Geology-Hawaii

LITHIFIED CARBONATE DUNES
OF OAHU, HAWAII

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE
UNIVERSITY OF HAWAII IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN GEOSCIENCES-GEOLOGY

JUNE 1968

By

Steven W. Pottratz

Thesis Committee:

Agatin T. Abbott, Chairman
Gordon A. Macdonald
Ralph M. Moberly, Jr.
Johanna Resig

We certify that we have read this thesis and that in our opinion it is satisfactory in scope and quality as a thesis for the degree of Master of Science in GeoScience-Geology.

THESIS COMMITTEE

Chairman

ABSTRACT

The lithified dune sands of Oahu, Hawaii consist of fine to medium-grained, yellowish brown, carbonate, sand grains indurated by a calcareous cement. The individual particles are primarily fragments of mollusk shells, echinoids, coral, algae, and foraminifera. Foraminifera are the most easily recognizable biological components of the lithified dune sands. *Amphistegina madagascariensis* d' Orbigny, *Marginopora vertebralis* Blainville, and the Miliolidae represent a large percentage of the foraminiferal population. Non-calcareous material comprises less than one percent.

The data obtained in this study indicate that the lithified dune sand contains no fragments larger than 2 mm in diameter. Beachrock samples all contain some grains larger than 2 mm. Thus, 2 mm is a convenient limit for distinguishing the two environments in the field.

In general, the lithified dune sands are better sorted than the beachrock sands and have a smaller mean grain size.

Analysis of the internal structure of the dune deposits indicates that remnants of longitudinal, pyramidal, and transverse dunes are present on Oahu.

Longitudinal dunes exhibit sets of strata dipping away from the crest of the ridge and away from each other, with separation angles approaching 180°. These strata are generally dipping to the north and south at angles exceeding 20°. The longitudinal dunes are elongate primarily east-west.

Pyramidal dunes are evolutionary forms from transverse dunes to longitudinal dunes. They are less elongate than longitudinal dunes and have sets of strata with separation angles of approximately 120°-150°.

Transverse dunes are perpendicular to the wind and have sets of strata dipping in a westerly direction. The sets of strata have average dip directions with separation angles less than 120°.

These dune forms develop, in some areas, at the leeward margins of the coastal plain as a result of the complex wind conditions and loss of transporting ability due to vegetation, change of slope, and increased rainfall at the base of the Koolau Range. In other cases they occur near the present day beach and may represent depositional ridges formed at the seaward margin of a previously vegetated area.

Examples of possible sand shadow deposits are also present on Oahu. One of these exists on a ridge 330 feet above Kahana Bay. Another possible sand shadow is present in the Kailua area. A third type of aeolian deposit, a sand drift, is exposed along the southwestern flank of Diamond Head.

TABLE OF CONTENTS

LIST OF TABLES

Page No.

LIST OF ILLUSTRATIONS

INTRODUCTION

General

The Hawaiian Islands are a series of volcanic islands extending northwest to southeast in the mid-Pacific. Oahu is the third largest of the eight major islands. The island of Oahu has been divided into four major geomorphic provinces by Stearns (1966). These have been designated as the 1. Koolau Range; 2. Waianae Range; 3. Schofield Plateau; and 4. Coastal Plain. Of the four the Coastal Plain Province is the most important in reference to this study.

The Coastal Plain Province is developed mainly along the north and south shores of the island. The plain is composed chiefly of marine deposits which have accumulated at various stages of sea level. A large part of the city of Honolulu and its suburbs is situated on a large portion of this coastal plain. At the extreme northern end of the island is a large section of coastal plain known as the Kahuku Plain.

On the coastal plain evidence of higher stands of sea level is found. Remnants of lithified sand dunes are a common feature of the coastal plain, especially along the windward coast of the island. These sand dunes represent one of the few sedimentary rock types exposed on the island. Although the presence of these deposits has been noted by Stearns and Vaksvik (1935), little work concerning them has been done.

Purpose

The primary objective of this investigation is to determine the type of sand dune form represented by these deposits using internal structure and areal morphology. The study also involved an analysis of the texture and foraminiferal assemblages present in the dunes.

Methods of Study

Measurements of the strike and dip of the strata (McKee and Weir, 1953) exposed in outcrops were made using a Brunton compass. Whenever possible, readings were made on the exposed bedding planes. In some cases only apparent dips were exhibited in the outcrops and pieces of 1/8" or 1/4" plywood were inserted between the strata to provide extended surfaces to measure. Using this method, the true dip was measured.

The irregularly weathered bedding plane surfaces present in the carbonate dunes of this area required several readings to be taken for each set of bedding. These measurements were then averaged to obtain an average dip direction for each set of strata.

Grain size determinations were made using the size scale proposed by Wentworth (1922). The rock colors were determined using the Rock-Color chart distributed by the Geologic Society of America in 1963.

PRESENT WIND CONDITIONS AS RELATED TO DUNE FORMATION

In general, the winds which dominate the Hawaiian Islands are fairly constant in speed and direction. This generally uniform flow is disrupted by topographic features and in many sections local wind regimes exist.

The island of Oahu has prevailing east-northeast tradewinds. Records of the U.S. Marine Corps Air Station, Kaneohe Bay, Oahu, over an eleven year period indicate that almost 60% of the winds are from the east-northeast or east (fig. 1). Occasionally winds from the northeast, south-southeast and southwest are experienced which disrupt the customary flow pattern. These disruptions, especially those from southerly directions, are associated with cold fronts which tend to move from west to east in the area. The cold fronts and associated southerly winds are more frequent during the winter months.

According to McKee's (1966) work with gypsum sands of White Sands, New Mexico, only wind velocities exceeding 15 knots are effective in dune development with sand of that density. This effective velocity is probably slightly less for Hawaiian sand dunes because of the porous character of many of the carbonate particles. Plotting only for winds effective in dune development yields the diagram in Figure 2.

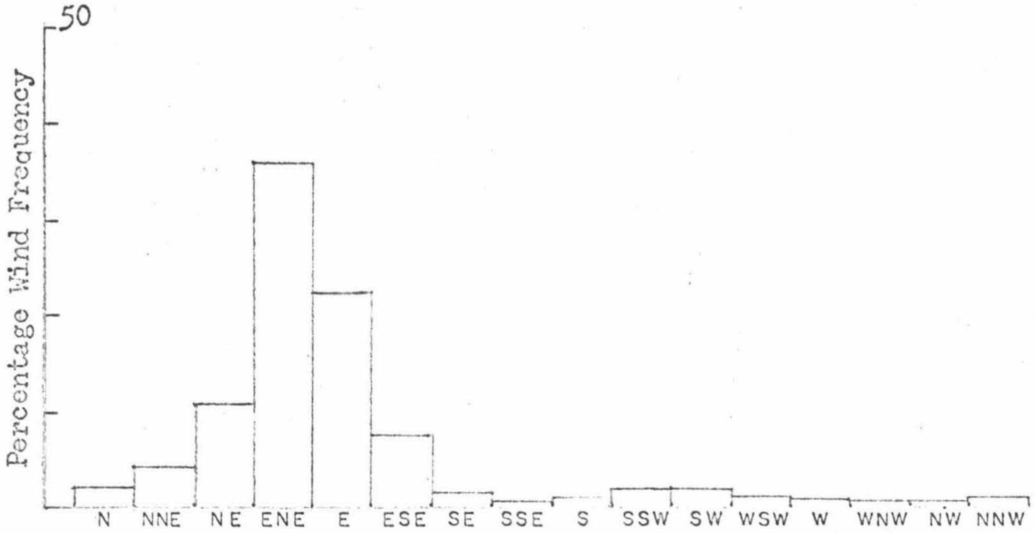


Figure 1. Eleven year summary of monthly wind records for the U. S. Marine Corps Air Station, Kaneohe Bay, Oahu, Hawaii.

