GEOLOGY AND GROUND WATER RESOURCES OF THE NUUANU - PAUOA DISTRICT

BY

CHESTER K. WENTWORTH

BOARD OF WATER SUPPLY

HONOLULU - 1941

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OF THE

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Honolulu, Hawaii
1941

TABLE OF CONTENTS

TABLE OF ILLUSTRATIONS

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Figure | Following page

Figure Following page

Figure | Following page

Figure Following page

INTRODUCTION

Location and extent

The Koolau Range forms the eastern and larger half of the island of Oahu. Honolulu is situated on the coastal plain and on spurs and in valleys of the leeward slope of the southeastern end of the Koolau Range. The Honolulu watershed, of which the Nuuanu-Pauoa district is a part, consists of about 10 miles of the leeward slope of the Koolau Range, inland from the Honolulu portion of the coast. The chief valleys in this part of the dissected leeward flank of the range, from west to east, are: Moanalua, Kalihi, Nuuanu, Pauoa, Makiki, Manoa, Palolo and Waialae. In addition to these valleys, of which all but Pauoa and Makiki head at the crest of the range, there are several other smaller valleys which do not reach the crest of the range and which dissect the triangular areas between the principal valleys listed. Details of the size and shape of these valleys have been given elsewhere (1). For the purposes of the present survey of geology

(1) Geology and Ground-Water Resources of the Kalihi District, Table p. 2, 1941.

and ground-water resources, the Honolulu watershed has been divided into five districts, as shown in Figure 1. Reports on three of these districts have been completed (2); the present is the fourth.

(2) Wentworth, C. K., The Geology and Ground-Water Resources of the Palolo-Waialae District, 1938.
______ The Geology and Ground-Water Resources of the Manoa-Makiki District, 1940.
______ The Geology and Ground-Water Resources of the Kalihi District, 1941.

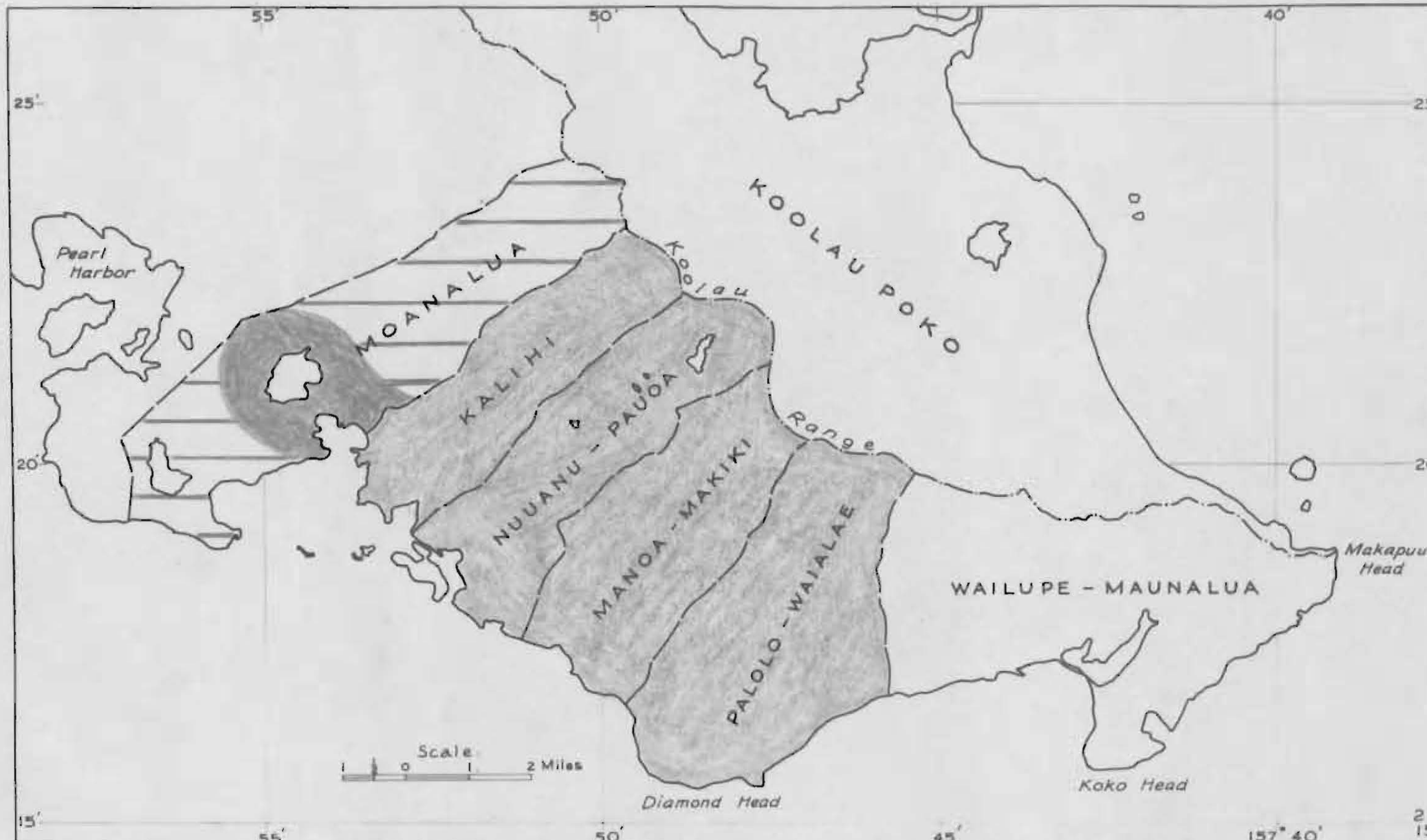

Figure 1 - Outline map showing geologic survey districts of the Honolulu watershed. The geologic survey has been completed for the area shown in blue. The red shows areas in which the geologic survey has been practically completed in the field, and the red cross-hatched pattern indicates areas where detailed field traversing has not been completed.

The Nuuanu-Pauoa district, covered in this report, includes the entire leeward slope, from the crest of the Koolau Range to the sea coast, between the northwestern boundary divide of Nuuanu Valley and the northwestern boundary of the Manoa and Makiki drainage basins. It is a nearly rectangular area about 6.5 miles long and averaging slightly over 1.5 miles wide. The total area is 10.78 square miles. Punchbowl and the area seaward from it are included somewhat arbitrarily in this district. Commencing from the seacoast, the boundary of the district follows the line of Pensacola Street and thence the line of Kanaha Stream and its small western branch to the Punchbowl saddle, thence inland along the crest of the Tantalus spur to and around the western rim of Tantalus bowl, thence across the divide at the head of Pauoa Valley to the crest of the east wall of Nuuanu and thence along this divide to Konahuanui peaks at 3105 and 3150 feet on the Koolau Crest. From Konahuanui, the boundary follows the Koolau crest across the Nuuanu pali saddle to the peak of Lanihuli at 2715 feet and thence seaward along the western divide ridge of Nuuanu past Moole and Waolani branches, continuing along the eastern edge of the Kapalama flow-slope facet and thence along the lower channel of Niuhelewai Stream to the coast and along the coast to the point of beginning. (Figure 13)

Purpose, scope and methods of study

The methods used in this study have been the same as those described in earlier reports in this series. In the earlier part of the Nuuanu work, done before ropes were used, chief attention was given to the floor of the valley, especially because diamond drilling was then in progress. A preliminary report on Nuuanu Valley was prepared, and attention was transferred elsewhere. Meantime, extensive use has been made of the method of the doubled rope, and the chief need in returning to Nuuanu has been to apply this method in traversing the higher mountain sections and the steeper valley walls. No new diamond drilling has been done in Nuuanu since 1934, except several holes in and near Dam No. 4; but it is expected that prior to the commencement of major underground operations in Nuuanu, some additional diamond drilling will be required, as outlined in a subsequent section of this report.

History and acknowledgements

The history of geologic studies on the Koolau Range and the Honolulu water problem have been briefly outlined in an earlier report of this series, and in a report which is now in process of revision by the writer and Horace Winchell. When the writer commenced the detailed geologic survey of the Honolulu watershed in 1934, much of his attention during the first year was given to studies of the geology of the valley bottom of Nuuanu and to study of drill cores made available through diamond drilling. It was not until later, however, in connection with study of the Palolo-Waialae district, that methods were developed which permitted adequate study of the more rugged and precipitous, interior mountain area and hence the mountainous part of the Nuuanu district has only recently been adequately examined.

A few traverses were made in upper Nuuanu by Horace Winchell, and the remainder of the work has been done by the writer with trail and rope assistance chiefly by Wah Kau Kong and to a lesser extent by Rijo Hori. Laboratory work and drafting have been done chiefly by Rijo Hori. During the summer of 1940, a series of Monday conferences was devoted to the problems of geology and ground water, and in January, 1941, the problem of bottom storage was discussed in detail at several Monday meetings of department heads and engineers. These meetings have afforded an increasingly helpful interchange of views, and the questions, comments, and constructive criticism voiced by various associates of the Board of Water Supply have been particularly useful and stimulating in developing various parts of this and other reports. The writer is grateful to his associates, as well as to numerous municipal, territorial and federal officials and to many private individuals for information, suggestions, and courtesies offered in furtherance of the work of this department.

GEOGRAPHY

Geomorphic divisions

The Nuuanu-Pauoa district is chiefly a part of the Koolau Range geomorphic province of the island of Oahu, with adjacent parts of the province known as Leeward Craters, Honolulu Section. (See Figure 2 and the table below) In the following table are listed the divisions into which the island has been divided on the basis of (1) its geologic STRUCTURE; (2) the PROCESSES by which its surface has been modified, such as weathering, stream action, attack of waves, etc.; and (3) the STAGE, or degree, of completion which has been attained in its modification by these processes in doing their characteristic work (1).

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(1) Wentworth, C. K., First Progress Report, Hawaii Territorial Planning Board, pp. 18-19, 1939.

Geomorphic Divisions of Oahu

Mountains		
1	Waianae Range	
2	Koolau Range	
Plateaus and Highlands		
3	Schofield Plateau	
4	Windward Highlands	
Mixed Lowlands		
5	Waianae Valleys	
6	Leeward Craters	(Honolulu Section)
7	Leeward Craters	(Koko Section)
8	Windward Craters	(Mokapu Section)
9	" "	(Manana Section)
Coastal Plains		
10	Ewa Plain	
11	Waialua Plain	
12	Kahuku Plain	

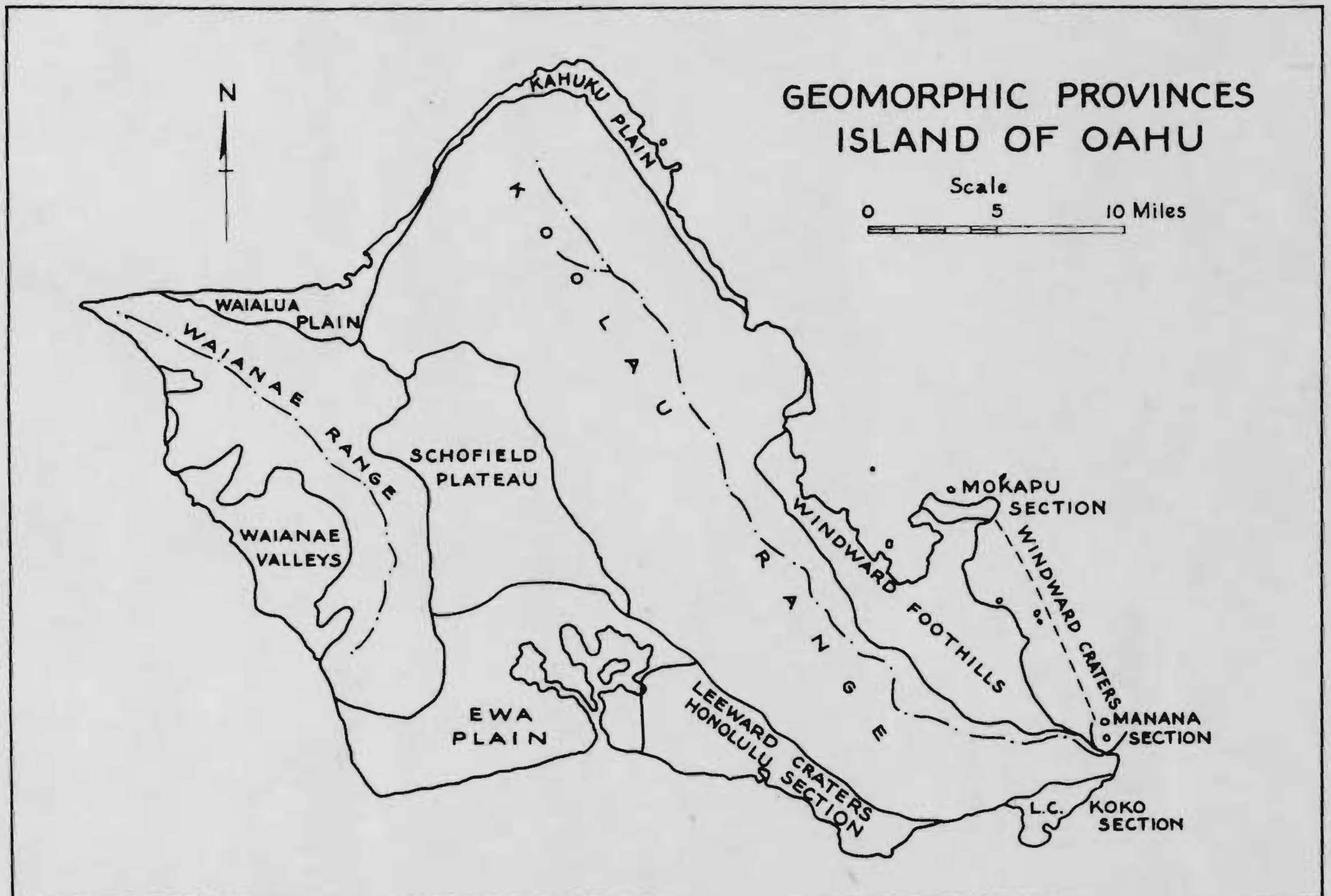

Figure 2 - Index map showing chief geomorphic provinces of the Island of Oahu. Included in each province is an area in which a similar general type of topography is found and in which a somewhat uniform development of land forms has prevailed during geologic time.

Topography and drainage

GENERAL

The Koolau lava dome was originally some 50 miles long and 20 miles wide at the level of the present ocean, with its long axis trending northwest-southeast (1). The highest part of the dome was

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(1) Wentworth, C. K., and Winchell, H., The Koolau Basalt Series, Oahu, Bull. Geol. Soc. Amer., (Abstract Vol. 51, No. 12, Part 2, p. 1953, 1940) (Manuscript in process of preparation)

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probably somewhat northeast of Konahuanui and may have reached 3500 or 4000 feet, but the crest for at least 20 miles was nearly as high, and it is not wholly clear that a well-marked central vent ever existed, the greater part of the lava flows having come from fissure openings along the dike complex which will be described below. The supposed original shape of the dome is shown in Figure 3 of the earlier Kalihi report, of this series.

The present Koolau Range can be divided naturally into three sections, the Koolaupoko windward section, the Koolauloa windward section, and the leeward section. (Figures 4, 5, and 6) The Koolaupoko section is that part of the windward slope lying southeast of Waikane which is marked by a conspicuous fluted cliff or pali cut well back to the crest of the range and which is flanked by a few eroded remnants of the lava flow dome surrounded by fans of weathered sediments. It is believed that in this section the erosion of the dome by streams and perhaps by the sea was aided by normal faulting in which large segments of the dome slipped below sea level.

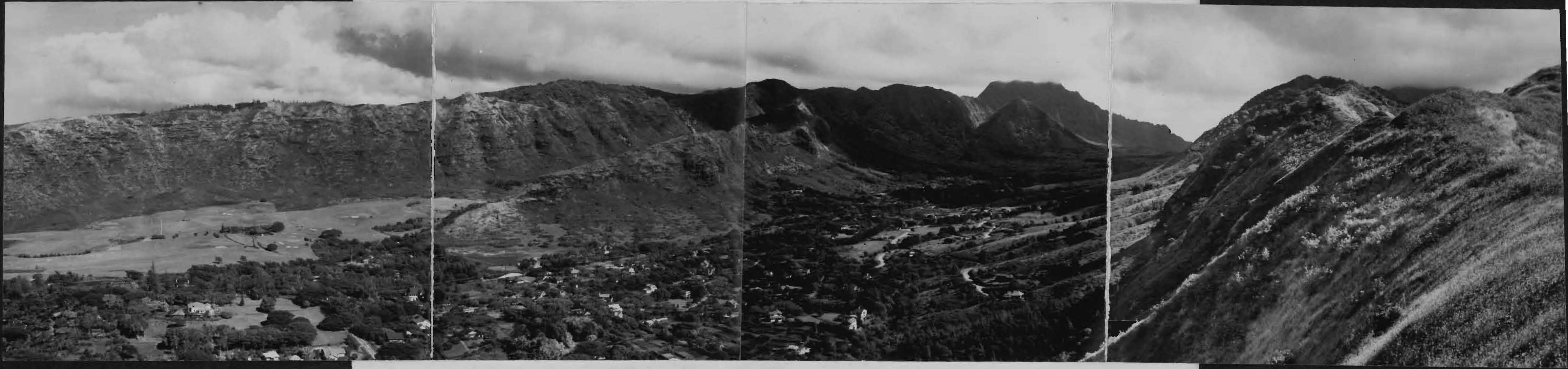

Figure 3 - Panorama of west wall and head portion of Nuuanu Valley from Pacific Heights spur at about 770 feet. At the left is the lower west wall, the Oahu Country Club golf course, Waolani Valley and sliver ridge. Near the center is the valley of Moole Stream and Moole sliver ridge, with the flat-crested peak of Lanihuli behind it. In the right center foreground is Dowsett Highlands and to the right the flanks and ridge of the Pacific Heights spur. (Negatives Nos. 12273-4-5-6)

Figure 4 - View inland from foot of west wall of Nuuanu Valley looking across the golf course of the Oahu Country Club. At the left is the west wall of the valley and in the center is the Waolani sliver ridge which separates the inland portion of the golf course from the main valley. The peak of Konahuanui is in clouds and a small part of the head profile of the valley is visible. Negative No. 21156

Figure 5 - View of head of Nuuanu Valley, Nuuanu Pali gap, and parts of the Kaneohe area. In the distant center is Pyramid Rock, and to the right is the tip of Ulupau Head, both parts of Mokapu Peninsula. Lanihuli is off the picture to the left and Konahuanui likewise to the right. Taken from elevation about 1950 feet, on east wall of Nuuanu, seaward from Old Faithful fall.
(Negative No. 21106)

Figure 6 - View of Nuuanu pali gap and windward topography of Kaneohe and northward in the distance. Taken from elevation about 1600 feet on east wall near head of valley. (Negative No. 21096)

The Koolauloa section lies northwest of Waikane and is a normally dissected sector with stretches of pali near the shore but with long interstream ridges preserving at their moderately accordant crests an indication of the original windward slope of the dome. The leeward slope of the range is maturely dissected by about fifty radial streams, mostly in deep valleys with few major tributaries. A more detailed description of the Koolau Range is to be presented elsewhere (1)

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(1) Wentworth, C. K., and Winchell, H., Op. Cit.,

NUUANU VALLEY

Nuuanu and Pauoa Valleys constitute a single drainage basin, since Pauoa channel joins the Nuuanu channel on the coastal plain. Waolani Stream forms a branch of nearly equal length on the west side but lies in a separate valley only in its head portion. Farther inland, there are several small branches to Nuuanu channel on the west side and one, Lulumahu, on the east. From the approximate line of Judd Street inland to the pali gap, a distance of about 4½ miles, Nuuanu Valley is a flat, or convex-bottomed trough, ranging from 1 to 1½ miles in width from divide to divide. Near the head, where its bottom is still nearly flat at about 1100 feet, the floor is overlooked by peaks and knife-edge ridges rising 1200 to 2000 feet above it. Seaward, the depth of the valley below the adjacent ridges declines nearly uniformly to only one or two hundred feet near Judd Street. Erosion by the branches Waolani, Moole, and Lulumahu, with courses nearly parallel to the main valley, has isolated parts of the upland to form characteristic "sliver ridges". (Figures 3 and 4)

At one time, when sea level was more than 1000 feet lower than at present, Nuuanu Valley was at least 900 feet deeper than now at the line of School Street, 400 feet deeper than now in the Reservoir No. 3 section and probably about 200 feet deeper near Dam No. 4. The longitudinal profile of its bottom must then have been concave, with a much steeper grade near the head of the valley, as is most common for valleys everywhere. At present, Nuuanu Valley bottom is extraordinary in having, from its head to the coastal plain, a nearly uniform longitudinal grade of almost exactly 200 feet to the mile, a condition of great practical advantage in road construction of the "pali" highway to Koolaupoko. This is due to the filling of the bottom of the valley by late lava flows of the Honolulu series, which will be described more fully in a later section of this report. Another peculiarity of the form of Nuuanu Valley is that its bottom is convex, or "high in the middle", in its cross-profile through much of its length. This, likewise, is due to the lava-flow filling which has forced the main stream, and drainage from the side walls, to flow on one side or the other, at the base of the steep walls or of flanking fans of detritus, as in the Dowsett Highlands section.

Filling by lava flows, invasion from the sides by growing fans, and local cutting by streams in the courses they have been forced to take, have produced during some hundreds of thousands of years the distinctive drainage pattern of the valley bottom. The transverse profiles of Nuuanu Valley, excepting the convex bottom, are similar to those of other major valleys. In the seaward portion, near the margin of the range, where the valley is bounded by flat, sloping facets such as Kapalama, the level profile of the facet is somewhat rounded by erosion and slumping for 100 or 200 feet horizontally, on approaching the valley wall. Then at possibly 50 feet below that level commences the nearly uniform slope of 45 to 60 degrees which reaches down the wall to the upper edge of the taluvial fans or to spur buttresses whose shape has been controlled by the flanking fans. These fans show a concave slope, commencing at 35 to 40 degrees and flattening to 20 or even 15 degrees, depending on how far out into the valley they run. The fans either merge and overlap at the axis of the valley or border on the lava fill of the valley, if such exists and is sufficiently convex to dominate the present surface.

Following the valley walls farther inland, they approach another type which is found in all the larger valleys near their heads. In this section, the present lateral profile of the valley commences at the top with a narrow ridge whose crest is a few feet wide and with slopes of 50 to 70 degrees. These slopes are either heads or short sections of the sides of small, alcove-shaped valleys whose bottoms slope at 45 to 60 degrees. This system of small perched valleys forms a fringe of topography which is extremely rugged, yet traversable with much labor by ordinary climbing and in contrast with the nearly continuous wall above which it hangs. (Figures 5, 6, 7, and 8) The wall section ordinarily commences several hundred feet below the drainage divide and extends downward at a slope of 60 to 80 degrees, with local patches of 85-degree slope for several hundred feet. In some places the upper part of the wall, often cut by the parabolic

Figure 7 - West wall of Nuuanu showing patch of "wall" topography with niches and alcove, or hanging topography above. These niches are the site of the "Upside down falls", so called because of the common blowing upward from them of a wisp of water. A fair share of the time these falls are dry, at other times too much water comes over to be effectively reversed by wind. Good performance is commonest in the freshening wind of clearing weather just after a period of concentrated rainfall. The over all declivity of this wall is about 80 degrees, with some parts reaching about 84 degrees. (Negative No. 12056)

Figure 8 - View of head of Nuuanu Valley from point near top of east wall above Luakaha. At the right are the east wall, boundary ridge, Lulumahu Valley, and Konahuanui in clouds. On the left Lanihuli is in the clouds. Reservoir No. 4 is in the center, with the large borrow pit on the right and the main highway marked by the row of trees on the left. (Negatives No. 12121-23)

notches formed by the alcoves of the hanging topography, extends nearly straight with no break for some thousands of feet. The lower part often alternates between those sections where the steep wall is cut down to the heads of small lower valleys and the intervening section where talus fans flank the wall or where there are buttresses of bedrock of the same form and shape. Occasionally these buttresses extend at the apex quite to the top of the wall section and merge with the hanging topography above, offering nearly the only feasible trail routes.

In other instances, the wall section is more or less deeply fluted. Here the axes of the furrows and those of the ribs may have the same slope, up to 70 or 80 degrees, and the grooves are cut one or several hundred feet horizontally back from the line of the ribs. The significance of this wall in relation to geomorphic processes appears to be that it is a section whose slope is stable with active undercutting and with coherence of the rock as the controlling factor. Except for narrow strips in protected spots, it is a zone without soil, and usually with a limited amount of forest cover though not necessarily devoid of plants. On the other hand, the hanging, alcove topography is in general soil-covered, and the angles of its slopes are determined by the capacity of the soil to cling to the surface. Often the soil cover is only a few inches thick, and soil avalanches are common. These evidently represent a perfectly natural method of slope maintenance. The repeated baring of slopes by soil avalanches and the opportunity these bared spots afford for the invasion of accidentally introduced plants is a process whose importance has probably not been fully recognized.

While it is not denied that grazing animals, pigs in the mountains, trail cutting, and increased runoff through forest destruction, have all contributed to the spread of objectionable plants, it is here emphasized that soil avalanches have always been common, have in large measure determined the angle of slopes and narrowness of ridge crests, and are probably still the most important element in the spread of certain plants.

Below the wall section, as has been said, the sides of major valleys consist of talus and alluvial slopes, the upper edge of which forms a serrated flank against the wall and the lower part of which merges into a more continuous lateral slope extending to the center of the valley. (Figure 9) In Nuuanu, the lower edge of these fans in many sections abuts against the rising mass of the convex lava fill of the valley bottom proper.

PAUOA VALLEY

Pauoa Valley is a much smaller valley than Nuuanu, and its head probably never reached the Koolau crest, the head branches of Nuuanu and Manoa having a common divide for about a mile leeward from Konahuanui. (Figure 10) Pauoa Valley also, at the time when sea level was 1000 feet lower, was a small lateral valley entering the main Nuuanu Valley from the east and with its bottom probably hanging at least 600 feet above the bottom of the main valley, being in this respect like Lulumahu and Moole Valleys. Pauoa Valley was deeply filled by cinders and basalt from the Tantalus eruption, and the lava flow forms part of the fill of its bottom out to the coastal plain and

Figure 9 - View of east wall of Nuuanu Valley inland from Dowsett Highlands. The immediate foreground is a private lawn on late Nuuanu basalt. The main channel of Nuuanu Stream runs between this immediate foreground and the taluvial spurs on which the Norfolk Island pines are planted. The dark cliffs at the upper left are outcrops of Koolau basalt. The spur in the middle shows accordance of slope between an upper surface cut on Koolau rock and the slope of the taluvial fan lower down. It is probable that at an earlier and more markedly aggradational period the taluvial fan extended higher. Negative No. 21154

Figure 10 - East wall and floor of Pauoa Valley from Pacific Heights ridge. On the floor of the valley is commercial vegetable gardening, and the various scars on the east wall are pits from which Tantalus cinders has been or is being removed for fill or top soil use. The cinder formation has slumped off most of the upper half of the wall, in which Koolau lava flows are exposed. (Negatives No. 21081-2-3)

beyond. In the lower mountain section Pauoa Valley has a normal cross-profile, but in the section opposite Tantalus cone, the steep-fronted fill of cinders clogs the valley to a depth of 200 feet or more and has the form of a small mountain galcier.

The present head of Pauoa Valley is nearly opposite Tantalus cone where the fill was perhaps most complete. That section of the former Pauoa Valley which is known as Pauoa Flats now drains to the Aihualama branch of Manoa Stream. This stream is slowly cutting headward into the volcanic fill which formed the flats. It is quite evident that the draining of Pauoa Flats into Manoa was started by the placement of the fill from Tantalus and that extension of the course of Aihualama over the Koolau ridge between Pauoa and Manoa was accomplished primarily by superposition rather than by headward cutting.

DRAINAGE PATTERN

The drainage pattern of the Nuuanu-Pauoa district has in part been mentioned above. Nuuanu Stream heads near the pali gap, with several branches flowing from the east side and a smaller number from the west above Reservoir No. 4. (Figure 13) The head of the valley, to the line of the dam, is practically unaffected by the volcanic fill. From this point seaward, Nuuanu Stream flows along or very close to the southeastern margin of the exposed convex volcanic fill, occupying the bottom of a gorge which is variously 30 to 80 feet below the adjacent crown of the convex valley bottom. Lulumahu is a parallel tributary which flows about a mile seaward from Konahuanui and falls nearly 2000 feet before it emerges from behind a well-marked sliver ridge. (Figures 11 and 12) The stream formerly joined the main Nuuanu channel a short distance below the position of Dam No. 4, but it has been diverted so as to enter the reservoir above the dam. On the east side, no other long tributary enters, all the others are simply short rills down the valley wall.

On the west side a series of tributaries is successively diverted down the valley by the volcanic fill. Makuku Stream (1)

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(1) Names of streams are in accordance with an approval of names by the Geographic Names Committee of the U. S. Dept. of Interior, as recommended by the local Hawaiian Advisory Committee and reported in a letter to Governor Poindexter dated February 20, 1935.

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rises on the west wall opposite the upper end of Reservoir No. 4 and flows past the west base of Makuku cone and down the western side of the volcanic fill to Reservoirs No. 3 and No. 2 and thence by No. 2 spillway across the valley to Nuuanu channel. This stream formerly reached the main channel via the gulch which passes through the goose-neck in the main road. Just inland from Reservoir No. 2, this stream is joined by Moole Stream which rises on the leeward slope of the peak, Lanihuli, and passes for about a mile and a fall of 1500 feet behind a sliver ridge comparable to that which separates Lulumahu from the main valley on the east side. The valley of Moole Stream has long been known locally as Hillebrand Glen (after Dr. William Hillebrand, long-time resident and authority on Hawaiian Botany). Almost immediately seaward of the point where the combined Moole and Makuku Streams break across the volcanic fill to reach the Nuuanu channel, the Niniko

Figure 11 - View up west wall of Nuuanu Valley. In the left foreground is the Waolani sliver ridge, and in the center below the flat-crested peak of Lanihuli is the Moole sliver ridge. View taken from point on the Waolani ridge. (Negative No. 12111)

Figure 12 - View seaward from top of main fall in Lulumahu Valley at about 1500 feet. The narrower part of the valley is about 800 feet deep, and its bottom lies over 1200 feet below the crests of adjacent ridges.
(Negative No. 12356)

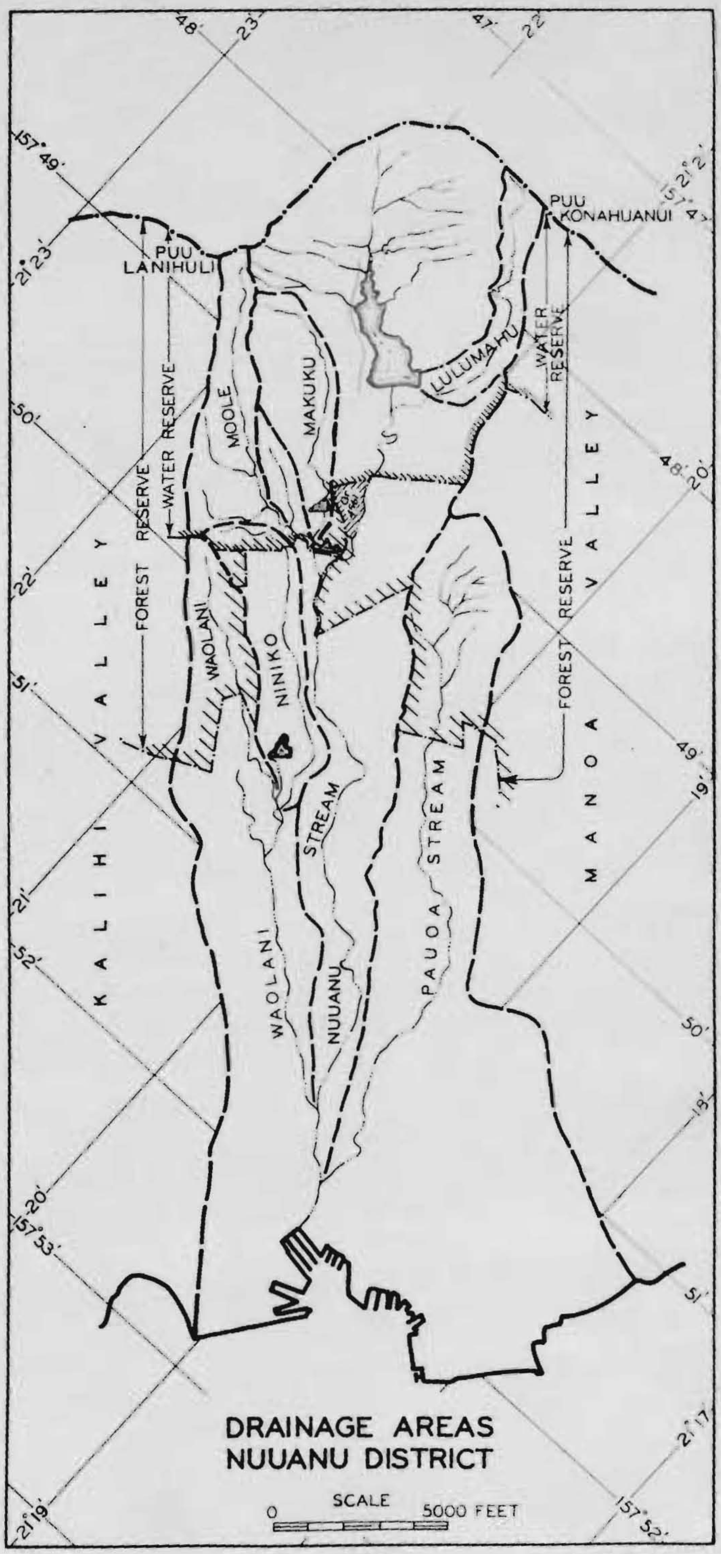

Figure 13 - Map showing drainage basins of Nuuanu and Pauoa Streams and their branches and the position of the Forest and Water Reserve boundaries. The small cross-hatched area east of Reservoir No. 3 is Grant No. 4561 held by heirs of the Cooke family.

Stream heads on the west wall and after reaching the west margin of the volcanic fill, flows down that margin to join Waolani Stream below the end of the Waolani sliver ridge. (Figure 11) The trunk of Waolani Stream follows approximately the west margin of the fill to a point just inland from School Street where it joins the Nuuanu channel. Just inland from Beretania Street the Pauoa channel enters from the east (1).

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(1) The above-described natural arrangement and connections of some of these stream courses has been changed by construction of box drains and paved channels for flood control purposes.

Pauoa Stream rises in a series of small branches palmately arranged on the western slope of Tantalus and flows down a simple and nearly straight course, which in an upper section is on the volcanic fill and which lower down falls off the western edge of the uppermost Tantalus lava flow in a picturesque water fall visible from parts of Pacific Heights. This flow floors Pauoa Valley, and still lower down, the stream crosses over to flow for some distance near the eastern edge of the filled valley bottom and thence close around part of the base of Punchbowl cone.

The boundary ridges east and west of Pauoa are comparatively narrow. The various branches of Makiki Stream have dissected the facet which lies to the east of Pauoa so that the boundary ridge is narrow nearly all the way from Punchbowl inland to the bowl of Tantalus with its three peaks. The Pacific Heights facet is of limited area and is somewhat dissected, so as to lose the more typical facet character which is so marked for Kapahulu and others. The apex of

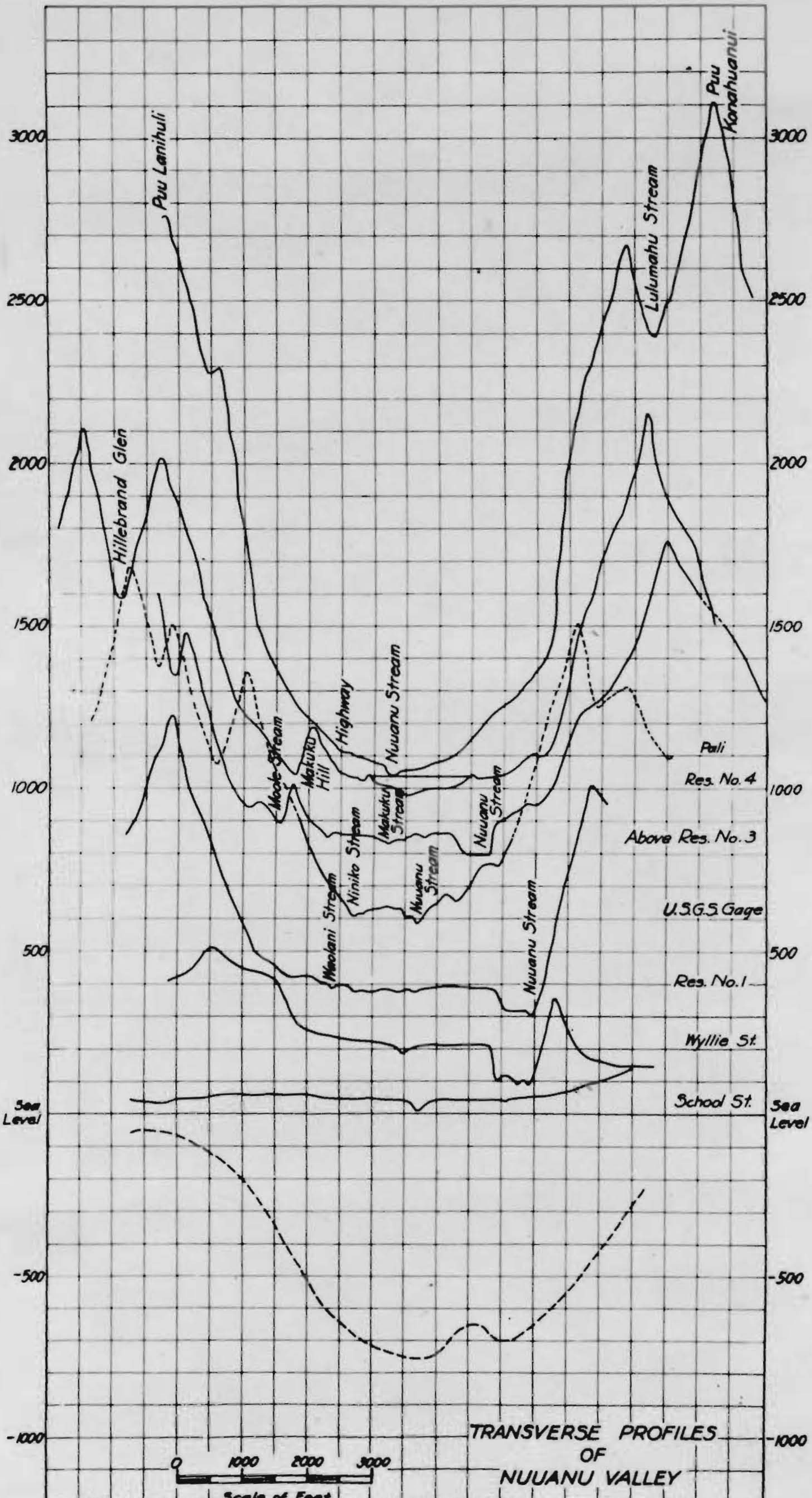

Figure 14 - Cross-profiles of Nuuanu Valley, vertical exaggeration five times. Note deep trench of Nuuanu Stream on east side in several profiles, and nearly equal lateral channels on two sides in the profile at U. S. G. S. gage.

the Pacific Heights facet stands at 900 and that of the large Kapalama facet at about 1300 feet.

COASTAL PLAIN

The coastal plain at its landward margin reaches elevations of 40 to 50 feet, and merges with fan slopes and with alluvial valley bottoms which rise progressively inland to 100 feet or more. The coastal plain in general has a flat slope of about 50 to 100 feet to the mile, and is only interrupted by the partly tidal mouths of the principal streams. The tuff cone, Punchbowl, is the chief interruption to the Nuuanu portion of the coastal plain.

The mass of Punchbowl lies on the older and deeper beds of the coastal plain and is surrounded and flanked by later sedimentary components of the plain. As far as can be seen from its exposed form, its base has a diameter of almost exactly one mile; and its rim, a diameter of about 1800 feet, both being nearly circular. On the seaward side, its base merges with a coastal plain surface at about 20 feet above sea level at Beretania and Alapai Streets, and its inland margin overlies coastal plain rocks at upward of one hundred feet above sea level. It lies exactly at the end of the Tantalus spur of the Koolau Range, and Punchbowl tuff lies on the surface of Koolau rock in the present road cut at an elevation of approximately 270. The natural elevation of this saddle was 289 feet. The rim of Punchbowl stands mostly between 400 and 460 feet, with a few rim points above this level, and one on the southwest side at 497 feet above sea level. The bottom of the bowl stands at about 350 feet and drains by a small branch of Kanaha Stream through a breach cut on the southeast side of the rim.

Climate

Climate of the Honolulu district in general has been outlined in other reports of this series. Annual rainfall in the Nuuanu-Pauoa district is shown on the isohyetal map of Figure 15. Maximum annual rainfall, so far as shown by interpretation of existing data, is on the east wall of Nuuanu adjacent to the Pauoa Flats "high", where somewhat over 160 inches falls. On the other side of the valley at an equal distance from the crest of the range the annual rainfall apparently does not exceed 115 inches. Rainfall along the range crest at the head of the valley is about 100 inches, that along the inner margin of the coastal plain is 50 inches and along the coast less than 25 inches. It has been suggested elsewhere that the "highs" and "lows" along the belt of maximum rainfall (which lies about 1 to 1.5 miles leeward of the range crest) are caused by saddles and peaks on the crest, but available data are insufficient for the development of any detailed local explanations, and it is certain that true conditions are far more complex than can be shown by the isohyetal map developed from a limited number of stations.

Vegetation and soils, settlement, etc.

General soil conditions in relation to elevation and slopes in the Honolulu district have been discussed elsewhere (1). Nuuanu

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(1) Wentworth, C. K., Manoa-Makiki Report, pp. 25-26, 1940.
__________ Kalihi Report, p. 18, 1941.

Foster, Z. C., Soils of Hawaii, Territorial Planning Board, First Progress Report, pp. 57-81, 1939.

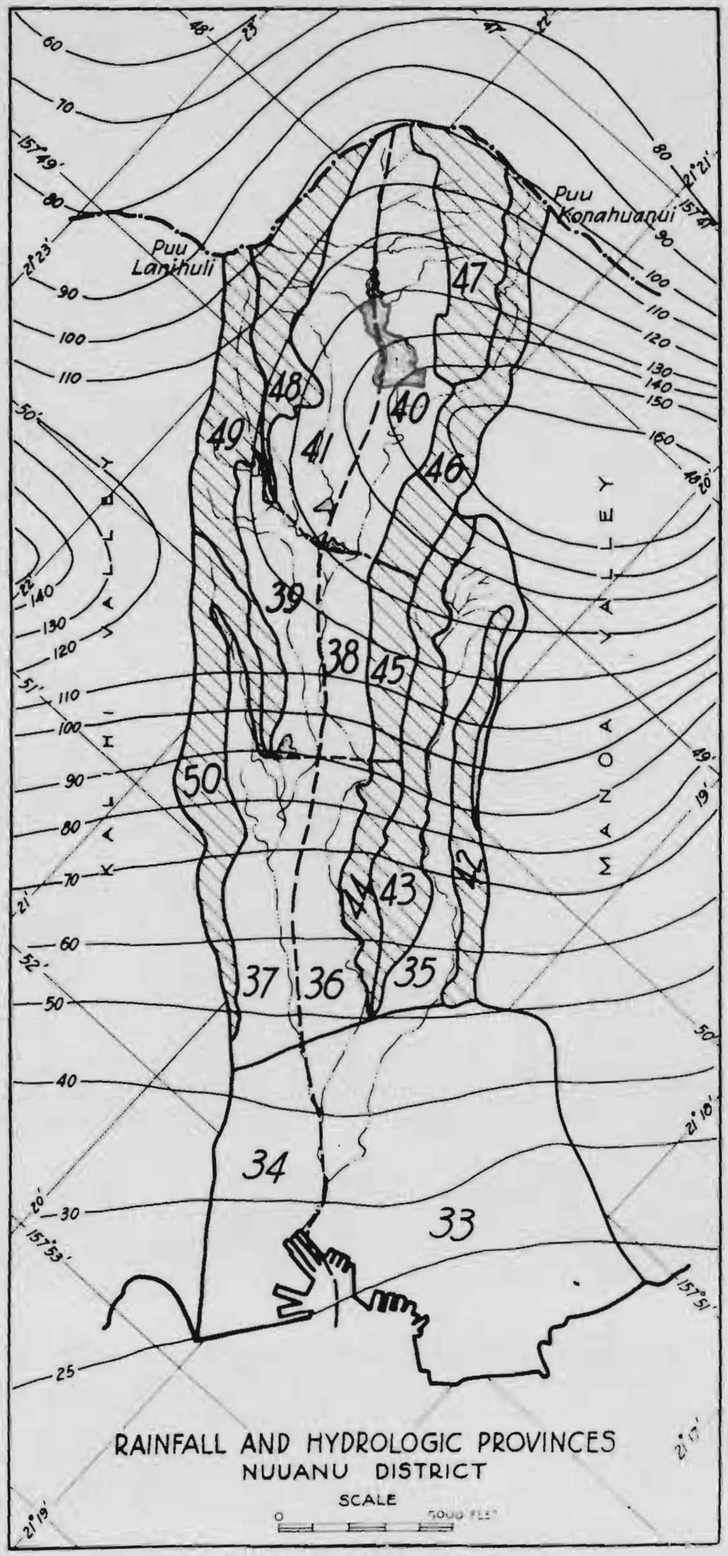

Figure 15 - Isohyetal Map of Nuuanu-Pauoa District, showing hydrologic provinces. (Tables, pp. 150-152, this report) The shaded portion indicates the maximum area from which infiltration is believed to reach basal water. Rainfall data from U. S. Weather Bureau, via Territorial Planning Board, 1940.

differs from the other major valleys in its accessibility from head to mouth by means of the main highway. A large amount of planting has been done on various slopes in the valley, and extensive areas have been cut or burned over in connection with building and care of reservoirs. More nearly native conditions are found in the Lulumahu and Moole branch valleys.

