altered to iddingsite or material closely resembling it. Similar alteration has been noted in old lavas of other Hawaiian volcanoes, but not in new lavas. It appears to result from ordinary weathering. Some of the alteration of the phenocrysts is probably of similar origin. However, in one of the picrite-basalts of the Paniau volcanic series, and in many specimens from other islands, olivine phenocrysts partly altered to iddingsite are enclosed in thin envelopes of fresh olivine and the groundmass olivine is fresh, indicating that the alteration to iddingsite occurred before crystallization of the groundmass.

A chemical analysis of an olivine basalt of the Paniau volcanic series from Kalaalaau Valley is given in column 3 of the table on page 50.

Basalts.—Of the seven specimens of basalt three are nonporphyritic, one contains rare phenocrysts of olivine up to 1.5 mm long, one contains moderately abundant phenocrysts of plagioclase up to 4 mm long, one contains phenocrysts of both feldspar and olivine up to 1.5 mm long, and one contains a very few phenocrysts of olivine, feldspar, and augite up to 3 mm long. Olivine phenocrysts are rounded and embayed by resorption, and they are altered around the edges to iddingsite. Feldspar phenocrysts are zoned from bytownite (Ab_{20-27}) in the center to labradorite (Ab_{37-46}) on the outside. In one specimen the outermost rims are calcic andesine (Ab_{54}).

The texture of the nonporphyritic rocks, and the groundmass of the porphyritic rocks, is intersertal or intergranular. They are composed of plagioclase, monoclinic pyroxene, magnetite, and ilmenite. Some contain interstitial glass, others interstitial chloritic material probably derived from the alteration of glass. Minute acicular crystals of apatite are enclosed in the feldspar in some specimens. The feldspar is generally labradorite (Ab_{36-45}), but in one nonporphyritic rock it is sodic bytownite (Ab_{28}), and in one of the porphyritic rocks it ranges from Ab_{40} to Ab_{54}. In two of the rocks the groundmass pyroxene is augite ($+2V=40°-55°$), and in three it is pigeonite with $+2V$ near 0°. The variation appears to be continuous, but observations are insufficient in number to establish this with certainty. Olivine was found in all rocks but one. In none does it exceed 2 percent, however, and in one it was identified only in rare partly-resorbed phenocrysts. The basalts probably grade into the olivine basalts, but this cannot be demonstrated by means of the few specimens available.

PICRITE-BASALTS.—The picrite-basalts are of the primitive type, and they differ from the olivine basalts only in the abundance of olivine phenocrysts. Like the basalts, they probably grade into the olivine basalts, but the number of specimens is insufficient to prove the gradation. Olivine phenocrysts range in abundance from 35 to 60 percent and attain maximum lengths of 5 to 10 mm. They have a 2V close to 90°. Many of them are much rounded and embayed by magmatic resorption, and all are partly altered to iddingsite. In one specimen collected in the gulch that descends the sea cliff 1.1 miles northwest of Pueo Point, the iddingsite is enclosed in a thin rim of fresh olivine, deposited contemporaneously with the olivine of the groundmass. No phenocrysts other than olivine are present in the specimens of picrite-basalt.

The groundmass of the picrite-basalts is intergranular or intersertal. It consists of plagioclase (Ab_{25-30}), augite ($+2V=40°-55°$), olivine, magnetite, ilmenite, and pale brown interstitial glass. Feldspar forms 18 to 30 percent of the rock.

ANDESITE.—No andesites are present among the specimens collected by Stearns. However, dikes of augite andesite are reported by Hinds,[6] and one of the rocks analyzed by Washington and Keyes contians normative andesine (column 5, page 50), and is described by them as containing modal andesine-labradorite (Ab_{50}). The rock is doleritic and is classed by them as an andesine basalt.[7] Apparently andesites of decidedly basaltic aspect occur among the Paniau lavas, but they must be very rare.

KIEKIE VOLCANIC SERIES

GENERAL STATEMENT.—Volcanic rocks of the Kiekie volcanic series, of Pleistocene age, comprise a series of lava flows, small lava shields,

[6] Hinds, N. E. A., The geology of Kauai and Niihau: B. P. Bishop Mus., Bull. 71, p. 97, 1930.
[7] Washington, H. S., and Keyes, M. G., op. cit., p. 338.

tuff cones, and one mixed cinder and lava cone, all of which were erupted much later than the Tertiary lavas of the main Niihau shield volcano. The two periods of volcanic eruption were separated by a long interval of weathering and erosion, during which valleys were cut and a broad platform was truncated by wave action. The Pleistocene volcanics were erupted at vents situated both on the wave-cut platform along the western edge of the island and on the higher remnant of the original shield volcano. Some cones contain fragments of coralline limestone, showing that the lava was erupted through reef.