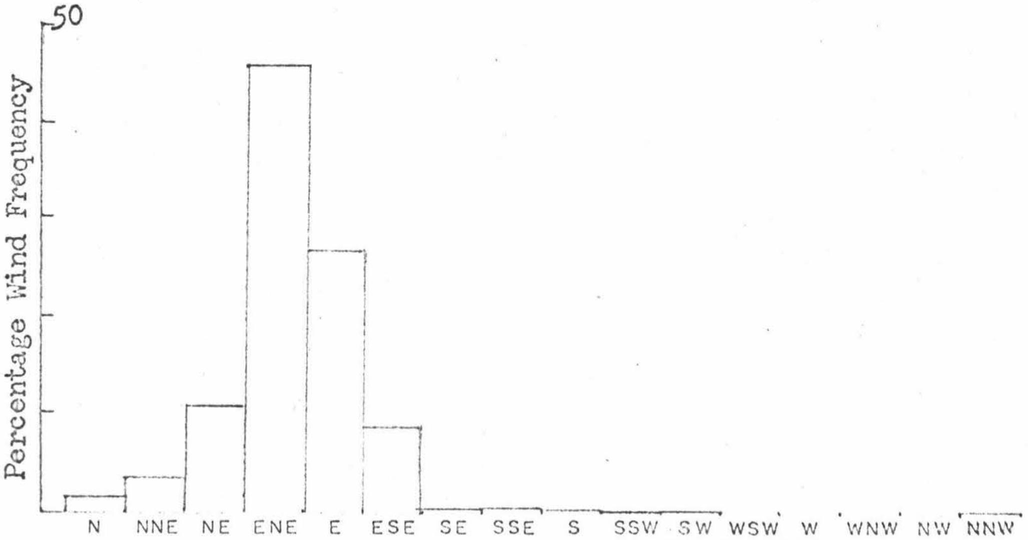


Figure 2. Eleven year summary of wind velocities greater than 13 knots for U. S. Marine Corps Air Station, Kaneohe Bay, Oahu, Hawaii. These are effective in dune development.

DIFFERENTIATION OF DUNES FROM BEACH DEPOSITS

Distinguishing Dune Sand from Beach Sand

There have been attempts by numerous workers to distinguish beach sands from dune sands. These studies involved both a comparison of textural characteristics and mineralogical differences. Some of these investigations concluded that there is no textural parameter for distinguishing between these two environments. This conclusion is based on the fact that the range of parameters for each environment overlapped (Waskom, 1958; Mattox, 1955). Some studies have been more successful and a brief discussion of these is warranted.

MacCarthy (1935) indicated that beach sand might be distinguished from dune sand by using average grain size and average degree of rounding for each environment. He found that in general dune sands are more rounded than beach sands and that each type of sand occupied a certain zone when average roundness was plotted against each size class. The relationship was best observed in the coarser and finer fractions of each sample.

Keller (1945) attempted to differentiate beach and dune sands by applying the ratio between the fine and coarse samples, F:C ratio, as determined by sieve analysis. The samples were classed as fine or coarse, F or C, depending on the relationship of the proximate admixtures to the chief ingredient or maximum (Udden, 1914). If the proximate admixture was coarser than the maximum, the sample was designated as coarse. If it was finer than the maximum, the sample was designated as fine. He found that the ratio for recent dune sand was $\frac{2.5}{1}$ or more. For beach sand, his results indicated F:C ratios of $\frac{1.1}{1}$ or less.

Like MacCarthy, Beal and Shepard (1956) tried to distinguish beach sands from dune sands using roundness values. They used the term roundness as curvature or roughness of the surface of a grain and noted that dune sands generally are more rounded than beach sands. Because of some overlap in the values obtained for beaches and dunes, the authors concluded that the difference was relative rather than absolute, making the stratigraphic use of the criterion impossible.

Mason and Folk (1958) tried to distinguish beaches from dunes by plotting skewness against kurtosis, as the differences between environments are reflected only in the tails of the grain size curves. Skewness is the quality, of a frequency distribution, of being asymmetrical with relation to the mean, mode and median. Kurtosis is a measure of the peakedness of a size distribution curve. For a more detailed discussion of these parameters see Mason and Folk (1958) or Folk (1966).

Friedman (1961) suggested that dune sands may be distinguished from beach sands on the basis of the skewness of curves derived by plotting frequency against grain size. Dune sands are generally positively skewed, whereas beach sands tend to be negatively skewed. The mineralogy of the sand does not affect the sign of the skewness.

Shepard and Young (1961) found that dune sands are usually rounder than beach sands, particularly if there are predominant onshore winds. They suggested that the chief reason for this difference is that the wind moves more of the rounder grains from the beach than the angular and flat grains.

The techniques cited above were developed in studies on unconsolidated dune and beach sands in which textural parameters were determined by sieving the samples. Little work has been done on comparisons between consolidated beach sands and dune sands. Existing sieving techniques are impossible on lithified carbonate sands, thus textural parameters must be derived from thin section studies.

Mattox (1955) feels that the use of shape characteristics, as proposed by some authors to discriminate beach from dune sands, is of little value because waves and long shore currents are continuously modifying and altering beach deposits in short periods of time.

McKee (1957) proposed the use of stratification and cross-stratification as a means of identifying beach sands from dune sands. Beach deposits can be recognized by the low angles and long, flat surfaces of the bedding planes, which usually dip toward the sea at angles up to 12°. The writer has observed similar attitudes in cross-sections of the beach at Waimea Bay on the island of Oahu. Dune deposits, on the other hand, consist almost wholly of steeply dipping cross-strata that have formed on the lee slope or slip face of the dune. The gently inclined cross-strata, which dip in the opposite direction on the windward side of the dune, are rarely preserved. The majority of the slip face planes of the dune dip at 30° or greater although dips as low as 16° have been found in some cross-strata (McKee, 1957).

Additional features which may be useful in distinguishing between beach and dune deposits are the gross shapes of the sand bodies, ripple marks, and inclusions of large pebbles or shells.

Comparison of Oahu's Lithified Dunes and Beachrock

The nature of the dune sandstone, calcareous fragments indurated by a carbonate cement, made it necessary to determine the textural characteristics of the rock from thin section measurements. Some of the samples were only loosely cemented and these were impregnated before thin sections were made.

There have been several attempts to convert thin section size distributions to those of sieve analyses (Friedman, 1958, 1962, Rosenfeld, 1953). A limitation of Friedman's method, is that it applies only to well-sorted sandstones with a high percentage of quartz. As most Hawaiian sandstones are predominantly calcarenites, Friedman's method cannot be applied. Rosenfeld concluded that there is no generally applicable correction factor.

In this study size parameters were determined through measurement of the short axis of the grains in thin section. Short axis values were selected over long axis measurements because the short axis appears to more closely approach the dimension which determines the separation of grains in sieving. This tendency is shown in Table I.

TABLE I. COMPARATIVE MEASUREMENTS OF SIEVED AND SECTIONED SAND

	Short Axis			Long Axis		
Sample No.	13	14	18	13	14	18
Percentage of grains within known size limits	55	58	68	18	24	24

A known exception to this is foraminifera, which compose up to 11% of the grains. Many foraminifera are somewhat disc-shaped and these are not separated according to the shortest axis when they are sieved.

The figures presented in Table I were obtained by sieving a sand sample, impregnating a portion of a known sieve size, grinding a thin section from the sample, and then measuring long and short axes using an ocular micrometer.

Although neither short axis nor long axis measurements result in close agreement with the known sieve size, the short axis measurements more closely approach the known size than do the long axis determinations.

Twenty-three dune samples and seven beachrock samples, fig. 3, were analyzed in this study to determine any textural parameter which would permit identification of Hawaiian lithified dune deposits. The results are presented in Table II. The dune samples all represent deposits having dip angles exceeding 20°. The beachrock samples all were taken from deposits of consolidated sand slightly above sea level and in some cases extending below sea level with dip angles not exceeding 10°.