Settlement of the flatter lands of Nuuanu is practically complete up to the elevation of about 600 feet, except for the areas of certain reservoirs and the golf course of the Oahu Country Club. (Figures 3 and 4) Some sections are closely settled, with lots of small size and close spacing of houses, as in the Puunui and Laimi Road areas, but much of the upper valley bottom is held in lots of large size and includes many of the more pretentious homes of "old" Honolulu as well as fine modern residences. A few of these are located along the Pali Road and Mamalahoa Road, as far inland as Reservoir No. 2 at the edge of the Forest and Water Reserve, and there are two inhabited residences in the original Cooke land holding (Grant 4561) in an area which is surrounded completely by Forest Reserve and on the west side only by Water Reserve. (See Figure 13) (1)

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(1) For description of line of Forest Reserve (promulgated Dec. 24, 1926) see Hawaiian Forester and Agriculturalist, Oct.-Dec., 1926, pp. 178-187.

For description of line of Water Reserve, promulgated March 31, 1916, see Rule III, Division of Forestry, Board of Commissioners of Agricultrue and Forestry.

On the lower coastal plain of the Nuuanu-Pauoa district is the older and most concentrated retail and industrial district of the city of Honolulu, and on the western and inland part of the coastal plain in the River Street-to-Palama section is the chief low-standard and slum section of the city, in which the famous Chinatown fire of 1886 took place.

The lower slopes of Punchbowl are thickly settled, and the same is true of much of the flatter surface of the Pacific Heights and Alewa Heights flow-slope facets. Pauoa Valley is generally settled on that lower portion of the bottom which has been widened by the fill of Tantalus lava flows. (Figure 10) In the V-shaped part of the valley bottom, from elevation 280 to about 700 feet at the Forest Reserve line, there are many small homesteads and much vegetable and flower growing. With the exception of a few houses which are just on the crest of the boundary ridge, the settled areas of Tantalus and upper Makiki are in the Manoa-Makiki district and have been mentioned in an earlier report.

The ridge crests and higher slopes inland from Dowsett Highlands on the east side of Nuuanu and inland from the Oahu Country Club on the west side are not open to the public and are accessible only on official permit based on sanitary clearance through the Territorial Board of Health. The same is true of the entire valley bottom of Nuuanu inland from Reservoir No. 2, except for the highway and the Cooke property at Luakaha. The Tantalus and Pauoa and Pauoa Flats areas are accessible to the public at present, the line of restricted Water Reserve being at the inland margin of Pauoa Flats.

GEOLOGY

General Geology of the Koolau Range

The general geology of the Koolau Range has been described elsewhere (1). The leeward part of the dome, with which we are here

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(1) Wentworth, C. K., Reports of this series; Palolo-Waialae District, pp. 33-34, 1938; Manoa-Makiki District, p. 28, 1940; Kalihi District, pp. 20-21, 1941.

Wentworth, C. K., and Winchell, Horace, The Koolau Basalt Series, (In course of preparation) Abstract, Bull. Geol. Soc. Amer., Vol. 51, p. 1953, 1940.

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concerned, consists of thin basaltic lava flows which were poured from vents along a rift zone. (Figure 16) In the rift zone, running parallel to the topographic trend of the range, there is a marked concentration of basaltic dikes with some sills, the whole of which has been called the dike complex (2). Both aa and pahoehoe lava flows

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(2) Stearns, H. T., Op. Cit., p. 96

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are common, the great majority of the flow units being under 10 feet thick, and exceedingly few are more than 20 feet thick. Minor systems of dikes and some scattered dikes and sills are found in the area outside the dike complex (3). They become fewer at increasing distances

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(3) Wentworth, C. K., and Jones, A. E., Intrusive Rocks of the Leeward Slope, Koolau Range, Oahu, Journal of Geology, Vol. 48, pp. 975-1006, 1940.

Figure 16 - Detail of wall at "Upside Down Falls" showing thin lava flows with interbedded tuff layers. Thick lava flows in cliffs and stream channels are commonly free of vegetation, but sections consisting of thin flows even when practically vertical, usually carry some growth of vegetation. (Negative No. 12064)

from the dike complex.

Thin beds of palagonite tuff, mostly of very limited areal extent are found interbedded in the Koolau mass at various levels and places. These have been supposed by the writer to be due to local phreatic eruptions and not derived from any dominant central vent. In one of the earlier reports all the known outcrops of palagonite tuff in the Koolau series were plotted in a composite cross-section to determine if these tended to occur in one or more dominant zones and hence, to indicate a historic break in the building of the dome. No significant indication of such a concentration for the whole Honolulu area was developed (1). It is, however, undeniable that a rather

(1) Wentworth, C. K., Kalihi Report, pp. 29-31, Figure 23, 1941.

marked concentration of thick and numerous tuff beds extends from central Manoa across Lulumahu and as far as Moole (Hillebrand Glen) valley. This matter is more fully discussed in the section on Koolau tuff.

The Koolau formation

BASALT FLOWS

In Nuuanu Valley, a fairly broad fill of sedimentary rocks and late volcanic materials occupies the bottom of the valley extending from the coastal plain practically to the head of the valley at the pali gap. In Pauoa Valley, sedimentary rocks and Tantalus volcanics occupy a much narrower valley bottom. Under these valley-bottom deposits, and in the intervening ridges and valley walls, lies the unbroken mass of thin lava flows, with subordinate tuff beds, dikes and sills, which is known as the Koolau formation. This mass accounts for about one half of the inland surface area as shown on a map, and probably at least 90% of the entire volume of the Nuuanu-Pauoa sector above sea level, as well as something of the order of 100 times as much volume below sea level down to the floor of the ocean. (Figures 17 and 18)

The Koolau formation lies under the coastal plain deposits at a depth of 50 feet or less immediately seaward from the ends of the range spurs. Opposite the lower end of Nuuanu Valley at the inner margin of School Street the Koolau rock of the ancient valley bottom lies more than 800 feet below sea level and stands at comparable depths below sea level under the present coast line (1).

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(1) Palmer, H. S. The Geology of the Honolulu Artesian System, Supplement to Report of Honolulu Sewer and Water Commission, Map, 1927.

The Koolau volcanic dome is of elliptical plan, about 50 miles long on a northwest-southeast axis, and originally about 20 miles wide. The highest part of its original crest probably reached 4000 feet above present sea level. The probable original form of the dome has been suggested by restored contours (2). Another lava formation,

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(2) Kalihi Report, Figure 3, 1941.

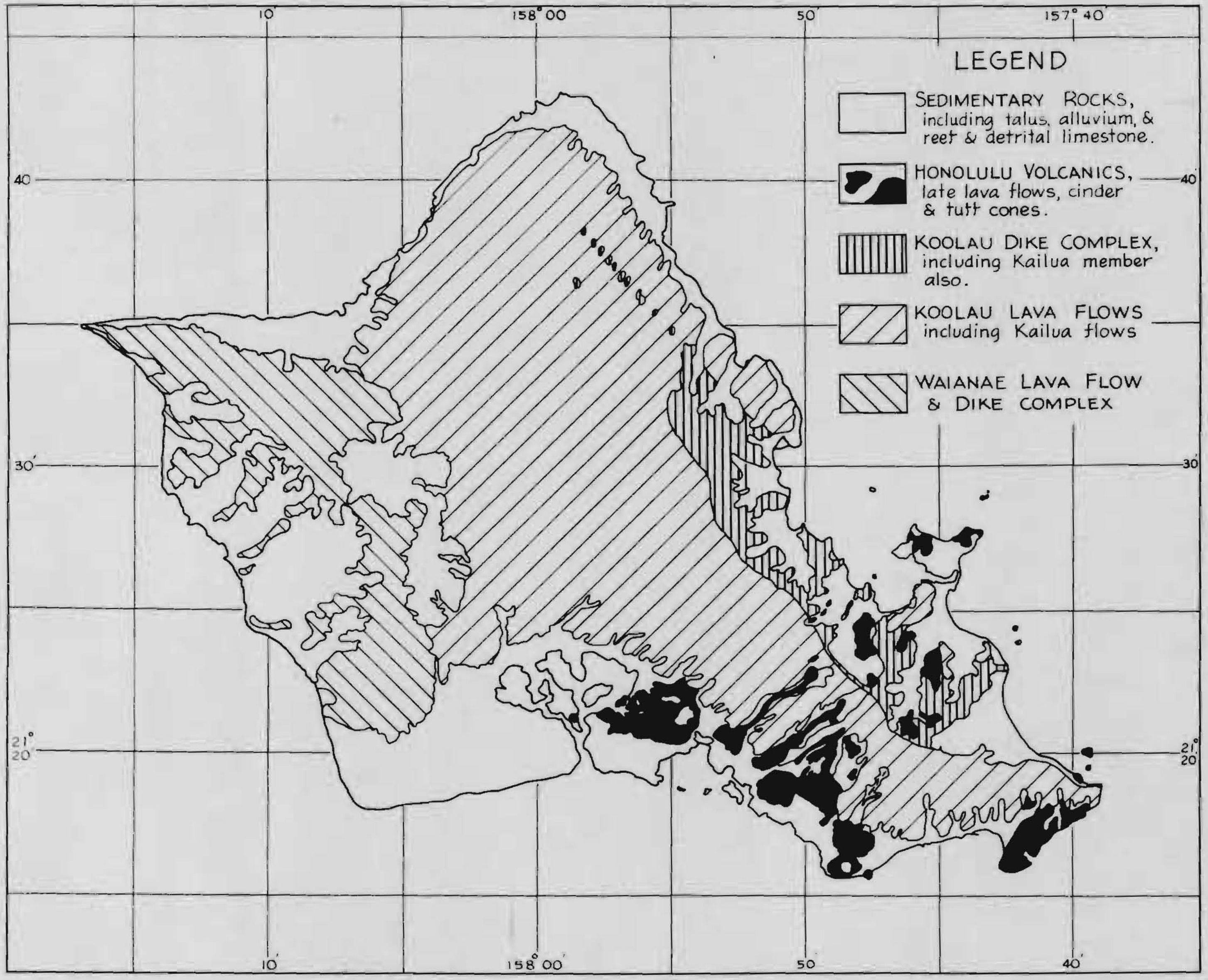

Figure 17 - Sketch map of Oahu, showing chief groups of rock formations. Based on Geologic Map of Oahu, Bulletin 2, Territorial Division of Hydrography and U. S. Geological Survey.

Figure 18 - Geologic map of Nuuanu-Pauoa District, Oahu. Scale 1 inch equals 500 feet. Working map on double-weight, bromide enlargements from U.S.G.S. photolithographs, in sections 1 minute of latitude (6060 feet) by 3/4 minute of longitude (4260 feet). (No copies yet made)

the Kailua series (1), has been recognized as forming a minor part of

(1) In his earliest report the Kailua series was considered by Stearns to be part of an eroded dome earlier than the Koolau dome (1935). In a later report (1940) he interprets the Kailua series as caldera filling subsequent to the building of most of the Koolau dome. Decision on this question is not pertinent to this report.

the Koolau dome in the Kailua-Kaneohe area; but it seems fitting that the name "Koolau" be applied to the much more widespread lava flow series which forms not only the surface of the dome and is structurally accordant with it but also is exposed to the bottom of all the deep leeward valleys, and in the deeper cutting of the windward side of the range except for the limited area of Kailua series and the belt of dike complex. This is the formation whose lava flows have built the dome as we see it today.

The Koolau series consists of at least 3000 feet of thin lava flows which lie at angles of 4 to 7 degrees for the most part and are conformable to such remnants of the upper surface of the dome as can be recognized. The upper limit of slope has been given as 10 degrees, but as far as the writer's observations go in Nuuanu and the Honolulu area, dips of more than 7 degrees are extremely rare and of limited extent. Despite the theoretical indication that flows near the top of the dome should have lower angles of slope than those near the periphery, such measurements as available, made both by the writer and his assistants and by Stearns, fail to show any such increase in dip toward the periphery (2).

(2) Wentworth, C. K., and Winchell, H., Op. Cit., Manuscript, pp. 18-20, 1941.

The Koolau formation of the Nuuanu-Pauoa district is wholly included in the leeward sector of the dome. In the inland portion it shows a material increase in the number of dikes and sills, but the margin of the dike complex is not encountered until one passes a few feet to windward of the present topographic crest and hence out of the Nuuanu-Pauoa district. Both pahoehoe and aa lava flows are found in Nuuanu and Pauoa. No systematic or rational description of their distribution has been developed. In some sections, where nearly complete exposure is found the lava flows will be wholly of the pahoehoe type for perhaps 50 feet or more; in other sections only aa flows will be found, but most commonly a section of one type will be broken by one or more flows of the other sort within 20 or 30 feet. In section, the pahoehoe flows are distinguished by their somewhat regular, cellular structure, the vesicles being arranged in a form of banding, often showing curved, infolded, billowy configurations. (Figure 19) The pahoehoe flows often show a glassy crust, or a yellow to red, oxidized crust or contact zone, top or bottom, which has resulted from the combined palagonitization and weathering of such a glassy zone. The aa flows are characterized by a more conspicuous, dense interior mass, usually overlain, and often underlain by a layer of loose, detrital clinker. The dense parts are of somewhat irregular thickness and show a few scattered, irregular vesicles of large size. Occasionally the vesicles show some banding, but often the mass retains all the other characteristics of an aa flow and should be so classified. (Figure 20) Both aa and pahoehoe flows may be as thin as a foot or less; a thick mass of 5, 10, or more feet showing no readily discernible structure is certainly an aa flow.

Figure 19 - Detail of pahoehoe flow of Koolau formation, near Makapuu Head. The banded arrangement of vesicles and the infolded structure are characteristic. (Negative No. 21008)

Figure 20 - Detail of a single aa flow of the Koolau formation, at the Waialae quarry. The massive, dense interior, with a few large, irregular vesicles, is characteristic. (Negative No. 12117)

Many, if not all, the resistant, conspicuous, ledge-forming flows in stream channels and in cliffs are aa flows, but where continuous sections outcrop a moderate percentage of pahoehoe flows is practically always found. Theoretically, the proportion of pahoehoe should be large near the vents and near the rift zone, but it is just in this section near the crest of the range where rocks are deeply weathered and where much of the surface is covered or obscure that the exposures are restricted to the few massive flows which are of the aa type, and neither in drill holes or in natural exposures has a section showing a predominance of pahoehoe flows for any great thickness been found.

No petrographic differences are known between the Koolau basalt of Nuuanu-Pauoa district and those of the remainder of the range, particularly the Honolulu section. (Figure 21) Winchell has prepared the following description (1):

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(1) Wentworth, C. K., and Winchell, H., Manuscript, pp. 31-35, 1941.

Petrography of the Koolau Series

General description of the lavas - Texturally the lavas of the Koolau Range vary but little. They may be described as intergranular-porphyritic, with variations in the groundmass toward equigranular or toward felty textures, depending upon relative absence or abundance of plagioclase laths. Some lavas contain appreciable amounts of glassy basis, making the texture intersertal-porphyritic. Other textural phases are represented by occasional variant specimens but are not common.

Phenocrysts may comprise 0 to 60 per cent of the rock; they are usually olivine, orthorhombic pyroxene, or plagioclase, or any combination of these in any proportion. Cross (1915, pp. 18-20) describes a number of Koolau basalts, all of which fall in the range above described. Dana (1889, p. 466) described one Koolau basalt in which olivine phenocrysts made up two thirds of

Figure 21 - Photomicrograph of Koolau basalt from bottom of Diamond Drill Hole No. 8 (west bank of Nuuanu Stream at No. 2 spillway) at 249 feet below bedrock valley at 465 feet above sea level. Negative No. 20302. (x 111)

the bulk of the rock. The writers' experience indicates that this is plausible, as a number of olivine-rich flows occur alternating with plagioclase-rich flows (or flow units?) in Wiliwilinui ridge, just east of Diamond Head. Some of these olivine-rich flows contain at least 50 per cent olivine phenocrysts; the alternating plagioclase flows contain an estimated 30 to 50 per cent of plagioclase phenocrysts. One of the flows exposed in upper Moanalua Valley contains plagioclase tablets 1/2 to 1 1/2 inches in diameter, in the amount of about 40 per cent of the volume of the rock.

Augite does appear as phenocrysts. Magnetite and ilmenite, hereafter referred to as "ore", frequently are included in olivine phenocrysts and undoubtedly crystallized in part before extrusion; ore appears to crystallize almost without break from before extrusion until after all other minerals except feldspar have finished crystallizing. It is very rarely or never included in feldspar crystals.

Olivine phenocrysts very frequently show iddingsite rims, sometimes at and sometimes just inside the boundaries of the olivine. Iddingsite in olivine phenocrysts has been interpreted as a product formed only during the short time when the lava was at or in the vent or actually moving; when the iddingsite is not at the actual boundary of the grain, further olivine must have been deposited during the later crystallization of the lava. The outside rims of olivine phenocrysts generally have the same crystallographic orientation as the centers, even though separated therefrom by the iddingsite. The mean index of refraction of the olivine is 1.680 to 1.690, and the optic axial angle is near 90 degrees, indicating a composition near the middle of the chrysolite range, or close to 15 molecular percentage of fayalite.

Orthorhombic pyroxene with very large optic axial angle and with its mean index of refraction close to 1.680 is found in Koolau lavas more frequently than not. As noted by Cross, its role is similar to that of olivine. The composition of this mineral, determined optically, is about 15% ferrosilite. It is present in several of the specimens of Koolau lavas analyzed for this study. Plagioclase, usually slightly zoned labradorite, forms phenocrysts in some Koolau lavas. The zoning is normal, from calcic core to sodic periphery, and only very rarely shows any reversal of this relationship. The most calcic cores observed have been determined (by extinction angles) as calcic labradorite, near 70% anorthite; 65% anorthite is an average figure. The peripheral zones of these phenocrysts usually have anorthite content around 55%, although one or two examples have been found where the composition is close to An 50.

The groundmass minerals of the Koolau lavas are feldspar, olivine, rhombic pyroxene, augite, ore, apatite (exceedingly sparsely distributed), and in some specimens, glass. Plagioclase usually occurs in the form of small lath-shaped crystals without any special arrangement. In some specimens they are numerous enough to overlap considerably in thin section, forming a felty texture; but many specimens contain less of this mineral, and the groundmass consists of more or less isolated feldspar laths surrounded by granular pyroxene in intergranular texture. These laths are usually of the order of .05 to .01 mm. long and 0.005 mm. in diameter, making accurate determination of their optical properties and hence of their composition, difficult. They appear to be sodic labradorite, corresponding in composition to the peripheral zones of the phenocrysts.

Small olivine grains, sometimes associated with rhombic pyroxene, may be found in the groundmass of some lavas. They are not abundant.

Rhombic pyroxene in the groundmass is difficult to distinguish from monoclinic types. It has been reported by E. S. Dana (1889), and by Cross (1915, pp. 19-20) who refers to its occurrence as "microphenocrysts of bronzite in a groundmass of augite" (1915, p. 20). The writer has not seen any rhombic pyroxene that does not belong to the phenocryst phase of the rock; euhedral outlines of these small grains and their relation to the surrounding groundmass invariably point rather to earlier crystallization of the rhombic mineral.

Monoclinic pyroxene forms 30 to 60 per cent of the groundmass and corresponding proportions of the whole rock. Its composition appears to be pigeonitic or augitic; grain sizes commonly smaller than the thickness of the thin sections prevent accurate determination of the optical properties, though powdered material in liquid mounts somewhat offsets these difficulties. In small grains the monoclinic pyroxene surrounds the feldspars in an intergranular pattern that would be ophitic if the individual pyroxene grains were larger. These micro-granular grains of pyroxene are equant, anhedral, and have smaller grains of ores both in and between them.

Ore, presumably magnetite and ilmenite in variable proportions, occurs in all Koolau lavas as equidimensional granules with dimensions very rarely exceeding 0.5 mm. The smallest grains are probably unresolvable particles in glassy portions of the rock; margarites and feathery skeletal forms are not uncommon in the glass also. Magnetite grains, identified by their octahedral habit, are common inclusions in olivine phenocrysts; ores are commonly associated with the granular groundmasses of the lavas; finally, they may occur as dust in the glass, demonstrating their formation from very early to very late in the history of the crystallization of the magma, from early intratelluric stages to the very end of crystallization.

Apatite forms negligible amounts of crystals in the Koolau lavas. In no case has a thin section of a Koolau rock been seen to contain more than about 0.1%, and most contain none, or sometimes one or two tiny grains. The mineral is very rare but appears to be very widely distributed in the Koolau series.

Much glassy interstitial material may sometimes be found in the Koolau specimens. Glassy material is usually very dark, sometimes almost opaque with exceedingly fine-grained magnetite. It is most common in the dike rocks but appears very frequently in chilled surfaces of flows.

In some specimens, interstitial feldspar occurs in extremely small grains and aggregates showing weak polarization effects. This material never occurs in grains large enough for positive identification; it may be an alkali feldspar, since there appears to be a slight correlation between its presence and the amount of potash in the rocks.

KOOLAU ASH AND TUFF BEDS

A few scattered tuff beds are found in all parts of the Nuuanu-Pauoa district, but the most conspicuous occurrence is in a belt which runs across the valley just inland from Reservoir No. 4, and includes Lulumahu and Moole Valleys also. In Lulumahu channel a prominent tuff bed is found at the top of the main falls, at the elevation of about 1500 feet, and several other beds are encountered higher up in the channel. There is a notable concentration of tuff beds in the east wall of Nuuanu Valley, lying between 1750 and 1850 feet at the perennial fall known as "Old Faithful", and a similar concentration in the west wall between about 1550 and 1650 feet in the vicinity of the so-called upside down fall. (Figure 22)

Despite the failure of earlier efforts to demonstrate existence of a zone of concentration over the whole Honolulu district, it is hard to avoid the conclusion that there is some continuity of tuff beds across Nuuanu, from Lulumahu to Moole, and that this is the same

Figure 22 - Outcrop of Koolau tuff bed in small valley at inland end of Dowsett Highlands taluvial fan. The tuff is about four feet thick, and its outcrop is eroded two or three feet back of the general surface of the rock wall. The lower part of the tuff bed is somewhat coarse and agglomeratic, but the upper part is fine grained, originally vitric material altered to palagonite. (Negative No. 13515)

zone as is found in the central and western branches of Manoa at 1100 to 1200 feet. The Nuuanu localities are nearer the axis of the restored dome (1), and this accounts for the greater elevations. At

(1) Figures 3 and 23, Kalihi Report.

all these localities in both Nuuanu and Manoa the tuff zones lie approximately 1100 feet below the restored surface of the dome. There has not as yet been any correlation of individual tuff beds from valley to valley, but the continuity of the general zone seems evident.

If these facts be taken as conclusive, it indicates that explosive activity may have occurred at some vent in the rift zone with sufficient frequency and in sufficient mass to account for an aggregate of possibly 20 feet of thickness over an area that may be estimated at not less than three or four square miles. It is not known with certainty, but it seems possible that some of these ash beds with local thicknesses of 8 or 10 feet, may average as much as 3 feet thick over an area of three square miles, corresponding to a volume of 9 square-mile-feet, or about 7 million cubic meters. Such a volume approximates the volume of many of the smaller pyroclastic cones of the Mauna Kea dome on the island of Hawaii (2). It might be expected

(2) Wentworth, C. K., Ash Formations of the Island of Hawaii, Haw. Volc. Observatory, Third Special Report, pp. 23-24, 70-72, 1938.

that an eruption which produced fine-grained material in sufficient quantity to drift 1 to 2 miles from the source would build a cone one to three hundred feet in height at its source. However this may be, the dome along the line of rifts has been eroded down at least 2000 to 2500 feet below its culminating level, and hence such cones could hardly remain in existence.

The origin of these tuff beds remains on a speculative basis with indication in the Nuuanu area that some of them may be derived from primary vents in the rift zone. Further discussion of this problem is deferred.

It is believed that these tuff beds play an important part in perching ground water and are largely responsible for the rather steady flow of Lulumahu Stream and of the Old Faithful fall. In view of the dissected nature of the topography, however, in which they occur, it does not appear that water supplies which could be developed locally by tunneling at certain outcrops of the tuff beds would be large enough to justify the expense of development and transmission of the water. This is discussed in a later section.

The petrography of the Koolau tuff has not been systematically studied, though a number of thin sections have been cut, and scattered field observations in considerable number have been made. The Koolau tuff is best described in comparison with the somewhat better known tuff of the various craters, Diamond Head, Punchbowl, Koko group and others of the Honolulu series. Like the tuff of the younger series, the Koolau tuff is generally palagonitized. (Figure 23) Because of its fine grain, and completely and usually rather cloudy palagonitized character, the original character is not easily discernible. The texture of the palagonite suggests that the Koolau ash consisted of finer grained glass fragments and that these were more largely elongated,

Figure 23 - Photomicrograph of Koolau tuff, specimen No. 10377, from west wall of Kalihi Valley near the head, at 1400 feet. The specimen contains fragments of crystalline basalt but consists largely of a fine-grained assemblage of palagonitized glass fragments, mostly in vesicular, shard shapes, which show a banded structure, of flow origin but emphasized by differing amounts of palagonitization. The practically opaque margins of shards and vesicles, places broken away from the rest of the mass, are nearly pure palagonite. Negative No. 20287. (x 116)

wisp-like fragments than is the case with the Honolulu tuff. Partly because of the fine grain and in appearance aggravated by the greater age and weathering of the Koolau tuff, the transformation to palagonite or to ferruginous alteration products is more complete with the Koolau tuff.

Another difference which is observable both in outcrop and under the microscope is the greater and more variable admixture of what appear to be accessory, lithic fragments along with the juvenile, wholly vitric material. In many outcrops, the base of the lens of tuff is coarse and agglomeratic, starting perhaps with a preponderance of accessory fragments of previously cooled Koolau rock and grading upward to finer grain and nearly 100% juvenile material, now in the form of palagonite. This character, suggesting very local origin, has contributed in large measure to the writer's interpretation of local, phreatic explosions, but further study of thin sections and material in outcrop is needed before this problem can be solved.

KOOLAU DIKE COMPLEX

Only a very narrow strip of the head of Nuuanu Valley chiefly east of the pali gap is mapped as dike complex. This consists of lava flows, in which dikes and sills are materially more abundant than in most of the surrounding country rock. No quantitative studies of the frequency of dikes in the dike complex have been published. Over most of the Koolau formation of the leeward slope of the range, the concentration of dikes and sills is not more than 1 or 2 to the mile; in the Waiakeakua section of Manoa, it reaches 40 to the mile in what would be called a subcomplex (1). In parts of the dike complex which

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(1) Winchell has recently presented arguments for regarding the concentration of dikes in the belt extending from Kaau Crater toward Diamond Head as the "missing" south rift zone of the Koolau center. This interpretation is no doubt admissible as one of several hypotheses, but the present writer is not convinced that it is the correct one. Whether, as Winchell says, Wentworth and Jones in a paper "Intrusive Rocks of the Leeward Slope of the Koolau Range" failed to recognize the major structural significance of the Palolo subcomplex depends on whether a trifold arrangement of rift zones and the consequent fixing of a center for each dome be regarded as typical and logically necessary for each dome of the Hawaiian area. That this is a common condition, is well known through study of the well-developed examples of Haleakala and Mauna Loa. The writer has felt that evidence either of a center or of a third rift zone for the Koolau dome is very meagre and has been unwilling to push the analogy so far as to assume that these must logically once have been developed, and hence that any suggestive clue might indicate their site or prove their existence. Without undertaking discussion of the question here, it is pointed out that there are perhaps as many domes without marked indication of three rift zones as there are with such arrangement, and it is the writer's view that development of an elongate dome over a single rift zone, without significant primary branching, does not involve any fatal tectonic or volcanic difficulties, and may easily be regarded as a more natural primary type (a)

(a) Winchell, H., The Honolulu Series, Manuscript Thesis, Harvard University, pp. 124-128, 1941.

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are readily accessible it is certain that the concentration is reached in places. Data are not at hand to justify setting an arbitrary limit of dike concentration as a criterion of dike complex. A concentration of 10 dikes to the mile would hardly be called dike complex; that of 100 to the mile would probably be so conisdered. Moreover, the question of proximity and compact relationship to the main area of the recognized dike complex is also a factor.

KOOLAU DIKES AND SILLS

As in other districts of the Honolulu area, dikes and sills are more numerous progressively as one approaches the summit of the range and the dike complex. As outlined elsewhere, central Manoa is unusually free from dikes and sills, but the number of these increases westward, and an exceptional development of sills, with some dikes, is found in the West Waihi-Lulumahu section. Two sills form the lips of two successive falls in Lulumahu channel at the elevation of about 1850 feet just inland from the Lulumahu-Waihi saddle on the Konahuanui trail. (Figure 24) These sills possibly represent the same zone as the one which outcrops at the lip of the high fall just below Old Faithful spring on the east wall of Nuuanu Valley and seems to correspond to thick sills found in East and West Waihi at about 1800 feet. Two or more sills outcrop in the east wall of Nuuanu opposite Dam No. 4 and in various other places as indicated on the detailed geologic map. (Figure 18) The possible hydrologic significance of the Old Faithful spring will be discussed below. No other point was found where the arrangement of dikes and sills appeared to justify exploration and development for water supply.

The general character of the dikes and sills of Nuuanu and Pauoa is described in the paper on intrusive rocks which has already been published (1).

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(1) Wentworth, C. K., and Jones, A. E., Intrusive Rocks of the Leeward Slope of the Koolau Range, Oahu, Journal of Geology, Vol. 48, pp. 975-1006, 1940.

Figure 24 - Sills in Lulumahu Valley at elevation about 1850 feet and 2000 feet inland from the top of the main fall. The lip of the fall is a large sill, and the rock pavement in the foreground is another. A small dike may be seen just to the right of the center. (Negative No. 21108)

Older sedimentary formations

OLDER ALLUVIUM

As in earlier reports, the older alluvium is defined as that part of the secondary or mantle rock cover which is almost completely weathered, so that nearly all hard kernels are eliminated and the whole reduced to a tight-rammed, compact, but readily carvable stuff which is the most impervious formation in the area. For a number of years, the great excavation in the borrow pit inland from the east end of Dam No. 4 was one of the most accessible and impressive examples of the weathered and mottled old alluvium. (Figure 25) Its character is still clearly apparent, but it is less fresh and somewhat more obscured by plant growth than it was in 1934, when the writer first saw it. Much of the older alluvium lies under other formations in the deeper parts of the valley-bottom fill, or in the basal portions of taluvial valley-side fans. Because of its gradation laterally and in section into intermediate alluvium, the mapping at any scale can only be suggestive, a combination of outcrop mapping, with an indication of supposed extent under vegetational cover.

The older alluvium is less conspicuous in its outcrops and influence on water behavior near the surface of the valley bottom in Nuuanu Valley than it is in Kalihi, owing chiefly to the greater depth of total fill and the larger amounts of secondary volcanic rocks in Nuuanu than in Kalihi. On the other hand, the results of diamond drilling in some 15 holes in Nuuanu Valley, combined with data from artesian well borings on the coastal plain and on the behavior of

Figure 25 - View of borrow pit in old alluvium at No. 4 Dam. The floor of the pit and the walls marked by steam shovel teeth, are in weathered, mottled, old alluvium ranging from sand size to boulders 4 and 5 feet across. A few boulders from the upper part may be hard, but the general character of this old gravel is shown by implication in the steam shovel markings. This is typical of the sedimentary formations which make up the cap rock. (Negative No. 12006)

underground water make it practically certain that the older alluvium is a continuous blanket overlying the Koolau bedrock surface over the whole width and length of the valley to within a few feet of the pali gap and probably having a general thickness of 50 to 100 feet. Additional lenses and lateral tongues of older alluvium are found between some of the basalt flows of the Honolulu series and large amounts of such material probably underlie the lower parts of most of the valley-side fans.

In the deeper parts of the valley fill, the older alluvium is of great hydrologic importance in diverting valley bottom water out to sea rather than to the basal water system as will be described below. In this respect, the older alluvium is the chief impervious component of the valley fill in forming a tongue-like extension of the cap rock, extending inland about six miles, with its bottom rising from minus 900 feet to plus 1100 feet, and in its seaward portion also serving as the controlling barrier between the Beretania and Kalihi (No. 2 and No. 3) Isopiestic Areas with their persistent basal and artesian head differences.

OLDER MARINE FORMATIONS

Very little is known of older marine formations except the very general data derived from artesian well drilling. Compilations of the logs of these wells by Palmer and by Stearns have been referred to elsewhere. These show a prominent mass of coral rock in the zone from about 60 to 200 feet below sea level. Below this depth most of the wells penetrated chiefly material classified as "clay" which is probably weathered old alluvium of terrigenous origin or weathered older marine mud, ultimately from the same source. A few coral formations are indicated in some of the wells, constituting perhaps 25% of the total between -200 and -800 feet. In a group of deeper wells opposite the mouth of Nuuanu Stream and slightly to the east, there are considerable amounts of "gravel" as noted by drillers, at depths from 400 to 850 feet below sea level. This may be detritus derived from Nuuanu Valley and deposited under water, offshore, where they have been somewhat preserved from weathering so that they retain the character of gravel as encountered by drillers.

The hydrologic functioning of the cap rock as a highly impervious barrier, which has to be penetrated by wells before they develop water and show the characteristic artesian head of a given area, indicates that the rocks composing it are chiefly tight and impervious, no doubt compacted by pressure of overlying formations and somewhat rammed through the volume expansion due to weathering. It is impossible to describe in detail the nature of the material and of its weathering, since we have little opportunity to determine its original character or its present structure from the very meagre well-cutting samples that are available.

The presence of calcareous members suggests that removal of calcium carbonate by leaching or by solution is by no means complete and hence would suggest a distinctly different weathering environment from that above sea level. On the other hand, there is no part of the deeper cap rock, as penetrated by artesian wells, where the reef formations are sufficiently continuous, or open-textured, to nullify the general character of the cap rock as a barrier, so that we are led to believe that even the coral rocks, without being wholly destroyed have been rendered relatively impervious by the changes which they have undergone.

Honolulu volcanic series

GENERAL

The formations dealt with in this section include at least two important basaltic lava flow series in Nuuanu, with vents at Makuku Cone and Luakaha Cone, the cinder formations produced respectively during eruptions at these vents, an extensive cinder and agglomerate formation with minor amounts of lava from some vent near the pali gap, the tuff cone of Punchbowl, with a small lava flow which was erupted from the same vent in its late stages of activity, and the cinder formations and basalt flows from the Tantalus vent, the latter known at the head of Aihualama Gulch and at various points down the various branches and main channel and valley bottom of Pauoa Stream. These volcanic rocks differ from the Koolau basalt series in being of ultra-basic composition, though differing somewhat among themselves, and in being far younger than the Koolau series. They were, without exception, erupted after the Koolau dome had suffered profound erosion and deep valley cutting, and the basalt and cinders of the later series lie on valley bottoms and sides and other details of the topography into which the dome had been carved. Because of this condition and because the surface on which they were expelled was somewhat weathered and mantled by weathered detritus, these rocks are mostly sealed off from the Koolau rocks so that any ground water they carry does not reach the Koolau aquifer or the basal or artesian water system. These late rocks are in large measure a part of the cap rock itself, and insofar as they are water carriers rather than barriers, they form mostly small, separate aquifer systems.

NUUANU VOLCANICS

Late lava flows of the Honolulu series are extensively exposed in the floor of Nuuanu Valley from Reservoir No. 4 to the coastal plain and are penetrated by various of the artesian wells of the Iwilei district (particularly Wells 114, 115-6, and 118) at a depth of about 100 feet below sea level (1). Along the floor of the upper

(1) From the position of the wells it has been supposed that these flows were of Nuuanu basalt, but no specimens are known to be extant. In 1939, Well 114-1 was drilled within a short distance of this group and the same lava flow was encountered at 70 feet. This has been reported as Kalihi or Kamanaiki basalt by Stearns (Bull. 5, pp. 133-134, 1940) presumably on the basis of microscopic examination and raises the question if the basalt of the holes is not also Kalihi basalt.

valley, in highway and other cuttings that do not represent a depth of more than 20 feet, there is exposed an upper lava flow overlain by a few feet of clinker and underlain by cinders. This lava flow undoubtedly came from Makuku Cone, which lies straight north of the west end of Dam No. 4. Another, and much thicker flow is revealed at many points in the channel and small lateral valley of Nuuanu Stream on the east side of Nuuanu Valley from the lower Luakaha falls seaward to Judd Street. This flow has been designated as the lower flow by Stearns, and may be the same as the flow penetrated by artesian wells in the Iwilei district, though this may be Kalihi basalt.

From the distribution of lava flows at the surface and from the depths of artesian wells and the behavior of artesian heads in areas east and west of Nuuanu Valley, there was reason for supposing that Nuuanu Valley had once been cut much deeper and is filled with sedimentary and other formations. To secure definite information on this point and to furnish data bearing on possible water development in the valley, two rows of diamond drill holes were bored by the Board of Water Supply in 1934. The row farthest inland, consisting of 9 holes (southeast to northwest, Nos. 7, 6, 10, 1, 2, 9, 4, 5, and 3) revealed a valley fill of slightly over 400 feet in thickness as shown in Figure 26. The logs of these holes are given in a subsequent section on diamond drilling. Because of the lensy form of lava flows and the similarity of composition, only an approximate interpretation of the section can be offered. The five holes which reached the ancient valley floor in Koolau rock all revealed a thick layer of completely weathered, compact, mottled, impervious old alluvium of 60 to 140 feet lying directly on the Koolau rock surface. These holes are well distributed across the valley, and there is no reasonable doubt that this layer of old alluvium forms an impervious cap rock which effectively prevents ground water in overlying formations from passing downward to reach the unweathered Koolau rock or the basal and artesian water bodies. A similar section was less completely revealed by three drill holes (8, 11, 12) on a line across the valley at Dam

No. 2 (Figure 27). Farther seaward the same fill of secondary formations serves as the barrier which impedes movement of water between Isopiestic Areas 2 and 3 (Beretania and Kalihi).

Three of the deep drill holes, just above the lower old alluvium, pass through the oldest lava flow of the Nuuanu series, at 300 to 350 feet below the surface, the greatest thickness being 50 feet. Above this flow, on the eastern side of the valley the drill holes show a thick section of cinders and cemented palagonite tuff which forms a part of the Lower Luakaha vent cone. In Hole No. 7, this cinder and tuff section is more than 250 feet thick and its thinning edge declines to a thickness of 50 feet at 1000 feet, and about 15 feet at 1700 feet distance. Because of this pyroclastic fill, the axis of the valley at this level was apparently shifted westward and its bottom narrowed in this particular section. In the valley bottom at this stage was poured a lava flow of the Nuuanu series which appears to be about 1700 feet wide and with a probable maximum thickness of 125 feet. This lava flow could possibly have come from the lower Luakaha vent, but its position in the valley suggests that it more probably came from farther inland. Above this flow are soil and alluvial layers of 5 to 20 feet which suggest a cessation of volcanic activity for a considerable period. This horizon is in general about 150 feet below the floor of the valley.

Above this level, as nearly as can be interpreted from the drill cores and drill logs, are several lensy lava flows, of which the lower flow, with a general thickness of 100 feet, probably came from Lower Luakaha cone. This is probably the flow which is so prominent

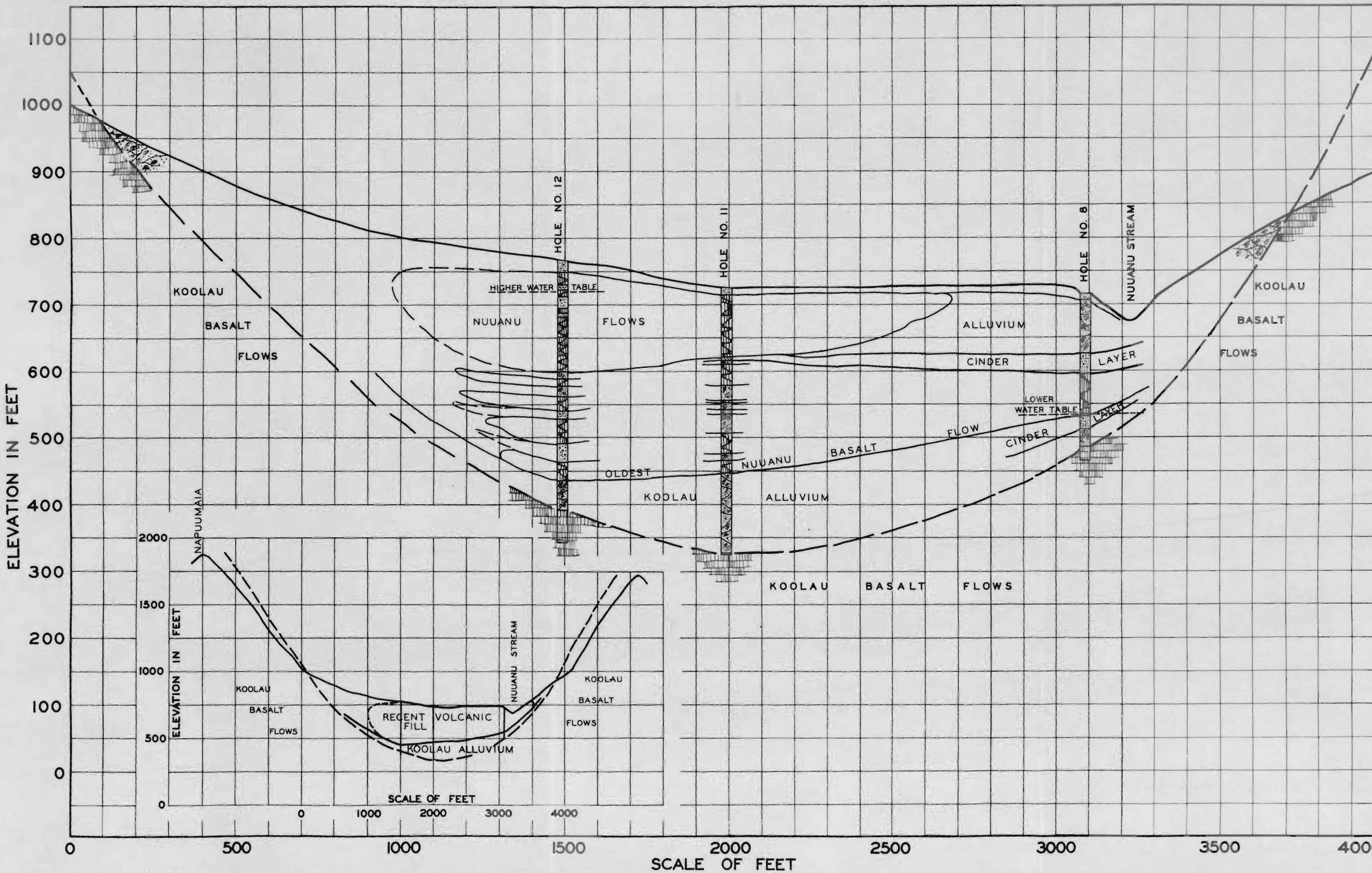


Figure 27 - Geologic cross-section of Nuuanu Valley bottom approximately on the line of Dam No. 2, based on Diamond Drill Holes No. 8, 11, and 12. The approximate form of the rock bottom is suggested, though the maximum depth is not so clearly proved as in the section above Reservoir No. 3, owing to drilling of only 3 holes.