The Kiekie lavas are preponderantly olivine basalt. Only one cone and its accompanying lava flow consist of rock transitional from olivine basalt to picrite-basalt. In general, they are similar to the Tertiary Paniau lavas, but in many of them the last-crystallized pyroxene is titanian, and one contains a little aegirine-augite. Melilite-nepheline basalt has been reported from one locality, but its occurence has not been confirmed. All of the Kiekie lavas have been stained by Shand's method, but in none of them was any nepheline found.

Lavas.—All but one of the specimens of the Kiekie lavas are olivine basalt. Most of them are porphyritic, containing many phenocrysts of olivine. However, these do not exceed 1.5 mm in length, and they are generally less than 1 mm long. A few specimens are nonporphyritic. No other minerals have been found as phenocrysts. The olivine phenocrysts have a 2V close to 90°. Typically they are slightly rounded by resorption. In some rocks they are slightly altered around the edges to iddingsite, but in others they are entirely fresh, and in none are they altered to the extent that they are in many of the older Paniau lavas. The olivine of the groundmass generally is entirely unaltered.

The groundmass is intergranular or intersertal. It is typically coarser than in most Hawaiian lavas, most specimens having an average grain size of 0.1 to 0.2 mm and one an average grain size of 0.3 mm. The groundmass of the Kiekie lavas consists of feldspar, augite, olivine, iron ore, highly acicular small crystals of apatite and, in some specimens, interstitial glass. The glass is generally black and opaque, owing to the presence of abundant finely-divided iron ore. The iron ore includes both magnetite and ilmenite, but magnetite is the more abundant. The plagioclase is bytownite ($Ab_{18\text{-}26}$), and thus slightly more calcic than that in the groundmass of the Paniau lavas. In all specimens but one, the pyroxene is entirely augite ($+2V=40°-60°$, generally 55°-60°). The single exception is a specimen collected at an altitude of 250 feet in Haao Valley, 2.25 miles S. 88° E. of Puuwai Village. In it the pyroxene ranges from augite with an optic angle of about 55° to pigeonite with an optic angle near 0°. In many of the rocks the last-crystallized augite has a distinctly purplish color and is probably titanian. This also contrasts with the Paniau lavas, none of which contain titanian augite. In a few rocks the augite shows poorly-developed hour-glass zoning. The type of pyroxene in the lavas of the principal vents of the Kiekie volcanic series is shown in the table on page 49.

Chemical analysis of olivine basalts belonging to the Kiekie volcanic series are shown in columns 2 and 4 of the table on page 50.

A specimen of olivine basalt collected 0.6 mile S. 3° E. of Kaununui Point is unusual not only for its very coarse grain (averaging about 0.3 mm), but also for the presence of a little aegirine-augite. The rock is nonporphyritic, with poorly developed diktytaxitic structure, composed of bytownite (Ab_{23}), augite, olivine, magnetite, and ilmenite. The texture is intergranular, and locally diabasic. The augite is brown in thin section, with $+2V=55°$, and moderate dispersion. Many of the grains have borders of purplish titanian augite. The aegirine-augite crystallized very late, forming pale green rims on some of the augite grains and small acicular crystals surrounding and projecting into vesicles.

Puulehua, the small cone 0.8 miles S. 86° E. of Nonopapa, was the vent of a lava flow transitional in composition between olivine basalt and picrite-basalt. It is probably the same as the lava collected by Powers at Nonopapa Landing and analyzed by Keyes (column 1, page 50). The rock is a medium-gray, sparingly vesicular aa. It contains many olivine phenocrysts up to 1.5 mm long, with 2V close to 90°, slightly resorbed, and altered around the edges to iddingsite. The groundmass consists of subhedral grains of bytownite (Ab_{25}), colorless augite ($-2V=50°$), olivine, and iron ore, in a matrix of anhedral bytownite. The average grain size is about 0.04 mm. The approximate mineral composition is: feldspar 30%, augite 50%, olivine 15%, iron ore 5%. The vent is one of five which lie along a fissure trending slightly west of north. The lava differs from those of the vents to the north and south principally in the greater abundance of mafic minerals, but also in the absence of titanian augite.