Measurements of the longest apparent axis of the largest observable grain in both the lithified dune samples and beachrock samples were made to determine if this criterion could be used to distinguish between the two environments. The results are presented in Table II.

Student's t test, for a small number of variants (Alder, 1962), was applied to determine if the means were of two separate populations. The dune samples were found to have a largest grain mean of 1.1 mm ± 0.1 mm with 95% confidence. The beachrock samples had a largest grain mean of

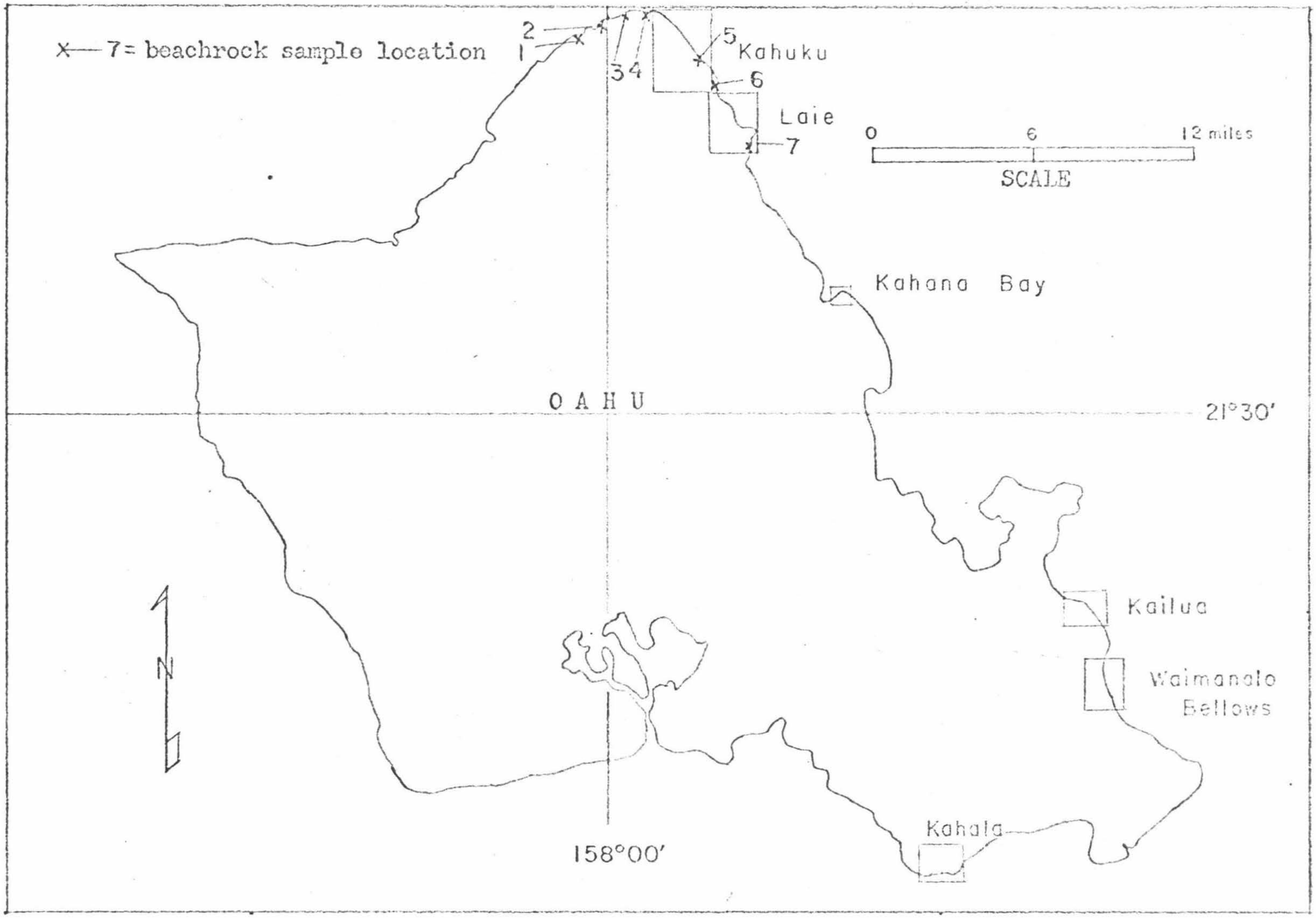


Figure 3. Index map showing the areas of lithified dune deposits discussed in the text. Beachrock sample localities are shown along northern coast.

TABLE II. SUMMARY OF TEXTURAL PARAMETERS DETERMINED BY MEASURING THE SHORT AXIS OF 300 GRAINS IN THIN SECTIONS.

Sample #	Mean ϕ	Sorting ϕ	Skewness ϕ	Kurtosis ϕ	Largest Grain mm	Average of 10 largest Grains (mm)
LSD						
1	2.04	0.51	-0.02	0.97	1.1	0.77
2	2.41	0.44	+0.04	1.09	1.0	0.57
5	1.89	0.46	+0.06	0.94	1.2	0.81
6	2.68	0.44	+0.15	1.05	0.8	0.57
7	1.45	0.52	+0.25	0.88	1.3	0.98
8	2.73	0.48	+0.19	1.21	0.6	0.50
12	2.38	0.50	-0.03	1.00	0.9	0.75
13a	2.05	0.65	+0.19	1.15	1.7	1.10
13b	1.92	0.46	0.00	1.00	1.5	0.88
14	1.92	0.48	-0.03	0.99	1.4	0.77
15	1.84	0.47	-0.01	1.01	1.3	0.87
18	1.62	0.41	0.00	1.01	1.7	0.90
20	1.85	0.44	+0.02	0.94	1.2	0.90
21	2.34	0.43	+0.02	0.99	1.0	0.58
22	2.44	0.46	0.00	0.98	1.1	0.66
101	2.24	0.43	+0.07	1.23	0.9	0.73
201	2.20	0.42	+0.19	1.15	0.9	0.68
202	2.33	0.38	+0.24	1.08	0.9	0.70
301	2.57	0.37	+0.10	1.15	0.6	0.50
303	2.10	0.45	+0.11	1.18	1.2	0.86
304	2.17	0.47	+0.04	1.13	1.1	0.80
601	2.41	0.42	-0.02	1.12	0.8	0.61
603	1.83	0.57	-0.14	0.97	1.2	1.08
LBR						
1	0.41	0.87	+0.26	1.41	5.5	2.64
2	1.41	0.80	-0.12	0.93	7.1	2.52
3	1.36	0.64	-0.08	0.88	2.8	1.42
4	1.63	0.67	-0.07	1.09	2.3	1.23
5	1.07	0.59	+0.25	1.07	4.9	1.48
6	1.43	0.67	+0.29	1.34	2.0	1.16
7	0.96	0.63	+0.19	1.17	4.2	1.81

4.1 mm ± 1.7 mm with 95% confidence. This means that if the largest grains in samples of Hawaiian lithified dunes are measured, the mean of these measurements will probably fall between 1.0 mm and 1.2 mm 95% of the time. Using the same technique, the largest grain mean for beachrock will probably be between 2.4 mm and 5.8 mm. The data here then indicate that the measurement of the largest grain in a sample can be used to distinguish between the two types of deposits on Oahu.

The largest grain mean for the dune samples was less than 2 mm and for beachrock was greater than 2 mm. Thus, the figure of two millimeters was selected as a convenient limit for distinguishing between the two deposits in the field.

Similar results were obtained when this same technique was applied to the mean values of the average of the 10 largest grains measured in a thin section. This separation between the means held true when the technique was also applied to the population mean and the mean sorting for each environment (See Table III). When student's t test was applied to the mean skewness and kurtosis for each environment, a definite overlap in these parameters existed (See Table III).