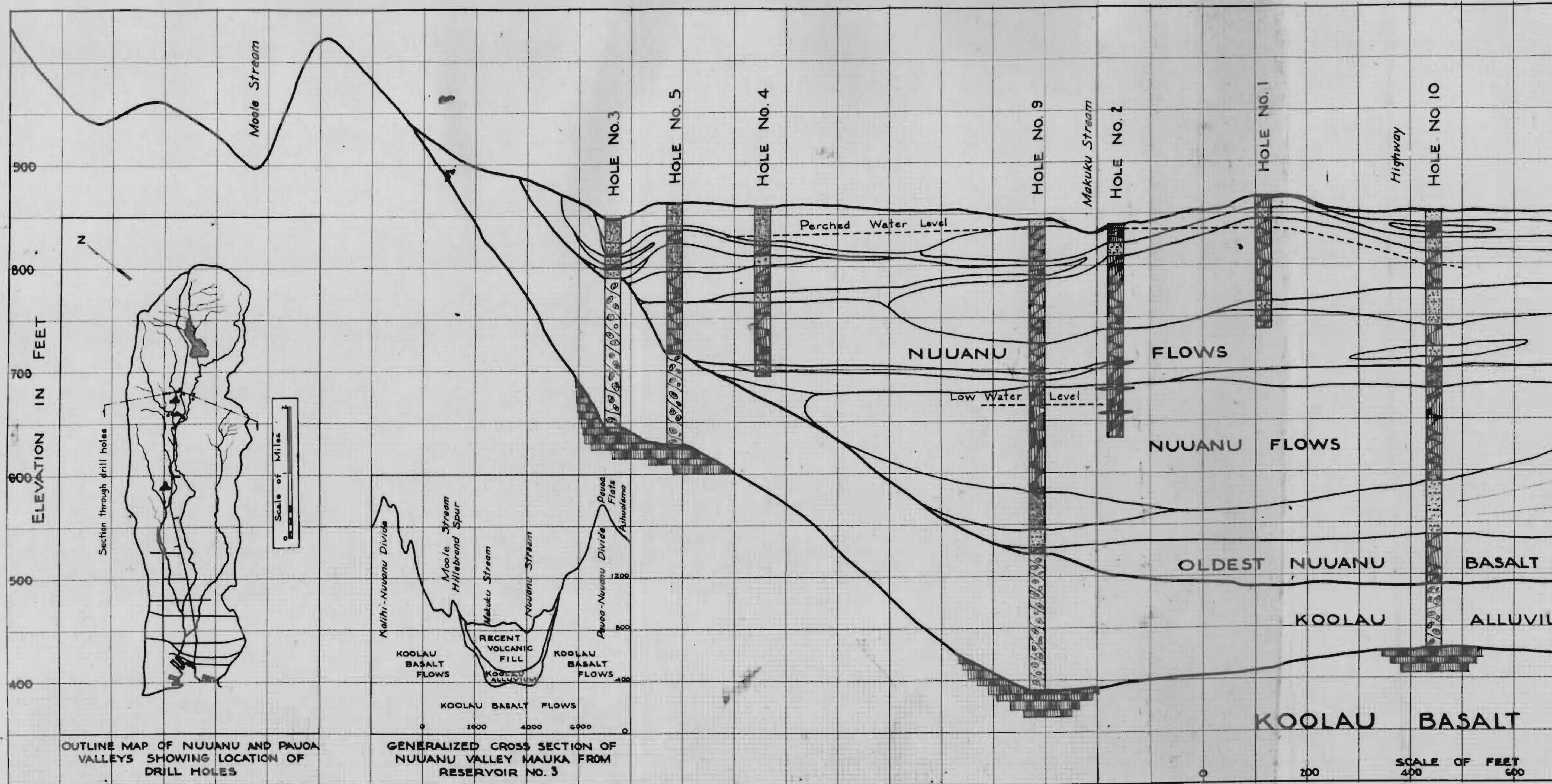
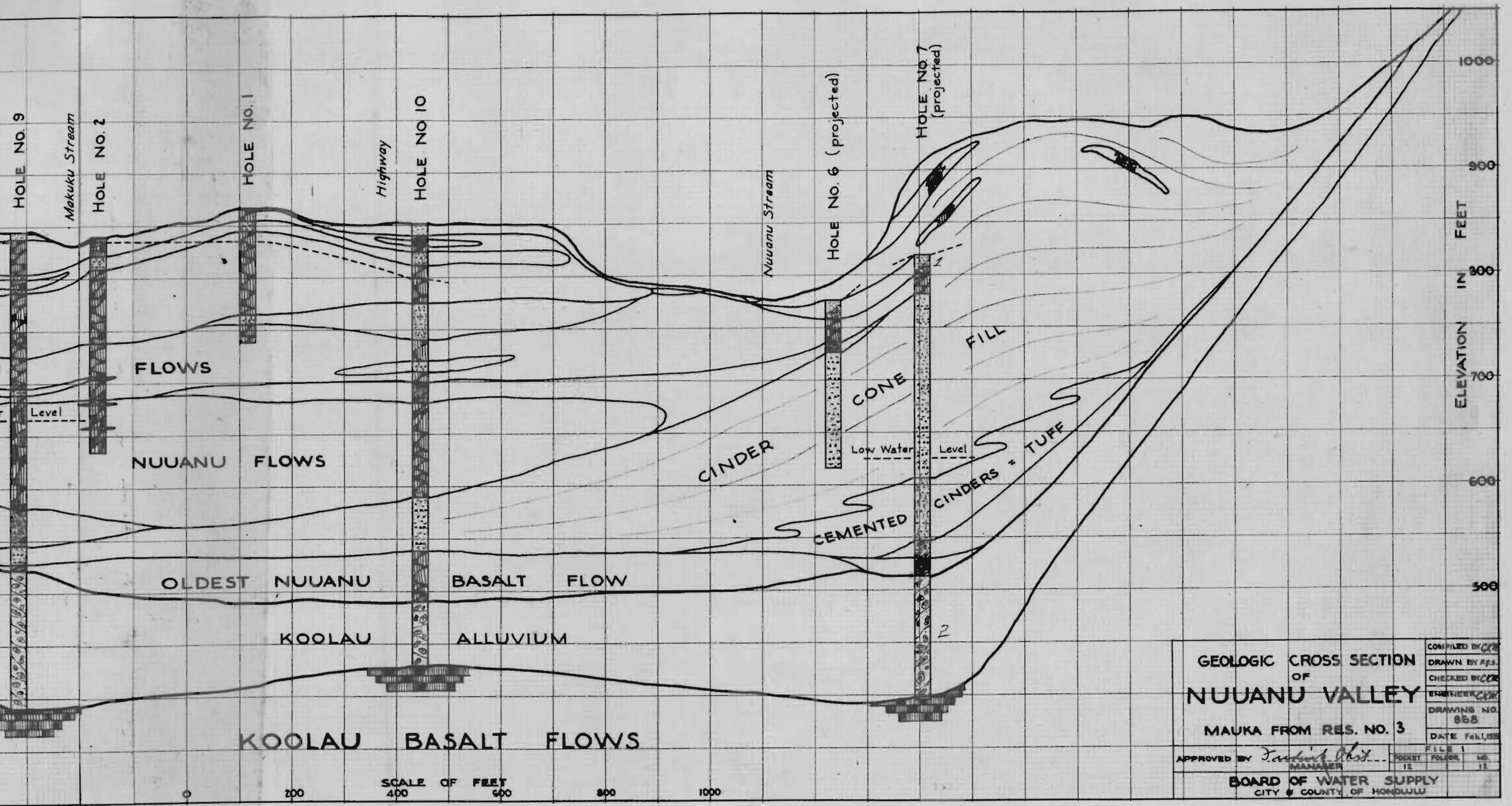


Figure 26 - Geologic cross-section of Nuuanu Valley bottom, based on diamond drilling and on petrographic study of the drill cores and other samples. This section is located just inland from Reservoir No. 3.



HOLE No. 9
Makuku Stream
HOLE No. 2
HOLE No. 1
Highway
HOLE NO 10
Nuuanu Stream
HOLE No. 6 (projected)
HOLE No. 7 (projected)
FLOWS
Level
NUUANU FLOWS
CINDER CONE FILL
Low Water Level
CEMENTED CINDERS = TUFF
OLDEST NUUANU BASALT FLOW
KOOLAU ALLUVIUM
KOOLAU BASALT FLOWS
SCALE OF FEET
0 200 400 600 800 1000
1000
900
800
700
600
500
ELEVATION IN FEET
GEOLOGIC CROSS SECTION OF NUUANU VALLEY
MAUKA FROM RES. NO. 3
APPROVED BY
MANAGER
BOARD OF WATER SUPPLY
CITY & COUNTY OF HONOLULU
COMPILED BY CKW
DRAWN BY RFS
CHECKED BY CKW
ENGINEER CKW
DRAWING NO. 868
POCKET 12
FOLDER
NO. 12

all the way down the east side of the valley in the Nuuanu Stream gorge and may be the one in the Iwilei artesian wells. Above it lie thinner flows or flow units with an interbedded cinder layer, the whole probably coming from Makuku vent and being the upper flow described by Stearns.

From data now available it is not practicable with certainty to distinguish in the diamond drill holes between flows which came from the Makuku vent opposite Reservoir No. 4 and those which came from the Lower Luakaha vent. Neither is it practicable to date the activity of each of these vents in relation to each other. The several lava units exposed in drill holes can be divided into several types, in which the chief differences are in the presence or absence of hourglass and zoned augite crystals. In the immediate surface exposures of the valley the uppermost flows contain the zoned augites, and the thicker flows exposed just under the surface flows in many places lack the zoned augites. But the diamond drill holes reveal both the zoned-augite-bearing flows and the other kind at various levels, though the zoned-augite-bearing flows appear to be less prevalent in the lower part of the section. Furthermore, the surface exposures on both vent cones indicate that the last basalt issuing from each was of the zoned augite type.

The interbedding of alluvium and other secondary, mantle rock formations with the flows in forming the several hundred feet of fill in the valley indicates that the volcanic episodes were spread over a considerable period, perhaps one or two hundred thousand years. The earliest of the Nuuanu flows probably was erupted in the earlier part of the period of general valley filling after the deep erosion of the

Koolau Range, which has been correlated with the Kaena and Laie stands of the sea (1). On the other hand, the later Nuuanu flows may well

(1) Stearns, H. T., Op. Cit., p. 68, 1935.

have come much later in Pleistocene time, as indicated both by their relation to the present surface at the vents, and by the relationship of slightly older Nuuanu flows to the coral reef formations as shown in the logs of artesian wells. There is nothing about the later Nuuanu flows to show that they are not as recent as the Tantalus basalt and cinders which have been described as Recent, or Latest Pleistocene; and there is much in the structure of Nuuanu Valley bottom to indicate that its flows of the Honolulu series cannot be allocated to a single earlier division of Pleistocene history. Unfortunately, we have no data to justify more specific correlation of these events.

Makuku Cinders

Makuku vent cone (On many maps indicated as Luakaha, see decision of Geographic Names Board in Letter to Governor Poindexter dated February 20, 1935) is a rudely circular mass of loosely cemented and much weathered cinders with an outside base diameter of about 1300 or 1400 feet and a high rim point on the southwest side, as common with pyroclastic craters in the trade wind belt. It rises about 150 feet above the outer and downhill base. The rim is only weakly developed on the northern side, and the circular, crater-like form is only clearly seen from points well above it on the west wall of the valley. From such positions the form and the origin of the mass is very clearly apparent (Figure 28). Cinders in this mass range from driblet material 3 to 6 inches across, found mostly near the vent, to more uniform, vesicular black cinders in the 4- to 16-millimeter range. Very little of this material is fresh enough to be suitable for thin sections, since it is chiefly found in a region of 125- to 160-inch rainfall. (Most of the fairly fresh black cinders of the Tantalus formation is found in regions of 40 to 80 inches of annual rainfall.) Small patches of cinders of this formation were found at various points within the area of No. 4 Reservoir, and east and south of it, where thicknesses of the mantling bed were no more than 3 or 4 feet. There is also a prominent bed of cinders lying under 10 or 15 feet of basalt in the middle portion of the valley flat at various points from Reservoir No. 4 downstream to Reservoir No. 3 and beyond. Tunnel No. 3, in particular, is driven in this cinder formation and derives its water largely therefrom. From its position it seems probable that this cinder bed came from Makuku vent, but part of it could have come from the Lower Luakaha vent during a contemporaneous activity. It is presumed that the Makuku cinder formation is identical petrographically with the late Makuku basalt described below.

Makuku Basalt

The lava flow which lies at the surface of middle Nuuanu Valley between Nuuanu Stream and Makuku Stream from No. 4 Dam down-valley to Reservoir No. 2, together with some remnants on the Makuku vent cone itself, is comparatively thin in most places. In drill holes 1, 2, 3, and 10, it has thicknesses ranging from 5 to 35 feet; its average may be no more than 10 or 15 feet. Petrographically this flow

Figure 28 - View of Makuku Crater from the west wall of Nuuanu Valley, seaward from the Upside-Down Fall, at about 1800 feet. Skyline at the middle distance is Pauoa Flats, with Tantalus on the right. In the left lowland is Nuuanu Reservoir No. 4. This crater marks a vent which has been the source of many lava flows of the Honolulu Series in Nuuanu Valley. (Negative No. 12475)

Figure 29 - Detail of Nuuanu basalt in lower gorge of Nuuanu Stream a short distance inland from Judd Street. Characteristic large blocks, with their surfaces marked by secondary cooling cracks, are shown. (Negative No. 12086)

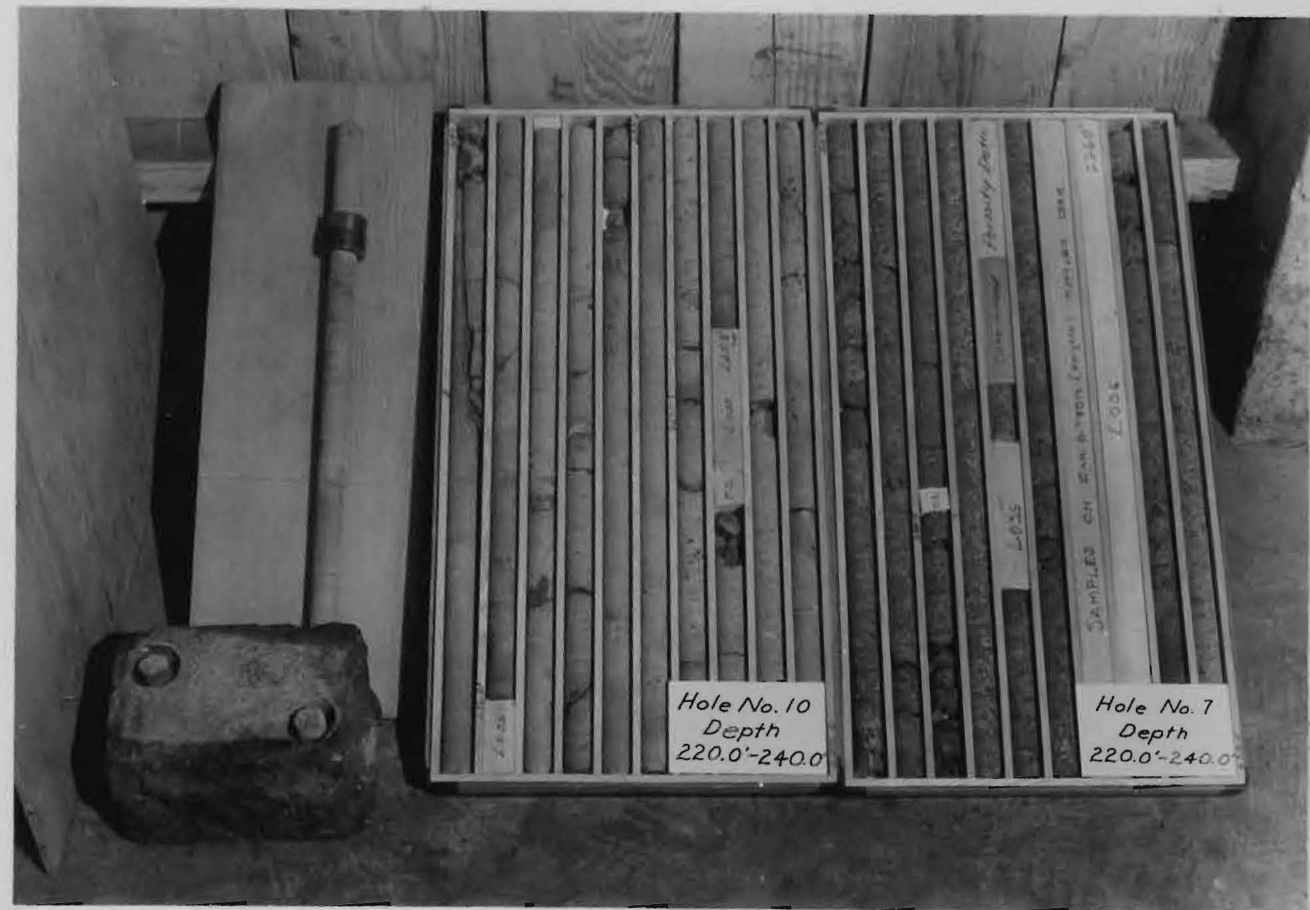


Figure 30 - Boxes of diamond drill cores, with diamond drill on a length of core, at the left. Core in the left-hand box is hard Nuuanu basalt; that in the right-hand box is brown, mottled, palagonitized cinder tuff from the Lower Luakaha cone at a depth of 220 feet below the surface. (Negative No. 12318)

is marked by large augite phenocrysts which show conspicuous hourglass extinction due to zonal growth. According to Winchell, this flow contains olivine and augite phenocrysts in a matrix of nepheline, melilite, pyroxene, magnetite, and accessory apatite (1). (Figures 31 - 36)

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(1) Winchell, Horace, The Honolulu Series, Harvard University Thesis, p. 73, 1941.

Two or three possibly detached arms of the same flow are found in drill holes 4 and 5 near the west edge of the valley bottom. Underneath the known Makuku cinder formation in the middle of the valley is a lava flow about 70 to 100 feet thick which lacks the zoned augites. Since this flow is found in holes 17 and 18 as far inland as the 930-foot surface contour, it is most likely that this flow also came from the Makuku vent. The remainder of the flows shown in the cross-section of Figure 26 as revealed by diamond drilling are sufficiently low in relation to the vent cone of Lower Luakaha that they could probably have come from this source, though it is more likely that they came at least in part from the Makuku vent. The data from a single line of drill holes are insufficient to determine which vent was the source, and it is of course possible that there are other, buried vents.

Luakaha Cinders

The upper and exposed part of the Luakaha cone forms a slight rounded projection of the lower slope of the eastern valley wall of Nuuanu immediately southeast of the Lower Luakaha Falls of Nuuanu

Figure 31 - Photomicrograph of Makuku basalt from block on the rim of Makuku Crater. The large crystals are zonally banded augites. Thin section and locality No. 85. (Negative No. 20284, x 108)

Figure 32 - Photomicrograph of Luakaha basalt from the northwest flank of Luakaha Crater, locality and thin section No. 741. The large phenocryst of olivine shows marginal and reticular alteration to the iron-magnesium mineral, iddingsite.
(Negative No. 20290) (x 151)

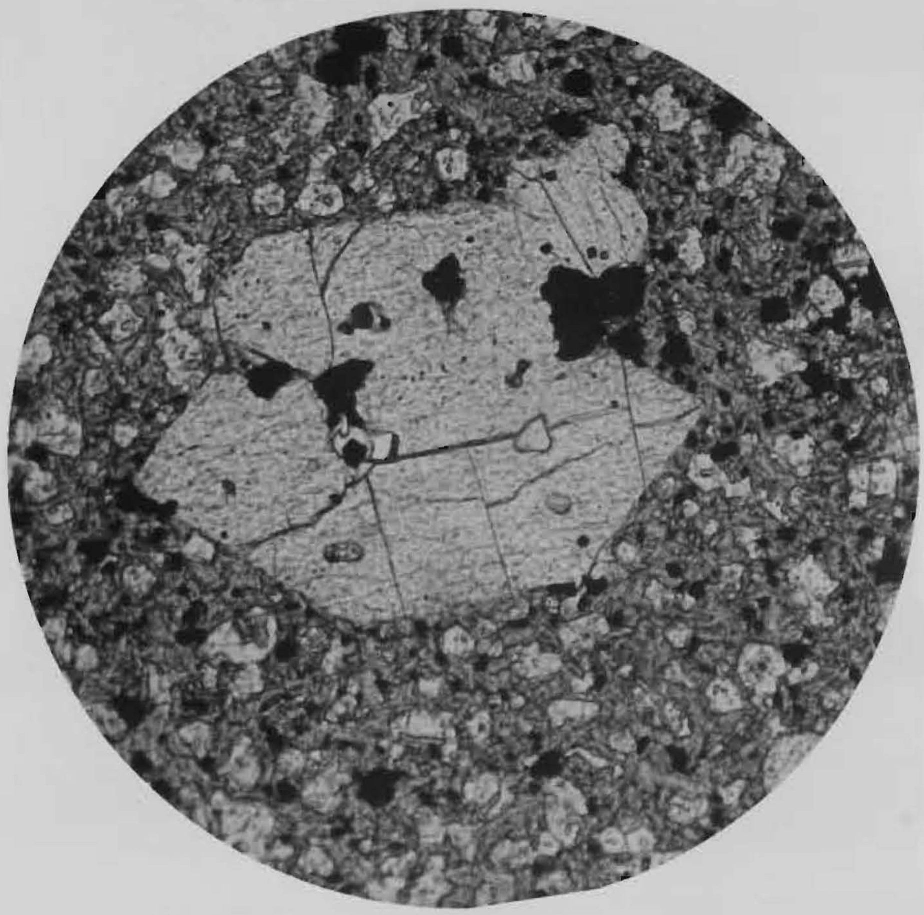

Figure 33 - Nuuanu basalt from west side of Nuuanu Stream at Kapena Pool. Locality and thin section No. 9961. This is one of the specimens chemically analysed under Geological Society of America Grant No. 297-39 and reported in detail elsewhere. The large crystal is olivine, the smaller light grains are chiefly nephelite, the black grains are magnetite, and the granular matrix of intermediate tone is chiefly augite. (Negative No. 20295, x 119)

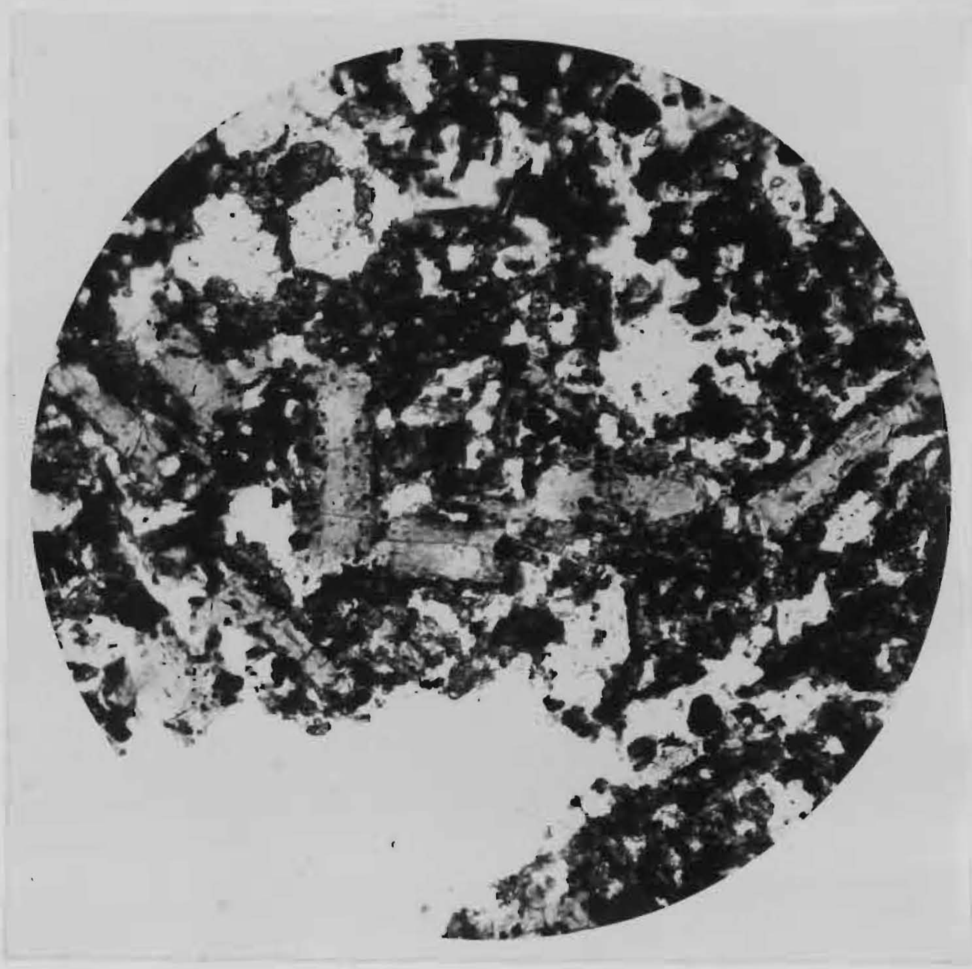

Figure 34 - Photomicrograph of Nuuanu basalt from a depth of 189 feet in Diamond Drill Hole No. 912 near the west end of Dam No. 2 in Nuuanu Valley. The elongate laths are crystals of melilite of an unusual bright yellow color. (Negative No. 20300) (x 98)

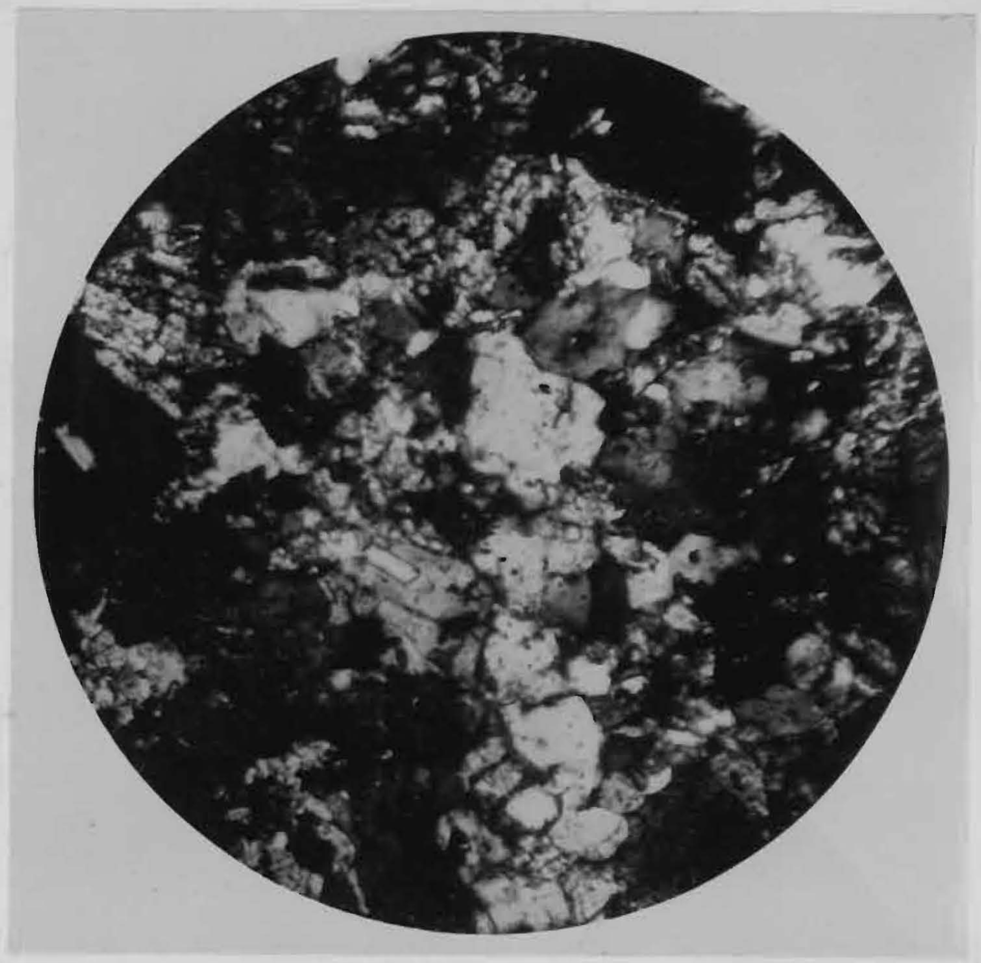

Figure 35 - Photomicrograph of Nuuanu basalt of 225 feet in Diamond Drill Hole No. 10. The matrix consists largely of augite and nephelite. (Negative No. 20304, x 97)

Stream. From the west, looking across the stream toward it the mass shows a slightly suggestive conical form, and from points above it on the east wall there is still more indication of its identity as a cinder cone. It is about 700 feet in diameter as exposed but probably was much larger at the base. Lower Luakaha falls is a cascade of Nuuanu Stream some 50 or 60 feet high, over the edge of thick Nuuanu lava flows. At its base the Nuuanu Stream flat widens to a circular, flat-bottomed cove about 500 feet in diameter which cuts markedly into the flow-mantled valley bottom on the west. Two possible explanations of this alcove are worthy of mention. The cove may have been produced by erosion and undermining of lava flows induced by the encroachment of the Luakaha cone during some of its later stages of building. On the other hand, the chief mass of the cone may ante-date the lava flow filling of the upper 100 feet or more of the valley bottom; and the lava flows may have been molded against the cone, the cinders of which have later been scoured away to form the chief part of the alcove. In view of the depth of cinder and tuff filling and evidently greater age of the cone, the latter explanation is much more plausible.

In its upper portion, the Luakaha cone is composed of medium to coarse cinders and driblet lapilli, with some trickle masses of basalt in it, as well as some heavy lava flow masses locally. The diamond drilling in Hole No. 7 passed through 250 feet of pyroclastic material, the lower 60 feet being well-cemented, mottled palagonite tuff from which excellent cores several feet long were cut. (Figure 30) Below this was 15 feet of weathered talus or alluvial material and then about 15 feet of the earliest Nuuanu basalt, followed by about 110 feet of oldest alluvium lying on Koolau rock at about 400 feet above sea level.

Luakaha Basalt

A large mass of Nuuanu basalt passes steeply down the northern slope of the cone toward the lip of Lower Luakaha Fall. It is not quite certain whether or not this mass came of the same eruption which furnished one of the major flows which lies across the valley at 700 to about 775 feet, but this is quite possibly the case, since it is of similar petrographic character, with the zoned augites in abundance. Beyond observing that any of the lava flows in the lower valley, either at the surface or deeper could have come from this vent, equally as from the Makuku or from both in a simultaneous activity, we lack data to specifically ascribe a given flow to the Luakaha vent. (Figure 29) Both the type of basalt with zoned augites and that without are found in lava flows exposed in various parts of the valley floor and in the inner channels of Nuuanu and other streams. In general the type with zonal augites occurs near the top, and that without the augites occurs in thicker flows, deeper in the valley crop section. According to Winchell, the earlier type consists of nepheline basalt with a very small amount of melilite. Some specimens show no discernible melilite (1).

(1) Winchell, Horace, The Honolulu Series, Harvard University Thesis Op. Cit., p. 71, 1941.

On the other hand, in certain flows encountered by drill holes at depths of 150 to 200 feet below the floor of the valley (Diamond Drill Hole 12, 180 to 200 feet) there are shown in thin section numerous yellow laths of a mineral identified as melilite. This identification has beem confirmed by G. A. MacDonald (1), but no studies have been

(1) Oral Communication

made to determine the significance of the yellow color, though it is of considerable value in correlating lava flows from hole to hole in the section.

Some further data on the petrography of Nuuanu basalts, particularly in relation to other lavas of the Honolulu series are presented by Winchell (2), and much additional information is contained

(2) Winchell, H., The Honolulu Series, Thesis, Harvard University, Manuscript, 1941.

in notebooks of this division. Neither are included here because they are not considered pertinent to the purposes of the present report. (Figures 31-36).

Pali Breccia

Numerous exposures of coarse cinder, and breccia beds, mantled with parallel structure on the very steep slope of the windward cliff opposite the head of Nuuanu Valley and some exposures of tuff in the gap itself show that there must have been a vent from which Honolulu basalt issued in this vicinity. (Figure 37) Stearns has located a vent at an outcrop of breccia south of the Pali Road but considers that a part of the Pali volcanics may have issued at points farther

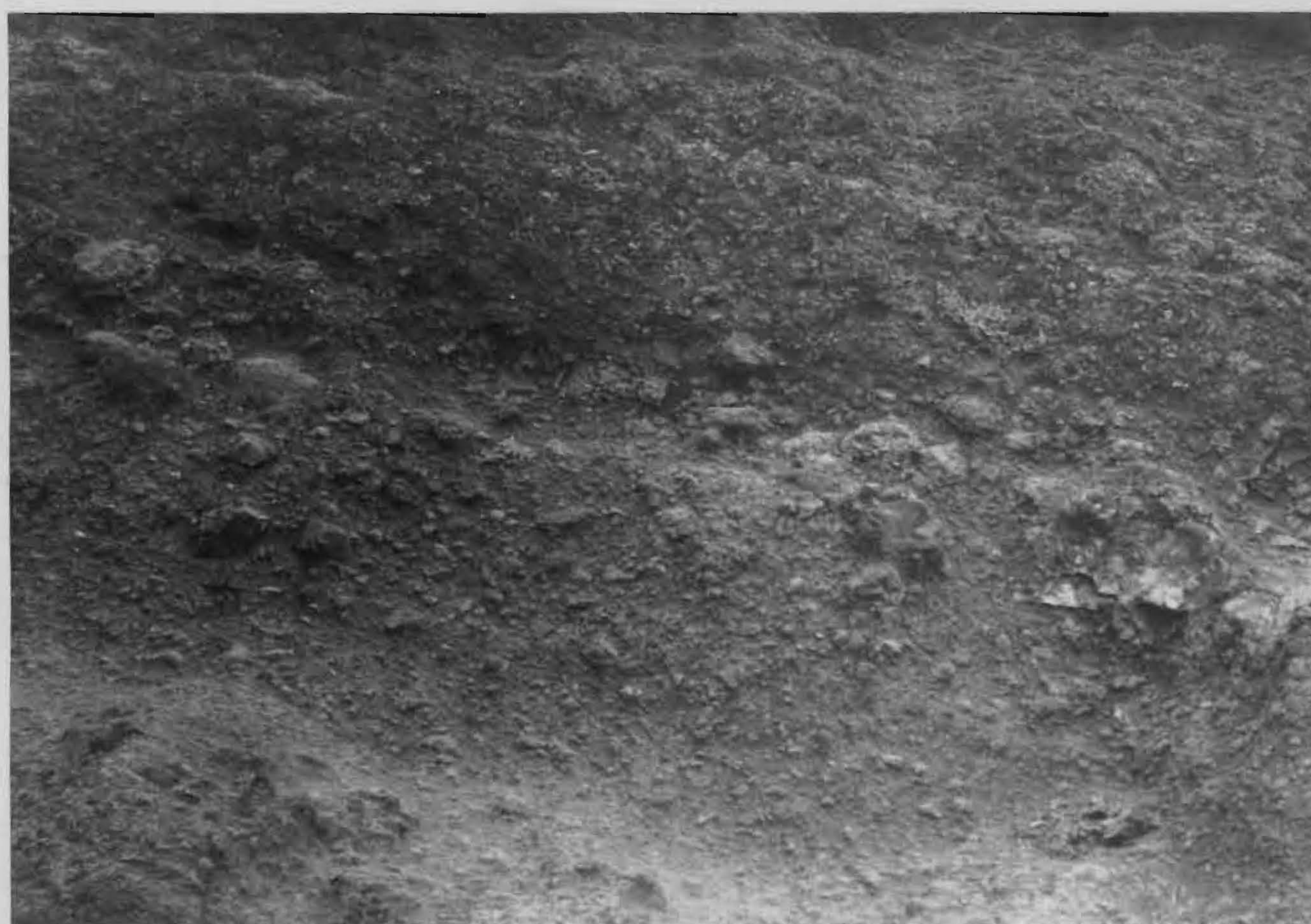

Figure 37 - Outcrop of Pali Breccia, near "Half-Way House". (Negative No. 21040)

northeast (1). Stearns also states that the Pali volcanics are

(1) Op. Cit., pp. 116-117, 1935.

younger than the Nuuanu volcanics since a layer of "fine pumice" attributed to the Pali vent is found interbedded with alluvium in the area of Reservoir No. 4 where it overlies Nuuanu basalt. Since the diamond drilling in Nuuanu Valley revealed such a succession of lava flows and other volcanic formations, evidently erupted at somewhat extended intervals from the Makuku and Luakaha and perhaps other vents, and since the cinder (pumice) of this bed is very similar to the banks on the very flanks of Makuku cone, the present writer considers that this cinder bed found at various points in the Reservoir area could just as likely have come from a late eruption at the Makuku vent. Moreover, in the light of the probable topographic history of Nuuanu Valley and the close relationship between the cinder beds and the present surface, the attribution of this cinder bed to the Pali vent does not seem consistent with the dating of the Pali vent eruption with a stage as early as the Kaena. As to the latter dating the writer has no pertinent additional information.

Pali Basalt

Only a very small area of the Pali basalt has been mapped, at about 500 feet, above one of the turns of the old highway below the halfway house. A few small trickle flows are interbedded with the cinders and breccia from the same vent, all on the windward slope of the range and hence just outside the area strictly covered by this report. The following statement on the petrography of the Pali basalt is quoted from Winchell (1):

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(1) Winchell, H., Op. Cit., pp. 84-86 and p. 166, 1941.

> Specimens of the flow from this vent and of the presumed dike-feeder, exposed at the roadside, contain considerable olivine, plagioclase, nepheline, pyroxene, and magnetite, with minor amounts of biotite and apatite. The olivine shows central areas of lower birefringence, surrounded by zones of higher birefringence, and in some cases there is a rim of iddingsite between (Fig. 33). The outer rim may have a different orientation from the olivine core if separated by an unbroken iddingsite rim (Fig. 34). In the central portions, the mean index of refraction and the optic angle correspond to olivine with about 15 per cent fayalite and 85 per cent forsterite. The peripheral portions are too narrow to give interference figures in thin sections, and are very difficult to distinguish in powder form, but the birefringence difference between the core and the rim can be estimated without the necessity of knowing exactly how thick the section is. This datum indicates that the rim olivine contains about 7 per cent more fayalite than the core, or about 22 per cent fayalite and 78 per cent forsterite. Other minerals in this lava show their usual features. The plagioclase is labradorite and the rock is nepheline basanite.

As pointed out by Winchell in subsequent discussion, the Pali basalt lies much nearer the Koolau basalt in composition than most members of the Honolulu series but less near than the Koko basalt and tuff. The Pali basalt carries the highest amount of nepheline of any of the feldspar-bearing rocks.

PUNCHBOWL VOLCANICS

Punchbowl Tuff

Punchbowl is a circular cone with an exposed outer diameter of about 5000 feet, a rim diameter of 1800 feet and rim elevations ranging between 400 and 500 feet. (Figure 38) With the slightly larger Diamond Head, it is typical for this variety of crater in the Honolulu district. (Figure 39) Practically all of its mass consists of tan to brown palagonite tuff. (Figures 40 and 41) At its landward margin in the Awaiolimu Drive road cut, the base of the Punchbowl tuff, at about 800 feet from the nearest point of the rim, lies on Koolau basalt of the Tantalus spur at 270 feet above sea level. The tuff at this point is about 30 feet thick, and its outcrop ends practically at this saddle. On the seaward side, the base of the Punchbowl tuff at the Beretania Pumping Station lies on a coral reef formation at about 60 feet below sea level.

On the basis of the relationship of the Punchbowl basalt to reef formations and the testimony of Wells 72 and 73 concerning the buried valley of Kanaha Stream, Stearns believes it most likely that Punchbowl was formed during the Waipio low stand of the sea (1). No

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(1) Stearns, H. T., Op. Cit., pp. 145-148, 1935.

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further data are available to the present writer, and he has no basis for specific dissent from this conclusion; but it should be recognized that both the scale of positive and negative stands of the sea (the best time scale we have), and the data from wells, terraces, or the like, from which Stearns has made his correlations of the various Honolulu volcanic episodes are mostly based on single instances, or similarities of materials not yet absolutely traced; and the present writer cannot avoid feeling that while the reasoning is based on correct principles and applied with zeal and ingenuity, the fundamental

Figure 38 - View of Punchbowl Crater looking southwestward from Pacific Heights Road above B. W. S. pumping station. (Negative No. 21169)

Figure 39 - Contact of Punchbowl tuff (upper, banded) on Koolau basalt (irregular, blocky) in bank of Auwaiolimu Drive, southeast of Tantalus Drive bridge in Punchbowl saddle. (Negative No. 21166)

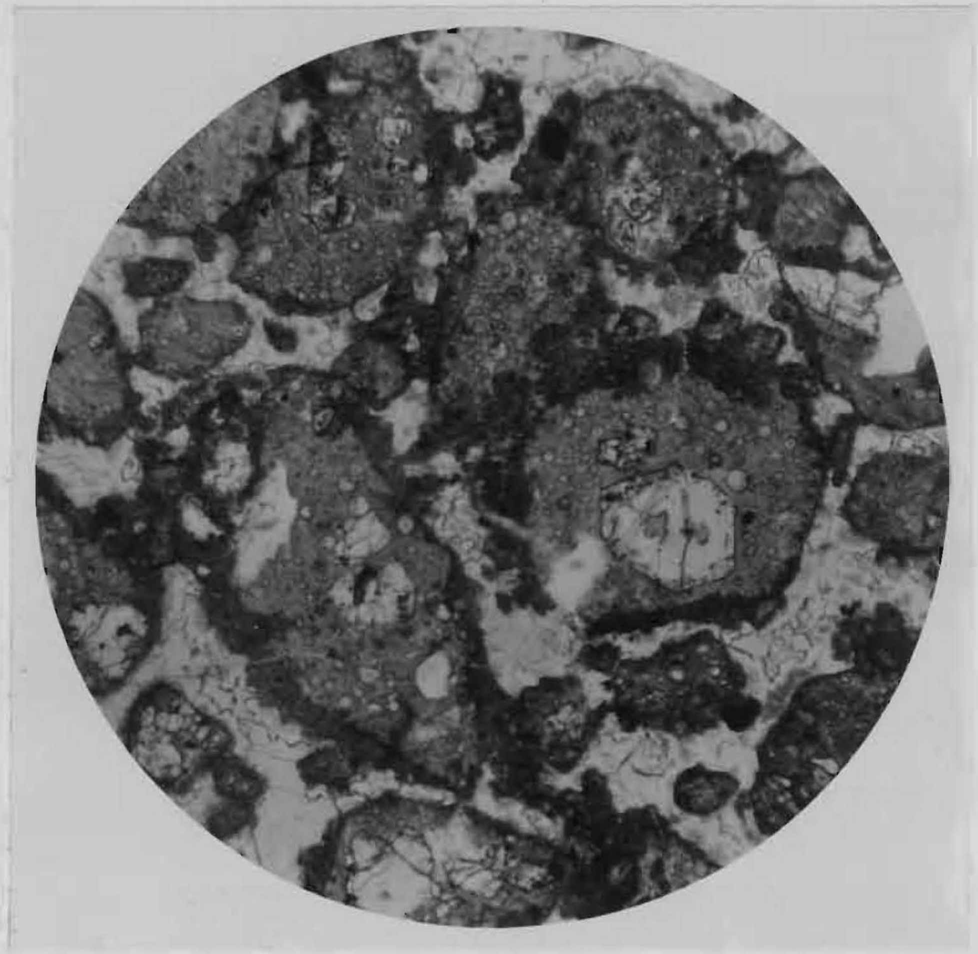

Figure 40 - Photomicrograph of Punchbowl tuff from northeast upper slope of Punchbowl. Locality and Section No. 151 of 1923 collections (Bishop Museum Bulletin 30, p. 106, 1926). Shows assemblage of glassy pyroclastic pellets cemented by secondary calcium carbonate. The light green pellets are rimmed by darker orange-yellow palagonite. (Negative No. 20315) (x 44)

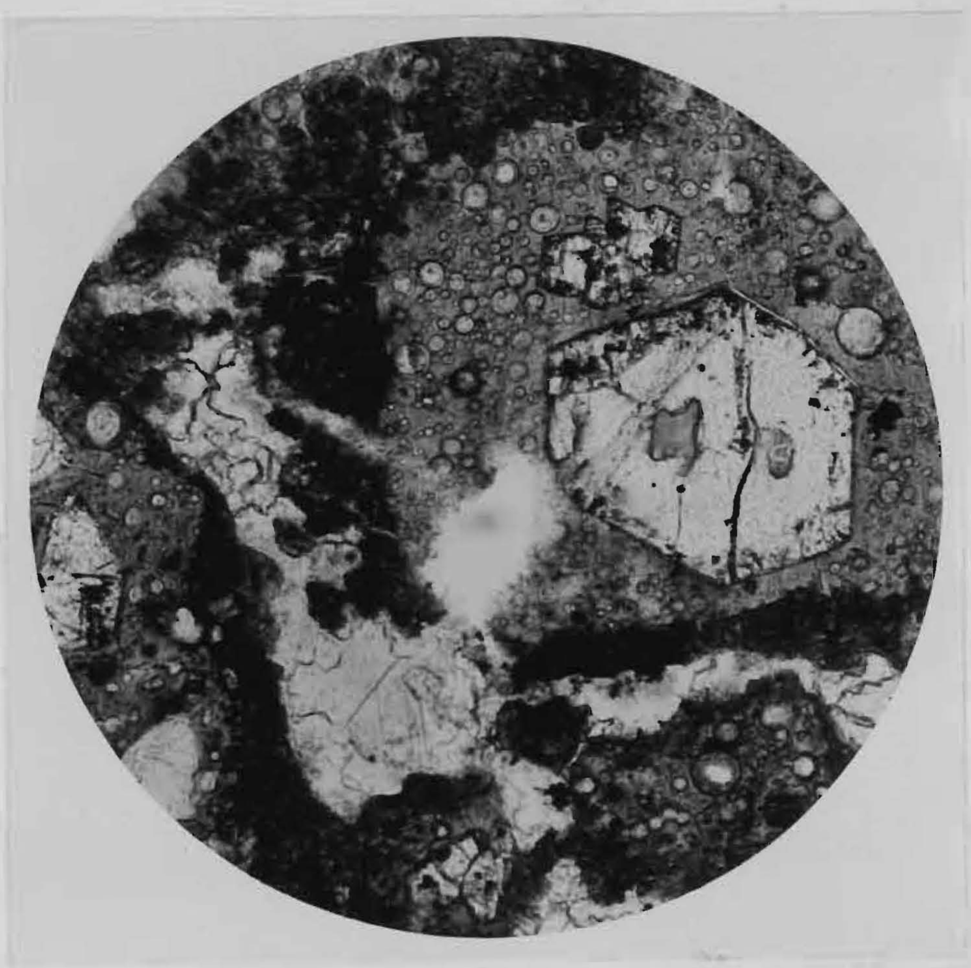

Figure 41 - Photomicrograph of Punchbowl tuff from same section as Figure 40. Shows details of one of the larger glassy pellets, which includes a large crystal of olivine, in which are in turn inclusions of magnetite. The clearer glass is light green, contains a few crystallites, and is highly vesicular. The margins of vesicles are palagonitized, and many are filled with spherulitic inclusions, possibly of zeolite. (Negative No. 20311) (x 96)

data are not beyond question and the conclusions remain too tenuous to justify positive statements.

Speaking in general, this tenuity becomes more disquieting in such instances as the Honolulu episodes of Kalihi and Kamanaiki where wide differences in age are developed by Stearns for flows whose age relationship cannot be directly demonstrated and where homology might suggest closer age relationships. Only much greater detail in subsurface explorations, if such are ever made possible, will develop a more reliable determination of age relationships.

Details of structure and petrography of Punchbowl have been discussed elsewhere (1) (2). In the writer's earlier work in 1923,

(1) Wentworth, C. K., Pyroclastic Geology of Southeastern Oahu, Bishop Museum Bulletin 30, pp. 55-60, 92, 1926.

(2) Stearns, H. T., Op. Cit., pp. 145-148, 1935.

the black volcanic sand found in the crater bowl and around the outer slopes in places was attributed to a second eruption of Punchbowl, an interpretation which was challenged by Stearns, who found evidence adequate to show that the black sand is simply a part of the widespread black sand from the later Tantalus and Sugarloaf eruptions. The greater probability of the latter interpretation is freely conceded.

Punchbowl Basalt

The only exposures of Punchbowl basalt are on the southern rim in and near the road loop and at the small gap in the east rim. Stearns believes that the lava formed a lake in the Punchbowl bowl which later was drained through a fissure. The writer earlier thought the flow came from a point near the road loop and passed through the gap and some distance down the small branch of Kanaha Valley, but more detailed examination with better exposures and more brush cleared away indicates that no lava flow passed down the valley and that such blocks as are now in the valley were let down in the course of encroachment of the valley head across the rim. As has been pointed out, all the basalt found in place dips inward toward the center of the bowl and lies on the inner slope of the rim. Whether the lava formed a complete lake in the bowl, rising to the highest point at a time when the whole rim was much higher, or whether, as seems more likely to the present writer, the lava was thrown or spilled on the inner slope of a part of the rim from a localized vent nearer the southeast side, will be difficult to determine unless extensive additional data are revealed by drilling or other excavations.

A dike was noted in the excavation of the Punchbowl Reservoir at Alapai and Crescent Streets (1), and a lava flow about 15 feet

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(1) Stearns, H. T., Op. Cit., p. 148, 1935.

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thick is revealed in the logs of Wells 88A to 88F at the Beretania Pump Station. The most plausible interpretation is that made by Stearns to the effect that this flow came from the Punchbowl vent by way of the above-mentioned dike on the seaward slope of the cone.

The Punchbowl basalt is described by Winchell as a "granular porphyritic nepheline basalt with more olivine than augite phenocrysts, both major constituents in a groundmass made up of moderately abundant magnetite, dominant pyroxene, only a little less nepheline than pyroxene, and some accessory apatite." (p. 106) It falls in the prevailing group of the Honolulu series which are nepheline and nepheline-melilite basalts. (p.169) (Figure 42)

TANTALUS VOLCANICS

<u>Tantalus Cinders</u>

The Tantalus volcanics have been described in part in the Manoa Report (1), along with the related Sugar-Loaf and Rocky Hill volcanics.