Melilite-nepheline basalt described by Hinds was said to come from a flow interbedded with the lavas of the Niihau shield volcano (Paniau volcanic series), at a point about 0.75 miles above the mouth of Keanauhi Canyon.[8] This was the only specimen of nepheline basalt in Hinds' collection, and none has been found by other workers. Keanauhi Valley was traversed by Stearns, who was watching for rocks resembling the nepheline basalts of Kauai and Oahu, but he found no such rock. As a result of field experience on the other Hawaiian Islands

[8] Hinds, N. E. A., Melilite and nephelite basalt in Hawaii: Jour. Geology, vol. 33, p. 534, 1925.

the nepheline basalts can be recognized in hand specimen with a considerable degree of accuracy. On both Kauai and Oahu it is known that the nepheline basalts (and melilite-nepheline basalts) never occur among the lavas constituting the main lava shields, but are restricted to flows erupted after a long period of erosion. It is therefore unlikely that melilite-nepheline basalt occurs among the Paniau lavas of Niihau. If it is present in Keanauhi Valley it probably represents an unrecognized post-erosional flow belonging to the Kiekie volcanic series.

TUFFS.—Lehua Island, just north of Niihau, and Kawaihoa Point, at the southern end of Niihau, are remnants of tuff cones built by submarine explosions. Kaula Island, 22 miles southwest of Kawaihoa Point (fig. 3), is of similar origin. Much tuff from the Lehua explosions occurs on the northern end of Niihau. Samples of this tuff and magmatic lapilli contained in it were collected by Stearns, as well as several samples of similar material from Kawaihoa cone. The tuffs of Lehua and Kaula islands have been described by Palmer.[9]

The tuffs are gray or brownish-gray when fresh, weathering to reddish or yellowish-brown. They consist largely of grains less than 1 mm in diameter, with less abundant grains up to 5 mm long, generally concentrated in thin beds, and a few larger essential lapilli. Accessory blocks of older lava and accidental blocks of limestone also occur. Examination under the microscope reveals the principal constituent of the tuff to be pale greenish-brown glass. The larger grains are generally altered around the edges, and the smaller ones throughout, to yellow or orange palagonite. A few grains of olivine and a very few of augite are recognizable. Secondary calcite is abundant.

The small magmatic lapilli are largely glass, but in the larger ones glass is subordinate to mineral grains. They are olivine basalt. A lapillus 3 cm long, in the tuff of the Lehua Island explosions on the northern end of Niihau, is dark gray to black and nonporphyritic in hand specimen. In thin section it is found to contain microphenocrysts of olivine and augite up to 0.7 mm long, in an intersertal groundmass. The olivine phenocrysts have an optic angle close to 90° and are altered around the edges to iddingsite. The augite is nearly colorless, with $+2V=60°$ and moderate dispersion. The groundmass consists of bytownite (Ab_{21}), augite, olivine partly altered to iddingsite, and iron ore, in an abundant matrix of black opaque glass. Some of the augite grains have purplish titanian borders.

Many essential lapilli and small bombs occur in Kawaihoa cone. One is brownish-gray, with many phenocrysts of olivine up to 2 mm long. The vesicles are filled with calcite and a zeolite, probably heuland-

[9] Palmer, H. S., op. cit., pp. 24-26.

ite. The olivine phenocrysts have an optic angle close to 90° and are rounded and embayed by resorption. Some are slightly stained brownish green around the edges, but they are otherwise unaltered. The groundmass is intersertal, composed of bytownite, monoclinic pyroxene, some of which is slightly purplish, olivine, iron ore, and glass.

In Lehua Island, Palmer reports accessory blocks of nonporphyritic basalt and porphyritic basalt with feldspar phenocrysts,[10] probably derived from underlying Paniau lavas. On Kaula Island he reports accessory blocks of nonporphyritic basalt, and porphyritic basalt containing phenocrysts of olivine, as well as many fragments of dunite. One block was reported to contain red garnets and another biotite. Kawaihoa cone contains accessory blocks of olivine basalt closely resembling the lavas of the Kaumuhonu shield, which lie just to the west and probably underlie the Kawaihoa cone. The rock has many small olivine phenocrysts, and the late augite of the groundmass is purplish. The vesicles are filled with calcite and a zeolite having low birefringence,