The data here indicates that, in general, the lithified dune sands are better sorted than beachrock sands and have a smaller mean grain size. Skewness and kurtosis values overlap between the two environments.

In this study, the high angle of dip of the bedding planes, the internal structure of the deposit, and the lack of inclusions of large pebbles or shell fragments greater than 2 mm have been used as evidence that the sand structures are of an aeolian origin.

TABLE III. CONFIDENCE INTERVALS (95%) FOR STUDENT'S t TEST FOR TEXTURAL PARAMETERS.

	Largest grain (mm)		Average of 10 largest grains (mm)		Population Mean ø		Sorting ø		Skewness ø		Kurtosis ø	
	dune	beach	dune	beach	dune	beach	dune	beach	dune	beach	dune	beach
X (Mean)	1.1	4.1	0.8	1.8	2.10	1.18	0.46	0.70	+0.06	+0.10	1.01	1.13
95% Conf. Lim.	±0.1	±1.7	±0.1	±0.6	±0.15	±0.38	±0.03	±0.09	±0.04	±0.17	±0.05	±0.18
Range	1.0-1.2	2.4-5.8	0.7-0.9	1.2-2.4	1.95-2.25	0.80-1.56	0.43-0.49	0.61-0.79	0.02-0.10	0.07-0.27	0.96-1.06	0.95-1.31

CHARACTER OF THE LITHIFIED DUNE SAND

Composition

The lithified dune material consists of fine to medium-grained, pale yellowish brown carbonate sand grains bound by a calcareous cement. The rock weathers to a dark gray color. The individual particles are for the most part fragments of mollusk shells, echinoids, coral, algae, and foraminifera, with occasional whole foraminiferal tests. Non-calcareous material is rare, usually comprising less than one percent. The carbonate grains appear to be of two different types: some appear as distinct grains with definite margins, whereas others have less definite borders and appear only as ghost grains surrounded by cement.

In general, the lithified sand is quite porous, having a porosity visually estimated at 15-25%. Solution cavities are common and in many cases they have been filled by reprecipitated calcite probably derived from the upper portion of the dune by percolating ground water. Another feature frequently found is a thin coating of calcite covering some portions of an outcrop. Shortly after a rain shower, water can be seen dripping on these deposits from overhanging ledges in the upper section of the dune. Individual strata range in thickness from a few millimeters to as large as 18 cm.

Texture

The short axis mean for each sample was determined graphically using the relationship proposed by McCammon (1962a). The range of mean size is 1.45ϕ (0.43 mm) to 2.73ϕ (0.15 mm). The sand comprising the lithified dunes is fine to medium-grained (Wentworth, 1922).

The degree of sorting was determined using the measure proposed also by McCammon (1962a). Using this measure, a perfectly sorted sediment would have a value of zero. The dune sands are in general well sorted, if the values for sorting of the dune sands, found in Table II, are applied to a scale proposed by Folk and Ward (1957).

Skewness and kurtosis were determined as suggested by Folk and Ward (1957). Friedman (1961) found that recent dune sands in general are positively skewed. There is an indication that this is true for the Hawaiian lithified dunes (Table II). Positive values up to a limit of +1.00 are found in cumulative distribution curves with tails in the fines. Perfectly symmetrical curves have a skewness value of 0.00. The measure varies from -1.00 to +1.00 although Folk and Ward (1957) contend that natural sediments with skewness values exceeding +0.80 are very rare.

The measure of kurtosis is 1.00 for normal curves. Bimodal distributions or distributions with flat curves have values less than 1.00, whereas excessively peaked distributions have values 1.5 to 3 or even greater. Values obtained for Hawaiian lithified dunes deviated somewhat from 1.00, some being slightly less, some slightly more. No trend is indicated (Table II).

Foraminiferal Analysis

Foraminifera, the most easily identifiable biological components of the lithified dune sands and beachrock samples, were examined in thin section. The individuals present in each sample and their relative abundances are given in Table IV.

TABLE IV. FORAMINIFERA PRESENT IN THIN SECTIONS AND THEIR RELATIVE ABUNDANCE

	Sample Number	Amphistegina madagascariensis %	Marginopora vertebralis %	Miliolidae %	Soritidae %	Cibicides lobatulus %	Heterostegina %	Textularia %	Total Foraminifera %
	ISD								
	1	77	8	13	1	-			8.7
	2	38	7	34	4	17			3.3
	6	42	2	17	9	29			4.7
	5	87	4	-	4	4			1.0
	7	63	30	3	2	2			1.7
	8	42	10	30	-	18			2.0
Kahuku-Laie Area	12	70	5	12	4	9			8.0
	13a	30	55	15	-	-			9.3
	13b	27	44	26	-	2		1	6.3
	14	26	48	26	-	-			2.3
	18	61	32	7	-	-			1.7
	20	76	8	6	2	8			9.3
	15	89	-	11	-	-			2.3
	21	86	-	6	-	8			6.3
	22	61	8	15	-	15			1.3
Kahana	101	63	4	15	4	14			7.3
Kailua Area	201	34	42	24	-	-			3.7
	202	46	12	40	-	2			2.7
Waimanalo-Bellows	301	20	24	56	-	-			2.3
	303	49	36	10	1	3			11.0
	304	44	32	16	1	7			4.3
Kahala Area	601	70	6	12	6	6			5.3
	603	60	16	8	2	14			4.7

TABLE IV. (Continued) FORAMINIFERA PRESENT IN THIN SECTIONS AND THEIR RELATIVE ABUNDANCE

Sample Number	Amphistogina madagascariensis %	Marginopora vertebralis %	Miliolidae %	Soritidae %	Cibicides lobatulus %	Heterostegina %	Textularia %	Total Foraminifera %
LBR								
1	90					10		
2	70	30						
3	82	10	8					
4	44	38	16	2				
5	75	20	5					
6	73	25	2					
7	62	22	12		4			

In general, the foraminifera in both the beachrock and lithified dune sand are represented by the same species. *Amphistegina madagascariensis* d'Orbigny, *Marginopora vertebralis* Blainville, and the Miliolidae represent a large percentage of the population (Plate I). *Amphistegina* is usually the most abundant foraminifer in both the beachrock and lithified dune samples. In a few instances, however, the lithified dune samples have higher frequencies of *Marginopora* and in one case, the Miliolidae occur most frequently of the three types.

Differences in population may be attributed to several factors. The high percentage of the Miliolidae in Sample 301, from Waimanalo, may reflect a source area which contains an abundance of the Miliolidae. The samples with more abundant *Marginopora* are primarily those which are closer to the source area and the present day shoreline. Shepard and Young (1961) believe that the wind is selective for rounder grains which are easily transported inland from the beach. Therefore, the large disc-shaped test of *Marginopora* might be more difficult to transport than other, more rounded forms.

A constituent of the lithified dune sections, but rarely present in the beachrock sections, is *Cibicides lobatulus* (Walker and Jacob) (Plate II). *Cibicides* is smaller in size than *Amphistegina* and *Marginopora*. This may indicate that *Cibicides*, along with other fine particles, is removed from the beaches by the wind. A similar relationship is found in reference to the Soritidae.

Aside from this limited variation, no major differences in the areal distribution of foraminiferal species were noted. Furthermore, individual dunes were remarkably consistent in their relative percentages of component species.

DUNE FORMS AND STRUCTURES

Bagnold (1933) proposed that only two true sand dune forms exist. These he designated as the barchan, or crescentric dune, and the seif, or longitudinal dune. Hack (1941) additionally suggested parabolic and transverse dune forms from studies he conducted in the Navajo country of Arizona.