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(1) Wentworth, C. K. Geology and Ground-Water Resources of the Manoa-Makiki District, Board of Water Supply, 1940.

In this report, we are concerned solely with the Tantalus cinders of the cone, of adjacent Pauoa Valley and the corresponding black ash of the Punchbowl area and with the Tantalus basalt which is interbedded with the Tantalus cinders in upper Pauoa Valley and forms part of the floor of lower Pauoa Valley. (Figures 43 and 44)

Tantalus crater is marked by three peaks on a rim about 1400 feet in diameter, each rising slightly above the 2000-foot contour and surrounding an elongate hollow with its floor at about 1800 feet. Tantalus cone stands almost precisely on the ridge of Koolau rock between Manoa and Pauoa Valleys, and its lower parts show an elongate character imposed by the underlying topography. The eastern slope of Tantalus is abruptly continuous with the steep west wall of Manoa Valley which shows mostly bare Koolau rock down to 700 feet, and the

Figure 42 - Photomicrograph of Punchbowl basalt from near breach in rim. Locality and Section No. 1042 of 1923 collections (Bishop Museum Bulletin 30, p. 92, 1926). In the center is a large, zonally extinguishing augite phenocryst with an olivine phenocryst on one side. The matrix, mostly obscure in this photograph, consists of augite and nephelite with magnetite. (Negative No. 20307) (x 99 , crossed nicol)

Figure 43 - Section of dipping beds of ball lapilli of the Tantalus cinder formation in trail bank on north side of cone. This is a good example of the form of bedding mentioned in the text, where the finer lapilli are at the base and the coarser at the top of each bed. The coarsest of these lapilli are about one inch in diameter. (Negative No. 13204)

Figure 44 - Tantalus basalt in channel of Pauoa Stream at elevation approximately 500 feet. This is practically the original surface of the lava flow, the stream having cut a few potholes and smoothed the surfaces of the joint blocks. (Negative No. 13191)

northwestern slope of Tantalus merges with the southeast wall of Pauoa Valley down to 1200 feet.

The latter, having been originally a smaller valley and lying more nearly on the windward side of Tantalus, has been profoundly altered by the fill of Tantalus cinders. Nearly straight north of the vent the fill of cinders formed a topographic divide across Pauoa Valley, throwing the drainage of the ash-filled head of Pauoa over the ridge into Manoa along the course of the present Aihualama Valley. From the cinder divide which is now the head of Pauoa Valley for about three quarters of a mile seaward, the valley is filled 100 to 300 feet deep with cemented cinders on which a palmate system of head branches has been developed. These branches have cut deeply into the cinder fill in the downstream parts. Because of the manner of erosion of the porous cinders (1), these small branches have carved some extraordinarily narrow and deep canyons and some very steep headwalls. On the eastern wall of Pauoa Valley, cinder accumulations continue nearly to the end of the spur, alternating with the parts of the wall from which they have been stripped. The partly weathered cinder formation has been extensively dug commercially in this area for fill and garden soil. On the top of the Tantalus spur of the Koolau Range, leeward from the vent, and in adjacent valleys of the Makiki system, Tantalus cinders forms a mantle which in some places is probably 50 or 75 feet thick but in many others is thin enough so that the underlying

(1) Wentworth, C. K., Ash Formations of the Island Hawaii, Hawaiian Volcano Observatory, Third Special Report, pp. 64-65, 1938.

weathered Koolau rock or residuum is revealed in road cuts 10 to 20 feet deep. Because of this mantling relationship, mapping at any scale must be an approximation.

Driblet material in masses up to 6 inches across, together with lava balls and bombs, are found in parts of the cone near the vent, but most of the cone is composed of cinder lapilli in the grades 4 to 16 millimeters. Mantle bedding of striking sweep and uniformity of bedding is characteristic of the black sand and cinders, both near the vent and one to two miles away, on Punchbowl and beyond. When fresh, the cinder and black sand particles are megascopically black irridescent bits of glass in the form of vesicular ribbons or droplets. Under the microscope, the glass is transparent, light green and marked by microlites and bubbles. The Tantalus eruption appears to have been especially productive of magnetite crystals which have become freed from the glass. Fine black magnetite sand, possibly with some ilmenite, is especially noticeable in roadside rills in the vicinity of Tantalus.

Nearer to the vent there are beds composed chiefly of small balls, ¼ to 2 inches across and occasionally larger. These balls may be in part due to aggregation within the throat of the vent, or to the accretion of finer dust around a single heavier nucleus in the atmosphere during flight, or finally to such accretion (snowball fashion) by rolling on slopes after landing. Some possible light is thrown on this matter by the observed fact that in any given unit of these ball beds, the size of the balls increases progressively upward. For example, in a bed 9 inches thick, the balls forming the base may average ¼ inch across and may increase very uniformly through the 9 inches to an average of perhaps ¾ inch. Both top and bottom of the bed are very distinct and may lie in contact with the bottom and top respectively of beds of similar range of coarseness. It is difficult, using any assumption in regard to expulsion mechanism, or flight behavior, to explain such uniform increase of size, a condition quite the reverse of what would normally be expected. It is suggested, tentatively, that such a gradation may be due to progressive accumulation by rolling down a slope, the balls capable of reaching a given spot being in general only those enough larger than those just laid down to pass over the existing surface, and increasing as a given layer is built up. These balls usually have a core of solidified lava, or of more compact, heat-welded ash, which is surrounded by less compact material taken up in the course of its growth in the air or in rolling on the slope.

In places the finer parts of the Tantalus pyroclastics are somewhat palagonitized, but for the most part they are merely cemented or bonded by compacting or by a slight deposition of lime so as to stand in vertical walls 5 to 20 feet high. The mechanical composition and porosity of a few samples were determined in the course of earlier studies by the writer, and the following table of porosities is taken from that report (1).

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(1) Wentworth, C. K., Pyroclastic Geology of Oahu, Bishop Museum Bulletin 30, pp. 96-98, 1926.

SPECIFIC GRAVITY AND POROSITY OF BLACK ASH

Number of Sample	Diamond Head			Punchbowl					Avg.
	50	85	161	1	515B 2	3	535	559	
Gross specific gravity as poured into graduate.......	1.30	1.08	1.08	.99	1.00	1.00	.82	.83	1.02
Net specific gravity of fragments as broken.........	2.44	2.37	2.57	2.39	2.40	2.47	2.25	2.41	2.41
Porosity including open vesicles of fragments.......	.470	.544	.581	.586	.585	.597	.637	.655	.577

These data show that a deposit of such material may have a porosity of 50 to 60 per cent, subject to be somewhat reduced by cementation. The permeability of two samples collected in Pauoa Valley was measured as 3140 to 3300 gallons per day per square foot per foot per foot, respectively (1).

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(1) Palolo-Waialae Report, p. 183, 1938.

Tantalus Basalt

This basalt was extruded from the Tantalus vent during the eruption which produced the Tantalus cinder formation. The basalt overlies some of the cinder and underlies the later part of it. It is exposed in the edge of Pauoa Flats, in the small "cirque" which

Aihualama Stream has cut at the top of the Manoa wall. Here it lies on a thin layer of talus and alluvium above the surface of Koolau rock. Similar relationships are shown in the axis of Pauoa Valley at about 950 feet. The basalt is exposed in various deeper parts of channels cut in the lower parts of branch channels of Pauoa Stream on the western base of Tantalus cone and somewhat discontinuously down the channel of Pauoa Stream to the head of the lower valley flat. (Figure 18) The form of lower Pauoa Valley flat indicates clearly that the basalt spreads across the floor and passes seaward to merge with Nuuanu basalt in the upper structure of the coastal plain. Tantalus basalt was revealed in three diamond drill holes in Pauoa Valley in the vicinity of Booth Spring as being 20 to 30 feet thick, with an interbedded lens of tuff in places. Under the basalt was 60 to 70 feet of somewhat cemented cinder tuff, lying on 5 to 30 feet of weathered talus or other secondary detritus which in turn lay on the Koolau rock.

Stearns has stated that the Tantalus basalt forms the barrier cutting off Pauoa Flats from the existing Pauoa Valley and that the Tantalus basalt was erupted toward the end of the Tantalus eruption (1).

(1) Stearns, H. T., Op. Cit., pp. 161-162, 1935.

These statements do not seem to the present writer either quite consistent with each other or with the outcrops he has seen. It seems more likely that the basalt was midway during the eruption, that the barrier was well established by accumulation of cinders in the narrow valley opposite the vent and that the part of the basalt which undoubtedly lies under a considerable area in the Pauoa Flats may be distinct from the basalt which lies between considerable thicknesses of cinder tuff in various parts of the east side and the axis of Pauoa Valley.

According to Winchell, the Tantalus flow is unusual petrographically for its "high percentage of melilite plates, sections of which are elongate, giving the rock a felty appearance in thin section. Flow texture is developed locally....... Few augite or olivine phenocrysts, much pyroxene and nepheline, and considerable magnetite characterize...... the Pauoa (Tantalus) flows." (1) (Figures 45 - 47)

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(1) Winchell, H., Op. Cit., pp. 118-119, 1941.

Intermediate sedimentary formations

INTERMEDIATE ALLUVIUM

As has been set forth in earlier reports, the intermediate alluvium here described is intermediate in hydrologic character between the highly impermeable older alluvium and the small amounts of recent alluvium of stream channels. It probably covers a wide range of age, though in general its surface parts are not so old, nor so fixed in character as the older alluvium, and on the other hand, its deeper parts are no doubt materially older than the typical recent alluvium. To a large extent, it is hillside material which is subject to downslope movement and to addition from the top. More complete discussion has been offered in earlier reports (2).

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(2) Wentworth, C. K., Geology and Ground-Water Resources of the Kalihi District, pp. 43-45, 1941.

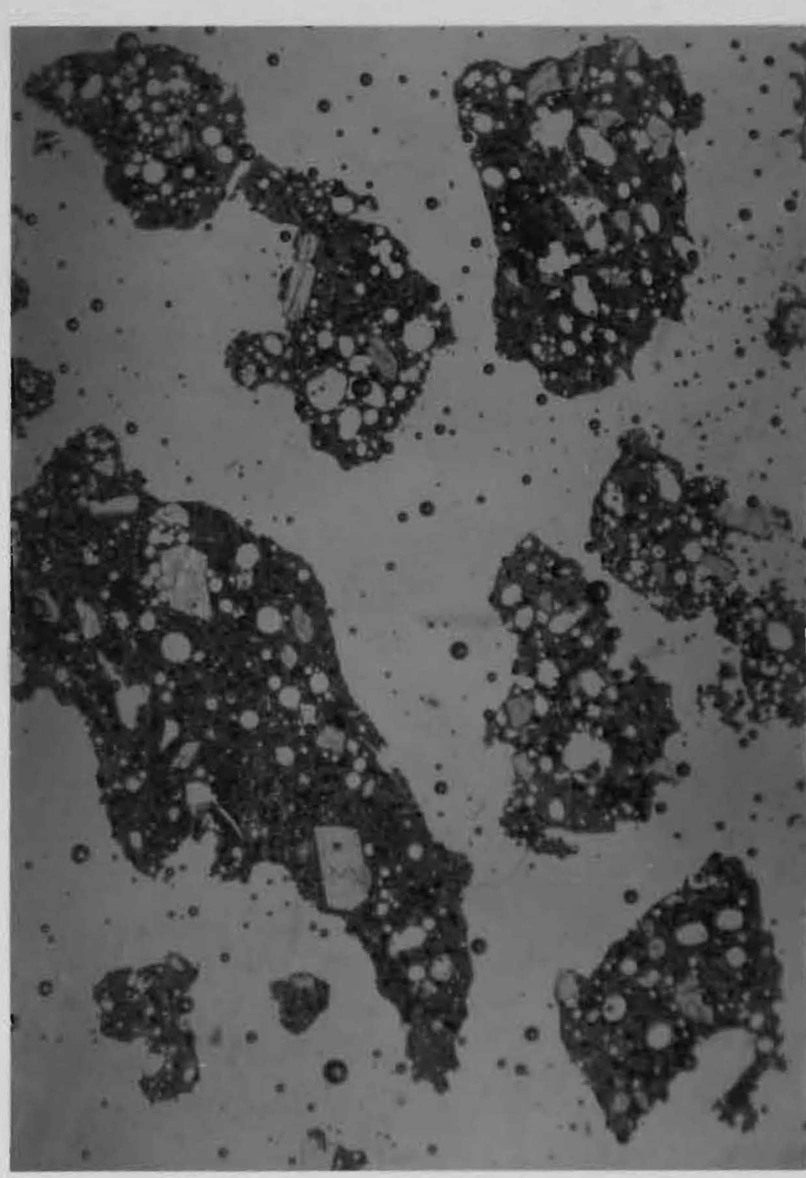

Figure 45 - Photomicrograph of thin sections of lapilli of Tantalus cinders. The lapilli are of glass, vesicular, with phenocrysts of olivine and microlites of other minerals. (Negative No. 20318, x 15)

Figure 46 - Photomicrograph of Tantalus basalt from channel of chief eastern branch of Pauoa Valley at 1275 feet elevation. Matrix is dark, emphasizing the conspicuousness of the phenocrysts of olivine and melilite with transverse peg structure. Section and locality No. 1093, collected by Sohlberg. (Negative No. 20317) (x 96)

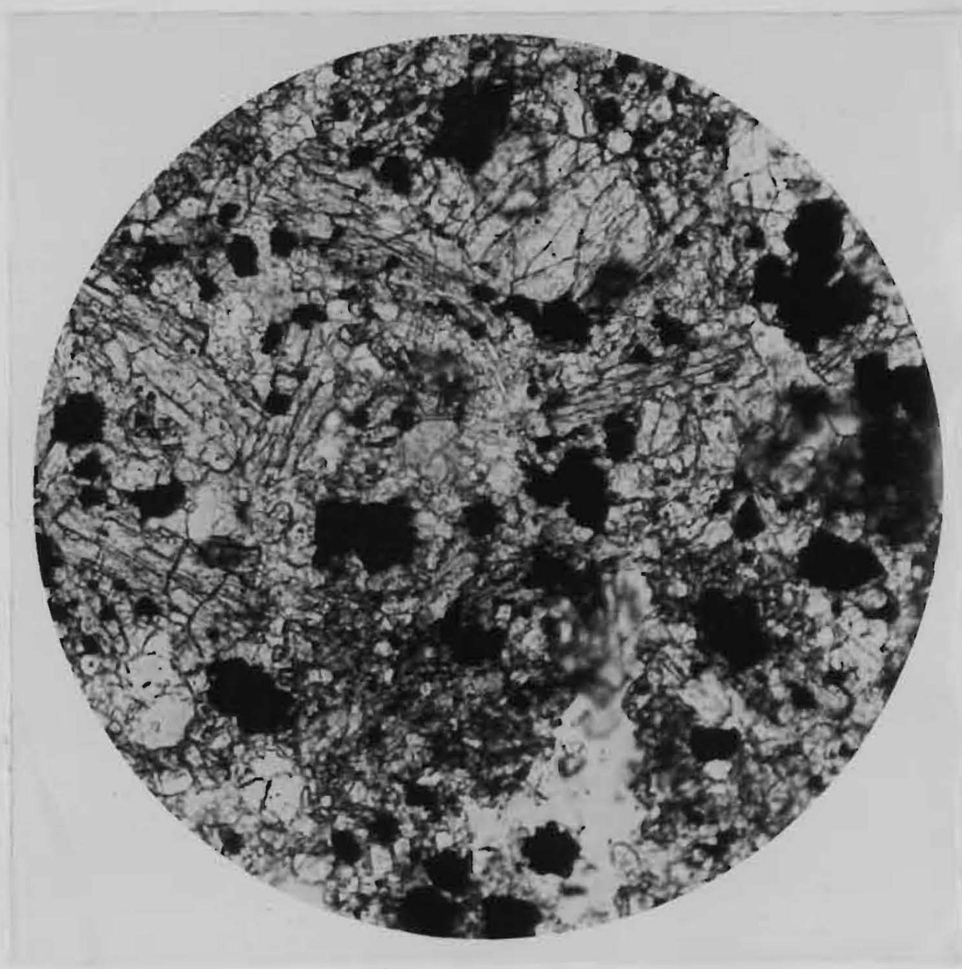

Figure 47 - Photomicrograph of Tantalus basalt from locality and specimen No. 4460, near Pauoa Stream channel upstream from bridge of Pauoa Road. (Negative No. 20320, x 131)

In the Nuuanu-Pauoa district there are large areas of lateral alluvial fans and of mantle rock on parts of the steeper mountain slopes which cannot be classified as older alluvium and which in turn are not recent alluvium. These have been mapped as intermediate alluvium. This formation in its entirety is thus by far the most important formation serving to retain and hold up surficial ground water. It is also chiefly involved in the soil avalanches which are common and important in the mountain area. (Figure 48)

INTERMEDIATE MARINE FORMATIONS

The seaward margin of the coastal plain in the Nuuanu-Pauoa district is underlain by consolidated reef formations, concerning which the chief information comes from well logs. A compilation of sections indicated in these holes shows that in the eastern part of the area reef formations extend from slightly above sea level with little break to about 200 feet below sea level. In the part seaward from Punchbowl a few thin reef masses are found at sea level, below which are some 60 feet of Punchbowl tuff, lying on reef limestone which goes down to 200 feet below sea level. Below 200 feet, the coastal plain formations consist chiefly of weathered land debris ("clay" in the drill logs). The upper part of the cap rock, including both marine and terrigenous materials, belongs in the category of intermediate sedimentary formations, but no detailed description is possible.

Figure 48 - Scar of large soil avalanche on the west wall of Lulumahu Valley opposite the West Waihi saddle. (Negative No. 13772) This slide took place probably in late August, 1939, having been first recorded on September 6.

Recent sedimentary formations

RESIDUAL FORMATIONS

On the little-dissected surfaces of the flow-slope facets, such as that of the Kapalama area (upper Alewa Heights) and parts of Pacific Heights, the weathering of lava flows through some hundreds of thousands of years has produced a mantle 10 to 50 feet thick of weathered residuum which has remained sufficiently in place to show the major volcanic structures. This material is relatively impermeable and is still in the process of formation, though parts of it are very old. Because it lies at the present surface and forms the soil and subsoil, it is mentioned here as a recent sedimentary formation. This material is important chiefly because it retards the absorption of rainfall into the underlying and more permeable rock.

Many of the ridges are mantled for a few feet at their very crests by Koolau residuum, and partly weathered Koolau rock is found at the surface in most parts of the mountain area even on very steep slopes except where active streams or rapid undermining suffice to uncover sound rock. It is impossible to discriminate sharply between weathered Koolau rock and what we here call Koolau residuum. In the mapping, because of the very subtlety of this discrimination, it has only been practicable to map as residuum those areas which are large enough and so topographically situated as to be readily recognized and to be regarded as hydrologically significant in the natural disposition of rainfall, hence, practically only the broader facet areas, or broad places on the ridges.

The Koolau residuum in its most fully weathered form is an almost structureless red laterite, the upper part of which forms the red soil of many of the present and earlier pineapple fields. In many places some 10 to 15 feet of such red laterite is present. Within the upper parts and increasingly downward there are slightly less weathered parts which tend toward lighter brown or buff or yellow colors and in which the original vesicles of the lava flows persist. To see these best, the residuum must be broken apart, rather than cut. Still farther downward is an increasing expression of structure, both of original forms of lava flows, aa or pahoehoe structures, dikes, and sills if any, and also of early secondary structures such as spheroidal weathering. Often on drier scars, bared of vegetation, the partly weathered rock breaks into small polyhedral masses of gray-green and red colors on the surface, and the rock which is still in place shows structural details very clearly. A striking feature is the highly characteristic color of individual lava flows, which shows especially in the notable mottling of weathered gravels.

EOLIAN, TALUVIAL AND COLLUVIAL FORMATIONS

In a region of steep slopes, rugged topography and rapid changes of slope and of vegetation and climate, there is a rapid transition between residual materials and the various transported components of the mantle rock. In a few localities, leeward of bare scars where wind scour is active, there are banks of eolian lag material consisting of pellets and small fragments of weathered rock in the 1- to 4-millimeter sizes. These banks are rarely more than three or four feet thick or more than a few square yards in extent.

In a few places at the base of steep cliffs, there are small loose-textured accumulations of blocks, but such are much more restricted than in colder, drier regions; and practically all the fans and cones that flank the lower valley walls are made up of materials sufficiently weathered and sufficiently intermixed with fines that the whole is compact and free from large openings. In the higher parts of such masses, nearest the cliff, where the slope of accumulation is 35 to 45 degrees, the movement of the material under the impetus of gravity is undoubtedly aided by water, both flowing over the surface in rills and also in wetting the whole mass to reduce its internal friction. The existing slopes are unquestionably adjusted by the frequency and amount of saturation. During dry periods, and during ordinary wet periods, these masses are stable, but after exceptional rains and protracted ground saturation there is some slumping and surface erosion. On lower slopes, where the material is mostly finer in grain, water is also an important agent in the transportation and the determination of slope stability. Because of this, it is not quite correct to speak of this material as talus; on the other hand, though this material grades seaward and streamward into true alluvium, it is hardly alluvium as a whole, despite the custom in Hawaii of speaking of alluvially-filled valleys. In these reports and in the writer's note, the composite term "taluvium" has been used to designate the material which is intermediate between talus and alluvium. Some of this material would be called colluvium by geologists, and to it the term "cumulose" might also be applicable; but since the mode of accumulation is not easily characterized, it seems best not to apply terms which have acquired elsewhere a somewhat specific connotation. In view of the importance of weathering modifications and of saturation by water in promoting the movement of such materials by creep, it appears that the arrangement of particles originally established either by direct fall or by movement under the impetus of water of discrete particles is subject to extensive modification.

The resulting lack of ordinary sedimentary bedding in much of the weathered, coarse detritus has led to identification of some of it as mudflow material (1). The present writer understands by the term

(1) Stearns, H. T., Op. Cit., pp. 19-20, 1935.

"mudflow", a material which was placed en masse as a mud after moving some distance downslope as a mud. In this sense he doubts if any appreciable part of the Hawaiian material is true mudflow. It seems more likely that the deposits in question have been deposited progressively upward from the bottom like any other sedimentary materials but that in course of weathering and drying and wetting the mass has been so rammed and kneaded and in places slumped that only the grosser bedding structures remain, if indeed these survive.

RECENT ALLUVIUM

This term is here used in a practical hydrologic sense rather than in the stratigraphic sense as post-Pleistocene. Recent alluvium here means stream channel gravels of loose texture which are subject to more or less concurrent reworking, or flood-plain deposits which are subject to active growth by further overflow of the stream. Owing to difficulties of mapping in detail, not all such has been mapped as recent alluvium but has probably been incorporated with intermediate alluvium, especially since the underlying parts probably belong to the latter category. Deposits of coarser stream gravel which are physically suitable for the storage and release of ground water are very restricted in Hawaii, and are of wholly negligible hydrologic importance. The finer-grained flood plain alluvium is found over extensive areas but is not a satisfactory water yielder from which to develop water. Despite the fact that its porosity is probably high (40 to 50% or higher) its permeability is moderately low.

It is important to emphasize the fact that Hawaii is for the most part a rugged land, with steep slopes and only short streams of rapidly changing characteristics. This means that alluvial deposits are lensy, irregular, often coarse-grained initially, but subject to rapid change of character by weathering. Many of the streams may carry boulders of large size in occasional floods and only the weathered silt and clay at other times. (Figure 49) Alluvial sand is especially deficient in Hawaii (1).

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(1) Wentworth, C. K., Diamond Head Black Ash, Jour. Sed. Petrology, Vol. 7, pp. 97-102, 1937

RECENT MARINE FORMATIONS

In this category are included modern sand beaches and other shore deposits in active process of formation. In this district these are at a minimum, since the shore line is so fully occupied by piers,

Figure 49 - Boulder gravel deposited on Konia Street east of Houghtailing Street during flood of February 27, 1935. View is looking northwest along Konia toward Houghtailing. The flood flow of Niuhelewai with a drainage basin approximating 300 acres exceeded the capacity of a culvert passing diagonally under both streets at the intersection, and the channel and culvert became blocked, passing the flood over Konia Street and forming a deposit of several hundred cubic yards, with boulders up to 7 by 4.5 by 2 feet and a total of 11 boulders measured at over 1 ton (12 cubic feet) each. (Negative No. 12416)

wharfs, seawalls and the like. Back of the shore line fixed by these works there has been extensive artificial fill in the construction of streets, buildings and grounds surrounding them.

Diamond drilling and other test holes

A large amount of excavation and some test-hole boring has been done in the coastal plain and built-up section of the city in this district without placing any subsurface data on record. It is unfortunate that in Honolulu, as in nearly all growing communities, the need of making permanent public record of subsurface conditions is not recognized. A half dozen or more public agencies, as well as many contractors and builders, are constantly excavating in the city area today, and except for the none-too-complete records of artesian wells and the occasional records of conditions encountered on some important job, usually kept through the zeal of an occasional employee, no systematic keeping, or pooling, of subsurface data is yet accomplished. No single office, or contractor, can see the prospect of adequate tangible return to justify a systematic inspection of excavations and recording of the data, and no specific public agency or branch office has been charged with such a duty.

The chief subsurface data available for the Nuuanu area are those based on (1) artesian wells, of which only a few have been carefully logged in a manner clearly interpretable today; (2) a series of pits and exploration holes put down in connection with the reconstruction of Nuuanu Reservoir No. 4, in 1932-1934; (3) a total of 15 diamond drill holes in Nuuanu and 3 similar holes in Pauoa, drilled in 1934 and 1935 in connection with geologic studies; and (4) additional diamond drill holes put down in 1937, near the east end of Dam No. 4 in an effort to determine the nature of the East End leak. Records of the diamond drill holes are detailed below.

ARTESIAN WELLS

The data available from artesian wells up to 1925 were summarized by Palmer in his report on the Honolulu Artesian System (1).

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(1) Palmer, H. S., The Geology of the Honolulu Artesian System, Supplement to the Report of the Honolulu Sewer and Water Commission, pp. 1-68, 1927.

Palmer compiled the available data in manuscript form, but neither the text nor graphic logs were then published in detail. Later, the same data, with additions from very few newly drilled wells, were used by Stearns in his discussion of the structure of the Honolulu coastal plain (2). Still later a compilation of logs and hydrologic data for

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(2) Stearns, H. T., Op. Cit., pp. 165-172, 235-272, plate 20, 1935.

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all the wells on Oahu, was published as a part of the same series (3).

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(3) Stearns, H. T., and Vaksvik, K. N., Records of the Drilled Wells on Oahu, Hawaii, Territory of Hawaii, Division of Hydrography, Bulletin 4, 1938.

Stearns, H. T., Territory of Hawaii, Division of Hydrography, Bulletin 5, pp. 131-147, 1940.

The general findings from these wells have been summarized in plate 20, of Bulletin 1, on the Geology and Ground-Water Resources of Oahu and the unnumbered Artesian Map of the Honolulu District, contained in Palmer's report of 1927. From the standpoint of geologic interpretation, the result is far short of what would have been achieved by a similar amount of core-drilling, but it must be remembered that the wells were drilled for the practical development of water and it was not then recognized, nor indeed is it wholly recognized today how important the preservation of information may later become.

DIAMOND DRILL HOLES IN NUUANU AND PAUOA VALLEYS

Studies of areal geology in Nuuanu Valley had clearly indicated that the floor of the present valley has been produced by the filling of a once deeper valley, and the morphology of the valley, with the peculiar arrangement of its streams, together with the known depth of the mouth of the valley, suggested a fill of considerable thickness. The probability that the valley fill constituted a water barrier and that water falling on the valley floor was passed out to sea without reaching the artesian basin made its exploration by drilling a project of sufficient practical importance; and in August, 1934, this work was commenced. Through the courtesy of J. H. Foss, of the East Maui Irrigation Company, the services of an experienced diamond driller, J. M. Heizer, were made available. The latter, after many years of drilling on the mainland, had already done considerable small-diameter drilling in Hawaii and had developed certain very useful methods of drilling and casing holes under the troublesome conditions found in

Hawaii. Very much of the success of the diamond drilling project has been due to Mr. Heizer's skill and patience in this work and to his intelligent cooperation in emphasizing the exploratory phases.

The first seven holes and Holes No. 9 and 10 were located approximately in a line across the valley floor just inland from Reservoir No. 3 and where the elevation of the floor ranges from 830 to 870 feet, with the bottom of the gorge of Nuuanu Stream at 775 feet below Lower Luakaha Falls. The section revealed by these holes is shown in Figure 26. Of especial interest was the presence of two perched water tables, separated from each other and from the basal water. In order to trace this condition down the valley and determine the depth and grade of the ancient valley bottom, Holes No. 8, 11, and 12 were drilled at convenient points approximating a line across the valley at Reservoir No. 2. The cross-section found here is shown in Figure 27. The hydrologic conclusions reached and queries raised by these holes will be discussed in a later section.

In Pauoa Valley, Hole No. 13 is at the margin of the valley bottom just inland from Booth Spring, Hole 14 is in the bottom of a small branch valley on the Tantalus side about 700 feet inland from Booth Spring; and Hole 15 is on the east margin of the valley bottom about 300 feet seaward from the spring, below the road on the east side of the valley. Each of these holes reached the Koolau rock at the base of the valley fill, and each revealed a water table in the Honolulu volcanics, as set forth in detail below.

The diamond core drilling in these two valleys, which was the first of importance on Oahu, demonstrated the manifold value of this method for exploration purposes. The recovery of cores in the Honolulu basalt and in the underlying Koolau basalt was relatively high and permitted positive identification of formations and a study of their character. It was also possible, when needed, to take tube samples of weathered cinders or alluvium, and from these data a practically complete log of the section could be drafted. (Figures 26 and 27) The cores are of small diameter, about 0.92 inches, and they have been transferred to composite cardboard and wood storage boxes 25½ by 13½ by 1½ inches which hold 20 feet of core. Even with complete recovery, and allowing space for access, the cores from 50,000 feet of drilling can be stored in a room 10 by 20 feet up to a 10-foot height.

After drilling, nearly all the holes were cased with 1-inch galvanized pipe, coupled with small-diameter couplings, which would pass the rock parts of the hole. The lower sections were usually provided with holes to allow access of water and in many of these holes weekly measurements of the elevation of water table have been made, yielding a large body of important data on the behavior and fluctuations of the water table. The complete logs are tabulated below. (Figure 50)

Figure 50 - Diamond drill rig and drill crew at Hole No. 14 in Pauoa Valley. Left to right, J. M. Heizer, Harry Iwai, Noboro Morishige, Solomon Hoopai. (Negative No. 12313)

Diamond Drill Log
Hole No. 1 Nuuanu Valley

Lat. 21° 21' 18" N
Long. 157° 49' 12" W
50 ft. northwest of Old Pali Road at junction with Kamehameha Highway.

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0	866.5	1.5	Vesicular, grey, olivine basalt, 0.35 core.	July 25, 1934
1.5		1.9	Vesicular, gray olivine basalt, with secondary druse in vesicles, 1.67 core.	0 - 6' Soil, B. M. 865.3. Root of Tree.
3.4		2.2	Vesicular, gray, basalt more weathered toward bottom, 1.17 core	
5.6		2.0	Sounder at top, dark basalt, with increased weathering at bottom, 1.42 core	Med. hard basalt
7.6		1.4	Brown, earthy, soft material, no core	Will not core.
9.0		1.0	Brown, earthy, soft material, .75 core	Casing seated at 10 ft.
10.0	856.5	2.8	Sound, vesicular light gray, basalt, 2.8 core	
12.8		2.2	Sandy-textured, red, sticky material, 1.85 plug	No leaks to 15 ft. Bottle sample - Leaks water (100%) at 15.0'
15.0		1.0	Coarse, gritty, dark brown material with some clay, 0.8 plug	Bottle sample
16.0		7.8	Cinders, red, earthy	
23.8	842.7	4.2	Slightly speckled, brownish-gray basalt, 4.0 core	No sample - Casing seated @ 23.8' New 100% leak @ 25.0' Increasing hardness with depth
28.0		4.0	Similar to above, harder and grayer, 3.72 core	
32.0				

Diamond Drill Log
Hole No. 1
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
32.0				
		2.0	Slightly mottled gray basalt, 1.67 core	23.8 - 101.1 basalt rather broken, 40%, leaky. This formation gradually grading into blue color and hardening with depth. At 25' rock would be classed as "hard to very hard."
34.0	832.5			
		5.0	Hard, continuous, light-gray basalt, with very few vesicular zones, 4.36 core	
39.0				
		1.0	Badly broken rock to 40.4, no core	
40.0				
		2.1	Somewhat shattered, darker gray basalt 1.92 core	Finish day's run
42.1	824.4			
		4.5	Fine-grained, dense, nearly black basalt 4.50 core	Commence day's run
46.6				
		4.7	Same, 4.54 core	
51.3				
		4.1	Continued, hard, dense, fine-grained basalt, 3.95 core	
55.4				
		3.5	Same, slightly pitted weathered zone from 56.3 to 57.5, 3.47 core	
58.9				At 62.5 to 63.0
		4.9	Slight fissuring and pitting of surface of core. Otherwise ditto. 4.54 core	
63.8				
		4.6	Continuous, dense basalt dark gray slightly coarser grain, 4.44 core	60' - 1" pipe placed in hole on completion with bottom end resting on broken rock.
68.4				
		3.9	Same, slightly more, pitted and weathered at bottom, 3.63 core	
72.3				
		2.4	Gray, slightly coarser grained basalt, slightly weathered, 2.31 core	
74.7				

Diamond Drill Log
Hole No. 1
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
74.7				
		3.2	Slightly pitted, oxidized gray, hard basalt 2.79 core	
77.9				At top of this pull was single piece of core 3.90' long. Broken en route to laboratory.
		4.5	Hard, slightly granular basalt, 4.5 core	
82.4	784.1			
		4.6	Dark gray, hard basalt, 4.6 core	
87.0				
		9.5	Same, a few rusty seams, a few phenocrysts olivine, 9.50 core	Changed to 10' core barrel.
96.5	770.0			
		3.2	Slightly more oxidized more seams and breaks 3.2 core	
99.7				
		1.4	Pinkish gray, somewhat oxidized basalt, 1.35 core	
101.1				
		2.1	Broken, somewhat weathered basalt, 0.25 core	Ground inclined to cave.
103.2	763.3			
		3.3	Red "clay" with lumps 1.80 core	50% water leak. Bottle sample
		3.2	Same, no sample attempted	103.2 - 109.7 Red clay? With lumps in layers of very porous "honey-combed" old decomposed basalt.
109.7				
		1.7	Pinkish-gray oxidized basalt fragments 0.8 core	
111.4	755.1			
		6.6	"Clay" with lumps 0.35 core	Bottle sample, no more attempted.
118				
		3.0	Same, no sample attempted.	(7/26/34) At 10:00 A.M. commenced carrying casing down through rock, from 23.8 on down.
121.0				
		3.3	Purplish gray, weathered basalt, 2.85 core	
124.3				

Diamond Drill Log
Hole No. 1
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
124.3				
		4.4	Harder, black, nearly fresh basalt, 4.2 core	Same on 7/27/34, 7/28/34 and prior to 9:00 A.M. on 7/30/34.
128.7	737.8			

BOTTOM HOLE NO. 1

Diamond Drill Log
Hole No. 2 Nuuanu Valley

Lat. 21° 21' 19" N
Long. 157° 49' 14" W
450 ft. northwest of Old Pali Road at junction with Kamehameha Highway.

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0	838.0	1.0	Red soil. No sample	11 A.M. 7/30/34 drill started
1.		2.2	Irregularly and coarsely vesicular medium gray basalt 1.13 core	1 - 5.2 medium hard basalt.
3.2		2.0	Similar but slightly harder vesicular basalt, 1.68 core	
5.2		4.0	Harder, darker, less vesicular basalt, broken 1.02 core	5.2 - 9' badly broken basalt
9.2	828.8	2.3	Brown mud and lumps 1.3 core	9' - 11.5 Red clay? With gravel. Gravel predominates toward bottom. This formation leaks badly. 100% leak
11.5		4.4	Weathered, vesicular, amygdaloidal basalt 4.29 core	11.5 - 17.3 Porous medium hard basalt. Bottle sample.
15.9		1.4	Medium grain, gray somewhat vesicular basalt, 1.40 core	
17.3			Brown, gritty, lumpy residue from ash, 1.20 core	17.3 - 35 Red Clay? Grading into gravelly clay toward bottom. Bottle sample - no more samples attempted.
24.0		16.0	Continued, soft material, no sample	35' - 37' Red honeycombed decomposed basalt. Caves into hole. 100% water leak. Bottle sample.
40.0 +		6.8	Continued soft, brown, no sample attempted	
46.8				

Diamond Drill Log
Hole No. 2
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
46.8				
		4.5	Compact, dark gray, medium grain basalt, 4.5 core	7/31/34 37' - 46.8' Red Clay? Casing seated at 46.8
51.3				
		5.0	Continued about same, hard long cores 5.0 core	100% water leak at 48'
56.3				
		5.8	Gray, slightly vesicular basalt, somewhat broken 5.23 core.	46.8 - 92' Rather hard gray basalt at about 88' slight sand? Leak into Hole. Sample in bottle.
62.1				
		6.0	Somewhat vesicular basalt fairly hard, some breaks 5.95 core	
68.1				
	769.9	7.8	Slightly vesicular, hard gray basalt, 7.75 core	
		9.1	Slightly more weathered vesicular, rather durable basalt, 8.95 core	8/1/34
85.0				
		4.0	Vesicular core, somewhat broken but fairly fresh 3.95 core	Bottle sample
89.0	744.8			
		1.5	Similar but denser 1.45 core	
90.5				
		2.0	Vesicular, broken, somewhat weathered basalt, 1.5 core	
92.5				92.5 - 96.5 gravelly clay
		0.8	Gritty, dark, drab detrital material, 0.5 core	Bottle sample
93.3				
		3.2	Soft material, no sample attempted	
96.5				
		3.5	Coarsely vesicular, weathered basalt, 1.15 core	
100.0				

Diamond Drill Log
Hole No. 2
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
100.0				
		12.9	Weathered basalt	100 - 112' Cut with chopping bit as too soft to core well. From about 110 formation changes color frequently to gray, which color predominates from this depth.
		1.8	Weathered, vesicular basalt at top, grades to hard, dark gray basalt at base, 1.8 core.	
114.7				
		6.6	Continued hard, medium gray basalt, 6.4 core	
121.3				
		6.0	Coarsely vesicular gray basalt, weathered toward base, 3.0 core	Bottle sample marked "sand" picked up at 132.5 but is believed to have run into hole from about 88'.
127.3				
		5.3	Weathered gray to brownish at top, toward bottom becomes purply brownish, closely vesicular weathered, still firm basalt, 2.0 core	
132.6				
	705.4	1.9	Soft, red-brown material 0.55 core	132.6 - 134.6 Red Clay? with lumps of rotted red basalt
134.5				
		0.9	Vesicular, gray to purple weathered basalt, .42 core	
135.4				
		1.7	Similar weathered basalt .38 core	
137.1				137' - 145' Medium hard to hard basalt.
		1.0	Weathered at top, gray, sound at bottom, 0.8 core	
143.2				
			Increase in weathering, more vesicular, 1.55 core	
145.0				

Diamond Drill Log
Hole No. 2
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
145.0				145 - 151.5 Red Clay? with lumps of rotted red basalt
	693.0	6.5	Red, clayey material with lumps, 0.6 core	
151.5				Bottle sample - remainder sample not attempted
		4.8	Coarsely vesicular brown, soft, weathered basalt, dry with structure intact, 2.5 core	
156.3				
		0.7	Soft clayey, with lumps	Bottle sample
157.0				
		2.0		No sample attempted
159.0				
		2.0	Partly weathered, gray, vesicular basalt 1.- core	159 - 173.4 Red clay with a few lumps
161.0				
		1.5	Soft, clayey material 0.8 core	
162.5				
		10.9	Soft material; cut with chopper	No sample attempted
173.4				
		3.6	Partly weathered, gray basalt, vesicular 0.9 core	
177.0				
		0.5	Red, clayey material as Bottle sample	177.5 - 178.8 Red clay? and rotted basalt about 80% clay.
177.5				
		1.3	Core .15' Brown, slightly vesicular basalt	
178.8				
		2.2	Core 1.0' Partly weathered, gray vesicular basalt	178.8 - 189'
181.0				
		4.0	Core 3.5' Gray, partly weathered vesicular basalt	
185.0	553.0			189. - 191 Rotted yellow basalt
		5.5	Core 7.3' 3.5' gray weathered ves. bas. 1.0' yellow brown w. Ves. Bas. 3.0' gray weathered ves. bas.	
195.5				

Diamond Drill Log
Hole No. 2
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
195.5				
		9.5	Core 7.6' Gray, fairly dense basalt 1st 2' as smaller nubbins, remainder as 5' chunks	191-204 hard basalt
204.0	634.0			

BOTTOM HOLE NO. 2

Diamond Drill Log
Hole No. 3 Nuuanu Valley

Lat. 21° 21' 26" N
Long. 157° 49' 22" W
1400 ft. northwest of Old Pali Road at junction with Kamehameha Highway.

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0	846.6	26.0	No sample attempted N.S.A.	Ground elevation. Clay with occasional boulder, water leak at 21'.
26.0		2.5	Grey, weathered, somewhat vesicular basalt, weathered to brown. 0.8 core	21 - 34.5' Alternate layers of clay and clay with coarse cinders or broken basalt
28.5		6.0	N.S.A.	
34.5		2.0	Grey, weathered, somewhat vesicular basalt. 0.6 core.	Hard, badly broken basalt.
		9.5	Soft claylike material of brown color in tube. 0.5 core	Red Clay?
46.0		4.3	Grey, slightly vesicular basalt. Core 2.7	46 - 55.5 Hard basalt
50.3		5.2	Fairly dense, gray basalt vesicular in places. 4.8 core	
55.5	791.1	1.3	Tube sample of brown clay-like material. 0.7 core.	
56.8		0.5	Red-brown clay-like material	Bottle sample No. 1
57.3		49.7	Red-brown clay in tube. 0.6 core	55.5 - 202.5 Red clay? and occasional lumps of rotted basalt
107.0		80.0	Grey-black basalt fragments in tube. 0.6 core	
187.0				

Diamond Drill Log
Hole No. 3
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
187.0				
		15.5	Fragmental in character	Bottle sample No. 2
202.5			Grey, slightly vesicular basalt nubbins,	25" water leak at 202.5';
		0.5	0.3 core	soft, broken basalt to 206.4'. Cores poorly
203.0				
		1.4	Grey, weathered basalt nubbins. 0.5 core	Wall caved into hole yielding red-brown clay.
204.4				
		2.0	Highly weathered vesicular basalt of grey-green color. 0.8 core	Wall again caved into hole. 8/10/34.
206.4	640.2			

BOTTOM HOLE NO. 3

Diamond Drill Log
Hole No. 4 Nuuanu Valley

Lat. 21° 21' 23" N
Long. 157° 49' 19" W
1100 ft. northwest of Old Pali Road at junction with Kamehameha Highway

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0	858.6			0 - 5' red clay
		40.7	No sample attempted. Soil and loose material near surface	5 - 40.7' red clay with occasional lumps or layers of rotted basalt.
40.7				
		0.5	Vesicular grey basalt 0.3 core	
41.2				
		1.8	Brown clayey material 0.6 core	Bottle sample No. 1
43.0				43.0 to 51.3' cores very poorly, because of rubble layers.
		0.5	Nubbins of grey vesicular basalt, 0.3 core	
43.5				
		7.8	Nubbins of grey vesicular basalt, 0.5 core	
51.3				About equal parts of red clay and lumps of rotted basalt.
		8.5	N.S.A.	
59.8				
	798.8	9.6	Grey vesicular basalt 5.0 core	Basalt of medium hardness, not badly broken to 89.4'.
69.4				
		2.6	Weathered close grained grey basalt, dull black spots appear to 71.0 2.5 core	
72.0				
	786.6	3.5	Fairly close grained grey basalt, no spots 3.5 core	
75.5				
		7.9	Somewhat vesicular grey basalt. 7.9 core	Close 8/13/34, smooth running
83.4				
		6.0	Close grained basalt with a few vesicles, lower 2" highly weathered. 5.1 core	
89.4				
	769.2	0.6	Yellow-brown clayey material	Bottle sample No. 2
90.0				

Diamond Drill Log
Hole No. 4
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
90.0				
		4.5	N.S.A. Highly weathered vesicular basalt with yellowish tinge.	Close 8/14/34 water runs out of casing top. Casing seated light, 100% water leak here.
94.5	764.1			
		9.5	Close grained grey basalt dull black spots general throughout. 9.5 core	
104.0	754.6			
		3.0	Close grained grey basalt, no spots. 2.9 core	
107.0				
		9.5	Fine grained grey basalt, no spots. 9.5 core	
116.5				
		3.0	Close grained grey basalt, wide yellow-brown stringers due to iron oxide. 2.9 core	
119.5				8/15/34, smooth running.
		5.2	Fine grained massive basalt 5.2 core	Casing carried to 122'.
124.7				
		8.3	Fine grained massive basalt. 8.3 core	
133.0				
		7.7	Basalt somewhat more vesicular here, spotted dull black. 7.7 core	
140.7				
		7.1	Fine grained massive basalt with black spotty substance in cross fractures. 7.1 core	
147.8				
		7.2	As above. 7.2 core	
155.0				

Diamond Drill Log
Hole No. 4
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
155.0				
	703.6		Brown clayey material,	
		1.0	tube sample, .6 core	
156.0				
		6.0	Clay-like material	Bottle sample No. 3
162.0				
	696.6		Extremely vesicular of	Too soft to core well. 1"
		1.2	purple color, black spots	in water-pipe 121'
			in crossing. 0.6 core	long placed in well,
				resting on broken rock
163.2				at 120? 8/16/34
	695.4			

BOTTOM HOLE NO. 4

Diamond Drill Log
Hole No. 5 Nuuanu Valley

Lat. 21° 21' 25" N
Long. 157° 49' 21" W
1280 feet northwest of Old Pali Road at junction with Kamehameha Highway.