Table showing type of lava at principal vents of the Kiekie volcanic series

Vent			Type of lava	Color of late groundmass pyroxene
Name	Type of cone	Location		
Lehua Island	Tuff cone	North of Niihau	Olivine basalt, nonporphyritic	Purplish
Pakehoolua	Lava shield	North end of Niihau	Olivine basalt, porphyritic	Colorless
Reservoir	Lava shield	Apana Valley	Olivine basalt, nonporphyritic	Purplish
Unnamed	Lava shield	0.5 mile north of Puulehua	Olivine basalt, porphyritic	Purplish
Puulehua	Lava shield	Western part of island	Transitional from olivine basalt to picrite-basalt	Colorless
Kawaewae	Cinder and lava cone	Do.	Olivine basalt, porphyritic	Purplish
Mauuloa	Lava shield	Do.	Do.	Colorless
Kaumuhonu	Lava shield	South end of island west of Kaumuhonu Bay	Do.	Purplish
Kawaihoa	Tuff cone	South end of island	Do.	Purplish

$+2V=55° \pm$, and $\beta=1.486$, probably heulandite. All three tuff cones contain accidental blocks of coralline limestone, indicating that the vents were blasted through coral reef.

[10] Palmer, H. S., op. cit., p. 28.

CHEMICAL ANALYSES

The accompanying table contains all the chemical analyses of rocks of Niihau known to the writer. All five analyses are quoted from the paper by Washington and Keyes.[11]

Chemical analyses of lavas of Niihau

	1	2	3	4	5
SiO_2	43.46	46.36	46.44	46.86	49.73
Al_2O_3	15.34	14.77	16.21	14.78	14.56
Fe_2O_3	1.46	2.13	1.98	1.78	3.60
FeO	8.17	8.82	7.85	9.85	8.55
MgO	12.60	12.42	9.45	9.93	6.89
CaO	11.39	10.84	11.21	10.98	9.66
Na_2O	2.61	2.16	2.52	2.88	2.25
K_2O	0.69	0.53	0.48	0.40	0.62
H_2O+	0.59	0.57	0.54	0.13	1.24
H_2O-	0.47	0.12	0.10	0.16	0.71
TiO_2	2.21	1.31	2.11	1.67	2.21
ZrO_2	n.d.	n.d.	none	n.d.	n.d.
P_2O_5	0.48	0.19	0.21	0.20	0.22
S	n.d.	n.d.	0.11	n.d.	n.d.
Cr_2O_3	n.d.	n.d.	0.07	n.d.	n.d.
MnO	0.16	0.14	0.21	0.15	0.11
BaO	n.d.	n.d.	none	n.d.	n.d.
Total	99.63	100.36	99.49	99.77	100.35
Norms					
or	3.89	2.34	2.78	2.22	3.34
ab	5.76	14.15	20.96	19.39	27.77
an	28.08	28.91	31.69	26.13	23.35
ne	8.80	2.27	....	2.84	....
di	22.92	19.43	17.67	22.34	18.24
hy	....	....	....	....	14.22
ol	22.23	24.63	17.93	20.38	2.36
mt	2.09	3.02	2.78	2.55	5.34
il	4.26	2.43	3.95	3.19	4.28
ap	1.01	0.34	0.67	0.34	0.67

1. Olivine basalt, transitional to picrite-basalt; Kiekie volcanic series. Nonopapa Landing; M. G. Keyes, analyst.
2. Olivine Basalt; Kiekie volcanic series. "Nonopapa cone" (probably the broad hill crossed by the road 1 mile northeast of Nonopapa); H. S. Washington, analyst.
3. Olivine basalt; Paniau volcanic series. Kalaalaau Valley; M. G. Keyes, analyst.
4. Olivine basalt; Kiekie volcanic series. "Puuwai cone" (probably the hill 1.25 miles northeast of Puuwai Village); M. G. Keyes, analyst.
5. Basaltic andesite; Paniau volcanic series. Keanauhi Valley; M. G. Keyes, analyst.

[11] Op. cit., pp. 339-340.

With the exception of analysis 1, all resemble rather closely analyses of rocks from other Hawaiian volcanoes. Analysis 1 in most respects appears intermediate between those of olivine basalt and an analysis of picrite-basalt from near Lihue, on Kauai.[12]

[12] Washington, H. S., and Keyes, M. G., op. cit., page 344, analysis 5.

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