A barchan is a crescentric-shaped dune form which has its tips or horns extending downwind. It is convex on its windward side and concave to the leeward. The slip face is generally transverse to the prevailing wind direction. The internal structure of a barchan dune, as reported by McKee (1966) from sections cut parallel to the wind direction, consists of steeply dipping strata inclined to the leeward at 26-34°. In cross-sections perpendicular to the wind direction, strata with apparent dips of 12-23° were observed sloping outward from the center. These strata were enclosed by bounding surfaces which dipped at only a few degrees. To test the fairly consistent dip direction suggested by the apparent dip exhibited in the walls of the trenches in the dune, several measurements of true dips were made. The results gave a spread of 60° with a mean in the approximate direction of the prevailing wind.

Parabolic dunes are long U-shaped bodies of sand with the tips, or horns, tapering to the windward. This type of dune appears to be a form developed by sand blowouts rather than a primary form. The horns are partially anchored by vegetation so that the central area advances more rapidly. The parabolic dune has been described as consisting of high-angle cross-strata, 20-34°, dipping to the leeward in cross-sections parallel to the prevailing wind (McKee, 1966). Along sections normal to the wind direction, cross-strata had apparent dips at primarily low angles away from the center, with a few attaining angles of 25°. A common feature seen in the cross-strata, which may be characteristic of parabolic dunes, is the concave-downward curvature of the high-angle foresets near the dune front. This concave feature seems to be related to the dune shape. The extreme frontal margin of the dune exposes the slip face and permits cross-winds to undercut its base and oversteepen the lower part.

Transverse dune forms are long, nearly parallel ridges extending perpendicular to the prevailing wind direction. According to McKee (1966), the cross-strata in sections oriented parallel to the general wind direction are inclined at angles of 30-34° to the leeward. Sections normal to the wind exhibit stratification which is apparently horizontal or dipping at very low angles.

The longitudinal or seif dune is elongate parallel to the prevailing wind direction. The structure of the longitudinal dune has been analyzed by McKee and Tibbitts (1964), working in Libya. They found that in sections perpendicular to the trend of the ridge, laminae dip away from the crest at high angles of 23-33°, except near the base where they dip much less. Bagnold (1941) also postulated a similar structure for seif dunes.

A structure commonly observed in the strata of all types of dunes is contorted bedding. It may be associated with small faults and irregular, small scale, folding. It appears to be caused by partial slumping on an oversteepened slip face.

LITHIFIED DUNE FORMS OF OAHU

Approximately fifty days were devoted to field work. More than 900 strike and dip measurements along bedding planes were taken at 35 different localities. To simplify discussion, the data are grouped into five different regions: The Laie-Kahuku, Kahana Bay, Kailua, Waimanalo-Bellows AFB, and Kahala areas (fig. 3).

Laie-Kahuku Area

Laniloa Point, or Laie Point, (fig. 4), on the northeast shore of Oahu, east of the town of Laie, is undoubtedly the best exposure in the area. The deposit is approximately 3400 feet long, 500 feet maximum width, and 50 feet high. The trend of elongation is nearly east-west. The material is composed of fragments of calcareous shell and reef. Foraminifera comprise approximately 6% of the grains by volume. Noncalcareous material represents less than 1%.

The structure of the deposit is clearly exhibited along both the northern and southern shores of Laniloa Point. Steep north-dipping strata comprise the full length of the north shore of Laniloa Point. An average of 27 measurements taken along the northern face of the deposit resulted in a dip direction of N 21° W at an angle of 23°. Using the same technique on 65 measurements along the south facing slope resulted in an average dip direction of S 05° W at 30°. The data are summarized in Table V.

Steeply inclined strata dipping in opposite directions at high angles and having opposing dip directions with separations approaching 180° have been described in recent longitudinal dunes by McKee (1964).

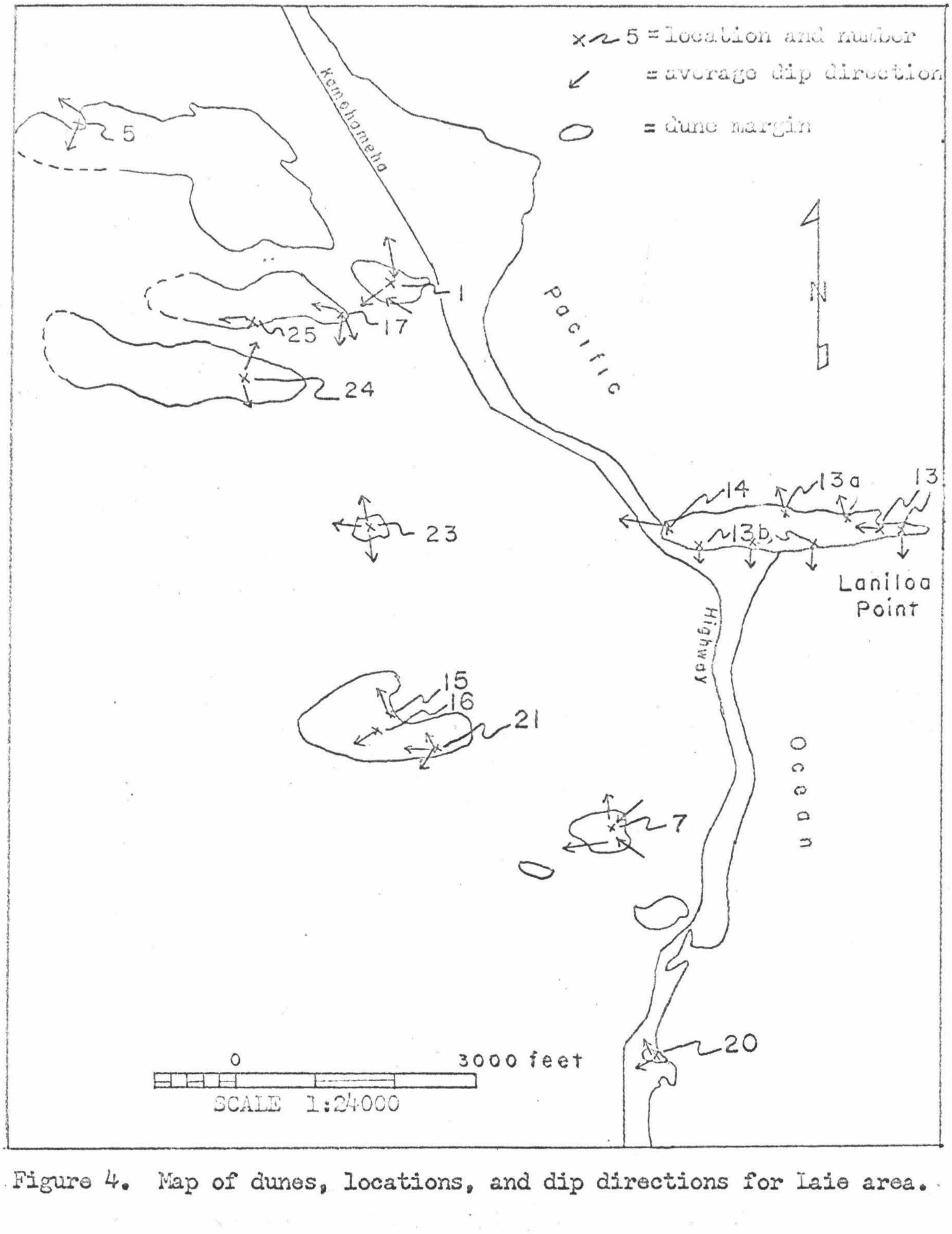


Figure 4. Map of dunes, locations, and dip directions for Laie area.

TABLE V. DATA SUMMARY FOR LAIE-KAHUKU AREA.