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0	861.6		Soil and alluvium	Ground elevation
		26.9	N.S.A.	8/21/34
26.9				
		1.1	Weathered, grey vesicular basalt. 0.2 core	Clay with lumps of rotted basalt.
28.0				
		0.6	Tube sample 0.6, brown clay-like material	100% leak here
28.6				Gravelly clay.
		7.4	Nubbins of grey vesicular basalt. 1.0 core	
36.0				
		4.0	Grey vesicular basalt, slightly weathered. 3.5 core	
40.0				
		2.0	Brown clay-like material no core	Bottle sample No. 1. 40 - 70.5' clay with lumps of
42.0				rotted basalt, clay represents about 70% of form-
	819.4	28.5	Soft material, not able to recover. N.S.A.	ation. Between 40 and 70.5', a slight leak develops each time rotted
70.5				basalt is encountered.
	790.9	4.2	First 2.5' basalt discolored by clay. Rest close grained grey basalt. 3.2 core	Accumulation of leaks causes 100% absorption at 70.5.
74.7				Weathered, brown basalt.
		6.7	Fine grained, grey basalt 6.7 core.	100% leak
81.4				
		6.3	Fine grained light-grey basalt. 6.3 core	8/22/34 84' down
87.7	773.7			
		8.0	As above. 0.8 core	60% leak at 91.0' down
95.7				
		7.4	As above. 6.4 core	73 - 147' uniformly hard
103.1				basalt. 100% leak at 105.0'.
		6.6	Fine grained light-grey basalt, vesicular in places. 6.6 core	
109.7				

Diamond Drill Log
Hole No. 5
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
109.7				
		9.2	As above, 9.2 core	111.0' down. 8/23/34
118.9				
		9.6	As above, 9.6 core	
128.5				
		8.5	As above, 8.5 core	134.0' down. 8/24/34
137.0				
		4.4	Light-grey, fine grained basalt, last 2' nubbins 4.0 core	
141.4				Sand at 143.6' believed run into hole from 139'
	720.2	2.2	Grey, vesicular, close grained basalt. 2.05 core	
143.6				
		3.4	First half fine grained grey basalt, second half grey, clayey basalt with black spots. 2.5 core	
147.0				147 - 180' clay with lumps or layers of rotted basalt. Believed water-tight.
	714.6	1.5	Brown, soggy, clay-like material. Tube sample 0.5	
148.5				
		54.5	N.S.A. Soft, yellow-brown clay-like material.	180-229' rotted basalt Believed water-tight. 200' down 8/25/34
203.0				
		0.5	Tube sample of above	
203.5				
		32.5	Soft, yellow-brown, clay-like material. N.S.A.	229- 237' There is no absolute check on when the soft, grey basalt appeared, change of formation at 229, too soft for bit.
236.0	625.6			
		1.0	Light-grey somewhat vesicular basalt. 0.7 core	
237.0	624.6		Bottom	88' of 1" pipe resting on rock in hole.

BOTTOM HOLE No. 5

Diamond Drill Log
Hole No. 6 Nuuanu Valley

Lat. 21° 21' 08" N
Long. 157° 49' 03" W
40 feet below Luakaha Falls in Nuuanu Stream Channel

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0	792.8	4.0	Soil. No sample attempted N.S.A.	Elev. of ground. 0 - 16' boulders, sand and gravel 8/28/34
4.0		1.0	Grey, slightly vesicular basalt. 0.8 core	Probably a boulder
		3.4	Gravel, N.S.A.	
8.4		2.6	Heterogeneous basalt, grey, vesicular, brown clayey, some with feldspar phenocrysts. 1.9 core	Boulders of varying composition?
11.0		5.3	Assorted basalts. Close grained grey type. Highly vesicular type. Phenocrystic type. 1.3 core	Boulders?
16.3		2.7	N.S.A.	Cinders or gravel
19.0	773.8	2.4	Medium grey fresh somewhat vesicular basalt. 2.2 core	Probably top of late flows
21.4		3.5	Non-vesicular close grained grey basalt. 2.9 core	50% leak at 21.0'
24.9		1.7	Same as above. 1.4 core	Medium to hard basalt, rather broken.
26.6		9.2	Close grained medium grey basalt 1.4 core	100% leak at 30'
35.8		3.4	Same as above. 3.3 core	
39.2		2.8	Basalt of purple-brown color, somewhat vesicular in character. 2.7 core	
42.0				

Diamond Drill Log
Hole No. 6
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
42.0				
			Tube sample 0.4 Tr	Tough red clay to 48'
		0.4	Red clay-like material	
		7.6	N.S.A.	
50.0				
			Highly altered basalt of reddish color and with black specks. 0.1 core	
52.0				
		9.0	N.S.A.	
61.0				
		2.0	Nubbins of altered reddish basalt.	Will not core, probably very leaky.
63.0			0.4 core	
		16.8	N.S.A.	
79.8				
	713.0	1.2	Nubbins of altered red-purple basalt. 0.7 core	
81.0				
		60.0	N.S.A.	114-161' Rotted red basalt with occasional streaks of tough gravelly clay
141.0				
			Tube sample 0.6	
		0.5	Red clayey material	
141.5				
		18.5	N.S.A.	
160.0				Finished hole 10/1/34
		1.0	Red-purple weathered tuff	Hole cased to 26.0'
161.0				
	631.8			

BOTTOM HOLE NO. 6

Diamond Drill Log
Hole No. 7 Nuuanu Valley

Lat. 21° 21' 04" N
Long. 157° 49' 06" W
275 feet southeast of Cooke Bridge across Nuuanu Stream

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0				
	801.8	17.2	N.S.A.	Ground elevation 10/7/34
17.2				
		0.8	Grey firm vesicular basalt 0.8 core	Soil and a few rotted boulders.
18.0				
		5.9	1.7' grey somewhat vesicular basalt. 1.1' Purple highly vesicular basalt. 2.8 core	17.2 - 22.0' medium hard basalt
23.9				
		5.3	Grey, somewhat vesicular basalt, generally massive. 2.5 core	22 - 23.9' rotted basalt with a trace of red clay
29.2				Medium hard basalt with occasional rotted spots
	772.6	1.4	Soft material N.S.A.	
30.6				100% leak at 29.2' Crumbly rotted basalt?
		4.0	Top 1' of fairly dense material, next 1.5' extremely vesicular, bottom of small nubbins. 3.1 core	Medium hard porous basalt
34.6				
	767.2	2.4	Brown clay-like material tube sample 0.7	100% leak at 34.6' Bottle sample No. 1. Rotted soft basalt and clay.
37.0				
		50.0	Soft material. N.S.A.	Cinders?
87.0				
	714.8	1.5	Brown-black cinders, distinctly not clayey, Tube sample 0.55	Bottle sample No. 2
88.5				Cinders? 87 - 110' rotted basalt slightly harder. Bottle sample No. 3
		25.5	Soft material. N.S.A.	
114.0				
		1.0	Fairly large brownish fragments, slightly adherent, not clayey.	Rotted basalt continues to harden to 213.2'.
115.0				

Diamond Drill Log
Hole No. 7
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
115.0				
		98.0	Soft material. N.S.A. tuff.	
	588.8		Very mottled basalt, tuff fragments in finer grained groundmass. 1.35 core	
215.0				
		11.0	Yellow-brown mottled to 221, then green-grey mottled, tuff. 9.2 core	
226.0			tuff	
		8.7	Above mottled effect is more spectacular here. 8.1 core	213.2' - 270.5' is very soft basalt
234.7			tuff	
		10.0	Highly mottled, somewhat rounded basalt fragment. 10.0 core.	
244.7				
		1.9	Mottled core of dark green-grey color. 1.9 core	
246.6			tuff	
		10.1	Mottled core, basalt fragments are outlined by thin coat of limonite, calcite present. 9.6 core	Unusual development of calcite. 6' 10" core unusual length for soft material.
256.7				
	545.1	9.4	Mottled "pseudo brecciated basalt, is less iron stained at certain horizons. 9.3 core	
266.1				
	535.7	4.6	To 267' grey mottled vesicular driblets, changing here to black-brown porous basalt. 4.2 core	
270.2				
	531.1	0.5	Denser, brown, heterogeneous basalt, with varicolored fragments visible. 0.5 core	270.5 290.0' firm, smooth basalt
271.2				

Diamond Drill Log
Hole No. 7
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
271.2				
		17.5	N.S.A.	
288.7				
	513.1	3.3	Extremely vesicular grey basalt, very rotten in the first half foot. 2.05 core	290 - 301' lumps of soft vari-colored basalt with some seams of cemented gravelly clay. ca. 30 per cent basalt, 70 per cent clay. Mass very changeable and broken
292.0				
		2.2	N.S.A.	
294.2				
		0.8	Dense grey basalt nubbins small zeolite crystals visible somewhat altered 0.5 core	
295.0				
		3.3	N.S.A.	
298.3				
		0.5	Grey basalt with small vesicles. 0.2 core	
298.8				
		1.1	N.S.A.	
299.9				
	501.9	1.1	Very fine-grained grey-green basalt with a few elongated vesicles. 0.3 core	
301.0				Bottle sample No. 3
		3.2	Soggy grey clayey material. Some red clay present	Tough clay grading through rotted basalt into hard basalt.
304.2				
		0.7	Altered vesicular grey and yellow basalt. 0.5 core	Tough clay, very compact and probably water tight.
304.9				
	496.9	67.1	N.S.A. except small ball of yellow clay.	Occasional lumps of rotted basalt.
372.0				
		48.5	N.S.A. Soft material	405 - 420' partly rotted basalt, gradually hardening
420.5				
	381.3	1.5	Vesicular grey basalt. Large vesicles partly filled with clay. 0.6 core	Medium hard basalt. 268.5' of 1" pipe. 9/21/34
422.0	379.8			

BOTTOM OF HOLE NO. 7

Diamond Drill Log
Hole No. 8 Nuuanu Valley

Lat. 21° 21' 56" N
Long. 157° 49' 24" W
250 feet south of Kamehameha Highway at Reservoir No. 2. Wasteway.

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0	715.0	47.0	N.S.A.	Ground Elevation. 10/24/34 0 - 9.0' is soil and loose rock.
47.0		20.0	Tube sample 0.6 Dark brown clay-like material	Bottle sample No. 1. Between 47 and 48'.
49.0		54.0	N.S.A.	
103.0	612.0	22.2	Tube sample 0.6 Sandy yellow heterogeneous material and small pieces basaltic material	9 - 120.3 half palagnite and half lumps of rotted basalt. No leak to 120'
125.2	589.8	1.1	Small nubbins of grey vesicular basalt. 0.2 core	50 per cent leak here. 100 per cent leak at 126.0'
126.3		1.8	Very vesicular grey basalt 1.8 core	
128.1		8.3	Extremely vesicular grey Vesicles very large. 5.6 core	
136.4		3.9	Vesicular grey basalt. 1.4 core	137 - 138 is an open cavity air forced out. 100 per cent leak at 140'
140.3	574.7	9.1	Medium vesicular tan-grey basalt. 7.7 core	100 per cent leak at 144'
149.4		5.8	Medium vesicular, tan-grey fine grained, dense basalt at 152 to 153 feet. 5.3 core	138 - 182 medium hard basalt
155.2		7.5	Very-slightly vesicular grey basalt. 7.3 core	
162.7		2.0	Slightly more vesicular and same color as above. 1.8 core	
164.7				

Diamond Drill Log
Hole No. 8
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
164.7				
		3.6	Slightly vesicular, tan to purple basalt. 2.9 core	
168.3				
		4.4	Highly vesicular grey basalt thin deposition of zeolite in vesicles. 3.8 core	
172.7				
		3.6	Highly vesicular weathered grey basalt to purple. 2.2 core	
176.3	538.7	1.4	Grey, medium vesicular basalt, brown spots on fractured surfaces. 1.1 core	
177.7				
		2.5	First foot grey, medium vesicular basalt, remainder of purplish-grey, highly vesicular basalt. 2.5 core	
180.2				
		1.8	Grey-purple, closely vesicular, basalt. Fewer and smaller vesicles than above. 1.3 core	
182.0	533.0	1.5	Tube sample 0.6 Sticky yellow-brown clay.	
183.5				
		4.0	Grey basalt, fairly large vesicles, yellow stains occasionally. 3.2 core	Medium hard basalt
187.5				
		1.0	Tube sample 0.6 sticky yellow-brown material slight tendency to lump.	Cased to 202.8. Rotted volcanic ash? Caves badly to 202.8' rotten basalt and clay. Temporary 100 per cent leak at 215' permanent 20 per cent leak below.
188.5				
		41.5	N.S.A. Soft Material	
230.0	485.0	1.0	Grey basalt, vesicles small but frequent. 0.6 core	

Diamond Drill Log
Hole No. 8
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
231.0		18.0	N.S.A.	Soft rotted basalt with occasional hard spots.
249.0				247.5' somewhat harder than above.
		0.8	Small nubbins of grey vesicular basalt, elongated white mineral noticed. 0.7 core	Hole finished with 219.6' of 1" pipe. 10/3/34.
249.8	465.2			

BOTTOM HOLE #8

Diamond Drill Log
Hole No. 9 Nuuanu Valley

Lat. 21° 21' 21" N
Long. 157° 49' 16" W
600 feet northwest of Old Pali Road near its junction with Kamehameha Highway.

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0	844.5			Ground elevation 10/3/1934
		9.0	N.S.A.	Clay, no leak
9.0				
		9.5	N.S.A.	About 80 per cent broken rotted basalt, 20 per cent clay to 42'
18.5				
		2.8	Grey, medium vesicular basalt. 0.7 core	
21.3				
		29.5	N.S.A.	48.0 half rotted basalt half clay to 50.3.
50.8	793.7			
		2.4	Grey basalt, slightly more vesicular than above. Black substance in fracture planes. 1.2 core	Soft basalt
53.2				
		1.3	Dense grey basalt, with a few widely spaced vesicles. 0.5 core	
54.5				
		1.0	Tube sample 0.6 Brown material, clay-like when wet.	Half clay, half rotted basalt to 60.1'
55.5				
		4.6	N.S.A.	
60.1	784.4	3.1	Fair-sized nubbins of weathered yellow to grey basalt, some large white-coated cavities. 2.7 core	Badly broken, rather hard basalt to 65.3'
63.2				
		2.1	Nubbins of grey slightly vesicular basalt. 0.9 core	
65.3				
		19.5	N.S.A.	About 80 per cent rotted basalt with clay.
84.8				

Diamond Drill Log
Hole No. 9
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
84.8				
		1.9	Dense, dark grey basalt having tendency to weather yellow along fracture planes. 1.4 core	Medium hard basalt to 104.5'
86.7				
	757.8	6.7	Dense fresh grey basalt, small amount of sludge at base. 6.7 core	
93.4				84.8 - 116.0? about 10 per cent leak.
		9.1	Fresh dense grey basalt. 8.4 core	
102.5				
		1.2	Fresh dense grey basalt 1.1 core	
103.7				
		0.8	Dense purple-grey basalt 0.7 core	
104.5				
		16.8	N.S.A.	80 per cent rotted basalt with thin hard spots and clay, somewhat inclined to cave.
121.5				
	723.0	3.4	Purple-grey basalt, mottled with black on broken surfaces. 2.6 core.	
124.7				
		1.2	Dense grey basalt 1.2 core	
125.9				
		0.6	Dense grey basalt. core 0.2	
126.5				
		2.0	Fairly vesicular basalt With purple tinge. 1.8 core	
128.5				
		1.1	Purple basalt similar to above. 1.1 core	
129.6				
	714.9	6.2	N.S.A.	Soft basalt
135.8				

Diamond Drill Log
Hole No. 9
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
135.8				
		4.8	Dense, slightly vesicular basalt with purple tinge. 4.5 core	No leak 135 - 169'
140.6				
		7.4	Highly vesicular purple basalt, covered with yellow alteration products. 5.0 core	121.3 - 214.6' Alternating half hard broken basalt, half very rotten, soft basalt
148.0	696.5			
		2.2	Dense, slightly vesicular purple basalt 2.0 core	
150.2				
		7.3	N.S.A.	Clay?
157.5				
		1.7	Highly vesicular altered purple basalt. 1.5 core	
159.2				Rotted basalt
		10.0	N.S.A.	100 per cent leak at 169'
	675.3	1.1	Medium vesicular purple basalt. 0.4 core	0.8' cavity below 170.3'
170.3				rotted basalt 171.1 -185.9'
		15.6	N.S.A.	
185.9	658.6			
		2.1	Fresh, highly vesicular purple basalt. 2.0 core	
188.0				
		8.0	Fresh, highly vesicular grey basalt. 4.5 core	
196.0				Formation between 194 and 214.6 somewhat inclined to cave.
	648.5	18.6	N.S.A.	
214.6	629.9			
		3.8	Dense, fresh, grey, mottled basalt. 3.8 core	
218.4				
		7.4	Dense, fresh, grey, basalt 7.3 core	Hard, grey, very uniform basalt to 253'
225.8				
		7.8	Dense, grey basalt. 7.7 core	
233.6				

Diamond Drill Log
Hole No. 9
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
233.6				
		8.8	Dense, grey, slightly vesicular basalt <u>8.7 core</u>	
242.4				
		9.7	Dense, grey, slightly vesicular basalt <u>9.6 core</u>	
252.1				253.0 - 263.6' hard badly broken basalt.
		2.2	Fine grained grey basalt slightly vesicular. <u>2.0 core</u>	
254.3				
		4.0	Dense, grey basalt, slightly vesicular <u>2.0 core</u>	
258.3				
		5.3	Small nubbins of dense grey basalt, very few vesicles <u>2.0 core</u>	
263.6				
	580.9	25.4	N.S.A.	Layers composed of about 80 per cent sharp cemented cinders, to 295'. At 273' there is a layer that caves badly. <u>Bottle sample No. 2</u> between 272 and 299'
		0.3	Bottle sample No. 1 Red clay.	
299.3				
	545.2	15.7	N.S.A.	295 - 314' rotted, red, soft basalt and/or tough gravelly clay. 314' rather soft basalt, with hard layers.
315.0				
	529.5	1.0	Nubbins of highly vesicular grey weathered basalt. <u>0.4 core</u>	
316.0				
		5.0	Highly vesicular, grey weathered basalt. Specks of pyrolusite in fractures. <u>1.6 core</u>	
321.0				
	523.5	78.0	Very fine gravel, appears to be basalt detritus, non-clay-like.	Bottle sample No. 3 at 399'
399.0				

Diamond Drill Log
Hole No. 9
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
399.0	445.5	0.2	Appears to be clay with small pieces of basalt.	Bottle sample No. 4
399.2		56.8	N.S.A.	
456.0	388.5	1.6	Altered, highly vesicular basalt, clay in seams. 1.2 core	Determined to be Koolau basalt from thin section
457.6	386.9			

BOTTOM HOLE NO. 9

Diamond Drill Log
Hole No. 10 Nuuanu Valley

Lat. 21° 21' 15" N
Long. 157° 49' 11" W
50 feet south of Kamehameha Highway at its junction with Old Pali Road.

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0	849.4			Ground elevation
		13.0	N.S.A.	11/9/34. 0 - 3' clay and gravel. 100 per cent leak at 6.0' 3 - 13' cemented, rotted cinders
13.0				
		3.0	Light grey basalt with extremely large vesicles, tendency to form yellow alteration product in seams. 2.7 core	Medium hard basalt
16.0				
		9.8	N.S.A.	Alternating half cinders and half clay
25.8				
		1.4	Slightly vesicular, dense grey basalt. 1.0 core	Hard basalt
27.2				
		1.8	Sticky red clay Tube sample 0.6	To 38.5' alternately clay and rotted cinders
29.0				
		9.6	N.S.A.	Hard basalt, rather broken to 66.1'
38.6	810.8			
		0.4	Dense, grey basalt, slightly mottled on freshly fractured surfaces. 0.4 core	
39.0				
		2.7	Dense, grey basalt, excessively fractured. 2.0 core	
41.7				
		3.7	Dense grey basalt with spots of pyrolusite and yellow alteration products in seams 3.25 core	
45.4				
		3.1	Massive, grey basalt, with few vesicles. 3.1 core	
48.5				
		6.5	Very dense, grey basalt, 6.1 core	
55.0				

Diamond Drill Log
Hole No. 10
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
55.0				
		5.8	Dense, grey basalt, slightly more vesicular than underlying layer, vesicles very small. 5.3 core	
60.8				
		5.3	Slightly vesicular basalt similar to above. 4.2 core	
66.1				
		8.2	Extremely dense, grey basalt without vesicles 7.7 core	Very hard basalt
74.3				
		1.0	Dense, purplish basalt with a little clay 0.2 core	
75.3				
		1.0	Tube sample 0.6 Sticky red clay	Tough brown clay with layers of soft clay to 110.5'
76.3				
		34.2	N.S.A.	
110.5				
		9.3	Upper 1' broken vesicular purple basalt, remainder dense grey, slightly vesicular basalt. 9.3 core	110.5 - 128.5' hard grey basalt.
119.8				
		8.7	Mostly grey, fresh, slightly vesicular, massive basalt. Bottom 2.5' of badly broken nubbins with purple tinge, 8.7 core	
128.5				
	720.9	0.5	Tube sample 0.5 Sticky red-brown clay.	125.5 - 138.3' is gravelly clay. At 128.5' a cavity a few inches deep was found.
129.0				

Diamond Drill Log
Hole No. 10
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
129.0				
		9.9	N.S.A.	At 157' there was a considerable movement of water sufficient volume to cause suction of air in casing. This water was entering hole at 53' and leaving at 128.5 - 182.2' very porous, partly rotted basalt with occasional harder lumps. Somewhat inclined to cave. At 166' there is a 4" cavity, hole inclined to cave at this point.
138.9				
		9.4	Highly vesicular, broken altered, purple basalt, pyrolusite present as spots on fracture surfaces, and heavy coating of clay or hematite present <u>3.35 core</u>	
148.3	701.1			
		19.6	N.S.A.	
167.9	681.5	9.6	Dense, medium vesicular grey basalt, some pyrolusite present in fracture planes. <u>9.3 core</u>	
177.5				
		4.2	Top is fresh grey basalt only slightly vesicular but lower foot is altered "honey-combed" yellowish basalt. <u>2.75 core</u>	
181.7				Frothy layer which is inclined to cave. 182.2 - 201.0' hard badly broken basalt.
		9.4	Dense, grey basalt with a few large vesicles <u>8.3 core</u>	
191.1				
		7.2	Weathered, purple tinted basalt somewhat more vesicular than above, pyrolusite in fracture planes. <u>5.0 core</u>	
198.3				
		3.5	Nubbins of weathered, purple grey basalt. Pyrolusite and white alteration products in seams and fractures. <u>1.8 core</u>	
201.8				Hard basalt to 261'

Diamond Drill Log
Hole No. 10
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
201.8	647.6	4.2	Purple-grey basalt with a few comparatively large vesicles. 3.0 core	
206.0		3.2	Grey, weathered, medium vesicular basalt. Purple tinge disappearing. 1.4 core	
209.2		2.8	Medium vesicular, grey slightly weathered basalt pyrolusite present 1.5 core	
212.0		7.0	Dense, light grey basalt with a few large vesicles 7.0 core	
219.0		6.3	Top 2' is dense, light grey basalt, base is finely mottled basalt. 5.7 core	
225.3		1.8	Yellow-grey basalt, similar to above except for increased weathering. 1.8 core.	
227.1		9.1	Dense, grey basalt slightly vesicular in places. 8.6 core	
236.2	613.2	4.3	Very dense grey basalt 3.9 core	
240.5		3.2	Dense, grey basalt with yellow limonite-like alteration along broken seams. 2.6 core	
243.7				

Diamond Drill Log
Hole No. 10
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
243.7				
		8.0	Grey, massive basalt, very slightly vesicular. 7.8 core	
251.7				
		9.3	Massive basalt of grey color, slightly broken towards base. 8.05 core	
261.0				
		0.5	Nubbins of grey vesicular basalt, highly weathered. 0.35 core	
261.5	587.9			
		0.8	Tube sample 0.6 Sticky red clay	Red lumpy clay
262.3				
		39.4	N.S.A.	Partly rotted basalt with occasional lumps to 295' becoming slightly softer below.
301.7	547.7			
		0.5	Non-vesicular, weathered red-brown basalt. 0.45 core	
302.2				
		12.4	N.S.A.	Medium hard basalt
314.6				
		5.8	Highly vesicular and weathered grey basalt. 1.3 core	To 320' rotted basalt with occasional slightly harder lumps and occasional layers of partly cemented cinders, generally very porous.
320.4				
	529.0	10.2	N.S.A.	Caves badly
330.6				
		7.4	Broken, fairly dense grey basalt, slightly vesicular. 6.9 core	Hard, badly broken basalt.
338.0				
		9.3	Broken, grey to black basalt, very slightly vesicular. 3.45 core	
347.3				
		2.5	Massive grey basalt with specks of pyrolusite in fracture planes. 1.9 core	
356.2				

Diamond Drill Log
Hole No. 10
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
356.2				
		4.1	Broken, dense, gray basalt with small amount of clay near bottom. 1.5 core	
360.3	489.1			
		61.2	N.S.A.	Compact clay with occasional lumps of rotted basalt
421.5				
		1.5	Light green-grey, highly vesicular, weathered Koolau basalt. 0.4 core	Medium hard basalt. 80' of 1" pipe placed in hole.
432.0	417.4			12/1/1934

BOTTOM OF HOLE NO. 10

Diamond Drill Log
Hole No. 11 Nuuanu Valley

Lat. 21° 21' 07" N
Long. 157° 49' 33" W
60 feet south of Mamalahoa Road in Lewis Lot.

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0	726.0			Ground elevation
		10.9	N.S.A.	12/3/1934 0 - 4' clay and gravel. To 10.9' partly rotted basalt, seams filled by clay.
10.9				
		5.0	Badly broken, somewhat vesicular, weathered, grey basalt. 1.5 core	10.9 - 36.0' medium hard basalt.
15.9				
		9.5	Fairly fresh, finely vesicular, grey basalt. 8.8 core	10 per cent water leak between 0 and 36'
25.4				
		6.8	Light grey basalt, vesicles small and closely spaced. 6.6 core	
32.2				
		5.3	Grey basalt, darker than above and more massive. Bottom portion highly weathered and discolored. 3.6 core	100 per cent water leak at 36' rather soft brown basalt to 37.5'
37.5				
		1.0	Tube sample 0.6 Yellow brown sticky clay	
38.5				37.5 - 60.8' clay with lumps of rotted basalt and layers of cinders. No water return
		22.3	N.S.A.	
60.8	665.2			
		0.9	Nubbins of dark grey basalt. 0.4 core	
61.7				
		1.6	Badly broken dark grey basalt. 1.5 core	
63.3				
		1.6	Broken, massive, dark grey basalt. 1.6 core	
64.9				
		4.5	Fresh, dense, grey basalt 4.5 core	100 per cent leak at 65'
69.4				

Diamond Drill Log
Hole No. 11
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
69.4				
		6.3	Grey, fresh, dense basalt. 5.3 core	60.8 - 103.4' very hard basalt.
75.7				
		9.3	Massive grey basalt. 9.3 core	
85.0				
		7.9	Massive grey basalt 7.75 core	
92.9				
		8.8	Dense, non-vesicular grey basalt. 8.8 core	
101.7				
		1.7	Massive, non-vesicular grey basalt, somewhat broken. 1.3 core	
103.4				
	622.6	0.8	Tube sample 0.6 Red-brown clay-like material, not particularly plastic. 0.8 core	Clay and gravel
104.2				
		2.8	N.S.A.	Clay and gravel
107.0				
	619.0	1.4	Weathered basalt of violet color. Pyrolusite along fracture planes. 1.3 core	Badly broken, medium hard, purple basalt
108.4				
		4.7	N.S.A.	Clay and gravel
113.1				
		3.0	Violet to grey, weathered basalt, limonite stain evident. 1.9 core	
116.1				
		0.9	Brown, weathered basalt of ochre-like appearance 0.4 core	
117.0				
		5.7	Nubbins of highly vesicular weathered basalt. 1.4 core	
122.7				

Diamond Drill Log
Hole No. 11
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
122.7		8.2	Very vesicular, weathered basalt, badly stained with brown in middle of section otherwise grey in color. 1.5 core	At 125' hole inclined to cave.
130.9	595.1	8.0	Highly vesicular, weathered light grey basalt. 1.2 core	136.0 - 136.5 a cavity. At 138' hole takes 4 gallons per minute
138.9		7.4	Slightly vesicular basalt light grey in color and slightly weathered. 1.5 core	
146.3	579.7	22.7	N.S.A.	113.1 - 219.0' medium hard, broken basalt, occasional spots of clay and rotten porous basalt 154 - 156' a cavity, very soft clay or rotten aa to 158'. At 166' 44 gallons per minute will not fill hole. A considerable volume of water can be heard falling into hole.
169.0		1.8	Light grey, weathered, vesicular basalt. 1.0 core	
170.8		12.1	N.S.A.	
182.9		6.3	Light grey, somewhat vesicular basalt, lower portion has large vesicles. 4.7 core	
189.2	536.8	30.4	N.S.A.	
219.6		5.0	Slightly vesicular, light grey basalt. 4.1 core	Hard blue basalt to 249.2'
224.6		8.4	Massive, grey, non-vesicular basalt 8.3 core	
233.0		7.8	Massive, grey non-vesicular basalt. 7.5 core	
240.8				

Diamond Drill Log
Hole No. 11
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
240.8				
		8.4	Massive, grey, non-vesicular basalt, lower portion somewhat broken. 7.55 core	
249.2	476.8			To 277.4' alternating between medium hard and rather soft partly rotten basalt.
		10.2	N.S.A.	
259.4				
		10.1	Highly weathered, purple to grey basalt, very vesicular, spots of pyrolusite along fracture planes. 2.9 core	
269.5	456.5			
		7.9	Vesicular and somewhat weathered, grey basalt. 3.8 core	50 G.P.M. will not fill hole at this point.
277.4				
		121.6	N.S.A. (soft)	To 396' dark blue basalt, ranging from rather soft to medium hard (Koolau?). Hole somewhat inclined to cave all the way from 256'
399.0				
		0.7	Extremely weathered basalt also a nubbin of tuff on top, Core, a few nubbins	
399.7	326.3			12/15/34, - 64' of 1" pipe in hole.

BOTTOM OF HOLE NO. 11

Diamond Drill Log
Hole No. 12 Nuuanu Valley

Lat. 21° 21' 12" N
Long. 157° 49' 34" W
475 feet north of end of Mamalahoa Road

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0				Ground elevation. 12/17/34
	767.0	17.9	N.S.A. Soil and surface material	To 3' clay and gravel. To 17.9' rotted, crumbly basalt with small seams of clay, no leaks to speak of.
17.9				
		5.6	Finely vesicular, light grey basalt, highly weathered. 2.5 core	To 26' medium hard rather porous, badly broken basalt.
23.5				
		2.5	Similar to above, but fresher and even more vesicular. 1.5 core	
26.0				
		0.5	Tube sample 0.2. Sticky brown clay	To 29.0' clay with lumps of rotted basalt.
26.5				17 - 37' hole leaks about 1.5 G.P.M.
		2.5	N.S.A. (soft)	
29.0				
		8.7	Extremely vesicular basalt lower foot highly weathered vesicles very large.	Porous, medium hard, grey basalt
37.7				
		0.8	Tube sample 0.6 Sticky yellow-brown clay.	5.5 G.P.M. fills hole
38.5				Gravelly clay with occasional lumps of rotted basalt.
		6.2	N.S.A. (soft)	
44.7				
		7.5	Rather dense and comparatively fresh, grey basalt with occasional vesicles. 6.8 core	To 54.4 rather hard basalt hole leaks 0.5 G.P.M.
52.2				
		2.2	Slightly more vesicular than above. 1.95 core	
54.4				Hole leaks 3.0 G.P.M. and water will stand at 32'
	712.6	5.6	Soft yellow clay-like material	Bottle sample No. 1 54.4-55.1'
60.0				
		1.0	Extremely weathered, greenish-yellow basalt. 0.5 core	
61.0				

Diamond Drill Log
Hole No. 12
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
61.0				54.4 - 70.0' clay with lumps of moderately hard basalt
		10.8	N.S.A. (soft)	
71.8	695.2			
		3.4	Upper 2.0' grey, massive basalt, remainder highly broken. 3.4 core	
75.2				
		2.1	Massive grey basalt 0.1 core	Hole takes 11 G.P.M.
77.3				
		3.5	Very massive, fine grained basalt, grey.	70 - 85' very hard blue basalt
80.8				
		0.8	Massive grey basalt as above. 0.5 core	
81.6				
		2.8	Dense grey basalt similar to above. 2.3 core	
84.4				
		0.6	Nubbins of dense, grey basalt. 0.25 core	Bottle sample No. 2 Gravelly clay
85.0	682.0			
		5.7	Yellow-brown, clay-like material of sticky character.	
90.7				
		0.7	Slightly vesicular, grey basalt. 0.5 core	Very hard basalt to 134.7'
91.4				
		1.2	Very slightly vesicular grey basalt. Core 0.5	
92.6				
		2.6	Small nubbins of massive, grey basalt. 0.25 core	
95.2				
		6.1	Upper portion is vesicular, somewhat weathered basalt. Lower part is massive. 2.7 core	
101.3				
		7.9	Massive, grey basalt with few vesicles. 7.8 core	
109.2				

Diamond Drill Log
Hole No. 12
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
109.2				
		8.5	Similar to above, slightly vesicular. 8.0 core	Hole takes 20 G.P.M. without filling.
117.7				
		9.5	Very massive, dense, non-vesicular, grey basalt. 1.75 core	
127.2				
		7.5	Similar to above 6.75 core	
134.7	632.3			
		1.0	Soft, yellow-brown, clay-like substance.	Bottle sample No. 3 Clay
135.7				
		0.8	Several nubbins of dense grey basalt. 0.3 core	Hard basalt.
136.5				
		4.5	N.S.A.	Partly rotted, very porous brown basalt
141.0				
		1.0	Highly vesicular weathered basalt.	
142.0				
		15.2	Grey to purple, vesicular weathered basalt. 0.25 core	141.1 to 168.4 badly broken basalt, ranging from soft porous to rather hard
157.2				
		3.1	Purple-grey basalt with rather large vesicles. 2.85 core	
160.3				
		1.5	Basalt similar to above. 1.25 core	
161.8				
		6.6	Similar to above but more weathered. 3.8 core.	Clay and lumps of rotted basalt.
168.4	598.6	10.3	N.S.A.	
178.7				
		2.0	Slightly weathered basalt has changed to a decided grey color. 1.75 core	Medium hard, rather broken basalt with occasional soft rotten spots. To 208.3'
180.7				

Diamond Drill Log
Hole No. 12
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
180.7				
		8.5	Weathered grey basalt, becoming increasingly vesicular with depth. 6.55 core	
189.2				
		15.0	N. S. A.	
204.2				
		4.1	Highly vesicular weathered grey basalt. 1.95 core	
208.3				Soft rotted basalt with seams of tough clay.
		6.0	N.S.A.	
214.3				
		9.6	Upper 2' slightly vesicular and weathered, lower portion massive grey basalt. 9.3 core	Medium hard basalt
223.9				
		3.6	Vesicular grey basalt with large vesicles, grading to highly weathered brown basalt to base. 3.0 core	Medium hard basalt grading into brown rotted basalt in last foot.
227.5				
	539.5			
		0.9	Brown clay-like material Tube sample 0.4	Brown lumpy clay
228.4				
		9.6	N.S.A.	Brown lumpy clay. To 276.3' hard badly broken basalt.
238.0				
		3.0	Nubbins of dark grey non-vesicular basalt. 2.3 core	
241.0				
		2.1	Similar to above dark grey basalt. 1.3 core	
243.1				
		3.0	Nubbins of dark grey basalt. 2.45 core	
246.1				

Diamond Drill Log
Hole No. 12
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
246.1				
		2.1	Similar to above 1.9 core	
248.3				
		2.0	Similar to above, pyrolusite in seams. 2.0 core	
250.2				
		2.0	Nubbins of slate-grey basalt non-vesicular 1.6 core	
252.2				
		4.7	Same as above but slightly less broken. 4.7 core	
256.9				
		9.5	Fairly fresh grey basalt with pyrolusite spots in seams and fracture. 9.5 core	
266.4				
		3.2	Fresh grey basalt with a slight tinge. 3.2 core	
269.6				
		4.7	Dense, purple-grey basalt of non-vesicular tinge. 4.2 core	
274.3				
		2.0	Slightly more weathered than above, some pyrolusite in seams.	
276.3				To 304.1' red clay with lumps of rotted basalt.
		0.1	Tube sample 0.1 Red-brown clay-like material	
276.4				
		28.0	N.S.A.	To 327.6' very porous basalt
304.4				
		6.7	Very highly weathered and vesicular grey basalt. 2.7 core	
311.1				
		9.4	Weathered purple-grey vesicular basalt, vesicles are extremely large. 9.4 core	
320.5				

Diamond Drill Log
Hole No. 12
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
320.5				
			Same as above, but purple. 7.0 core	
327.6				
		1.0	N.S.A.	Clay
328.6				
	438.4	2.1	Highly vesicular, light grey weathered basalt. Abundant olivine. 1.7 core	To 334' rather soft grey basalt, changes to hard every foot or so. Soft is too soft to core. Hard is almost too hard to chop.
330.7				
		42.6	N.S.A.	330 - 373' cemented cinders with occasional hard lumps a few inches thick.
373.3				
		3.1	Light grey, medium weathered basalt. 1.8 core	
376.4				
		6.6	Highly vesicular and weathered grey basalt 1.2 core	373 - 424' about half grey soft basalt, and about half softer streaks a few inches to a few feet thick.
383.0				
	384.0	2.0	A few chunks of very highly weathered basalt. 0.65 core	
385.0				
		29.3	Light grey, slightly weathered basalt, shows white microliths probably plagioclase. 2.1 core	
414.3				
		5.7	N.S.A.	
420.0				
		1.7	Weathered basalt light grey in color, white microliths. 1.35 core	
421.7				
		1.4	N.S.A.	
423.1				

Diamond Drill Log
Hole No. 12
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
423.1				Hole finished with 46' of 1" pipe.
		0.9	Nubbins of highly weathered medium grey basalt 0.35 core	
424.0	343.0			1/5/1935

BOTTOM OF HOLE NO. 12

Diamond Drill Log
Hole No. 13 Pauoa Valley

Lat. 21° 20' 10" N
Long. 157° 49' 39" W
Near Booth's Spring, opposite last house up Pauoa Valley, map elev. 720 ft

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0				Elevation unknown 0 - 3' soil
6.0		6.0	N.S.A.	3 - 6' cinders and lumps
		4.8	Very dense grey basalt. Non-vesicular except 7 - 8' 4.75 core	
10.8				
		0.6	Massive grey basalt 0.6 core	
11.4				
		2.4	Dense grey non-vesicular basalt 2.4 core	At 13' water stands at 4.2' 1/8/35
13.8				
		9.6	Massive, grey, non-vesicular basalt. 9.6 core	
23.4				
		9.5	Massive grey basalt to 25.9' below is highly vesicular basaltic tuff. 9.1 core	Leakage to depth of 50' not more than 0.5 G.P.M.
32.9				
		7.2	Dark grey, highly vesicular basaltic tuff. 5.75 core	
40.1				At 50' leakage is 1.5 G.P.M.
		10.3	Vesicular, dark grey, basaltic tuff. 9.0 core	
50.4				
		3.6	Dark grey, vesicular basaltic tuff. 2.6 core	To 92' frothy, sharp, partly cemented cinders, with occasional lumps inclined to cave.
54.0				
		5.0	A few nubbins of reddish, vesicular, basaltic tuff. 0.15 core	At 62' leakage is 6.5 G.P.M.
59.0				

Diamond Drill Log
Hole No. 13
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
59.0				
		6.0	N.S.A.	
65.0				
		1.5	Purple to grey, highly vesicular, cinder tuff. 0.3 core	
66.5				
		1.8	N.S.A.	
68.3				
		7.8	Nubbins of scoriateous, purple, weathered tuff. 1.2 core	
76.1				
		6.9	N.S.A.	
83.0				
		8.5	Weathered cinder tuff. 0.7 core	
91.3				
		3.7	N.S.A.	Gravelly clay
95.0				
		1.8	Basaltic detritus, consisting of chunks of weathered basalt and mixed clay.	
96.8				
		3.9	Chunks and layers of weathered basalt, mixed with ash and cinders. 3.0 core	
100.7				
		1.7	Small nubbins of weathered basaltic tuff. 0.45 core	
102.4				95 - 124' medium soft greenish-grey, partly rotted basalt with seams and layers softer brown basalt.
		13.6	N.S.A.	
116.0				
		2.6	Highly vesicular, grey basalt. 0.7 core	
118.6				
		3.4	N.S.A.	
122.0				Hole finished with 12' of 1" pipe.
		2.0	Weathered, vesicular, grey basalt. 2.0 core	1/15/1935
124.0				

BOTTOM OF HOLE No. 13

Diamond Drill Log
Hole No. 14 Pauoa Valley

Lat. 21° 20' 11" N
Long. 157° 49' 33" W
About 700 ft. above Booth's Spring in lateral valley cut by road 200 ft. above last house, map elev. 810 ft.

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0				Elevation known approximately 1/16/1935. To 3.5' soil and cinders, to 5.9' broken rock.
		5.9	N.S.A.	
5.9				
		4.3	Dense, grey, fresh basalt lower foot highly weathered slightly vesicular basalt 3.0 core	Up to 20' hole does not leak more than 0.5 G.P.M. though at 20' no water stands in hole after 16 hours.
10.2				
		9.4	Half a foot of weathered basalt at top, mostly fresh grey basalt, basaltic tuff at bottom. 7.95 core	
19.6				From 5.9 - 46.0' medium hard to hard blue basalt. A small amount is too soft to core.
		5.2	Compacted basaltic cinder agglomerate. 0.65 core	
24.8				
		9.8	Fresh grey basalt 9.25 core	
34.6				
		11.3	Blue-grey basaltic cinders. 2.0 core	To 76.8' frothy red basalt or cemented cinder with occasional layers of clay. Clay about 20 per cent of mass, caves badly.
45.9				
		10.9	N.S.A.	
56.8				
		0.6	Tube sample 0.5 Brown-yellow clay.	
57.4				
		19.4	N.S.A.	Water stands in hole at 65' can be heard at 71- 83'agglomerate of cemented clinkers and calcite.
76.8				
		1.2	Light colored basaltic tuff. 1.2 core	
78.0				
		5.0	Basaltic tuff, cemented with white material. 3.8 core	
83.0				To 85.1' leakage 6 G.P.M. very leaky to 87' sharp cinders, inclined to cave
		7.0	N.S.A.	
90.0				

Diamond Drill Log
Hole No. 14
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0				Elevation known approximately 1/16/1935. To 3.5' soil and cinders, to 5.9' broken rock.
		5.9	N.S.A.	
5.9				
		4.3	Dense, grey, fresh basalt lower foot highly weathered slightly vesicular basalt 3.0 core	Up to 20' hole does not leak more than 0.5 G.P.M. though at 20' no water stands in hole after 16 hours.
10.2				
		9.4	Half a foot of weathered basalt at top, mostly fresh grey basalt, basaltic tuff at bottom. 7.95 core	
19.6				
		5.2	Compacted basaltic cinder agglomerate. 0.65 core	From 5.9 - 46.0' medium hard to hard blue basalt. A small amount is too soft to core.
24.8				
		9.8	Fresh grey basalt 9.25 core	
34.6				
		11.3	Blue-grey basaltic cinders. 2.0 core	To 76.8' frothy red basalt or cemented cinder with occasional layers of clay. Clay about 20 per cent of mass, caves badly.
45.9				
		10.9	N.S.A.	
56.8				
		0.6	Tube sample 0.5 Brown-yellow clay.	
57.4				Water stands in hole at 65' can be heard at 71 -.
76.8				
		1.2	Light colored basaltic tuff. 1.2 core	83' agglomerate of cemented clinkers and calcite
78.0				
		5.0	Basaltic tuff, cemented with white material. 3.8 core	
83.0				
		7.0	N.S.A.	To 85.1' leakage 6 G.P.M. very leaky to 87' sharp cinders, inclined to cave
90.0				

Diamond Drill Log
Hole No. 14
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
90.0				
		11.0	Light colored basaltic tuff. 6.95 core	To 104' black basaltic cinders cemented by calcite.
101.0				
		3.1	Basaltic tuff. 3.0 core	
104.1				To 110.7' very compact brown gravelly clay.
		0.9	Tube sample 1.0 Sticky brown, cindery material.	
105.0				110.7 - 113.0' green-grey Koolau basalt.
		7.2	N.S.A.	
112.2				
		0.3	Nubbins of grey mudrock or basalt. 0.05 core	
113.0				
		3.0	N.S.A.	
116.0				
		7.7	Highly vesicular light grey basalt. 3.1 core	Same as above but softer.
123.7				Less than 0.5 G.P.M. leakage between 90 and 156.5'
		4.3	Highly altered grey to brown basalt. 1.3 core	
128.0				
		15.2	N.S.A.	116-128' green-grey soft basalt. Koolau
143.2				
		13.3	N.S.A.	Compact red and brown gravelly clay.
				Soft grey basalt with thin layers of tough brown clay. Clay represents about 10 per cent of formation. Hole finished with 85' 1" pipe.
156.5				

BOTTOM OF HOLE NO. 14

Diamond Drill Log
Hole No. 15 Pauoa Valley

Lat. 21° 20' 07" N
Long. 157° 49' 45" W
Near Mango tree below next to last house in Pauoa Valley, map elev. 650 ft.

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0				Elevation known approximately 1/25/1935. To 5.5' gravelly soil. To 9.1' medium hard, badly broken, grey basalt.
		9.1	N.S.A.	
9.1				
		2.8	Fairly fresh green-grey basalt 2.7 core	
11.9				Water stands at 5'
		5.6	Dense green-grey basalt, weathered zone at about 17' 5.6 core	Medium hard basalt
17.5				To 40.6' frothy rotted basalt inclined to cave. Hole 20'deep water stands at 8.5'
		19.3	N.S.A.	
36.8				
		2.0	A few nubbins of highly weathered basalt. 0.25 core	
38.8				To 46' hard grey basalt
		1.8	N.S.A.	
40.6				
		4.4	Dense grey basalt 3.6 core	
45.0				
		1.0	Dense grey basalt 1.0 core	
46.0				
		1.1	Grey, coarse cinder-tuff, yellow cementing material 0.95 core	To 72.5' soft, partly rotted basalt, caves badly
47.1				
		21.2	N.S.A.	
68.3				Less than 0.5 G.P.M. leak to here.
		1.0	Red cinder-tuff, cemented with yellow material 0.2 core	
69.3				Leak of over 3 G.P.M. No other leak to 100.2'
		3.2	N.S.A.	
72.5				
		1.9	Basalt-cinder-tuff, red and grey particles cemented, with yellow binder 1.9 core	To 100.2' agglomerate of cemented clinkers and calcite
74.4				

Diamond Drill Log
Hole No. 15
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
74.4				
		1.9	Similar to above 1.9 core	
76.3				
		8.8	N.S.A.	
85.1				
		2.3	Grey cinder-tuff 1.8 core	
87.4				100.2 - 104.3' grey-green medium hard, basalt. Koolau?
		13.7	N.S.A.	
101.1				
		0.8	Weathered, vesicular basalt olivine crystals prominent 0.55 core	
101.9				
		2.4	Rather dense, grey basalt with clay zones.	
104.3				Hole finished with 97.8' 1" pipe. 2/1/1935

BOTTOM OF HOLE NO. 15

Diamond Drill Log
Hole No. 16 Nuuanu Valley

Lat. 21° 21' 20" N
Long. 157° 49' 10" W
In gutter of Old Pali Road, 500 ft. northeast of junction with Kamehameha Highway. Map elev. 884 ft.