Location	Number of Readings	Range of Readings	Average dip Direction	Average dip Angle	Maximum Angle of dip
1	12	N50°W-N10°E	N14°W	29°	33°
	8	S24°E-S34°W	S05°E	26°	36°
	16	S28°W-S78°W	S48°W	28°	35°
	16	N21°W-N89°W	N63°W	31°	36°
2	22	S50°W-S84°W	S75°W	29°	33°
3	22	S75°W-N59°W	N90°W	26°	31°
4	20	S58°W-N65°W	N82°W	27°	30°
5	11	S18°W-S62°W	S41°W	25°	32°
	8	N50°W-N83°W	N70°W	30°	35°
6	29	S37°W-N76°W	S69°W	27°	37°
	10	N25°W-N19°E	N01°E	25°	36°
7	21	S80°W-N54°W	N73°W	31°	36°
	15	S30°W-S60°W	S44°W	30°	34°
	30	S35°W-N52°W	S84°W	31°	36°
	12	N04°W-N22°E	N08°E	27°	34°
8	71	S05°W-S70°W	S36°W	29°	35°
	7	N41°W-N15°W	N25°W	17°	21°
	5	N10°E-N15°W	N01°E	21°	31°
9	20	S74°W-N79°W	S83°W	25°	32°
10	4	N25°W-N58°W	N41°W	29°	31°
11	6	N10°W-N29°W	N20°W	27°	38°
12	25	N29°W-N82°W	N50°W	18°	26°
13	65	S25°E-S50°W	S05°W	30°	40°
	27	N06°W-N33°W	N21°W	28°	34°
	10	N65°W-S86°W	N81°W	13°	18°
17	4	S20°E-S40°E	S25°E	35°	37°
	9	S06°W-S20°W	S13°W	35°	40°
	6	N72°W-S87°W	N81°W	27°	29°
18	34	S01°W-S61°W	S33°W	32°	39°
	7	N00°W-N35°W	N23°W	31°	37°

TABLE V. (Continued) DATA SUMMARY FOR LAIE-KAHUKU AREA.

Location	Number of Readings	Range of Readings	Average dip Direction	Average dip Angle	Maximum Angle of dip
19	15	S15°E-S32°W	S10°W	28°	39°
20	8	S28°W-S40°W	S32°W	25°	29°
	8	N01°W-N65°W	N32°W	28°	34°
21	6	N05°W-N41°W	N21°W	26°	35°
	17	S78°W-N70°W	N87°W	30°	34°
	9	S60°W-S70°W	S64°W	29°	32°
22	10	S17°W-S33°W	S24°W	28°	29°
	10	N13°E-N24°W	N10°W	19°	28°
23	7	N06°W-N18°W	N09°W	30°	34°
	7	S04°E-S22°E	S10°E	24°	27°
	5	N58°W-N80°W	N73°W	30°	32°
24	9	N86°E-N50°W	N23°E	28°	32°
	7	S60°E-S15°W	S30°E	24°	34°
25	6	S76°W-S88°W	S81°W	31°	34°

The relationship of the cross-stratification and the elongate form of Laniloa Point parallel to the dominant wind direction strongly suggest that it is a remnant of a longitudinal sand dune.

At the extreme western end of the dune (location 14, fig. 4), strata dipping almost due west are exposed. Another set of strata with a similar orientation is exposed in the central interior portion of the dune at the eastern end. A nose or anticline-like structure associated with this unit at the eastern end of the dune is oriented with the crest of the structure parallel to the direction of elongation of the dune. It also plunges at a high angle, 26°, in the direction of elongation. Prevailing westerly dips of the strata and the anticline-like structure are interpreted as possible remnants of a slip face formed at the leeward end of the elongate dune as it was extended inland.

South of Laniloa Point, at location 20, fig. 4, similar structures are found. Although the elongate pattern is lacking, opposing dip directions occur. Also exhibited at this location is an anticline-like structure like the one at Laniloa Point, fig. 5. The average dip directions for this location are S 32° W on the south side and N 32° W on the north. The angle of separation of the two units does not approach 180° but the two sets diverge from the crest at 116°. The structure here is similar to that suggested by McBride (1962) as an asymmetrical pyramidal dune. An asymmetrical pyramidal dune is an evolutionary form between a transverse dune and a longitudinal dune. The trend of the anticline-like structure was determined as N 78° E.

At location 23 also, west of Laniloa Point, opposing cross-stratification is exposed. Here, at approximately 90-100 feet above sea

Figure 5. Photograph of anticline-like structure exposed in a lithified dune deposit at location 20.

level, about 15 feet of steeply inclined strata occur. At the crest of this exposure two major sets of strata dip away from each other and away from the crest. Average dip directions for these two units were calculated and resulted in N 09° W and S 10° E. Dip angles for the two sets averaged 30° and 24° respectively. Here, as at Laniloa Point, a third set of strata, dipping in a westerly direction, was found. As before, these strata may be representative of the advancing leeward end of the dune ridge.

Other interesting features seen on Laniloa Point, but better exhibited at location 23, are circular holes about 1-1½ feet in diameter and several feet deep, superimposed upon the main structure. These are molds of tree trunks which were covered by the dune as it was extended inland. Subsequent decay and removal of the material by rainwater has left only the mold of the former trunk. Another feature commonly seen in many exposures but especially well displayed at location 4, fig. 6, is contorted bedding. Similar features have been described in recent dunes by McKee (1966).

Other locations exhibit cross-stratification relationships similar to those described above. The average dip directions, dips, and ranges of readings for these locations are presented in Table V.

Several other deposits having elongate forms and resembling elongate dunes on aerial photographs are present in the area, but outcrops are insufficient for a complete structural analysis. Strata exposed in the available outcrops dip generally in a westerly direction, but sets of strata with average dip directions separated by angles approaching 180°, were not detected (See Table V). The writer believes that

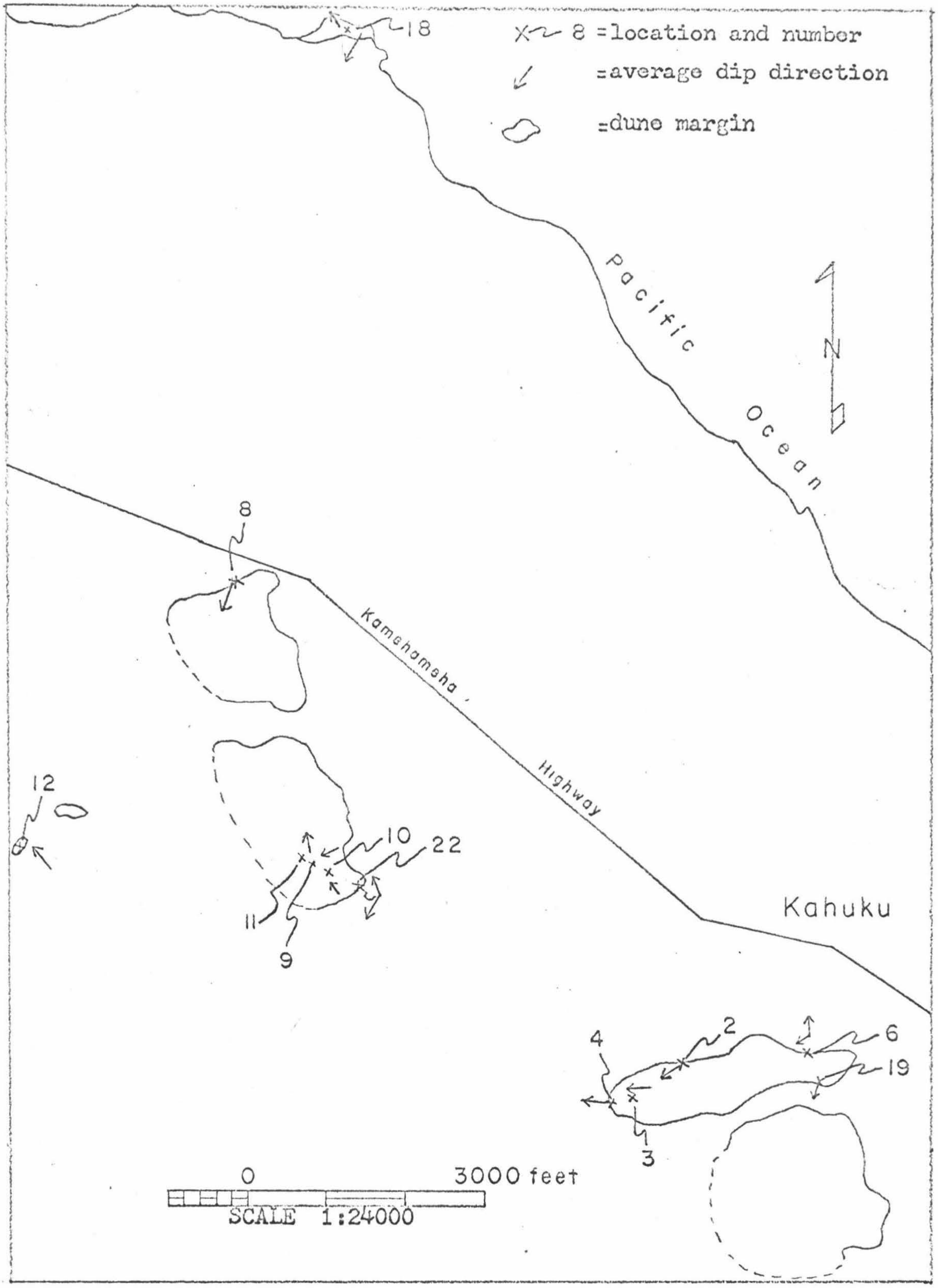


Figure 6. Map of dunes, locations, and dip directions for Kahuku area.

these dunes represent evolutionary stages of dune development from transverse to longitudinal forms, as proposed by McBride (1962). The inland extensions of most of these ridges begin to lose their identity and gradually merge with the slopes of the Koolau Range, so that the inland contact between the dunes and the range is difficult to determine. This made it necessary to estimate the positions of many of the inland contacts.

Approximately $1\frac{1}{2}$ miles along the highway, WNW of the town of Kahuku, at location 8 on the map, an exposure of long, consistent strata is displayed in a cliff face. The general trend of this cliff, as measured from a topographic map, is N 80° E, almost parallel to the prevailing wind. The strata are strikingly continuous, some extending an estimated 50 feet up the cliff face. Seventy-one measurements were taken in a distance of about 600 feet along the base of the cliff. The average dip direction calculated from these measurements was S 36° W. Two minor sets of cross-strata, less than thirty feet wide, were observed. These resemble scour and fill structures described by McKee (1966).

Measurements taken approximately 0.6 mile south of location 8, (localities 9, 10, 11) gave similar results. As seen from Table V, average dip directions of S 83° W, N 41° W, and N 20° W were obtained. These measurements were made at small outcrops exposed on the upper surface of the deposit. At location 22, in this same area, two major sets of strata with average dip directions of S 24° W and N 10° W flanked the base of the cliff. Although the angle of separation between the two units approaches 180°, the typical elongate form is lacking. West of these localities, at location 12, an average dip direction of N 50° W was measured (fig. 6).

The general elongation of the deposit perpendicular to the present prevailing wind, and the direction of dip semi-parallel to the prevailing wind, suggest that this deposit may be the remnant of a transverse-type dune. Such a dune may have migrated inland as a transverse ridge across the flat coastal plain in this area, or could have assumed several small parabolic or barchanoid forms in transition. An alternate explanation is that this deposit is the remnant of a depositional ridge caused by the loss of competency of the wind to transport sand. The prevailing wind would thus sweep sand along corridors between longitudinal dune ridges, irregularities in vegetation, or topographic lows, and deposit the sand at the inland margin of the coastal plain. This loss of transporting ability could be due to a combination of the effects of vegetation, topography, and increased rainfall at the base of the Koolau Range.

The two units measured at locality 22 indicate the possibility that this is a remnant of an asymmetrical pyramidal dune form covered later by the depositional ridge.

South of the Church College of Hawaii, location 7, a complex dune structure is exposed (fig. 4). Four fairly large and consistent sets of cross-strata are observable. Although the internal structure is clearly exposed, the orientation of the cross-stratification makes interpretation difficult. A summary of the data is presented in Table V.

A cliff perpendicular to the prevailing wind, oriented north-south, approximately 300 feet long and estimated to be 50 feet high, revealed two sets of long, continuous strata (fig. 7). Most of the strata extend from the base of the cliff to the top. The southern 200 feet is composed of stratification with an average dip direction of N 73° W. The northern 100 feet consists of strata dipping S 44° W. An exposure approximately parallel to the prevailing wind, along the southern portion of the deposit, displays strata dipping S 84° W. Another set exposed on the upper surface of the hill, and also composing the upper 10 feet of a cliff along the north side of the deposit, has an average dip direction of N 08° E. This upper unit has a lower margin which is concave upward and is approximately 30 feet wide. This is clearly a scour and fill feature resulting from a later cross-wind from the south. The relationship of the other units, with dips toward each other, is suggestive of attitudes which might be attained on the slip face of a barchanoid form; or perhaps this is a remnant of an area which experienced converging dune slip faces from separately migrating dunes.

Kahana Bay Area

Approximately 1000 feet due south of Mahie Point, fig. 8, at an elevation of about 330 feet, another sand body is exposed. The deposit is nearly 120 feet long, 40-50 feet wide and about 30 feet high. It is situated in a saddle of a north-south trending ridge. Directly to the south, the ridge extends up into the Koolau Range. Just north of the deposit is a knob, which is at the end of the ridge, and extends about 70 feet above the saddle area. The east and west margins of the ridge

Figure 7. Photograph of long continuous strata of a lithified dune exposed at location 7.