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0				3/27/1935
	877.6	11	N.S.A.	Ground elevation. Soil and surface detritus. 6 gallons, 44 sec. insufficient at 11' Necessary to blast.
		10	N.S.A.	Gravelly caved material probably a good aquifer.
		6	N.S.A.	Crumbly broken basalt probably a good aquifer.
		2	N.S.A.	Tough smooth clay.
		16	N.S.A.	Smooth very soft clay
		1.7	N.S.A.	Tough smooth clay
46.7				
		0.5	Core 0.25	Hard basalt.
47.2				
		0.4	N.S.A.	Leaky cavity.
47.6				
		7.9	Fine grained, dense, grey basalt. 7.85 core	Very hard basalt, not badly fractured. Hole finished with 55' of one inch pipe. Water test 6 gallons, 13 sec. does not fill hole.
55.5				
	822.1			3/28/1935

BOTTOM OF HOLE NO. 16

Diamond Drill Log
Hole No. 17 Nuuanu Valley

Lat. 21° 21' 23" N
Long. 157° 49' 06" W
On Old Pali Road, 1,400 ft. from junction with Kamehameha Highway, map elev. 924 ft.

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0	925.3			#? 3/29/1935 Ground elevation
		6.4	N.S.A.	Rocky soil
6.4				
		1.6	Highly weathered, vesicular basalt. 0.5 core	3 - 13' badly broken slightly rotted basalt with red clay in the fractures, leakage is less than one half G.P.M.
8.0				
		5.3	Weathered, slightly vesicular basalt. 0.35 core	
13.3				At 13' leaks more than 4 G.P.M. 13.3 - 13.7 tough clay.
		12.6	Fine vesicular, grey basalt 9.1 core	13.7 - 16' cinders and lumps
25.9				
		3.8	Fine vesicular basalt, somewhat weathered near base. 3.1 core	29.1 - 32.5' clay-like rotted cinders. To 40' cinders and lumps, very open.
29.7				
		7.3	Slightly vesicular basalt. 0.9 core	Hole leaky 33 - 40' filled at rate of 6 gallons, 43 sec. Hole finished with 40' one inch pipe.
37.0				
		3.0	Core not accounted for only in Driller's Log.	
40.0	885.3			3/30/1935

BOTTOM OF HOLE NO. 17

Diamond Drill Log
Hole No. 18 Nuuanu Valley

Lat. 21° 21' 23" N
Long. 157° 49' 02" W
On Old Pali Road about 2,000 ft. from junction with Kamehameha Highway, map elev. 952 ft.

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0	942.4	16.0	N.S.A.	Ground elevation 4/1/1935 0- 14' clay and occasionally lumps of very rotten basalt. No leak to this depth.
16.0		8.9	Nubbins of slightly vesicular basalt. 0.6 core	14 - 16' leak about 2 G.P.M. 16 - 22' no leak. 22.5' leak carries off all drill water.
24.9		15.6	N.S.A.	14 - 40.4' rotted broken basalt, somewhat gritty a few hard enough to cut with diamond bit. Hole caves a little between 16 and 57.5'
40.5		1.5	Weathered vesicular basalt. 0.4 core	40.4 - 41.8' medium hard broken basalt.
42.0		15.5	N.S.A.	41.8 - 57.5' clay varying from soft to rather firm.
57.5		6.2	Dense grey basalt. 6.5 core	Very hard basalt at 63.7' 6 gallons, 40 sec. does not fill hole. 62.9' of one inch pipe left in hole.
63.7	878.7			4/2/1935

BOTTOM OF HOLE NO. 18

EXPLORATION AT NO. 4 DAM

Dam No. 4 was completed in 1910. During and after its construction there was discussion concerning leakage and the details of the foundation. In 1931, J. B. Lippincott was employed as a consultant to make a report on the dam, its leakages, and its safety (1). In his report there were recommendations for certain improvements and repairs to the dam. In carrying out this reconstruction job (37-W) a series of exploration holes was drilled approximately along the line of the proposed sheet piling which Lippincott had recommended. The section revealed by this drilling is shown in Figure 51. This drilling was done by wash boring, supplemented by shot drilling on encountering hard rock. This method does not permit effective progress in hard, sound basalt, and only sufficient drilling was done at rather heavy expenditure of time to secure short core samples at the surface of the Honolulu lava flow that extends across the valley at elevations 920 to 980 feet. On examining thin sections of these samples under the microscope, the writer finds that the mass of rock encountered in Holes 8 and 10 at 940 feet is also Honolulu basalt, rather than Koolau rock as identified earlier on the basis of megascopic study only.

While these exploration borings were doubtless adequate as a prelude to practical construction, it is unfortunate from the standpoint of more complete understanding of the geologic structure of the

(1) Lippincott, J. B., Report on Nuuanu Dam No. 4, Board of Water Supply, Third Report, pp. 162-169, 1931.

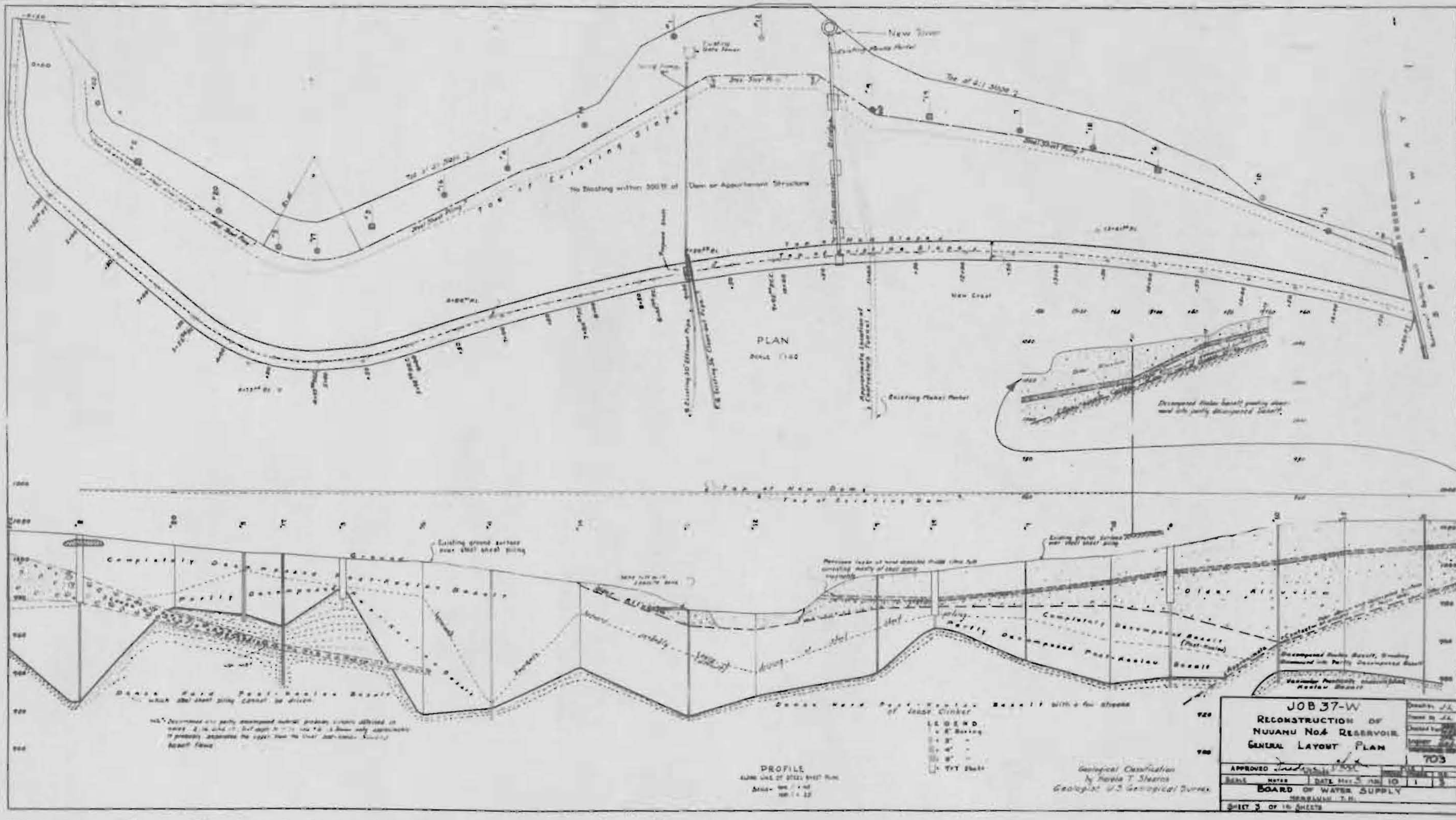

Figure 51 - Photostat reduction of Drawing No. 3 of Job 37-W, showing cross-section revealed by exploratory drilling approximately along the line of the upstream toe of the dam. Based on examination of drill samples by H. T. Stearns. The black and white photostat shows the original interpretation. The red color shows slight modification based on microscopic examination of the rock sample from the bottom of hole 10 by the writer. While the drilling done at this time gave information on the feasibility of driving sheet piling, it was inadequate in its capacity to penetrate hard rock and thus fell short of yielding the geologic data that would be very valuable.

valley and the total leakage from the reservoir that the borings were not made with a diamond bit which would have permitted drilling clear through the Honolulu basalt and probable underlying alluvium to the Koolau floor of the valley. Data from such drilling would have been especially useful in interpreting the history of volcanic eruptions from the Makuku vent.

ADDITIONAL DRILLING AT EAST END LEAK

In 1936, a number of holes were diamond-drilled on and adjacent to the east end of Dam No. 4 in an effort to determine the cause of the heavy leakage at that point. Logs of those holes are presented below.

Diamond Drill Log
Hole No. 30 Nuuanu Valley

Lat. 21° 21' 16" N
Long. 157° 48' 39" W

East End, Dam No. 4

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0	1029.65			0 - 3 ft. firm gravelly clay. Casing carried to 15.8 ft.
		19.9	Soil fill in turn-around.	
19.9	1009.75		N. S. A.	3 to 35.1 ft. Firm red and brown clay consisting chiefly of a mass of rotted clay-like lumps. This formation does not leak except at 26.5 ft. Does not core.
		1.2	May be weathered taluvium with red lumps of altered tuff or basalt? (brown) Bottle sample	
21.1	1008.55			
		4.2	N.S.A. Soil?	
25.3	1004.35			
		1.0	Bottle Sample. Dark brown, granular to fine earth.	
26.3	1003.35			
		1.6	Bottle sample of brown to dark brown with few lumps of palagonitized tuff.	Water stands at 26.5 ft. with hole at 28.2 - 6 G.P.M. leak at 26.5
28.2	1001.45			
		6.9	No Sample Attempted	Subsequent drilling caused this leak to diminish to about 2 G.P.M. probably due to borings sealing off the hole.
35.1	994.55			
		1.3	Bottle sample brown granular earth.	35.1 - 74.8 - Same as (dirt) above but slightly less firm. Shows a tendency to leak. Does not core.
36.4	993.25			Water stands at 27.2 ft.
		2.6	N. S. A.	
39.0				

Diamond Drill Log
Hole No. 30
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
39.0	990.65			
			Bottle sample brown and tan earth, granular appearance but rubs to fine powder.	
40.2	989.45			
		5.0	N. S. A.	
45.2	884.45			
		1.0	Bottle sample tan with some brown earth. May be some tuff.	
46.2	883.45			
		4.2	N. S. A.	
50.4	979.25			
		1.1	Bottle sample of fine brown earth.	
51.5	978.15			
		3.9	N. S. A.	
55.4	974.25			
		1.0	Bottle sample of fine brown earth.	
56.4	973.25			
		6.9	N. S. A.	
63.3	966.35			
		1.9	Bottle sample of fine brown earth. Some tan earth present in three above samples. May have fallen down hole.	
65.2	964.45			June 3. Water stands at 29 ft. Water at this depth leaks at rate of 5-1/2 G.P.M. in a.m. before becoming muddy from chopping but when muddy from chopping the leak diminishes to 2 G.P.M.
70.4	959.25			
		1.0	Bottle sample, brown dirt with some gravel and reddish and tan lumps.	
71.4				

Diamond Drill Log
Hole No. 30
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
71.4	958.25			
		4.8	N. S. A.	74.8 - 92.8 Medium hard porous basalt showing moderate number olivines, a few small leaks. The first, 2 ft. of this formation is somewhat broken and soft.
76.2	953.45			
		5.5	Irregularly vesicular, blue-grey Nuuanu basalt and augite phenocrysts. Core 5.0. T.S. 80.5	
81.7	947.95			
		3.3	Slow change to compact grey Nuuanu basalt at 85. with few irregular vesicles 5 to 10 mm. dia. Core 3.2	
85.0	944.65			
		2.0	Nuuanu basalt as at 85.0	
87.0	942.65		Core 1.5	
		5.8	0.2 weathered brown top to slightly weathered blue-grey, irregularly vesicular. Lava flow. Core 5.4	87.5 - 88.5 Crevice and heavy leak. 89.9 leak
92.8	936.85			
		1.2	Bottle sample mixed black, brown, red lumps of weathered basalts.	92.8 - 96.0 Rotted cinder.
94.0	935.65			June 3
		2.0	N. S. A.	June 4 Water stands at 29.0 feet
96.0				

Diamond Drill Log
(Hole No. 30)
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
96.0				96 to 98.1 Caving, broken, leaky basalt or cinders.
		2.1	N.S.A.	
98.1	931.55			
		3.0	Brown tuff inclusions and surfaces in broken vesicular, blue-grey Nuuanu basalt. Core 1.4	98.1 - 101.1 medium hard olivine basalt.
101.1	928.55			
		3.9	Bottle Sample. Medium brown dirt, with some white deposits.	Soft to 105 ft. - compact gritty clay.
105.0	924.65			105.6 to 106.3 leak also at 109 - No. 1 110.8 - 113.3 - 119.0
		6.5	Nubbins and short pieces, coarsely to finely vesicular blue-grey Nuuanu basalt. Some weathered material. Core 5.0 ft.	105 to 147 Same as 98.1 - 101.1. Occasional rotted spots.
111.5	918.15			
		4.0	Nuuanu basalt as above Core 1.8	
115.5	914.15			
		11.0	Grey vesicular Nuuanu basalt in nubbins and short pieces. Core 5.2	116 - 117.6 Cavity and heavy leak 119.4 June 4 122 - 123 Cavity and heavy leak. June 5
126.5	903.15			
			2.7 ft. ca. one Nuuanu flow. Grey vesicular rock with weathered 0.2 zone at bottom. 4.2 ft. mottled blue-grey fairly dense Nuuanu basalt and few large irregular vesicles.	131.5 June 5
133.5				

Diamond Drill Log
Hole No. 30
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
133.5	896.15	17.1	Thin Section. (0.2 out) 2.4 dense grey basalt and white zeolites and few vesicles. 7.5 pieces of variable Nuuanu basalt, brownish to grey. Core 17.0	
143.6	886.05	3.4	Short pieces of grey vesicular basalt. Core 1.7	142.6 to 146 Leak.
147.0	882.65	14.9	Chop N. S. A.	147 to 161.9 Clay with occasional lumps of pithy rolled rock. Inclined to cave.
161.9	867.75	9.8	0.2 Koolau dike rock Grey dense rock. Thin section. 1.0 Nubbins and pieces of Koolau basalt. Very vesicular, thin section from bottom piece. Core 1.2	June 7 - Rather soft basalt.
171.7	857.95			10:30 a.m. June 8, 1937

BOTTOM OF HOLE NO. 30

June 9 Water stands 29.97' below top of pipe.

Diamond Drill Log
Hole No. 31 Nuuanu Valley

Lat. 21° 21' 17" N
Long. 157° 48' 41" W

Near East End Dam No. 4

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0	1016.2		Elev. on Frame ca. 1 ft.	
		11.0	above ground.	
11				Casing 10.8'
		1.0	Bottle sample, brown earth + little tuff.	0 - 12' Rotted gravel-clay, quite firm.
12				
13.8				
		0.5	Bottle sample, red-brown earth.	12 to 16.7' Cindery. Slightly leaky, (trace of clay), rather soft. 16.7 to 17.0'. Moderately hard lump of rotted rock.
14.3				
		4.7		
19.0				
		1.0	Bottle sample, mixed red and yellow chunks covered with brown muddy earth.	17 to 43.2' Alternating rotted gravel-clay and cindery spots, rather soft; occasional spots of smooth silky clay alternating with thin layers of fine gravel an inch or so thick, inclined to cave.
20.0				
23.7				
		1.0	Bottle sample, brown earth with yellowish lumps (small)	
24.7				
		18.5		42 ft. June 9 June 10
43.2				
		2.0	Grey, vesicular, olivine basalt porphyry. Core 1.5	Hard grey basalt, rich in olivines (boulder?)
45.2				

Diamond Drill Log
Hole No. 31
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
45.2				
			Bottle sample	45.2 to 78' Rotted gravel-clay, rather firm for first five feet but softer below. No leaks but in spots inclined to cave.
		1.1	Granular, red, brown and black particles - rotted taluvium.	
46.3				
		17.2		
63.5				
		1.2	Bottle sample of mixed red, brown, yellow, and black (1/4") pieces of weathered talluvium.	
64.7				
		14.8		
79.5		3.1	Nubbins and short pieces of dense grey Nuuanu basalt. Core 2.0	78 to 79.5 Broken, sharp caving basalt. (Depth of casing) 79.5 to 129.2 Medium hard basalt showing frequent olivines, rather broken and with many frothy, caving, partly rotted spots. Cores very poorly. No heavy leaks though the sum of many small leaks carries off all drilling water (6 G.P.M.) when a depth of 117' had been reached. Below this point rock is less broken and harder.
82.6		3.1	Broken, slightly vesicular basalt, two zones of vesiculation. Core 2.2	
85.7				June 10
			Nubbins of moderate to very vesicular, dark grey basalt, and yellow and brown earth. Core 2.5	June 12
96.0				

Diamond Drill Log
Hole No. 31
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
96.0		4.0	Nubbins of grey vesicular basalt, some with small and numerous vesicles. <u>Core 1.8</u>	
100.0		6.6	Through 2½ ft. of slightly vesicular grey basalt top and bottom, rep. by nubbins of vesicular basalt. <u>Core 4.1</u>	June 12
106.6		9.4	Fragments of very vesicular dark grey basalt. <u>Core 1.4</u>	June 14
116.0		14.4	Nubbins and half foot pieces of vesicular light grey Nuuanu basalt. <u>Core 13.4</u>	129.2 to 130.4' Clinker or broken basalt.
130.4		0.6	Bottle sample of fine brown earth.	Gravelly clay (are these gravels water-worn?
131.0		11.5	Pieces of slightly vesicular, grey basalt, tending to very vesicular at bottom. <u>Core 2.1</u>	Lumps of medium hard basalt in mass of rotted clinker.
142.5		0.8	Bottle sample of red granular earth.	
143.3				June 14
		93.5	Chop	June 15 142.5 to 236.8' Tough clay, red on top, very little grit. Probably quite impervious. The muddy water occasioned by drilling this clay sealed off practically all the leakage in formations above and water again returned to surface. Would this seem
236.8				

Diamond Drill Log
Hole No. 31
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
236.8	779.3	3.4	Thin section Nubbins of dark grey vesicular basalt. Core 1.2	to indicate that these leaks were in the form of seepage? (Seeps)
240.2		7.3	Nubbins of slightly vesicular blue-grey Nuuanu Basalt. Black coatings. Core 2.6	June 15 June 16 236.8 to 259.2 Medium hard to hard basalt, many frothy, partly rotted spots. A few olivines and many small feldspar crystals, inclined to cave.
247.5		4.7	Pieces of grey, vesicular Nuuanu basalt and few green coatings. Core 2.9	
252.2		6.2	Pieces of slightly vesicular to dense, grey Nuuanu basalt. Core 6.0	June 16 June 17
258.4		13.7	0.6 grey vesicular basalt. 1.5 very vesicular, oxidized basalt. Thin Section at 270. Core 2.1	
272.1		14.5	Nubbins of very vesicular oxidized Nuuanu basalt. Core 1.8	276' June 17 June 18
286.6		3.8	Nubbins of grey vesicular basalt. (Nuuanu) Core 1.0	259.2 to 290.4' - Probably same flow as above but more porous and soft, inclined to cave.
290.4				

Diamond Drill Log
Hole No. 31
(Cont'd)

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
290.4				
		9.8		Firm clay-like material. June 18
300.2				June 19
		6.2	Nubbins of slightly vesicular blue-grey Nuuanu basalt. 304 ft. - Thin section Core 1.8	300.2 to 336.3 Medium hard to hard, badly broken basalt June 19
306.4				
		4.0	Short pieces and nubbins of vesicular grey Nuuanu basalt. Core 2.7	June 21
310.4				
		2.2	Nuuanu basalt as above Core 1.3	
312.6				
		2.8	Slightly less vesicular than above basalt. Core 2.4	
315.4				
		3.4	Nuuanu basalt as above Core 1.8	
318.8				318' June 21 June 22
		4.7	Half-foot pieces of grey vesicular Nuuanu basalt. Core 4.5	
323.5				
		3.0	Slightly shorter pieces of above type basalt. Core 2.8	
326.5				326' June 22 June 23
		4.1	Half-foot pieces and fragments of above basalt. Core 3.5	
330.6				
		5.7	As above, divisions made by withdrawing drill. Core 2.2	
336.3				

Diamond Drill Log
Hole No. 31
(Cont'd)

Depth	Eleva-tion	Thick-ness	Material	Driller's Log and Remarks
336.3			N. S. A.	
		42.7		350' June 23
379.0				June 24
		1.5	Bottle sample of brown adobe-like mud.	336.3 to 380.5 Very compact clay, red on top, grey below.
380.5				
		6.2	0.1' dense, light-grey Koolau basalt with few irregular vesicles, thin section. 3.9' Nubbins and 1/2 foot pieces of oxidized, mottled rust and grey vesicular Koolau basalt. <u>Core 4.0'</u>	380.5 to 381.7 Partly rotted basalt. 381.7 to 386.7 Rather soft basalt or agglomerate. Koolau?
386.7				
386.7				June 24

BOTTOM OF HOLE NO. 31

Diamond Drill Log
Hole No. 32 Nuuanu Valley

Lat. 21° 21' 17" N
Long. 157° 48' 37" W

Near East End Dam No. 4

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0	1027.4			
		11.2	No sample attempted N.S.A.	Rotted, firm, gravel-clay, no leak.
11.2				
		2.3	N.S.A.	Partly rotted ash, leaks 2 g.p.m.
13.5				
		27.9	N.S.A.	Rotted, firm, gravel-clay, very slightly leaky. Between 32 and 38, formation rather soft and quite leaky, which leaks, however, sealed up from the muddy water during a few minutes of subsequent drilling. Cased to here.
41.4				
		0.9	Pieces of vesicular, grey basalt, with lt. grey feldspar phenocrysts. Core 0.8	Hard, grey, porous basalt with many feldspar crystals.
42.3				
		43.8	N.S.A.	Firm clay
86.1				
		6.1	Short pieces of earth-stained grey basalt, with large and small vesicles. Thin section at 91 ca. Core 3.3	Hard, porous basalt
92.2				

BOTTOM OF HOLE NO. 32

Diamond Drill Log
Hole No. 33 Nuuanu Valley

Lat. 21° 21' 22" N
Long. 157° 48' 40" W

Near East End Dam No. 4

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0	1040.1			
		12.0	N. S. A.	Compact gravel-clay. Does not leak.
12.0				
		10.0	N. S. A. (in center of earth dam)	Soft clay or rotted ash. Leaks badly. This formation is sufficiently soft that drill rods can be pressed into it by hand. Does not cave.
22.0				
			N. S. A.	Clay, generally rather compact, though with occasional softer spots.
92.0				
			N. S. A.	Frothy, very open basalt.
93.5				
			N. S. A.	As above but more open. Heavy leak.
98.1				Hard basalt. Approximately 98 ft. of pipe placed in hole resting on bottom. The first two joints from bottom not drilled. Next two drilled in usual manner. Remainder of pipe above this not drilled.

BOTTOM OF HOLE NO. 33

Diamond Drill Log
Hole No. 34 Nuuanu Valley

Lat. 21° 21' 18" N
Long. 157° 48' 38" W

Near East End Dam No. 4

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0	1022.5			
		14.0	N. S. A.	Firm rotted gravel-clay. Does not leak.
14				
		31.0	N. S. A.	Same as above but with thin spots of partly rotted ask, slightly leaky and somewhat less firm.
45				
		9.0	N. S. A.	Formation softest and most leaky. At 56 these accumulated leaks had absorbed all drilling water though the mud from subsequent drilling to 75 ft. had practically sealed all leaks.
56.x				
		19.0	N. S. A.	
75				
		6.7	Nubbins and pieces of vesicular-grey basalt. Nubbins are earth stained. <u>Core 3.3</u>	Hard porous basalt showing frequent olivines.
81.7				
				76 ft. of pipe placed in hole 1.5 bottom length sleeve of which rests on diamond drill hole at 75. Next length above not drilled, next two lengths drilled in usual manner. Top length not drilled.

BOTTOM OF HOLE NO. 34

Diamond Drill Log
Hole No. 35 Nuuanu Valley

Lat. 21° 21' 16" N
Long. 157° 48' 38" W

Near East End Dam No. 4

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0	1025.8			
		0.5	N. S. A.	Through concrete spillway floor.
0.5				
		0.5	N. S. A.	Broken rock (fill)
1.0				
		85.5	N. S. A.	Rotted firm gravel-clay. Occasionally rather soft spots, very slightly leaky except at 22.5 at which point a heavy leak, which leak, however, was sealed off by mud from subsequent drilling. Formation rather soft between 22.5 and 28.0
86.5				
		1.5	N. S. A.	Partial cavity in frothy rock showing heavy leak.
88.0				
		0.1	N. S. A.	
88.1				Hard basalt

BOTTOM OF HOLE NO. 35

Diamond Drill Log
Hole No. 36 Nuuanu Valley

Lat. 21° 21' 18" N
Long. 157° 48' 35" W

Near East End, Dam No. 4

Depth	Elevation	Thickness	Material	Driller's Log and Remarks
0	1028.5			Rotted firm gravel-clay. In places slightly gritty.
		65	N. S. A.	Does not leak above 65'
65				Between 65 and 69 formation slightly softer and rather leaky.
			N. S. A.	Formation slightly softer and rather leaky.
69				
			N. S. A.	
87.6				Leak of 3 G.P.M.
		8.4	Nubbins and pieces of grey vesicular basalt. Brown earth-stained. Core 2.8	Heavy leak and cavity at 90.4'.
90.4				
			Loss.	
96.0				At depth of 96', water stands 23.8'.

BOTTOM OF HOLE NO. 36

Physical properties of rock formations

No new determinations of rock properties have been made since 1938, when the results of certain tests were presented in the Palolo-Waialae Report (1). As has been pointed out elsewhere, the hydrologic

(1) Wentworth, C. K., Geology and Ground-Water Resources of the Palolo-Waialae District, Board of Water Supply, pp. 168-187, 1938.

and related characteristics of the lava flows of Hawaii are based on such a coarse-meshed structure that results from laboratory tests are not of practical applicability to field problems. The two most important properties are porosity and permeability, which are interrelated but are quite distinct. The index or percentage of porosity is the percentage of open spaces in the rock referred to the whole volume as a base, whether the spaces be large or small, connected or interconnected. The percentage of effective porosity is the percentage which the total water yielded by a rock mass bears to the total volume of the rock mass (2). This is obviously controlled by the size and degree of

(2) Meinzer, O. E., Outline of Ground-Water Hydrology, U. S. G. S., Water Supply Paper 494, pp. 19, 28, 1923.

mutual interconnection of openings in the rock.

Permeability is the capacity of the rock to permit the movement of water through it under pressure (3). It is a common habit of speech,

(3) Meinzer, O. E., Op. Cit., p. 44, 1923.

but a very bad one, to attribute easy movement of water through rocks to their porosity, rather than to their permeability. As a matter of fact, most clays and silts, which are relatively impermeable, have as high or higher percentages of porosity (35 to 60%) as do sands and gravels which are relatively permeable. The difference is that in the finer-grained rocks the openings, though very numerous, are small, whereas in the coarser rocks the less numerous openings are larger and facilitate much more ready movement of water through them.

Effective determination of porosity of any mass of rock requires its isolation. Isolation of a mass of rock large enough to yield regionally significant figures is difficult and has not been achieved. Determination of porosity by measuring yield against water table lowering, which is a practical method in some regions, is probably not practicable at present in Hawaii because of (1) the large and unknown changes in rate of lateral inflow and outflow due to head changes, and (2) the probable large and unknown effect of head changes on inflow from or outflow to bottom storage under the Ghyben-Herzberg theory. This again is a failure of isolation of the area in question.

The yield, under given cross-sectional and hydraulic conditions, is a function of average cross-section of water-transmitting openings transverse to the direction of water movement and of average velocity parallel to this direction. The product of these two quantities in suitable units give "Q" per unit of time, which, divided by the transverse area of the rock section, is the permeability. The percentage of the rock section which is in the form of water-transmitting openings is the percentage of porosity. But until we can analyse the two reciprocal factors, velocity and cross-section, which go to make up the quantities of water transmitted and measure the former, we cannot deduce the latter in this way. To date no data adequate to work out this value have been obtained.

Unfortunately, we are not able to deduce porosity and also permeability approximately from mechanical analysis as is done with sand and gravel formations. Both the properties depend on size and number of openings. Porosity is a simple product of size and number; permeability is a more complex function, which in the case of openings like those in sands and gravels, which have some statistically systematic relationships, can be approximated by deduction from the size distribution of the grains. The nature of the openings and the irregularity and coarseness of mesh in the lava formations of the basal aquifer have so far defeated any such approach.

Valid determinations of porosity and more accurate measurements of permeability can doubtless be made on the basal aquifer, but they will only be made with more adequate numbers and arrangements of measuring points in connection with large, well-controlled operating stations and with due regard to some of the inherent difficulties of the problem in Hawaii. These include (1) the high permeability, which favors low gradients and low drawdowns as well as discontinuous pumping, all making measurement more difficult; (2) proximity of the rainfall source areas and variability of rain which produces sharp and frequent fluctuations of the water table, and in turn may induce significant changes in the rate of transfer to or from bottom storage in the case of basal water bodies; (3) proximity to the ocean and effects of head changes on leakage; (4) presence of semidiurnal fluctuations of the water table, the cause of which is not fully known; (5) high permeability and high porosity, both of which make for relatively slight water table changes and relatively indeterminate drawdown figures which extend for long distances and in part extend beyond regions accessible to measurement.

Rainfall

Mean annual rainfall in the Nuuanu-Pauoa district ranges from under 25 inches along the waterfront to a maximum of over 160 inches on the eastern divide boundary of the district about a mile leeward from Konahuanui and the crest of the range. The general distribution of rainfall, based on the best available data up to about 1939, is shown in Figure 52 (1). West of the 160-inch maximum area which

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(1) Map based on data and isohyetal map compiled by W. F. Feldwisch, Territorial Planning Board, Urban Supplement, Plate 156, 1940.

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centers on Pauoa Flats and the basin of the Aihualama branch of Manoa Stream, the maximum declines across Nuuanu Valley so that it amounts on the western boundary to less than 120 inches. According to the drawing of the isohyets, the rainfall along the crest of the range across the Nuuanu Gap is about 100 inches, though the rainfall at the gap is probably highly variable and not necessarily well determined by the record of 102 inches at Konahuanui on the east and 93 inches at Lanihuli on the west. From the leeward coast to the line of maximum rainfall, there is a steady increase, at the rate of about 20 inches of rainfall per mile across the coastal plain, rising to a rate of increase of more than 40 inches per mile in the midsection of the valley and between isohyets 70 and 150 inches on the east margin of the district.

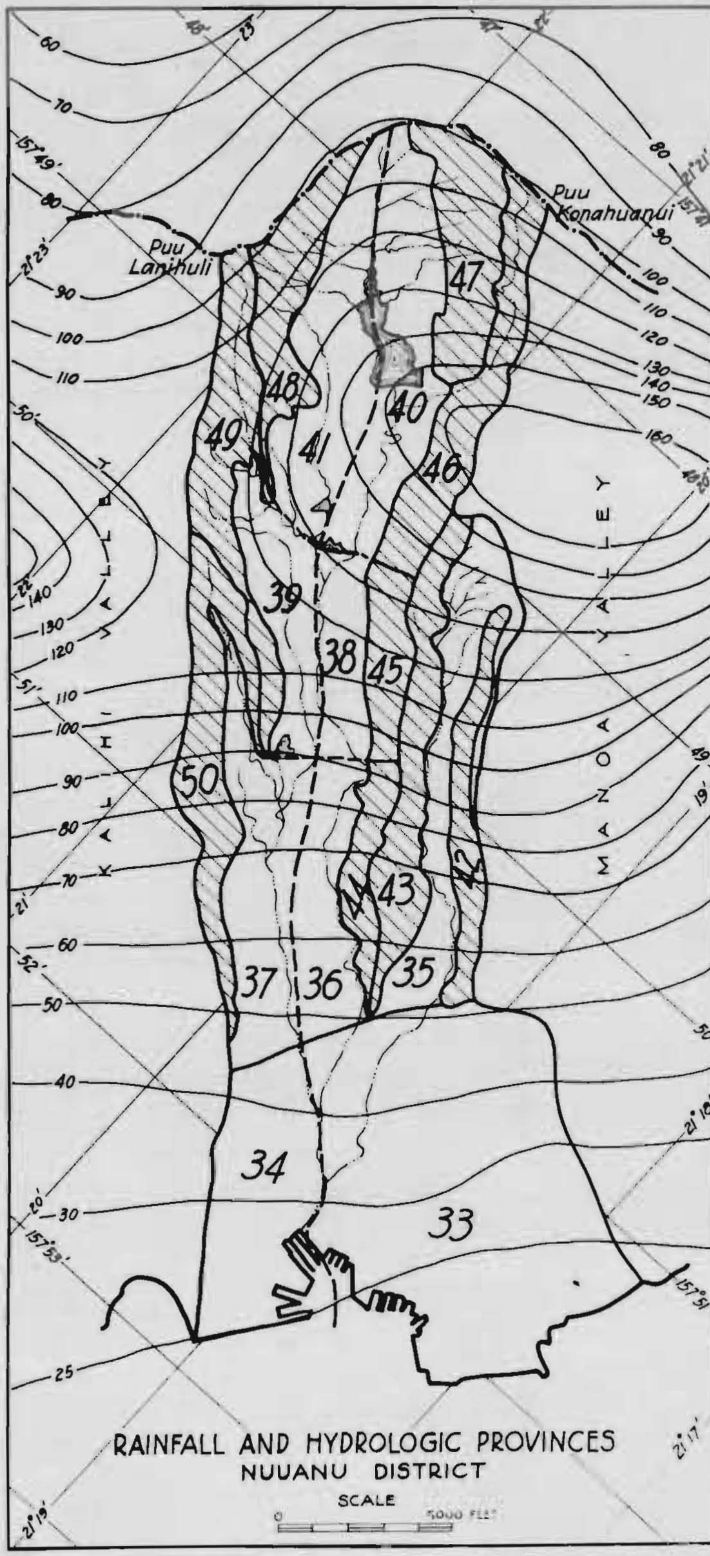

Figure 52 - Isohyetal Map of Nuuanu-Pauoa District, showing hydrologic provinces. (Tables, pp. 150-152, this report) The shaded portion indicates the maximum area from which infiltration is believed to reach basal water. Rainfall data from U. S. Weather Bureau, via Territorial Planning Board, 1940.

The average rainfall of the whole district is 85 inches, as compared to Palolo-Waialae, 48; Manoa-Makiki, 81; Kalihi, 83; and Moanalua, 77 inches. For the mountain areas of the several districts, the following averages were found: Palolo-Waialae, 79; Manoa-Makiki, 107; Nuuanu-Pauoa, 110; Kalihi, 101; and Moanalua, 140 inches. In this district, as in the Honolulu watershed generally, there are many local variations not indicated by the existing data which are due to topographic features in their relation to the prevailing winds. More detailed measurements would be of the greatest value in promoting a more intimate understanding of rain-producing factors and perhaps in the interpretation of local and general extremes and in long-range prediction. Meantime, however, the averages as shown by isohyets are sufficient to calculate total rainfall quantities in the various hydrologic unit areas (Figure 52) with greater accuracy than any estimates we can make as to general or local percentages of infiltration.

ANALYSIS OF RAINFALL, HYDROLOGIC AREAS, AND WATER QUANTITIES

I	II	III	IV	V	VI	VII	VIII	IX
Hydrologic Unit Areas (1)	Area (Square Miles)	Average Annual Rainfall (Inches)	Total Annual Rainfall (Square-Mile-Inches)	Mountain Rainfall (M.G.D.)	Cap-Rock Rainfall (M.G.D.)	District Totals (M.G.D.)	Isopiestic Totals (M.G.D.)	**Valley and Isopiestic Areas**
(42) East Wall, Pauoa Valley	0.30	95	28.5	1.36				
(43) West Wall Pauoa Valley	0.47	100	47.0	2.24				
(44) East Wall Nuuanu Valley (makai)	0.20	70	14.0	0.67				
(45) East Wall Nuuanu Valley (middle)	0.23	113	26.0	1.24				
(46) Lulumahu Valley & East Wall Nuuanu Valley	0.50	150	75.0	3.57				
(47) East Wall Nuuanu Valley (head)	0.45	125	56.3	2.68				
MOUNTAIN AREA, EAST PAUOA-NUUANU	2.15	115	246.8	11.76				

I	II	III	IV	V	VI	VII	VIII	IX
(33) East Nuuanu Coastal Plain & Punchbowl	2.52	33	83.2		3.96			
(35) Pauoa Valley Bottom	0.57	100	57.0		2.71			
(36) East Nuuanu Valley Bottom (makai)	0.44	68	30.0		1.43			
(38) East Nuuanu Valley Bottom (middle)	0.30	110	33.0		1.57			
(40) East Nuuanu Valley Bottom (mauka)	0.76	135	102.6		4.89			
CAP-ROCK AREA, EAST PAUOA-NUUANU	4.59	67	305.8		14.56			
							54.58	BERETANIA ISOPIESTIC AREA (No. 2)
(50) Waolani Valley & West Nuuanu Wall	0.55	85	46.7	2.22				
(49) Moole Valley & West Wall Nuuanu	0.52	115	59.8	2.85				
(48) West Wall Nuuanu (head)	0.39	115	44.9	2.14				
MOUNTAIN AREA, WEST NUUANU	1.46	104	151.4	7.21				
						18.97		NUUANU-PAUOA MOUNTAIN AREA

I	II	III	IV	V	VI	VII	VIII	IX
(34) West Nuuanu Coastal Plain	0.77	32	24.6		1.17			
(37) West Nuuanu Valley Bottom (makai)	0.68	67	45.6		2.17			
(39) West Nuuanu Valley Bottom (middle)	0.42	115	48.2		2.30			
(41) West Nuuanu Valley Bottom (mauka)	0.71	130	92.3		4.40			
CAP-ROCK AREA, WEST NUUANU, NUUANU BARRIER TO NUUANU-KAPALAMA DIVIDE	2.58	82	210.7		10.04			
						24.60		NUUANU-PAUOA CAP-ROCK AREA

NOTE - Quantities shown in this table differ in some instances from apparently comparable amounts shown in a table in another report, for three reasons: (1) The other table was in part constructed from data based on a slightly different breakdown of drainage areas, (2) The other table was worked up in part using rainfall isohyets available in 1935; for the table above a more recent isohyetal map has been used, which differs in minor respects from the earlier map, (3) Errors of a few hundredths are due to differences in measurements by planimeter, of the same area but by different persons on different maps. None of the differences are of sufficient magnitude to significantly affect the final conclusions.

(1) These areas are shown on Figure 52.

Runoff

Runoff records have been made in a number of places in Nuuanu and Pauoa Valleys (1). (Figures 53, 54, 55) Unfortunately, many of

(1) Surface Water Resources of the Territory of Hawaii, Territorial Planning Board, Summary of Records, 1901-1938, pp. 23-37, 1939.

these records are for short periods or have a serious break of several years. The longest records are: Kahuawai Spring, 14 years; Booth Spring, 10 years; Nuuanu Tunnels at Lower Luakaha, 13 years; Nuuanu Reservoir, 26 years; and Nuuanu Stream, 26 years. Only the latter represents a definitive major drainage basin. Complete details of these records are shown in the report cited. The Nuuanu Stream record at the station below No. 2 Reservoir gives an average of 5.8 M.G.D., and minimum and maximum of 0.68 and 11.3 M.G.D. for the years 1926 and 1930 (and 1932), respectively. This is from an area of 3.4 square miles, of which about 1.8 square miles is classed as mountain area tributary to the basal water (2). The discharge of 5.8 M.G.D. amounts

(2) Total area tributary to the U. S. G. S. gage referred to, as measured on the larger scale maps used for the breakdown shown on the accompanying table of hydrologic areas appears to be about 5% less than the 3.4 used as the official figure.

to 1.7 M.G.D. per square mile of drainage. The total rainfall within the area tributary to the station is 20.02 M.G.D., according to an estimate based on the breakdown of hydrologic areas shown above. No means is at hand for estimating the part which is runoff from the

Figure 53 - Fall of Moole Stream above Moole Ditch intake in Hillebrand Glen after heavy rains. (Negative No. 12306)

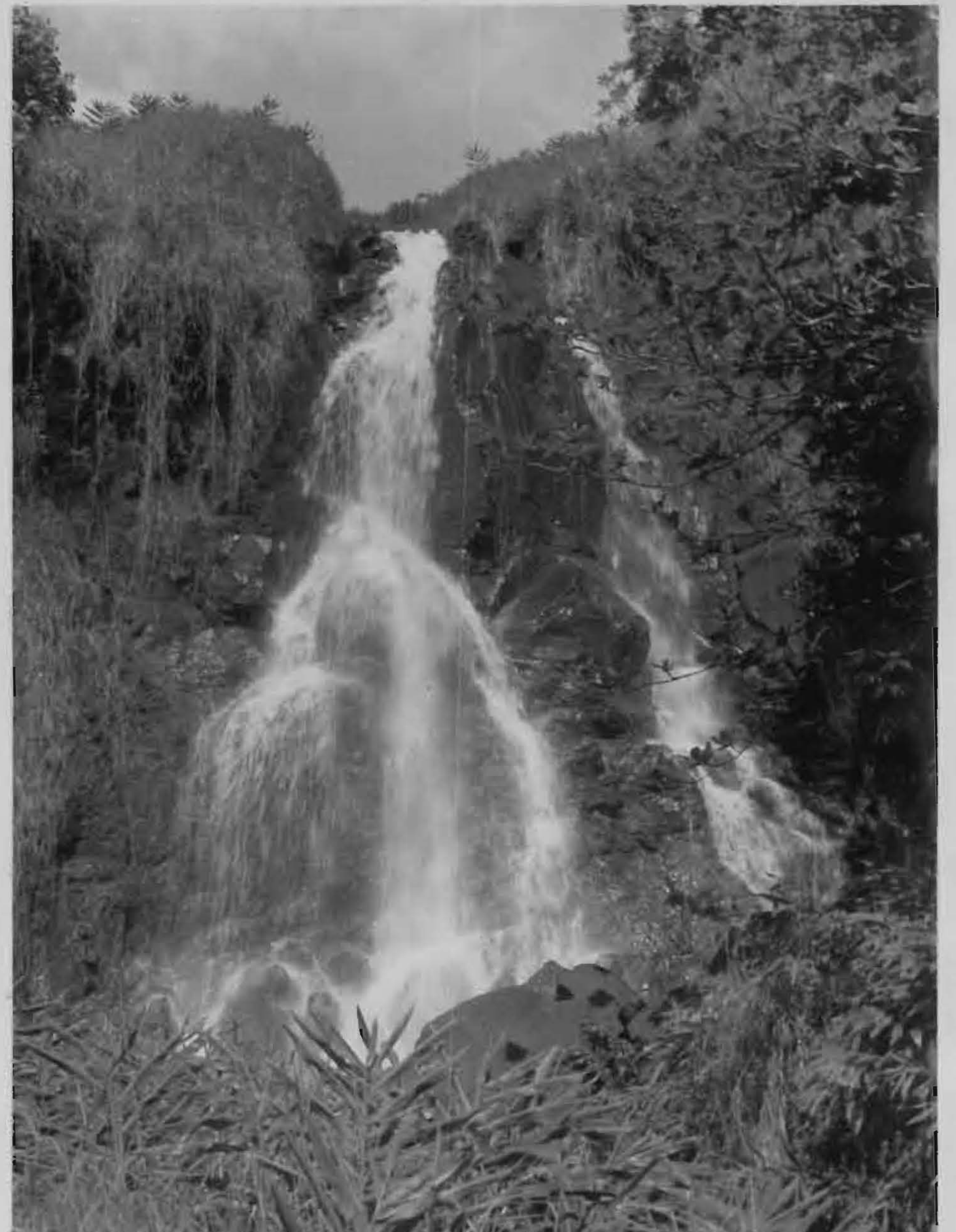

Figure 54 - Fall of Nuuanu Stream at Lower Luakaha over massive Nuuanu lava flow into alcove thought to have been caused by the base of Luakaha cinder cone. (Negative No. 12212)

Figure 55 - Fall of Pauoa Stream over northwest edge of Pauoa lava flow. Above this point the stream flows on the lava flow near the middle of the valley, but here the stream turns to the northwest side and bears against Koolau rock and alluvium. (Negative No. 13196)

mountain area (peaks, ridges and valley walls of Koolau rock) and that which is derived from rainfall on the valley bottom and adjacent alluvial fans. Measurements made by Kunesh and his assistants in 1927-1928, show discharge at the 200-foot elevation for Nuuanu Valley ranged from 1.15 to 2.4 times the contemporary discharge at the U. S. G. S. gage station, with an average of approximately 1.75 times. The total area tributary to Nuuanu and Waolani Streams at 200 feet is 5.44 square miles, with a total rainfall of 29.77 M.G.D. The discharge of 1.75 x 5.80 M.G.D., or 10.15 M.G.D. represents 34% of the rainfall, as against 29% at the U. S. G. S. gage. Thus it appears that some of the shallow underground water probably re-emerges into the stream between 632 and 200 feet. This is the total rainfall under discussion, consisting of 14.81 M.G.D. of rainfall in areas tributary to the basal supply and 14.96 M.G. of rainfall on the valley bottom and not so tributary. We have no valid basis for determining separately the contrasted rates of runoff, and can do no better than to assume them equal, making a runoff from the mountain rainfall of 5.1 M.G.D. for Nuuanu Valley alone. The mountain rainfall of Nuuanu and Pauoa together is about 18.97 M.G.D., of which 34% amounts to 6.45 M.G.D., as a possibly somewhat high estimate of total mountain runoff. In two earlier reports a total runoff from the mountain area of Nuuanu and Pauoa of 5.50 M.G.D. was estimated. (Manoa-Makiki Report, p. 77g, 1940; Kalihi Report, p. 66, 1941) These amounts are materially lower than earlier estimates where rainfall on the Nuuanu and Pauoa Valley bottoms was included and all runoff counted, but in any estimate dealing strictly with mountain (Koolau rock) areas, as to rainfall, runoff and infiltration, no valid basis is known for estimating mean runoff from the mountain areas of Nuuanu and Pauoa to differ greatly from the range 5.5 to 6.5 M.G.D.

Evaporation and transpiration

The writer has no basis for offering new estimates of rates or quantities of evaporation and transpiration. Kunesh used 20% of total rainfall as the assumed evaporation and 30 inches of rainfall where available, for the amount of transpiration (1). Applied to the

(1) Kunesh, J. F., Honolulu Sewer and Water Commission, 1929, Plate F.

mountain (Koolau rock) rainfall for Nuuanu-Pauoa of 18.97 M.G.D., the 20% for evaporation amounts to 3.79 M.G.D.; and the 30 inches of rainfall applied to the corresponding area of 3.61 square miles, gives a total for transpiration of 5.16 M.G.D.

Measurements of evaporation and transpiration at Kaukonahua and Luakaha stations suffice to show that the percentage of rainfall dissipated in this way may be as low as 10% at a high-level, cloudy station in a rainy year, or as high as 50% at a sunny station in a dry year (2).

(2) Stearns, H. T., Territory of Hawaii, Division of Hydrography, Bulletin 5, pp. 147-157, 1940.

While the measurements reported at Kaukonahua and Luakaha were of sufficient duration to give a fair suggestion of range, they can hardly be said to yield a valid average even for those stations. In view of the probable large variation from place to place, one can only guess what the average transpiration plus evaporation would be for the mountain intake area of Nuuanu and Pauoa Valleys. It seems likely that it would be nearer the value found for Luakaha than for Kaukonahua. If, as Stearns asserts, Luakaha is optimum for consumptive use, the average for the mountain intake area might be slightly less than the 33% average for three years at Luakaha. The possible effects of forest cover as distinguished from grass should also be considered, but we lack the data to make any valid correction. We must admit that the evaporation plus transpiration cannot be fixed closer than perhaps between 25 and 45%. In Kunesh's estimate of 1929, based on the rainfall for the entire area, evaporation and transpiration in the Honolulu district amounted to about 56%. The rate for inland districts would in general be less than for the whole area of the district. Forty-five per cent of 18.97 M.G.D. is 8.54 M.G.D.; 25% is 4.74 M.G.D. These values represent the extreme range which seems plausible.

Infiltration

No direct method of measuring or estimating infiltration is available. Either by subtracting the other components of rainfall, or by attempting to estimate leakage of various sorts to add to discharge, possibilities of very large errors are encountered. By using the customary hydrologic formula and subtracting evaporation and transpiration (assumed at 6.00 M.G.D.) and runoff (taking 6.00 M.G.D.) from the total of 18.97 M.G.D. of mountain rainfall, the remainder for infiltration is 6.97 M.G.D. This figure for the Nuuanu-Pauoa district is less intelligible in relation to basal water yields than one for either of the basal water areas, 2 or 3 (Beretania and Kalihi). Discussion and further breakdown of these data is given below.

Principles of ground-water occurrence and movement

The writer does not propose to add to the discussion of this subject which has been included in previous reports (1). The ground water of the Honolulu district can be classified as follows:

(1) Palolo-Waialae Report, pp. 215-227, 1938.
Manoa-Makiki Report, pp. 82-87, 1940.
Kalihi Report, pp. 69-72, 1941.

Surficial ground water

Vagrant percolating water

Perched and restrained water (includes some water in valley-filling cap-rock tongues)

Free basal water

Artesian basal water

Cap-rock water (cap-rock water can be perched, as noted above, can be under artesian pressure, can maintain a water table not hydrostatically connected to the ocean, or with underlying or adjacent basal water, or may be so related)

Occurrence of ground-water bodies

SURFICIAL GROUND WATER

This is the water which is contained in the soil, sub-soil and other mantle rock and weathered bedrock near the surface of the ground. The mantle rock with the subjacent, relatively impermeable weathered bedrock is evidently much more generally marked by local saturation with water than the less weathered, more open-textured bedrock which lies below it. Except for small springs and perhaps the development of a very few gallons of water for small camps, the surficial ground water is of no direct value for water supplies (1).

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(1) There are several small springs and water seeps in the Haleakala Crater area on Maui, and others in the summit areas of Mauna Kea and Mauna Loa which would fall in this class and which are of limited but critical value in these upland desert areas.

Most important functions of the surficial ground water are the temporary storage of water which is later released either to stream flow or to vagrant percolating water, and the maintenance of the forest and other vegetation. As a regulating agent it is a most important link in the hydrologic chain. There are no special features of the surficial ground water of the Nuuanu-Pauoa area which require to be noted here.

VAGRANT PERCOLATING WATER

The vagrant percolating water of the Nuuanu-Pauoa district is comparable to that elsewhere. Its general features were discussed in the Kalihi Report (1). Because of the broad filled bottom of Nuuanu

(1) Wentworth, C. K., Kalihi Report, 1941, pp. 73-74.

Valley, even near its head and in areas of high rainfall, it is pertinent to discuss the conditions of vagrant percolating water underneath the cap-rock tongue of the upper valley bottom. Drill holes reveal the existence of two perched water bodies in the cap-rock tongue and strongly indicate that the bulk of this water is discharged through the permeable layers of the cap-rock fill to the ocean without reaching the basal water body. However, it can hardly be doubted that some water leaks through the cap-rock tongue and passes downward to the basal supply as vagrant percolating water. We can only surmize that this water enters the Koolau rock in more concentrated form than it usually does from the surficial water in the thinner mantle rock; hence, it is probably less typically vagrant or even percolating. There is no other source for vagrant percolating water in the Koolau rock under the cap-rock tongue than from leaks in the latter, the cap-rock tongue being the local mantle rock in exaggerated thickness. If the points of leakage from the cap-rock tongue were determinable or accessible from the lower end, they would be good points of development, but as matters lie, the nearest approach and most practicable development is of the perched bodies revealed by drill holes.

In general, as in other areas, direct development of percolating water is not feasible, and points of concentration by perching or restraint must be sought.

PERCHED AND RESTRAINED WATER

The east wall of Nuuanu Valley, inland from Reservoir No. 4 and adjacent Lulumahu Valley, displays a zone of dikes and sills at elevations 1500 to 1700 feet opposite No. 4 dam and rising with the lava flows to around 2000 feet near the head of the valley. In the same zone are a number of thick and probably fairly widespread tuff beds. The tuff beds are probably part of the same horizon or zone and also outcrop on the west wall of Nuuanu and in Moole Valley. These two structures serve to perch some water, as indicated particularly by the perennial spring which feeds "Old Faithful" fall on the east wall of Nuuanu and by the rather steady flow of Lulumahu Stream. At several points in Lulumahu Valley and at other points on the east wall of Nuuanu there are indications of the yield of small amounts of water from above both sills and tuff beds in this area. (Figure ______)

It is probable that moderate amounts of water could be developed by tunneling in one of the tuff beds, probably at the chief spring source of "Old Faithful" fall. The maximum amount of water that might be developed can be estimated on the basis of area and rainfall. The maximum area tributary to this zone of ash beds and sills can hardly exceed 0.125 square mile, and the average rainfall is about 115 inches, corresponding to about 0.7 M.G.D. Infiltration can hardly exceed 0.2 M.G.D., and it appears doubtful if more than 0.1 M.G.D. could be developed at one point, or without a long tunnel. In view of the long pipe line through difficult country which would be required, it appears unlikely that the cost would be justified.

In early days, no doubt encouraged by the perennial flow at "Old Faithful" fall, a tunnel was driven into the cliff on the inland side about 20 feet above the base of the fall. The azimuth of the tunnel is about S 45 E, and it is about 165 feet long, with a branch 18 feet long which turns to the left about 15 feet from the end of the main drift. Several lengths of 3-inch pipe lie inside the tunnel, but there is nothing to indicate that it was ever used to convey water from the tunnel. For about 20 feet in from the portal there is a moderate amount of drip water from the rock which is kept saturated by surface flow down the cliff. The remainder of the tunnel is quite dry. According to Palmer (1), in 1920, there was a flow estimated at

(1) Palmer, H. S., Possible Occurrence of High-Level Ground Water in the Honolulu Region, Manuscript Report, p. 67, 1921.

2000 gallons per day coming from this tunnel, the mouth of which was "caved and blocked by talus". In 1941, when visited and entered by the writer this tunnel was open, and the mouth gave no indication of ever having been caved. However, there was at the base of the cliff makai from it a talus mass of blocks and finer debris which quite likely in 1920 may have been enough larger to block the opening and make it impossible to enter, difficult to determine if the mouth was or was not caved, and to make it wholly obscure whether the water seeming to emerge from the tunnel was indeed coming from it or from the talus via the tunnel mouth. In 1941, the face of the cliff below the tunnel was wet, there was water and muck six inches deep in the first 12 feet of the tunnel, and perhaps as much as 1,000 to 2,000 gallons daily may have moved through this section. It was entirely clear, however, that no water was truly developed in the tunnel itself.

This tunnel is an example of one dependent on vagrant percolating water, not having encountered any concentrated flow, despite the proximity of the perching sills and tuff beds. Evidently the geologic structure was not fully understood by those responsible for driving it. It is surmized that this tunnel may have been one of many driven by the late W. A. Wall, who was superintendent of the waterworks for some years prior to 1925, but no direct information has been available.

Another tunnel driven in the east wall of Nuuanu Valley is known as the Dowsett tunnel. Its plan and length were surveyed by Fred Harvey. Located at 775 feet elevation, it has a total length, including several branches, of over 500 feet, but developed no water except a small amount directly infiltrating from surface channels. According to Stearns, there are no dikes or other structures favoring water concentration (1). These two tunnels are the only known efforts

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(1) Stearns, H. T., Op. Cit., pp. 391-392, 1935.

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to develop high-level water from Koolau rock in either Nuuanu or Pauoa Valleys. In order to emphasize the contrasted character of the various tunnels driven in the valley bottom of Nuuanu and Pauoa, they will be described and their water considered as inland cap-rock water.

The question is frequently asked as to whether perched or restrained water will be encountered in driving the so-called "pali" vehicular tunnel. The most recent plan for this tunnel called for a drift somewhat over 4,000 feet long, passing underground at approximately

1030 feet, just inland from the No. 4 Reservoir, and running downgrade to emerge at the so-called half-way house junction on the windward side. Without drill holes or other exploration, any estimate of the possible development of water must rest on general knowledge of the geologic conditions. Proponents of the idea of water development here refer to the successful water production by various tunnels in the Waiahole area, at Luluku, and in the Waimanalo area. Later, large amounts of water were encountered by the Haiku Tunnel, recommended and located by the writer, and excavated under the direction of H. A. R. Austin as a part of the 1940 improvement of the rural water systems. Success of all these tunnels is based on their tapping water restrained between dikes of the dike complex. In the various tunnels of the Waiahole system, water is encountered between 800 and 900 feet in elevation, and pressures indicated that restrained water rose to above 1,000 feet. At Luluku, water is developed at about 650 feet; at Haiku, water is developed at about 550 feet, but pressures and former stream flow indicate that water is restrained up to at least 700 or possibly 750 feet.

In the Waiahole area and particularly northward, the dike complex includes substantially the whole windward slope and in places small areas of leeward slope; and in this area the maximum rainfall reaches 250 to 300 inches. In the Haiku area the crest of the range has been cut back to leeward by the erosional encroachment of the pali and heads of valleys, so that the dike complex only appears in some of the windward spurs and in the windward slope up to 1000 feet but lies far short of the crest of the range. At Haiku Valley the entire dike complex is cut across down to at least as low as 400 feet and probably under the valley fill to near sea level, so that there is no continuity between restrained water bodies north and south of this valley. Southward of Haiku Valley the exposed western edge of the dike complex stands mostly not over 500 to 600 feet in elevation except in the spur back of the Territorial Hospital and in the northeastern flank of Konahuanui.

Restriction of the areas of high-dike complex, and progressively lower rainfall, together with lack of high-level continuity along the complex, contribute to a lowering of the restrained water body and reduction of probable amounts of water available in the area from Haiku to Waimanalo. Moderate amounts of water have been developed in the windward flank of Konahuanui in several tunnels at elevations of 400 to 550 feet (1), but there does not seem good prospect that water could be developed in large quantity at materially higher elevations.

(1) Stearns, H. T., Op. Cit., pp. 411-415, 1935.

When the Haiku Tunnel was planned, the presence of a strong spring flow in the north branch, somewhat leeward of the line of the dike complex, led the writer to hazard a tentative belief that there might be a high-level water table in the Koolau rocks to leeward of the dike complex and up to 700 feet or more. On driving the tunnel and on progressively finding that the water was coming from the windward, or dike complex, side of the tunnel, with dry rock on the leeward side, it became increasingly evident that the water developed by the Haiku Tunnel was in fact derived from the dike complex and that it only locally was escaping to the leeward side and then had originally passed outward between scattered offshoot dikes to the north branch of Haiku Stream. Thus, all the evidence here, as elsewhere, despite the early suggestion that an exception might be found, points to the controlling effect of the dike complex as the effective restrainer of high-level water.

On the basis of all this evidence, the prospect of encountering water in important amounts in the pali tunnel, if and when it may be excavated, seems very slight. Such a tunnel will lie for most of its length under the end of the valley-bottom tongue of cap rock, where vagrant percolating water may be more concentrated in certain spots. If, by good fortune, the tunnel should pass under a point whence water is leaking downward from the cap rock, so much as 50,000 gallons daily might perhaps be developed, but this is unlikely. For a short distance the windward end of the tunnel will pass through the dike complex, but it is thought wholly unlikely that this will be saturated or that more than 25,000 or 50,000 gallons could be developed in this section. In the writer's estimate water developed in the pali tunnel may possibly total as much as 25,000 to 50,000 gallons but is more likely to be less than 25,000 than to be as much as 100,000 gallons daily. Whether such an amount would justify piping to the windward system, or piping plus pumpage to get it to the Honolulu system will depend on conditions obtaining at the time, but in any event its value would be slight.

A number of years ago, the suggestion was made by Palmer that since there are various springs and productive tunnels on the windward side of the Koolau Range, there was indication of the presence of water bodies held up by some horizontal perching member at 550 feet or higher (1). In accordance with that concept he recommended tunneling

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(1) Palmer, H. S., Op. Cit., p. 98, 1921.

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under the mass of Konahuanui from the valley of West Waihi, at some such elevation as 750 or 800 feet. On the basis of more complete understanding of the structure of the Koolau Range and particularly the part played by the dike complex in supporting the windward springs, it is now clear that for lack of evidence the concept of a horizontal perching member under a water body which feeds the springs can be rejected and that it is very doubtful if such a water body exists outside the dike complex, and possibly near subordinate complexes such as that of Waiakeakua in east Manoa. Kunesh, Stearns, and the present writer, in turn, based on consideration of rainfall quantities and geologic conditions have concluded that this project would not be a profitable one (2).

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(2) Kunesh, J. F., Report of the Honolulu Sewer and Water Commission, 1929, pp. 110-113, Plate J.

Stearns, H. T., Op. Cit., p. 412, 1935.

Wentworth, C. K., Manoa-Makiki Report, pp. 100-106, 1940.

INLAND CAP-ROCK WATER

It has long been known that shallow underground water in large amounts is contained in certain cinder formations and lava flows which lie in the bottom of Nuuanu Valley. In 1934 and 1935, as a result of diamond drilling, structures were revealed and water table conditions outlined, which explained more fully the functioning of these water bodies. The water levels measured in these holes are tabulated below. From the diamond drill holes it appears that this valley fill includes porous and permeable lava and cinder formations, interbedded with soil layers and fans and tongues of relatively impermeable weathered detritus. Since in part the permeable components lie near the present surface over large areas and especially in the zone of high rainfall (100 to 160 inches) there is a large infiltration from rainfall. In addition all the runoff from the mountainous part of the basin passes across the valley bottom for greater or lesser distances. This leads to considerable loss from the channels into the ground. It is also known that there is much underground leakage from Reservoirs No. 2, 3, and 4, which thus become not only a protection against excessive runoff during storms but operate to store flood waters for a long enough period to cause much water to pass underground. For example, Reservoir No. 4 was computed in 1929 to have a seepage loss of about 1.0 M.G.D. at 45-foot head on the reservoir tower gage, and from 2 to 5 million gallons daily in the range from 51 to 57 feet on the gage. According to W. H. Samson, there has probably been no material change in this rate since 1929 and since the reconstruction of the dam (1).

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(1) Samson, W. H., Oral communication, June 20, 1941.

Because of this high rate of seepage loss, plus large leakages through and under the dam and which emerge below it, the reservoir is only filled to the spillway level (60 feet on the tower gage) for periods of a few hours at rare intervals during heavy local rainfall. It more commonly stands at some 40 feet on the gage even when no attempt is made at regulation. At present (October, 1941) its level is regulated to stand at an intermediate position as a safety measure during the national defense emergency. Without attempting a detailed calculation it appears that something of the order of 1.0 to 1.5 M.G.D. is infiltrated into valley-bottom formations from Reservoir No. 4.

(Figure 56)

None of the surface reservoirs of Nuuanu Valley have served as sources of water for the piped domestic supply since 1923, but there are several tunnels and developed springs which are connected with the public system (1). Farthest inland of these is Tunnel No. 4, which is

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(1) Stearns has published various details of construction and of geologic conditions found at the various tunnels, which in the main are not repeated here. (Op. Cit., pp. 391-394, 1935)

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on the east side of Nuuanu Stream at elevation 1027 feet, and a short distance inland from Reservoir No. 4. The tunnel has two branches, and the system comprises a total open length of about 830 feet with a reported additional length of nearly 1000 feet. One of the branches is reported to be connected with Nuuanu Stream channel in a fashion similar to several others of the Wall tunnels, and of the water yielded by this tunnel, it is not clear that all of it is truly ground water, since it is turbid during storms.

Tunnel No. 4B is driven on the east bank of Nuuanu Stream at elevation 968 feet. It is 228 feet long and is driven in mottled old

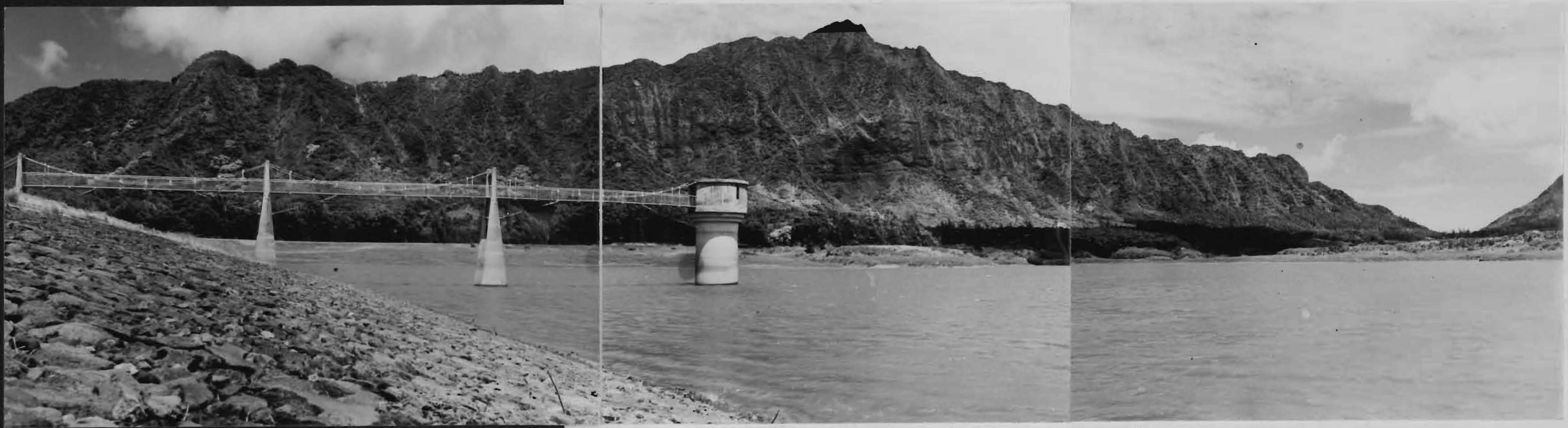

Figure 56 - Panorama from upstream face of Reservoir No. 4 to Lanihuli and west wall of Nuuanu Valley, showing gage tower and access bridge. (Negatives 13783-4-5, September 13, 1939)

alluvium. It is known to be overlain by permeable layers of Honolulu cinders, presumably from the Makuku vent, and its intake of water with little doubt comes from the cinders.

Tunnel No. 4C is also on the east bank of Nuuanu Stream about 800 feet outwest of Tunnel No. 4B at elevation 937 feet. It is 136 feet long and is driven in Nuuanu basalt. The water enters through the roof near the middle. The three tunnels described above, together with the so-called Nuuanu Six-Inch Spring described below, contribute to the combined flow which is measured at Lower Luakaha venturi meter, and which during the period 1931 to 1940, inclusive, averaged 1.177 M.G.D.

Nuuanu Six-Inch Spring, as now designated, is the effluent from an old natural spring which lay outside the toe of Dam No. 4 as originally built but was protected and fitted with a pipe before its site was buried under the extended toe provided in the reconstruction of 1932. The pipe is a six-inch line, brought out through the 24-inch pipe which underlies the dam (1). Presumably this spring, like others

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(1) Samson, W. H., Oral communication, June 21, 1941.

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in this vicinity, is fed chiefly from Honolulu cinder beds which lie near the surface of the ground. The average flow from this spring during the years 1936 to 1940, inclusive, was 0.652 M.G.D.

The flow from Tunnel No. 4 was formerly combined with the rather steady surface flow from Old Faithful Spring, but this latter water has not been put into the system in recent years. At present the so-called No. 4 system includes Tunnels No. 4, 4B, 4C, and the Six-Inch Spring, with an average total flow of 1.177 M.G.D., 1931 to 1940, inclusive, and of 1.520 M.G.D., 1936 to 1940.

Tunnel No. 3 is driven for a total distance of 554 feet from a portal at 810 feet. It is a few rods inland from Reservoir No. 3 and the Nuuanu Aerator and on the southeast side of Makuku Stream. The log of formations penetrated has been detailed elsewhere; they include alluvium and lava and cinders of the Honolulu series, the yield of water being from the latter two (1). Average discharge, 1931 to 1940,

(1) Stearns, H. T., Op. Cit., p. 392, 1935.

was 0.87 M.G.D. It has been believed by some that the water yielded by this tunnel is seepage from Reservoir No. 4 (2), but a more com-

(2) Idem, p. 392, 1935.

prehensive understanding of the geology of the valley developed since 1930, indicates that this is not directly the case. Seepage from No. 4 contributes to the shallower of the two perched water bodies in the valley, and Tunnel No. 3 derives water from this body. However, it is entirely clear that this perched body is of natural origin and was in existence long before Dam No. 4 was built. The two are causally and synchronously related only in the sense that they both tied into the shallow-water hydrology and rainfall of the valley floor.

Tunnel No. 3A is about a quarter mile up the valley from Tunnel No. 3 on the east bank of Makuku Stream at 900 feet elevation. It is

314 feet long and is driven in basalt of the Honolulu series, with some clinker. It is highly variable in discharge, deriving its water from a shallow water body and to some extent almost directly from surface channels. Its relationship to Reservoir No. 4 is similar to that of Tunnel No. 3, except that because of its position and elevation it is perhaps still less aided by seepage from the Reservoir.

Tunnel No. 3B is located at an elevation of about 930 feet, about 600 feet northeast of 3A on the northwest bank of Makuku Stream. It is 128 feet long, and is driven in Honolulu cinders and basalt (1).

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(1) Stearns, H. T., Op. Cit., p. 393, 1935.

The discharge from this tunnel is highly variable, and its water is no longer used.

Alewa Heights Spring is located at elevation 765 feet, a short distance seaward from the west end of Dam No. 3. In the period 1931-1940, its average discharge was 0.371 M.G.D., and for the latter part of that period, 1934-1940, its average was 0.459 M.G.D. It consists of a concrete chamber which covers and somewhat protects a natural spring which has been excavated and opened to a slight extent. The water comes from shallow water bodies in Honolulu basalt lava flows which either terminate here or have had their frontal margin somewhat steepened by erosion. In 1934, a series of tests was made to determine the relationship between the Alewa Heights Spring and Reservoirs No. 4 and No. 3. These indicated that when the spring discharge is in the range 0.50 to 0.75 and Reservoir No. 3 at full stage, about 25% of the spring discharge comes directly from the reservoir. On the other hand, though there is a general similarity between the discharge curve for the spring and the stage curve for No. 4 reservoir, these measurements showed that the discharge of the spring does not specifically follow the stage of Reservoir No. 4, and the relationship which does exist is that of common dependence on rainfall in the valley. Reservoir No. 3 is only about 300 feet away and about 43 feet higher than the spring at full stage. Reservoir No. 4 is 4400 feet away, and while its elevation is greater, there intervenes a hydrologic system too complex to justify the interpretation that No. 4 feeds the spring (1).

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(1) Board of Water Supply, Report 1933-34, p. 143 and chart, 1935.

Recently, Alewa Heights Spring showed signs of surface contamination, and the chamber was repaired and reconstructed on the inland side in an effort to eliminate the contamination without material loss of yield. The contamination was cleared up, and it is believed that the yield is no less than before, since certain leaks were repaired in the operation (2).

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(2) Downer, J. M., Oral communication, June 23, 1941.

Average used discharge of the various valley bottom springs and tunnels in Nuuanu for the period 1936-1940 is shown in the following table.

Source	Discharge M.G.D.	
Tunnel No. 4, " No. 4B, " No. 4C	0.868	
Six-Inch Spring	0.652	
Total of above.		1.520
Tunnel No. 3	1.213	
" No. 3A (1)	0	
" No. 3B	0	
Alewa Heights Spring	0.452	

(1) Since late in 1930, discharge from 3A has been diverted through Tunnel No. 3 and measured with the latter discharge.

In addition to the records of the above-listed points of development of shallow ground water in the Nuuanu Valley floor, the water table measurements taken weekly at diamond drill holes are of great value in indicating the behavior of the perched water. The records are summarized in the following table, in which the water table elevations have been given for the end of each month for convenient comparison with monthly rainfall at Lower Luakaha rain gage.

MONTHLY WATER TABLE ELEVATIONS IN DIAMOND DRILL HOLES
IN NUUANU VALLEY (1)

	Hole No. 1 (2)	Hole No. 2 (2)	Hole No. 3 (2)	Hole No. 4 (2)	Hole No. 5 (2)	Hole No. 7 (3)	Hole No. 8 (3)	Hole No. 10 (2)	Hole No. 12 (2)	Rainfall Lower Luakaha
1934										
July										9.42
August	835.80	833.73	827.17	829.43	829.32					7.82
September	837.14	834.88	828.22	829.95	830.70					17.03
October	835.54	833.08	826.85	828.63	828.75	618.61	534.40			7.26
November	837.09	834.52	828.10	829.70	829.75	616.91	534.70*			17.06
December	836.85	834.25	828.45	829.95	829.90	619.94	534.33	773.9 (4)		12.00
1935										
January	838.22	834.65	831.14	832.00	831.64	621.64	534.77	773.75 (4)	728.56	12.25
February			835.94	†833.59	†833.40	620.96	534.45	772.15 (4)	725.87	22.70
March	839.00		832.92	832.11	832.50	621.96	534.71	832.95	721.91	8.76
April	837.23		829.02	829.86	830.05	619.50	534.19	830.68	719.79	7.16
May	835.28		826.16	827.52	828.07	617.28	533.91	827.72	718.66	5.86
June			824.62	826.42	827.17	616.04	533.63	826.55	719.34	7.96
July			823.36	825.78	826.31	615.21	533.36	825.45	715.77	11.12
August			823.31	825.90	826.30	615.70	533.48	825.44	715.43	9.54
September			824.32	827.60	826.40	615.04	533.45	827.70	718.04	12.86
October			825.38	827.75	827.28	616.03	533.08	828.60	716.90	10.29
November			824.93	827.27	828.02	616.73	533.01	827.80	717.01	9.07
December			823.50	826.09	826.48	615.84	533.02	925.24	715.80	5.43

	(2) Hole No. 1	(2) Hole No. 2	(2) Hole No. 3	(2) Hole No. 4	(2) Hole No. 5	(3) Hole No. 7	(3) Hole No. 8	(2) Hole No. 10	(2) Hole No. 12	Rainfall Lower Luakaha
1936										
January			822.57	825.26	825.69	614.41	533.11	824.05	715.05	7.00
February			821.83	824.72	825.16	613.89	533.15	822.99	717.43	2.36
March			821.21	824.16	824.51	613.27	533.14	822.55	717.47	9.89
April			823.83	826.58	826.90	612.80	533.36	826.56	720.00	11.60
May			828.16	830.11	830.36	616.14	533.95	831.90	721.13	13.76
June			826.54	827.76	827.64	616.06	533.28	829.71	719.69	8.44
July			826.09	828.04	827.62	615.84	533.46	830.32	717.86	14.19
August			827.04	829.28	829.62	617.02	533.94	830.64	720.79	13.29
September						617.99			721.20	20.31
October						618.24			723.47	17.72
November						619.54			719.50	5.20
December						617.89			720.99	18.86
1937										
January			833.38	833.26	833.66	621.14			721.09	23.43
February			834.02	833.20	833.56	621.31			719.35	13.13
March			832.60	832.28	833.19	620.73			719.96	19.23
April			832.07	831.81	832.73	619.37			718.70	19.66
May			834.58	833.29	833.56	621.26			719.63	18.01
June			828.59	829.80	830.57	618.58		831.75	718.45	6.18
July			830.50	829.89	830.77	617.12			718.56	13.70
August			831.49	829.28	829.96	616.76		829.83	718.30	11.20
September			824.98	826.15	830.03	615.73		829.0	717.88	10.22
October			824.35	827.65	827.92	615.55		829.30	717.77	7.26
November			824.39	827.73	827.93	615.57		828.98	718.35	13.26
December			832.23	833.79	834.51	615.74		833.82	722.32	18.78

	(2) Hole No. 1	(2) Hole No. 2	(2) Hole No. 3	(2) Hole No. 4	(2) Hole No. 5	(3) Hole No. 7	(3) Hole No. 8	(2) Hole No. 10	(2) Hole No. 12	Rainfall Lower Luakaha
1938										
January			831.49	831.80	832.92	617.55		832.43	720.83	9.58
February			830.74	831.37	832.60	617.77		832.47	720.06	10.34
March						618.13			720.20	14.38
April			826.44	828.26	828.76	618.59			720.09	14.56
May			829.42	830.31	832.57	621.60			723.08	22.92
June			830.07	830.47	831.45	627.11			725.94	11.92
July			830.87	830.29	831.20	624.77			719.01	10.06
August			827.48	829.08	829.53	624.58			720.53	17.90
September			826.72	828.72	829.69	624.03			718.84	5.04
October						623.24			719.05	9.38
November			823.61	826.65	826.79	622.34		826.78	718.89	8.60
December						622.14			718.37	12.98
1939										
January						626.15			720.77	15.12
February			823.33	826.73	830.34	624.71			722.88	13.90
March			831.70	831.59	829.90	626.87			719.76	13.64
April			833.02	832.30	833.24	627.50			720.50	20.86
May			830.41	831.08	832.44	626.86			719.67	10.60
June			828.67	830.45	830.16	627.08			720.50	16.44
July			816.51	828.50	828.78	625.68			719.19	7.12
August			815.06	828.61	827.81	623.48			719.35	7.04
September			809.04?	827.00	827.26	622.53			718.45	8.34
October			829.12	830.59	830.83	623.25			720.63	21.86
November			829.39	840.53	830.80	624.86			719.51	15.04
December			827.96	829.43	829.75	624.51			719.48	4.84

	Hole No. 1 (2)	Hole No. 2 (2)	Hole No. 3 (2)	Hole No. 4 (2)	Hole No. 5 (2)	Hole No. 7 (3)	Hole No. 8 (3)	Hole No. 10 (2)	Hole No. 12 (2)	Rainfall Lower Luakaha
1940										
January			826.53	828.35	830.48	623.40			719.00	5.80
February			824.67	827.56	827.85	622.34			718.46	8.02
March			823.67	826.84	827.15	621.41			718.47	3.42
April			823.22	826.42	829.15	620.62			719.23	10.08
May			825.62	828.08	828.82	621.02			719.17	17.76
June			824.95	827.99	828.27	621.14			718.90	6.10
July			823.37	826.27	826.52	620.40			718.41	7.58
August			822.20	824.81	825.67	621.53			719.18	17.22
September			823.93	826.31	826.76	623.04			718.78	8.56
October			823.30	824.80	825.40	621.21			None	5.78
November			821.71	824.48	824.97	616.63			718.17	8.44
December			821.41	824.37	824.84	613.77			717.60	4.96
1941										
January			820.60	823.57	824.01	612.30			717.37	
February			819.88	822.89	823.31	610.43			716.77	
March			819.70	823.15	823.50	608.31			717.43	
April			820.6	825.1	825.3	607.47			716.71	
May			820.78	825.1	825.27	606.41			717.07	
June			820.4	824.5	824.6	605.03			717.31	

* November 26, 1934, others are for December 3, 1934. † March 1, 1935, others for March 2, 1935.

(1) Except as noted otherwise, the elevation given is for the weekly reading nearest the end of the month in question, either on one of the last four days of that month, or of the first three days of the following month.

(2) Upper, or shallower water table.

(3) Lower, or deeper water table.

(4) For a few weeks it appeared that this hole was being drained toward the level of the lower water table.

Examination of the data given in the preceding table indicates that there are two water tables and hence two perched water bodies in the cap-rock fill of Nuuanu Valley. One of these shown in Holes 1, 2, 3, 4, 5, 9, 11, and 12, lies about 20 to 30 feet below the surface. The other, indicated in Holes 7 and 9, is about 180 feet below the general floor of the valley.

Holes 3, 4, and 5, near the west margin of the valley flat, show at times a water table with a lateral slope toward the northwest edge of the valley (water table high in the middle) at other times, usually after heavy rains, a water table with a lateral slope in the opposite direction, toward the middle of the valley. This upper water table stands practically at the level of the adjacent Makuku Stream. Apparently immediately after heavy rains, flow from the valley sides surcharges the water table which is effluent into the stream. In drier weather the stream or related underground flow, is influent to the water table which is highest near the channel and lowest near the lateral margin of the valley flat. Measurements show that the highest water levels on the upper water body come one to two or three days after the heaviest rainfall; while the maximum level of the deeper water table is reached some ten days to two weeks after the heaviest rainfall. There is good reason to suppose that much of the water of the upper water body eventually reaches the lower body. The lower body is best indicated in the section of the buried valley which lies under the present channel of Nuuanu Stream below Lower Luakaha falls. The drill holes indicate that at an earlier geologic time the building of a cinder cone near Lower Luakaha falls narrowed the valley at this point and that a permeable cinder formation was spread down the axis of the valley, probably with some associated lava formations. The lower water table has a downvalley slope of about 83 feet in 1800 feet, or 4.6%, between Holes 7 and 8, which is somewhat less than the slope of the present valley floor in this vicinity.

It appears from the behavior of the water tables revealed in the drill holes in relation to rainy and dry periods that infiltrated rain water first reaches the upper water table and that later the lower water table is raised by water which percolates downward from the upper water body and also probably by slower infiltration directly from rainfall. In weather that provides less than normal infiltration the level of the water table falls but is maintained at a minimum level for a long time. From the structure of the valley revealed by diamond drilling and particularly from the fact of a thick and highly impermeable trough filling the bottom of the former deep rock valley, the conclusion is justified that a large amount of water is held up on the top of this trough, that the trough is probably narrower below Reservoir No. 2 than it is in the vicinity of No. 3, and that its upper surface has the shape of the former valley with an axis lower than the parts adjacent to it. Because the water table has the gradient of nearly five per cent, it is evident that the ground water must move seaward down the valley in large amounts. Until the cross-section has been more fully explored and the nature and arrangement of the permeable members more completely determined, it is impossible from the gradient of the water table to determine the quantities of water that pass down the valley. However, if formations of permeability comparable to the Koolau basalt exist in the valley, only moderate and very plausible cross-sections would be required to transmit any reasonable fraction of the known rainfall at the indicated water table gradient (1).

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(1) For example, with a section 50 feet deep, 300 feet wide, permeability of 10,000 Meinzer units and a grade of 5%, the discharge would be 7.5 M.G.D. This figure, of course, does not indicate actual quantities but only the discharge capacity of plausible areas of section under reasonable assumption as to permeability and grade.

The best estimate that we can make at present must be based on the quantities of rainfall and infiltration that can be postulated. The total rainfall on valley-bottom areas presumably tributary to the lower water table (Areas 40 and 41) at the No. 2 spillway is 9.29 M.G.D. In addition it is probable that the adjacent areas (46, 47, and 48) discharge out onto the valley fill considerable amounts of water which are later infiltrated. Total rainfall for the parts of 46, 47, 48 draining directly to the valley bottom approximates 6 M.G.D. It is thought that at least half this amount should be added to the 9.29 M.G.D. as potentially available for infiltration into the Nuuanu Valley bottom. If we take the round number of 12 M.G.D. according to various assumptions we can deduce infiltration at various amounts from 2.5 to 5 M.G.D. In view of the known infiltration from Reservoir No. 4 to an amount approximating 1 M.G.D., it is thought that the larger estimate is more nearly correct than the smaller. We have no valid method of estimating what proportion of this water might be developed. In an earlier report an estimate of 2.5 M.G.D. was presented (2).

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(2) Kalihi Report, p. 99.

FREE BASAL WATER

The Nuuanu district is practically the only portion of Honolulu in which we have no direct knowledge of free basal water. No exploratory drill hole has been put down so as to reach sea level inland from the cap rock, nor has any basal shaft been dug. There is no reasonable doubt that a basal water body stands in the permeable aquifer rocks and that its head agrees with and is the cause of the fluctuating artesian head of the Beretania area east of the axis of Nuuanu Valley and of the Kalihi area west of that axis. Just east of the boundary of this district, Diamond Drill Hole No. 39 has been drilled in the Papakolea section. The water level revealed in this hole is comparable to the head of artesian wells in the Beretania Isopiestic area, and there is no reason to doubt that basal water at this level extends to the axis of Nuuanu Valley. No exploratory hole reaches the basal water in the Kalihi Isopiestic area, but the behavior of this water is well known from the several springs in the valley of Niuhelewai Stream and seaward and eastward from Houghtailing and School Streets, and from its appearance in the box drain excavation mauka from School Street at the time, the flood protection drains were installed.

At that time the level of standing water yielded out of the Koolau rock walls of the excavation was compared and found to closely agree with the head of artesian wells at the Kalihi Station. This condition, of course, very forcefully explains the springs which enter Niuhelewai channel and readily show the possibility of developing basal water in this area, which is just on the boundary between Nuuanu and Kalihi. A plot of land covering the principal springs has been purchased by the Board of Water Supply, and it is planned to make certain preliminary explorations and determine the most satisfactory manner of repairing these leaks. In a strict sense the springs tap artesian water but are the closest active indication of the basal water which lies inland from the artesian water, and additional data will be derived from any explorations made at this point in connection with repair of the springs. (For further discussion, see Appendix I, Kalihi Report)

ARTESIAN BASAL WATER

Two isopiestic areas meet in the Nuuanu district, the Beretania or No. 2 area east of the Nuuanu Valley barrier, and the Kalihi or No. 3 area west of that barrier. The heads in these two areas are distinct, with the head in the Kalihi area commonly slightly less than a foot lower than that in the Nuuanu area. The Beretania area lies between the axes of Manoa and Nuuanu Valleys; and the Kalihi area, between the axes of Nuuanu and Kalihi Valleys. In the following table are listed the artesian wells in the Nuuanu-Pauoa district.

INVENTORY OF ARTESIAN WELLS
(Nuuanu-Pauoa District)

Number (1)	Status (1939)	Head (2)	Discharge (M.G.D.) (Average 1937-1938)
Beretania Area (Isopiestic Area No. 2) - Pauoa-Nuuanu, West of Pensacola Street			
79	Sealed (1927)	-	-
80	Industrial (Drilled 1936)	31.70	0.06
81	Irrigation	31.66	.004
82	Irrigation	31.60	.06
83	Unused (C & C)	31.67	-
84	Sealed (1928)	-	-
85	Domestic	31.50	.003
86	Irrigation	31.46	.01
87	Industrial	31.84	.008
88A to I	Board of Water Supply (Beretania Pump Station)	31.52 to 31.66	5.84
89	Industrial	31.61	.99
91	Domestic	-	.008
92	Industrial	31.51	.11
93	Industrial	15.29	.007
94	Industrial	30.30	.01
95	Industrial	31.26	.06
96	Irrigation	31.22	.006
97	Unused (T. of H.)	31.74	-
98	Unused	31.65	-
99	Irrigation (T. of H.)	31.42	?

Number (1)	Status (1939)	Head (2)	Discharge (M.G.D.) (Average 1937-1938)
101	Unused (U. S. A.)	29.77	-
102	Industrial	-	.44
103	Industrial	31.51	.51
104	Industrial	31.71	.23
105	Industrial	31.52	.13
106	Sealed (1925)	-	-
107	Sealed (1938)	26.56	-
108	Domestic	31.58	.004
109	Unused	31.82 (3)	
Kalihi Area (Isopiestic Area No. 3) - West Nuuanu (Nuuanu Barrier to Nuuanu-Kapalama Divide)			
110	Industrial	-	-
111	Industrial	-	.08
112	Sealed (1931)	-	-
113	Industrial	28.89	.07
114	Industrial	30.74	.15
115	Industrial	31.02)	
116	Industrial	30.73)	
117	Industrial	-)	1.40
118	Industrial	31.00)	
119	Industrial	30.77	.47
121	Irrigation	31.06	-
122	Swimming Pool	30.83	.08
123	Sealed (1929)	-	-

Number (1)	Status (1939)	Head (2)	Discharge (M.G.D.) (Average 1937-1938)
124	Domestic	31.00	.04
125	Irrigation	30.85	.001
126	Irrigation	30.79	.15
127	Domestic	31.01	.004

(1) New number series.

(2) Simultaneous head survey, August, 1938.

(3) This well is in Area No. 2 (see Memo, W. H. Samson, 1/3/1940) but was omitted from tabulation in that area.

SUMMARY OF ARTESIAN WELLS, NUUANU-PAUOA DISTRICT

Status of Wells	Beretania Area (No. 2) East of Nuuanu Barrier	Kalihi Area (No. 3) West of Nuuanu Barrier	Totals	Group Totals
Board of Water Supply	9	0		9
In Use	9		9	
Inactive				
Other Public Ownership	4	0	4	4
Private Ownership	20	15		35
Domestic	3	3	6	
Industrial	11	9	20	
Irrigation	4	3	7	
Unused	2	0	2	
Sealed	4	2	6	6
Total	37	17	54	54

A total of 54 wells has been drilled in the Nuuanu-Pauoa district, of which 37 are in the Beretania or No. 2 Isopiestic Area. Of the whole, 60% are still active and in private ownership, with 9 sealed, 9 under control of the Board of Water Supply, and 4 owned by other public agencies. (Figure 57)

DISCHARGE OF ARTESIAN WELLS IN THE NUUANU-PAUOA AREA
Mean Annual Total, 1939-1940

	Domestic	Irrigation	Industrial	Municipal	Total
East of Nuuanu Barrier (Area No. 2)	0.015	0.074	2.561	5.84	8.49
West of Nuuanu Barrier (Area No. 3)	0.124	0.151	2.17	----	2.445
Totals	0.139	0.225	4.731	5.84	10.935

It is not necessary to repeat here the writer's general views on the artesian water supply (1). Since the free basal and artesian

(1) Manoa-Makiki Report, pp. 126-135, 1940.
Kalihi Report, p. 87, 1941.

basal supply of the Honolulu area, with the similar and larger supply

Figure 57 - Flowing artesian well, No. 88E, at Beretania Pump Station. The ground elevation here is about 17 feet. In the interest of public education, this well is opened and allowed to flow for two or three minutes several times a year as a demonstration for groups of students from the public schools or the University of Hawaii. Water released in such a demonstration is worth about $1.00. (Negative No. 12430, March, 1935)

of the Pearl Harbor area is without question the most valuable water resource of the entire Territory and will always remain the major resource of the city of Honolulu, its development and management for long-term conservation is in the writer's opinion the most important problem facing the Board of Water Supply. We know that the city area extends farther east than the area of high basal head, that the city is still growing both by normal causes and in response to the present international emergency, and that there is rapid increase in real and precautionary military defense needs. Therefore, it seems certain that the problem of conserving the basal water so as to maintain storage both as a protection against the invasion of salt and against the unavoidable climatic fluctuations and of coordinating development and use between the Honolulu area and the Pearl Harbor area and between municipal, military, and agricultural users will be an important and continuing problem for an indefinite period to come.

Not only are the needs of these three users impossible to determine in advance, but the capacities in storage and in maximum, minimum, and average yield of the various parts of the basal system and the quantitative nature of the connections between these parts are so incompletely known and will require such long periods (decades or hundreds of years) for their empirical determination that while we can expect progressively to improve our understanding in many valuable ways, it is too much to hope for any completed solution within this generation. This, however, does not mean that returns of great value will not be realized within one, five or ten years, by persistent modification of existing practices based on hydrologic studies.

Within the past 25 years a number of attempts have been made to estimate the average annual increment of infiltration to the Honolulu basal system and the safe yield of that basin to artesian wells, and basal shafts. Estimates of annual increment have been made by subtracting runoff, evaporation, and transpiration from the rainfall. Each of these quantities is difficult of valid and complete measurement, even if measurements are carried over adequately long periods. Each of the fractions is less accurately measurable than the rainfall itself. Comparatively little new data has come from local measurements within the past 10 years, except that for rainfall. Chief contribution to the problem has been the geologic mapping of the Honolulu watershed and more complete recognition of the hydrologic nature of the various formations. Effect of this mapping has been to materially reduce the area over which rainfall is believed to contribute effectively to the basal supply. Considerable areas of valley bottom, ash-mantled slopes, and residuum-covered facets are now believed not to be effective contributors to the basal supply, as was formerly assumed on the basis of the 200-foot contour line as a boundary.

There can be little doubt that if infiltration contributes to a tight storage volume, its annual amount will be equal to safe annual yield and is equal to rainfall minus runoff, evaporation, and transpiration. While it is desirable to make additional measurements and estimates of runoff, transpiration and evaporation for various local areas, especially where there is favorable opportunity for checking infiltration, as in the Manoa Tunnel area, it is doubted if the real value of safe yield under various stipulations can be determined by that means alone. The writer's belief that a much larger and still very obscure factor enters the problem has been outlined elsewhere (1). This

(1) Wentworth, C. K., The Mechanism of the Ghyben-Herzberg Storage, Kalihi Report, Appendix II, pp. 109-137, 1941.

Wentworth, C. K., Eighth Biennial Report, Board of Water Supply p. 191, 1941.

factor is the behavior of bottom storage in the Ghyben-Herzberg lens.

While during June and July, 1941, the artesian head was falling at an alarming rate in response to the combination of heavy draft, some 40 per cent greater than two years earlier and deficient rainfall, and this behavior indicated too great a draft for contemporary and probably temporary rainfall conditions, there was much improvement in early September when the artesian head was no longer falling and a general rise appeared to have set in as a result of increased rainfall and reduced draft.

It has long been evident that the artesian head has a natural range of level of some two or three feet annually, and perhaps up to five or six feet between extreme high and low positions reached over periods of several years. These fluctuations are due in their more systematic form to the systematic differences between the lower winter draft and higher summer draft, but the extremes are due more to extremes in rainfall fluctuation. It is natural that the changes in head, trending chiefly in one direction often for a period of two years or more, should rouse much concern, particularly when the direction is downward, and that much relief is felt when, as has always been the case, the head again turns and the artesian level rises. It is to be expected that such periods of reduced rainfall and falling head, usually further aggravated by the increased draft of the summer period, will be marked by increased attention to studies of safe yield, measurements of head and salinity and various other indications of contemporary shortage. These periods of lowered head are sufficiently widely separated and each sufficiently different from its predecessor so that they cannot easily be dismissed as expectable, periodic fluctuations, and it is at present impossible to fully distinguish between the short and the long-term trends.

It is the present writer's view, however, that, despite the disquieting effect of a one- or two-year drought and a five- or six-foot lowering of head, these fluctuations are not in themselves the real occasion for worry, but are more in the nature of data for the solution of the problem of long-term trends and mechanism. It is his belief that the more disquieting state of affairs is that studies of long-term trends and establishment of experimental means for securing essential data for such studies continue to have so little attention and are so likely to be relaxed with each rise in the artesian head, or with the construction of each unit which for a time improves the operating condition of the Honolulu system.

It is therefore strongly urged that competent attention be centered on the long-term condition of overdraft which has seemingly been obscured by the lagging yield from bottom storage. The two types of overdraft are of course superimposed and are very much more evident when they result in net shrinkage in storage, both bottom and top, and hence when the artesian head is declining.

CAP-ROCK WATER

Large amounts of cap-rock water are known to be moving toward the coast in the coastal plain formations. Such water is now being used for cooling purposes in connection with air-conditioning systems at several points in the Nuuanu-Pauoa district. Information concerning such water has been chiefly collected by the Division of Water Resources from time to time as new shallow wells have been drilled or water has been encountered in excavating for foundations. No systematic simultaneous survey of current operating conditions has been made in recent years so that only rough estimates can be made. The total installed pump capacity indicated in the records, including some temporary installation, and not wholly and simultaneously operatable, approximates 4 M.G.D. It is very doubtful if actual average discharge from these installations exceeds 1.5 M.G.D. in the Nuuanu-Pauoa district.

The source of this water can only be surmized in general terms. It is carried generally in the more permeable coral layers and rises to static heads mostly from 0.50 to 2.0 feet. The greater part of it is probably leakage through cap-rock layers from artesian water, perhaps in places through the agency of leaking artesian wells. Some of it may come from cap-rock tongues, such as those that extend inland in Pauoa and Nuuanu Valleys and some from channels of streams flowing out on the coastal plain. A minor part is probably derived from rainfall on the coastal plain.

This water is not potable; some of it has a high chlorine content indicating large admixture of sea water, and it is generally bacterially contaminated. It is chiefly used as a cooling agent or thermal regulator in various types of air-conditioning or refrigerating systems.

Use of this water is of concern to the Board of Water Supply in several respects, as has been outlined elsewhere (1). On the one

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(1) Manoa-Makiki Report, pp. 133-135, 1940.
Kalihi Report, pp. 90-91, 1941.

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hand, any suitable use will in some measure, if not in full equivalent amount, operate to conserve artesian or basal potable water. On the other hand, since this water is in part derived by leakage from the artesian system and in some places at least is probably maintaining a back pressure against the avenues of leakage, any draft which lowers its head will in such places induce leakage at an accelerated rate. Furthermore, the systematic or drastic lowering of the water table in the cap rock is certain to impair the serviceability of the cap rock as an impermeable member and may cause other kinds of damage (2).

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(2) Manoa-Makiki Report, p. 132, 1940.
Honolulu Star-Bulletin, January 5, 1935.

Because of the practical certainty that effects produced by pumpage at one point will in fact extend beyond the limits of the property or vicinity and because the recognition of the kind and extent of those effects requires a wide scope and systematic continuity of measurements, it is quite evident that the determination of whether a particular sort of development or amount of use is in the public interest should be in the hands of the Board of Water Supply or some comparable agency.

It is evident that unless seaward leakage of the cap-rock water can be materially reduced by artificial structures, any draft from this water will result in lowered heads at least in the vicinity of the point of draft. A moderate use of this water is desirable; how much can be regarded as moderate and usable without producing serious counter effects will require a detailed surveillance of all pits and wells over a period of years.

Since this water is not potable, its quality will not be impaired by passing water which has been used in certain ways back into the ground. This is particularly true of water used only for cooling or thermal regulation, though it is of course true that the temperature will have been changed. It is desirable that tests be made to determine the changes in temperature and in other qualities, and standards be established so that authorization to return water to the cap-rock supply or denial of this right can be based on the principle of maintaining the quantity, quality and public usefulness of the cap rock and artesian supplies. It is evident that this will become a much more important problem in the future, and steps should be taken to continue and expand studies of the quality and behavior of this water and to fortify the legal authority of the Board of Water Supply in dealing with this problem in its relationship to the basal water supply and in the public interest.

SUMMARY AND RECOMMENDATIONS

Estimates of water quantities

The fundamental amounts of water available in various sectors of the Honolulu watershed are based on measurements of rainfall which have been made at numerous rainfall stations. It is well known that underground water migrates from areas of chief rainfall intake to areas of discharge. The boundaries of ground-water provinces doubtless differ somewhat from the topographic boundaries, but for successive major, radial segments such as the Palolo-Waialae, Manoa-Makiki, or Nuuanu-Pauoa districts, we have no basis for supposing that the rainfall source area tributary to the basal water part of the district differs materially from the topographic drainage basin of that area. We are certainly bound, as far as present knowledge goes, to take the rainfall totals, reduced by some plausible method to an infiltration residue, as the outside quantities which we can expect annually to be added to the basal and intermediate water bodies in given districts. Insofar as we can analyse or subdivide the area according to slope, geologic formations, or other conditions, into units having similar favorable or unfavorable conditions, we shall presumably improve the accuracy of our gross estimate. In foregoing pages this has been attempted.

Distinction must also be made between the probably annual increment and the fraction of this increment we can reasonably expect to recover. If a small area of ground, say 10 acres, were underlain by 100 feet of permeable and porous lava flows, and if beneath these there were a 20-foot layer of continuously impermeable red tuff with the slope of its upper surface everywhere converging to a known point, and if we could drill or tunnel to that point and draw water from it systematically, we might possibly recover 90 per cent or more of the total water infiltrating over the 10-acre tract. It is rarely, if ever, that such completely favorable conditions exist; more commonly there are known or unknown interruptions to the impermeable layer so that a part of the infiltrated water escapes by devious and unremediable leaks. Commonly in the case of high-level water, perched or confined, a considerable fraction of the water infiltrated in a given area escapes downward away from the perched body which may invite development. This has been demonstrated at Tunnel No. 3 in Manoa where an increase in head to 60 feet and 70 feet behind the concrete bulkhead has led to the leakage of roughly at least 80% of the natural inflow downward by devious routes and presumably to basal water. We do not here know the whole area tributary to the confined zone, nor do we know how much below the tunnel the confined body extends. Hence, if some quarter million gallons daily, more or less, escapes when the head is, say 60 feet, we can only surmize that at the head of zero when the tunnel is draining freely, there is still a considerable amount lost by downward leakage.

In the case of basal water, there are likewise natural leaks, and a significant fraction of the total infiltrated water must still escape by these routes even when we have reduced the head to the lowest value deemed prudent.

The total rainfall in the Nuuanu-Pauoa district of 10.78 square miles is 43.57 M.G.D. Of this total, it is computed that 18.97 M.G.D. falls in the mountain area directly underlain by Koolau rocks so that it is directly tributary to the basal water by infiltration. The remainder, or 24.60 M.G.D., falls on valley-bottom tongues of the cap rock, on Punchbowl rocks or on the coastal plain itself and is not believed to contribute effectively to the basal water. (See table of hydrologic areas on pages 150 - 152, and Figure 52) In an earlier section, the three quantities, runoff, evaporation, and transpiration, have been discussed. Here it was concluded that total runoff from the mountain area averages 5.5 to 6.5 M.G.D. On various bases the total of evaporation plus transpiration can be estimated as from 5.00 to 9.00 M.G.D. Subtracting these values from 18.97 M.G.D. gives a remainder of which cannot be over 8.47 and may be as low as 3.47 M.G.D., which may go to the basal supply from the Nuuanu-Pauoa district. The writer believes the most probable value is about 6 M.G.D. It is clear that this amount is insufficient to supply the existing draft, though we cannot accurately divide the draft of Areas 2 and 3 to determine how much of each comes from the Nuuanu-Pauoa area.

A better approach is to point out that the amount of infiltration estimated by the same method for the Beretania Area (No. 2) is 7.62 M.G.D. against a known discharge of 9.40 M.G.D. (1), and infiltration

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(1) Manoa-Makiki Report, page 77g, 1940.

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estimated for the Kalihi Area (No. 3) is 4.32 M.G.D., against a known basal discharge of 8.51 M.G.D. (1). Combining these two areas, the

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(1) Kalihi Report, page 67, 1941.

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estimated infiltration is approximately two thirds of the known draft. This result merits explanation in some fashion. Three possible interpretations can be listed. (a) The measurements of rainfall and estimates of runoff, evaporation, and transpiration are undoubtedly somewhat in error; if rainfall were larger and the other three factors, smaller so as to double the infiltration remainder, the evident deficiency would be remedied. (b) The area of effective infiltration into the basal water body may be larger than the limited area now thought most probable. If our present belief that comparatively little infiltration from the valley-bottom area reaches the basal water is not correct, this would materially increase the total amount of infiltration. (c) The basal water body above sea level may gain large amounts of water by lagging up draft from the bottom storage in response to long-maintained low artesian heads as compared to those prior to 1880. If this process is going on, it is entirely adequate to supply very large amounts of water.

At present, it is impossible to deny categorically the possible application of any one of these explanations, but the writer has very strong doubt that either (a) or (b) are sufficient to afford the full explanation. It is believed that rainfall quantities are known within less than 10%, that is, within 2 M.G.D., and it would be begging the question to assume that the direction of even this amount of error is such as to explain the excess of draft over infiltration. Similarly, measurements of runoff are sufficiently complete and longstanding to set up a minimum that can hardly be denied. A change in the estimate of runoff would likely be an increase, which would reduce rather than increase the infiltration residue. The writer does not known any independent justification for reducing the amounts estimated for evaporation and transpiration below a total approximating 35 per cent of the rainfall. Much as it might be of superficial interest to derive a larger and an adequate infiltration remainder, a heavy burden of proof would rest on any attempt to do so, and such an attack does not seem promising.

The marked reduction in infiltration amounts estimated in this study as compared to previous estimates is due chiefly to the restriction of presumed effective infiltration to areas of Koolau rock not overlain by thick accumulations of residuum, alluvium or other secondary impervious materials. The larger areas of cap rock such as the Nuuanu Valley bottom, are underlain by such thick masses of such impervious materials, which have been shown by diamond drilling to have such a character and continuity that they are believed to be highly effective barriers to the general downward percolation of rainwater to the basal water table. Smaller areas of residual material on ridge tops, from which drainage may pass over channels cut in Koolau rock are open to somewhat greater uncertainty as to whether the rain falling on them is in large measure prevented from reaching the basal water. Because of their small area, their addition to the intake area for basal water would not materially change the total amounts. On the basis of present field and laboratory studies of the formations involved, the writer sees no basis for material change in the general hydrologic classification of areas, as shown in Figure 52. Hence no great increase in infiltration estimates can be anticipated as a result of changes in mapping.

To the present writer, the most promising factor in resolving this descrepancy between known discharge and the seemingly inadequate infiltration lies in the probable yield from lagging adjustment of the diffusion zone, that is, from bottom storage. This problem has been discussed in detail elsewhere (1). It is only necessary here to

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(1) Wentworth, C. K., Kalihi Report, Appendix II, pp. 109-137, 1941.
_______________ Board of Water Supply, 8th Report, p. 191, 1941.

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emphasize that not only would such a lagging yield from bottom storage readily provide the amounts of water required to balance the equation, but that such lagging yield seems an absolutely necessary consequence of the Ghyben-Herzberg principle, and finally that such meagre data as we possess on the position of the diffusion zone certainly show that its rise is lagging by several hundred feet; and in its continued rise, probably even when the artesian head is rising as well as falling, there can hardly fail to be a large yield of water to the basal water body. Qualitatively, it seems inescapable that this process is going on and that there is a continuing, even if declining draft, on the bottom storage.

It is not yet practical to discuss this problem from the standpoint of individual areas or valleys as effectively as the Honolulu area as a whole. A compilation of rainfall, discharge, and artesian head data recently made under Mr. Samson's direction suggests that under average rainfall conditions the artesian head will remain constant under a total private and public discharge of approximately 30 M.G.D. This suggests a "safe yield" under current conditions which is materially less than the 41 M.G.D. earlier estimated by Kunesh (1).

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(1) Report, 1929, Honolulu Sewer and Water Commission, Plate 13.

It is the present writer's concept that until we are able, by means of an experimental installation of pipes for salinity measurements, to gage the position of the diffusion zone and to determine the true gain or loss or constancy of storage, each estimate of safe yield premised on maintaining the artesian head (constancy of top storage only) will be in error by whatever may be the current rate of change of bottom storage. And it seems reasonable to suppose that since the artesian head has been maintained for the past 15 years above its low level of 1926, the lag in the reduction of bottom storage has probably become much reduced since 1926, and the yield from bottom storage likewise reduced. It is therefore believed that whatever the ultimate safe yield of Areas 1 to 4 in the Honolulu district may turn out to be, the apparent safe yield, or draft which will be supplied by average rainfall so as to maintain artesian heads plus the current release from bottom storage, has probably slowly declined since 1926. Several possible conditions are suggested in Figure 58, which shows a number of logarithmic decrement curves computed with reference to the head changes in the Beretania Area in the past 50 years.

At this point it seems wise to consider the definition of safe yield. Meinzer, in 1923, defined safe yield as "the rate at which

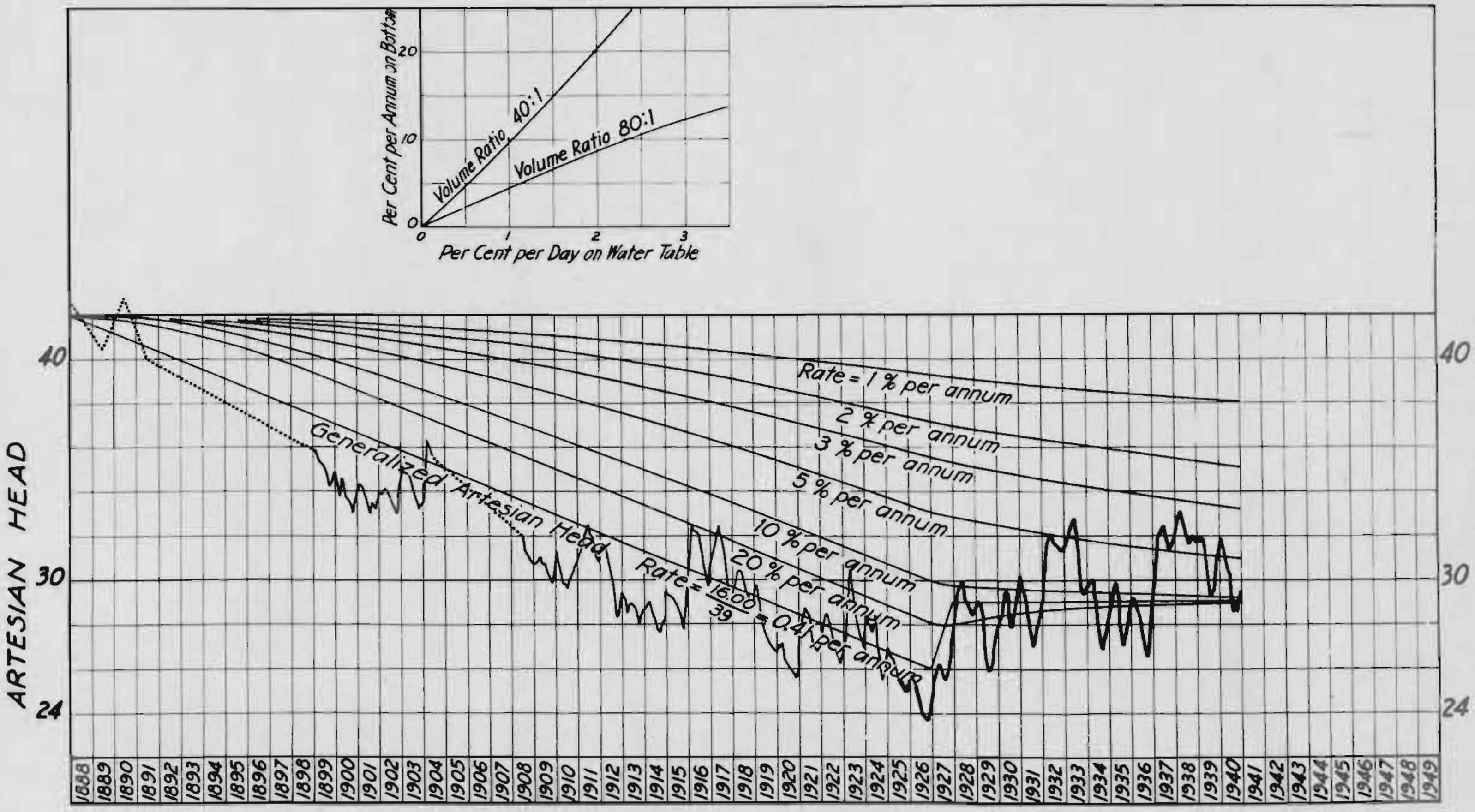

Figure 58 - Graph of artesian head in the Beretania area, with lines showing the position of the bottom equivalent head (Depth to line of balance divided by Ghyben-Herzberg ratio) according to various rates of restoration to balance. The upper line shows the position of this equivalent head on the assumption that the rate of movement of water from bottom to top storage is such as to reduce the lag by 1% per annum. It appears that if the rate of reduction of lag is somewhat over 5% the lag has been nearly eliminated at about 29 feet, but that if the rate is 5% or less, there must be a considerable residual lag due to marked reduction in artesian head prior to 1926. These curves are purely illustrative to indicate the hydraulic and mathematical consequences of certain assumptions, but it is believed that the true condition falls somewhere within the range shown.

water can be withdrawn from an aquifer for human use without depleting the supply to such an extent that withdrawal at this rate is no longer economically feasible" (1). This definition has been quoted and

(1) Meinzer, O. E., U. S. G. S., Water Supply Paper 494, p. 55, 1923.

apparently accepted by Stearns (2). However, a little consideration

(2) Stearns, H. T., Op. Cit., p. 324, 1935.

of the nature of ground-water bodies in Hawaii and of the Honolulu water supply system in particular shows that such a criterion is likely to be misleading and anything but safe. For example, the draft of water from certain artesian wells may indeed be economically feasible to a point where artesian levels and storage reserves have been so reduced as to produce serious consequences either in adjacent wells, belonging to the same or other owners, or to the future serviceability of the same well. To the present writer such usage seems not properly within the "safe" limit. An analogy would be the complete cutting off of an area of climax forest, without allowing for protection of future growth and for recognized forest management on a long-term basis. Such harvesting might be economically feasible but could not be designated as safe or socially prudent in a national or community sense. The term "safe yield" as defined by Meinzer seems founded wholly on the assumption of a natural resource which is replaceable at such a rapid rate that the problem of restoration of levels or reserve is negligible or on the assumption of an absolute ownership right to deplete at will with no responsibility to maintain comparable conditions into the future (1).

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(1) Use of the criterion of economic feasibility as to development and use of natural resources has been all too common in past decades both in the U. S. and in other parts of the world, but better types of human and national planning will be imperative in the future.

Whatever the application of the term elsewhere, it is evident that in actual practice most students of the Honolulu problem, in the use of the term "safe yield", have meant that amount of water as does not, with leakage added, exceed the contemporary additions from rainfall, and hence means maintaining the general, if not the momentary level of the artesian and basal head. Thus Kunesh, in defining absorption, makes it equal (except for leakage) to the measurable beneficial draft for the period for which the head is exactly the same at the end as it was at the beginning of the period (2). He then

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(2) B. W. S. Report, 1929, Plate 13.

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applies this dictum in deducing a "safe" average yield for the Honolulu area of 41 M.G.D.

It seems clear that there is less divergence in the concept of safe yield than in its definition or in its estimation. It has generally been recognized that the Honolulu artesian basin is fed by rainfall and cannot be expected over a long period to yield more water than that fraction of rainfall which infiltrates into the ground. While it is common practice on the mainland to take account of draft from storage when ground-water levels are being lowered, the full consequences of changes in head do not seem to have been considered in reference to the Honolulu system. During any given period when there is a head change, the real yield would be different from the yield supplied from infiltration by the amount obtained from top storage between the limits of the old and the new water levels. There is the further complication due to the far larger lagging yield from bottom storage which the writer believes is a necessary consequence of the Ghyben-Herzberg principle. If this concept be correct, it will not be true that storage is unchanged during a period when beginning and final basal heads are the same. Thus the full equation would read somewhat as follows:

Gains	Losses
(A) Infiltration	(D) Natural Leakage
(B) Top Storage decrease (Head Change)	(E) Top Storage increase (Head Change)
(C) Bottom Storage decrease (Not shown by any measure now made)	(F) Bottom Storage increase (Not shown by any measure now made)
	(G) Draft of all sorts

Then,

$$G = A + (B - E) + (C - F) - D$$

It has been assumed in the past that by taking periods when the head was the same at the beginning and end, it would be correct to disregard the terms, (B - E) and (C - F) on the ground that each would be equal to zero (1). The

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(1) Kunesh, J. F., Op. Cit. Plate 13, 1929.

Hoyt, S. T., Board of Water Supply, Biennial Report 1933-34, Appendix D., p. 150, 1935.

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writer concedes this to be true for (B - E), but as set forth in detail elsewhere, he believes that identity of heads at the beginning and end is no valid index that (C - F) is equal to zero (Bottom storage a constant), and if the concept of lagging discharge from Bottom Storage be correct, the simple equation

$$G = A - D$$

would be subject to large systematic but not easily determinable error over any given period, and particularly during the period of some years following such a general head reduction as that which took place from 1888 to 1926.

The problem of "safe yield", or what might less ambiguously be called "available yield" is dependent on the conditions to be satisfied for the present and in the future.

Condition I - Net Increment Yield

If it be insisted that no more water should be taken than annually reaches the basal water by infiltration, the condition is stated by the equation

$$G + E = A + C - D$$

when "E" represents the gain to Top Storage (and head) through "C", which is lagging release of bottom-storage water, and when these two are equal, so that omitting these equal terms,

$$G = A - D$$

This, by stipulation is a condition of head increase, which would eventually bring about balance at some higher head than the present one, if lag now exists, as thought to be the case. This rate of yield could properly be called "increment yield" and corresponds to what many have meant by "safe yield" and have attempted to define by a stipulation of maintained head while failing to recognize the probability of a long-maintained, lagging yield from bottom storage.

Condition II - Head Maintenance

If it be stipulated that draft be such as to maintain an average head approximating the present, the available yield would be indicated by the following equation,

$$G = A + C - D$$

and would be larger than the "increment yield", except that at a lower mean head the natural leakage, "D", would be slightly smaller and the residue, "G", would be slightly larger.

Condition III - Head Lowering to a Limit

Finally, it may be stipulated that in order ultimately to reduce natural leakage, the artesian system should be operated at a lower average head than at present and that basal head may be lowered to some limit previously agreed upon. In that case, the yield would be

$$G = A + B + C - D$$

With an active lowering of basal head, the amount of "C" would at first increase, as the head lag was increased. The amount of lag and of lagging discharge "C" might remain for some time at a maximum, and nearly constant value in accordance with the concept of limit of lag set forth elsewhere, and would then, as the head was lowered to the limit previously stipulated, slowly decline, probably over a period of many years. During this latter period, with basal head held constant, the equation would be

$$G = A + C - D$$

It is improvement in yield through reduced natural leakage which Stearns has urged as a chief advantage of marked reduction of heads through the use of basal shafts (the Maui type of his terminology). Without denying the validity of this reasoning as far as it goes, it is important to emphasize that if the concept of lagging discharge from Bottom Storage be correct, any benefit to increment yield from reduced natural leakage consequent on a marked lowering of basal head will be effectively masked for many years by the probably much larger benefit to actual yield due to lagging discharge from bottom storage caused by the same head lowering. It is impossible to lower the head to reduce natural leakage without setting in motion a reduction of bottom storage which for many years is likely to yield far larger amounts of water above current increment yield than will be gained by reduced natural leakage, and unless this factor is kept in mind and the problem approached with due regard for its long-term complexities, very erroneous conclusions may be reached as to the amount and source of the benefits.

To summarize the various conditions of operation it is pointed out that only during a period of balance between top and bottom storage can the simple equation,

$$G = A - D$$

hold. Whenever the bottom storage and top storage are out of balance, the head lag will cause, according to its sign, movement of water to or from bottom storage tending to restore balance, and since the volume capacity of bottom storage equivalent to even small amounts of head lag is very large, the resulting movement of water will seriously upset any simple equation which neglects this term. It is believed that during the past 60 years there has been and still is such a degree of unbalance that operation of the system on the basis strictly of increment yield is impracticable and that the actual yield will continue to include significant amounts of water moved because of shrinkage of bottom storage. In most ordinary ground-water systems changes in storage are recognized as a consequence of head changes; in this remarkable Ghyben-Herzberg system the changes in bottom storage are not made directly evident by head changes and yet are probably quantatively so large as to be the ruling factor in the behavior of the whole system.

To come to the point, it is the writer's belief that, (1) At present in 1941, the AVAILABLE YIELD to maintain artesian heads for Areas 1 to 4 is not over 30 M.G.D., (2) this AVAILABLE YIELD has declined materially since 1926 because of reduced release from bottom storage, and will continue to fall at a reduced rate, (3) the true NET INCREMENT YIELD depends on the head it is proposed to maintain in a given basin or the values to be maintained in the several areas of the Honolulu system, (4) the NET INCREMENT YIELD can be somewhat increased by general reduction of artesian heads, by transfer of draft from artesian wells to basal shafts and by the sealing of all leaking wells, (5) the benefit of an increase of NET INCREMENT YIELD due to lowered heads will be confused and masked during the long period of lagging release of water from bottom storage when it seems certain that the release from bottom storage will far exceed any gain due to decreased leakage, and that (6) without change in existing wells and stations the NET INCREMENT YIELD, despite reduction in national leakage, will probably fall to 25 M.G.D. or less in the next 20 years, but that with added basal stations, sealing of more wells, and all feasible infiltration tunnels the current AVAILABLE YIELD may be boosted to 35 or more M.G.D. for a number of years and ultimate NET INCREMENT YIELD may possibly be held at 30 M.G.D.

That it is desirable to build additional basal stations so as to exert complete control over artesian draft and heads in the Honolulu area, the writer is fully convinced, and he also believes that pumpage from these stations should be carried on so as to eventually discourage or outlaw private development of basal water in this area and in a fashion so coordinated with head measurements both on the basal water table and on the diffusion zone that understanding of the Ghyben-Herberg and general basal water mechanism can be expanded and perfected as rapidly as its size and complexity permit. He believes that it is impracticable at present to restrict pumpage to what he believes to be the NET INCREMENT yield, since it is probable that if this were done over the next 10 years there would be a material increase in artesian head due to release of water from bottom storage.

A more practical and far-sighted procedure would be to construct, while it is still pertinent, an observation well to measure the changes in the diffusion zone and bottom storage (which alone is an adequate credit-debit indicator of total ground-water storage) and continue for many years the desired measurements. Within the next 10 years a large amount of pertinent information can be obtained; within 25 years it should be possible to perceive the effects of excess pumpage at basal stations, the possibilities of recovery of bottom storage (something we know nothing about at present) and to predict more accurately the ultimate trends of population, defense and agricultural needs. When such data are more fully in hand, and only then, can a policy of water development and production be so formulated as to discriminate and compromise between the following doctrines, (A) That discharge should be reduced to NET INCREMENT YIELD, i.e., that use plus leakage should be confined to average increment from rainfall so as to avoid any depletion of storage, (B) That artesian and basal levels should be moderately lowered so as to reduce leakage and thus increase NET INCREMENT YIELD, (C) That artesian and basal levels in the Honolulu area should be markedly reduced so that more water can be drawn in from surrounding areas (or prevented from migrating to them).

Recommended Projects

No structures were found which favored the development of high-level, confined or perched water in the Koolau lava flows in the Nuuanu-Pauoa district. Five projects at lower levels, and of various sorts, are recommended. These are (1) Nuuanu Stream Recharge Infiltration Tunnel, (2) Nuuanu Valley Bottom Underground Development Tunnels,

(3) Pauoa Valley Bottom Underground Development Tunnel, (4) Punchbowl (Papakolea) Basal Shaft (Beretania Area) and (5) Diffusion Zone Test Hole. These are described below.

(1) Nuuanu Stream Recharge Infiltration Tunnel

This project is comparable to those described for other valleys. It is designed to divert surface water from Nuuanu Stream through a settling channel and ditch into an infiltration tunnel driven in Koolau rock in the valley wall. There is every basis for belief that such water would thence pass downward to the basal water table. The plan is to drive the tunnel in the east wall of Nuuanu Valley at an elevation of 722 feet about 300 feet seaward and southwest of the lower end of No. 2 spillway. According to a preliminary plan by Mr. Samson and Mr. Wallace (filed under 2-17-52) it is contemplated that a total of 4.0 M.G.D can be delivered to the tunnel with an intake ditch capacity of 10 M.G.D., and the proposed infiltration tunnel is 1000 feet in length. Subject to modifications in detail, which are likely to be indicated from experience after the construction and operation of the first of these projects, this plan is recommended as wholly feasible so far as geologic structure and underground hydrology are known or can be estimated from surface indications.

(2) Nuuanu Valley-Bottom Underground Development Tunnels

In an earlier section of this report under the heading "Inland Cap-Rock Water" the structure and hydrology of the Nuuanu Valley fill, as revealed by diamond drilling and other data, has been discussed and an estimate of 2.5 M.G.D. of developable water made. The problem here is to reach the fairly high gradient, narrow water table which appears to carry the accumulated valley-bottom ground water. This water table stands at about 625 feet elevation at Hole No. 7, just seaward from Lower Luakaha fall, and at about 533 feet at Hole No. 8 near No. 2 spillway. What its elevation is at points farther seaward can only be estimated approximately at present. In order to determine underground conditions at points farther seaward, it is recommended that probably not to exceed 3 diamond drill holes be drilled on a transverse line at Kimo Bridge.

From estimates which can be made at present it is believed that the most feasible point of development is practically under the U. S. G. S. gage station, where the water table probably lies at approximately 440 feet. Whether to approach this point by a tunnel some 2600 feet long from a point in Nuuanu Stream channel about 1400 feet below Kimo Bridge, or by a vertical or inclined shaft from some point above Kimo Bridge, which will involve pumping to a higher level in delivery to the surface is a matter to be determined by engineering considerations. The writer believes that additional diamond drilling is needed before the actual point of penetration to the water table can be determined to the best advantage, and further that a total of several hundred feet of exploration-development tunnel from the point of reaching the water table will be needed before the nature of ground-water movement and storage, and fluctuations in level can be outlined so as to plan the best form of development, delivery, and operation.

Whatever water can be had at this point by a combination of tunneling and possible underground barrier, weir construction can immediately or at any future time be handled in any one of the following three ways: (a) Deliver to the surface in Nuuanu Valley by gravity or pumping, (b) Deliver to an infiltration tunnel in Koolau rock either on east or west side of the valley, with chief benefit to Beretania or Kalihi basal water respectively, or (c) Deliver directly downward into Koolau rock by means of shaft or large-diameter drill holes with less certainty as to where the benefit would be felt. The determination of which procedure is best is essentially an engineering problem. The writer believes that the project as a whole should be undertaken in the following units:

(I) Diamond drill exploration, (II) Access tunnel or shaft, plus development and exploration tunnels with tests to determine amount of water available under various drawdown conditions, and (III) Whatever delivery procedure and construction is decided on. This plan would permit the most advantageous adaptation of plans to the amount of water developed and would also best facilitate the adoption in the future of an alternative method of delivery if that were indicated.

Procedure (c) above, is regarded by the writer as less advantageous than (a) or (b), but he has no particular choice between the latter except to point out that if future water supply requirements should change materially from the present, it would be simple to change the delivery of water from (a) to (b), or vice versa, if the development of water at an underground station be made a unit in itself. The simple drilling of large-diameter wells through the cap-rock tongue is not recommended by the writer.

(3) Pauoa Valley-Bottom Underground Development Tunnel

This project is similar to the Nuuanu Valley project, (2), except in being much smaller and in the fact that because of the shallower and steeper valley fill a part of the ground water emerges in Booth and Rose Apple Springs. No specific plans have been formulated, but the general procedure is to drive a shaft or tunnel to the base of the fill of Tantalus basalt and cinders and thence drive inland on the axis of the old valley along the upper surface of the lower member of alluvial fill. The tunnel should be driven from a point below Rose Apple Spring and should reach the axis of the cinder and basalt fill at elevation about 600 feet. This project develops the total amount now in sight at Booth and Kahuawai Springs, or possibly 0.4 or 0.5 M.G.D., but it is not certain whether the value would justify the costs of tunnel lengths that might be necessary. No basis in rainfall or geologic structure is known for estimating developed quantities materially larger than the present flow of the springs, though if conditions are favorable, some additional underflow might be found and necessitate revision of our view of the infiltration totals.

(4) Punchbowl (Papakolea) Basal Shaft

Plans for this project have already been drawn by the Engineering Division, and its construction has been under consideration for several years, in line with the policy of eventually moving the operating draft inland to basal shafts in each of the chief artesian areas, as is now the condition in the Waialae and Kalihi areas. Diamond Drill Hole No. 39 has been the site of weekly measurements of the elevation of basal water since 1938, and the head here has been found to stand within about 0.10 feet of the head at the Thomas Square well, index well for the Beretania area, and to fluctuate closely with it, except for short-term pumping disturbances. There are no special geologic conditions to be met, and it is believed that the chief problem to be met is that of determining the operating level, or ranges of level, which are to be provided for. During the past 20 years, the head of basal water in the Beretania area has fluctuated between 23.5 and 33.5 feet. It lies essentially with the Board of Water Supply to decide at what level the central basin shall be held for the next 25 to 50 years. It is recognized that with the basal type of station there is less danger of increasing the salt content, and it is the belief of the present writer that with installation of a basal shaft in the Beretania area, it will become accepted procedure to hold the artesian level below 30 feet and possibly below 25 feet at all times, and that fall of the basal level to as low as 20 feet will not be regarded with alarm. Under such operating conditions there should be a material increase in the total water available.

But contrary to the view of some, the writer does not believe that reduction of the general basal level to so low as 10 feet will ever be prudent procedure, even if it were possible, in view of the great reduction of storage capacity that would be involved and the probable damage to future operations that might appear in ways that are not wholly apparent at present.

It is suggested that the pump room floor be set at about 26 feet, with provision for protection against flooding up to about 32 feet, and that it be assumed that during the following 40 years to about 1980, the basal water will be held in general between 30 and 20 feet in the Beretania area. It is suggested that not less than 1000 feet of tunnel be provided, in two separate tunnels leading to a header sump (possibly a ring sump around 4 or 3 sides of the pump floor with capacity of at least 100,000 gallons, and with a lined bottom at about 15 feet above sea level. It is suggested that the tunnels be driven at basal water level, preferably when that is as low as 27 feet, and deepened in sections, without attempt to dewater, to about 23 feet. Such construction may serve for a long time, but if further deepening of the tunnel is needed, it may be necessary to work at the further deepening of one tunnel at a time when water levels are low and continue the use of water from the other tunnel. Such a procedure is not desirable, but its possible necessity should be recognized, and the general layout designed so that this would be mechanically possible.

(5) Diffusion Zone Test Hole

This project is recommended as the most direct approach to investigation of the movement of the diffusion zone and changes, either increase or decrease, in the amount of water in bottom storage. The fundamental aim is to sample the natural ground water at various levels in the aquifer from an upper portion in fresh water, through the zone of mixing, to a lower portion in full salt water. It is essential to do this without appreciable disturbance of natural conditions. It is also essential that such sampling can be carried on continuously for a long time, many years or decades. The general conditions to be met have been outlined elsewhere (1).

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(1) Kalihi Report, pp. 103-104, 1941.

The following additional suggestions are made here. The bore hole used can be either a new well of 8-inch diameter or larger or can be provided by deepening any suitably located available well. The essential requirement is an uncased section of probably 300 feet of hole in Koolau aquifer rock extending from fresh water to salt water in one of the developed artesian areas where past, present and future head and draft conditions are or will be matters of record and where in some degree they can be controlled. In such a hole should be placed, from bottom upward, alternating permeable and non-permeable plugs of crushed rock and concrete, respectively, of say 20 feet length each, with a new, small-diameter pipe placed with its lower end in each permeable section and leading to the surface. The upper part of the hole, above the experimental part, should either be sealed or allowed to fill with water to the static head, so that except for the small flow from the several small pipes, the hole is static and promotes no draft or inter-zone leakage disturbance.

The battery of small pipes should be led into a small, permanent collection station (a building 12 by 12 feet, more or less) at elevation 10 feet or so and fitted with valves and waste-collecting drain-pipe. Each valve should be adjusted and readjusted so as to hold the discharge from each zone to the smallest steady flow consistent with not too great delay in coming up from the intake end. A one-inch pipe holds about 4 gallons per hundred feet, or 40 gallons per 1000 feet. If this figure is about the operating depth and the flow were adjusted for .5 gallon per minute, it would take somewhat over 80 minutes for any change at the bottom to be fully represented at the top. This means that for daily sampling a rate of under 1000 gallons daily from each pipe would be sufficient to give currently representative water. For weekly sampling a still lower rate might be used, perhaps not over 50 to 100 gallons a day. The total flow from 10 pipes would be a small discharge compared to other disturbances in the system.

Operating for a short time would furnish a more competent guide as to procedure, but the writer believes that weekly samples should be analysed for chloride content for a year or two, with certain tests of daily or more frequent sampling. It is believed that such a station should be planned for operation for a quarter century or longer, with such additions or modifications as experience might dictate.

The question may properly be asked whether it might not be determined by electrical resistance methods what chloride content obtained at a given depth, either by fixed, permanently installed electrodes, or by a pair of poles introduced each time into the hole, if that could be done without excessive disturbance. This question has been discussed with Mr. Bryson and has also been referred to Dr. J. H. Swartz, Geophysicist, of the U. S. Geological Survey. Results of these inquiries are indicated in the following letter to Dr. Swartz and his reply;

March 28, 1941

Dr. Joel H. Swartz
U. S. Geological Survey
Washington, D. C.

Dear Dr. Swartz:

Recently I have given much attention to the problem of bottom storage, i. e., the water contained in the Ghyben-Herzberg lens below sea level, and reciprocally related hydraulically to the top storage as far as head is concerned. The crux of this problem is to determine the amount of lag in the movement of the diffusion zone and the total permeability or hydraulic modulus which determines the response per foot of unbalance.

Interest is growing, and I think it possible that in the next ten years we might drill a deep, large-diameter hole, in which some 10 or more small-diameter pipes might be successively sealed in, so as to tap natural water from zones 25 feet apart across the zone from salt water to fresh and permit fairly accurate measurement of the position and fluctuations of the zone of contact or balance. If weekly analyses were made of water from ten such pipes, each flowing continuously at perhaps 25 gallons daily (enough to give active circulation but not enough to seriously disturb natural conditions) we might in a few years learn much of great value.

However, the question arises as to how much could be done by geophysical means. A hole like that proposed, with installation, would possibly cost $15,000, and annual operations would take perhaps 40 or 50 man-days per year. Assuming good conditions, permanent installations, stations, etc., but recognizing the danger of urban disturbances, pipe lines, ground currents, etc., what could you do by electrical methods and at what cost? I assume we should have to take it over as a staff job, but I am interested in knowing how well you could compete with a fixed well in detecting (1) position of line of balance between salt and fresh, (2) top and bottom and hence thickness of diffusion zone, (3) movements of diffusion zone.

I find by consultation with our chemist that if we had water samples from ten points through a diffusion zone of 400 feet, there would be more than 100 easily discriminable grades of salinity between salt and fresh water, and it apparently would be easy not only to define the nature of the transition but also probably to easily detect a shift of as little as five feet, perhaps materially less, since there would be 10 samples.

I suspect that you cannot by any means compete with such a setup. However, what could be done electrically and what might it cost? I'll appreciate a reply when you find it convenient. The matter is not in any way urgent.

With kind regards to you and the family.

Sincerely yours,

(S) CHESTER K. WENTWORTH

341 Custom House
Baltimore, Maryland
May 6, 1941

Dr. Chester K. Wentworth,
Board of Water Supply,
Honolulu, T. H.

Dear Wentworth:

I was very glad to get your letter of March 28 and am very sorry my reply has been so long delayed. Your letter went first to the Survey in Washington and after being held there for several days was forwarded to me here at our office in Baltimore, arriving however while I was out in the field and being then held here until my return, hence the slowness of my reply.

I am tremendously interested in your plans for gathering data on salt water fluctuations and shall of course be only too glad to help in any way I can. This is a matter of great importance from all angles, economic as well as scientific. Geophysically it is, of course, of tremendous interest.

I should say off-hand that your drill hole is the proper way to attack the problem. While resistivity measurements do detect the change from fresh to salt water with a considerable accuracy, they measure an integrated value, a sort of weighted average of the resistivities of all the overlying beds included with the resistivities of the beds at the depth of measurement. They would therefore be affected by any resistivity changes in the overlying horizons as well as by the changes in the salinities of the basal water lens. This would be a disadvantage in a fundamental research study such as you propose. Also, while a change from fresh to ocean-salt water can be detected, we do not know as yet, largely because of the absence of just such calibration data your conclusions from surface resistivity measurements, no matter how sound, would not yet carry the weight which direct determinations of salinity in the drill hole would have. For these reasons I believe the drill hole would be preferable for so basic a research as you propose.

However, if such a drill-hole is put down, I should like very much to see a series of resistivity measurements run at regular time intervals as near the test well as possible to enable us to obtain the calibration data necessary to determine how small a salinity change can be detected by surface resistivity measurements. As a result of such calibration measurements, over an extended period of time, it might then be entirely feasible to run surface resistivity measurements in numerous other parts of the Islands for the purpose of collecting in other Island areas such data on salt water fluctuations.

Resistivity measurements would be considerably cheaper than your drill hole. Just how much cheaper would depend upon the depth you planned to reach and the detail (depth interval) desired. If you'll give me some idea of these factors I'll be glad to send an estimate of the costs of resistivity operations under those conditions.

For resistivity measurements it would be very desirable to have the well in a rural area away from pipe-lines and D. C. electrical disturbances.

I'm tremendously interested in this project of yours and shall be glad to hear all about it as it progresses and matures. If I can help in any way please let me know.

Incidentally I don't believe I have yet thanked you for a number of your papers recently received. I am very much ashamed that I haven't done so long ago. I have appreciated them very much indeed.

With best alohas from all the Swartzs.

Sincerely,

(S) JOEL H. SWARTZ

C. K. W.

By "surface resistivity" he apparently means the overall resistance between ground surface and given points in the drill hole. I can't see that this will give the desired information.

Salt content can be measured at the given points either by samples removed for titration or by resistivity (= conductivity) determinations obtained in situ by properly designed cells, using calibration curves. More rapid than titration but less accurate.

Other work permitting, some time during the next 3 or 4 months, I can prepare curves correlating SO_4Cl with specific conductance, if desired.

(S) L. T. B.

It appears, therefore, that at this stage, the direct sampling of water, with its analysis either by titration, by laboratory conductivity measures, or by gravity in a picnometer, would be required, but might later permit auxiliary use of the resistivity method at the same point, or elsewhere.

Wentworth, Chester Keeler, 1891-1969.

Geology and ground-water resources of the Nuuanu-Pauoa district, by Chester K. Wentworth. Honolulu, Board of Water Supply, 1941.

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