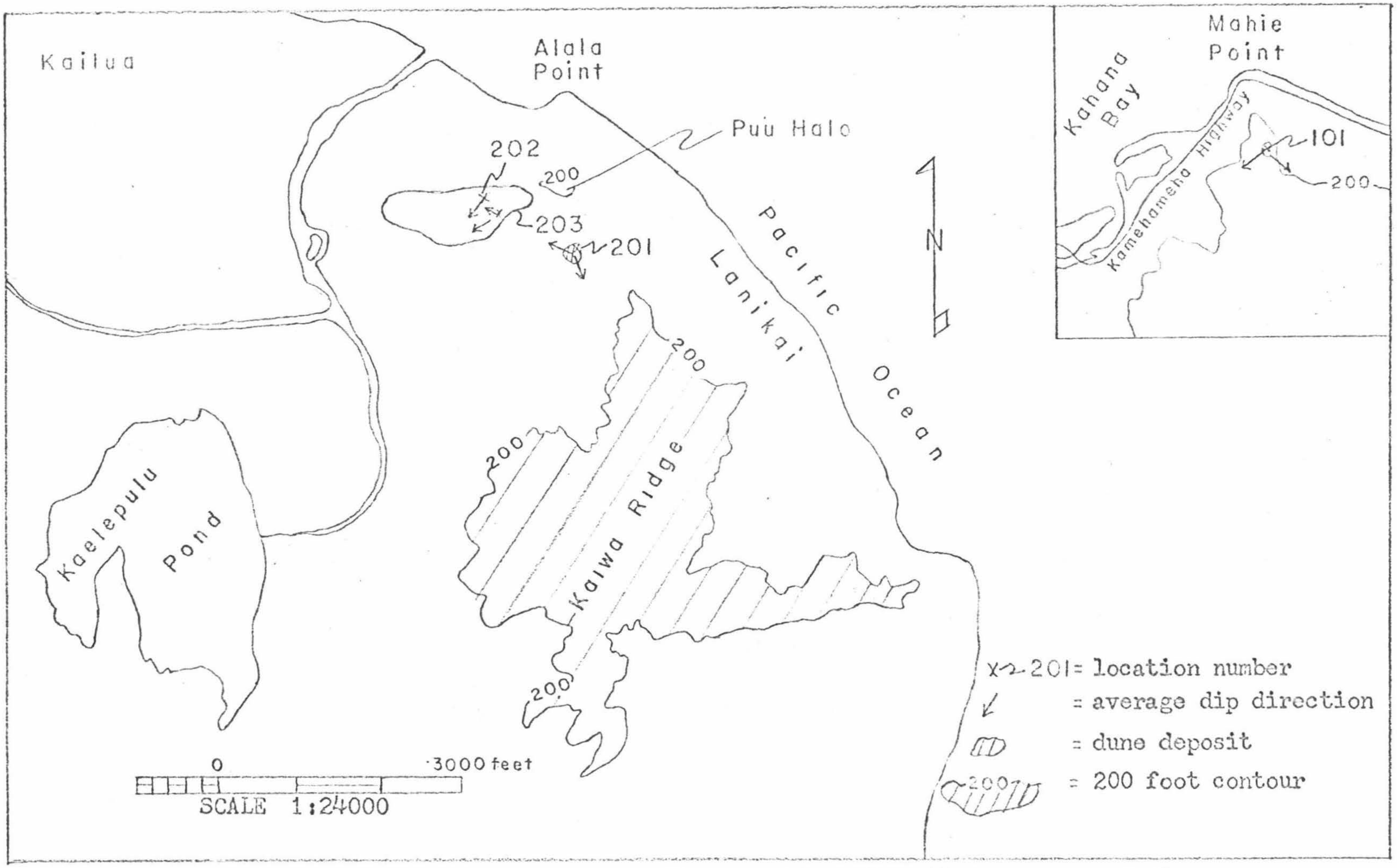


Figure 8. Map of dunes, locations, and average dip directions for Kahana Bay and Kailua areas. Orientation and scale apply for both areas.

are steep cliffs, the eastern being almost vertical and the western margin being more gently inclined, approximately 50° (fig. 9).

The sand particles which comprise the deposit are calcareous fragments of shell and reef material and occasional tests of foraminifera. Foraminifera comprise approximately 7% of the rock by volume.

Two major sets of stratification are observed in this deposit. In the central portion of the sand body these two sets, each from 3 to 5 feet thick, are in an alternating sequence. These sets generally dip away from the crest of the deposit and away from each other. Calculations of average dip directions for each set resulted in azimuths of S 56° W and S 53° E, with average inclinations of 22° and 29°, respectively (Table VI).

The character of the cross-stratification is suggestive of that seen in the elongate or pyramidal dunes of the Kahuku-Laie area. It is possible that this is a remnant of one of these dune forms. However, another possibility is that this is a remnant of a sand shadow deposit which accumulated to the lee of the knob directly north of the saddle.

The location of the source of the sand comprising this dune presents an interesting problem. Certainly the source was a beach or exposed reef area. The source could have been at a high elevation due to a higher stand of sea level. Another possibility is that Kahana Valley once extended further north or seaward and the valley floor in the area of the deposit was at a higher elevation. The valley would then serve as a channel for sand to be blown inland and deposited at a higher elevation.

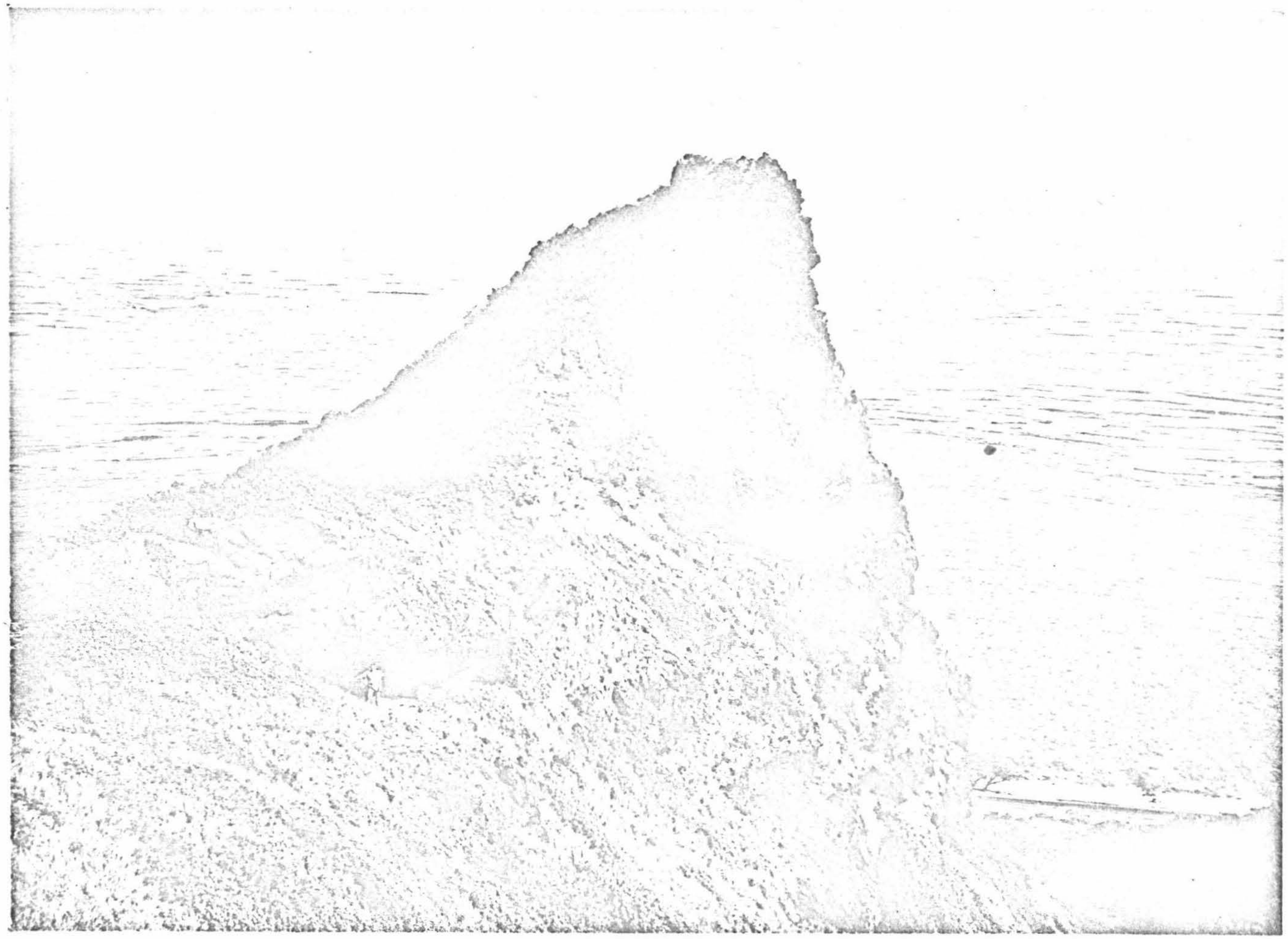


Figure 9. Photograph of lithified dune deposit located 330 feet above Kahana Bay.

TABLE VI. DATA SUMMARY FOR KAHANA BAY, KAILUA, WAIMANALO-BELLOWS, AND KAHALA AREAS.

Location	Number of Readings	Range of Readings	Average dip Direction	Average dip Angle	Maximum Angle of dip
101	14	S30°E-S85°E	S53°E	29°	34°
	5	S30°W-S78°W	S56°W	21°	26°
201	8	N49°W-N87°W	N66°W	28°	34°
	3	S18°E-S22°E	S20°E	30°	34°
202	5	S46°W-S63°W	S50°W	32°	34°
	5	N35°W-N74°W	N61°W	17°	22°
	3	S57°W-S72°W	S63°W	31°	33°
301	11	S30°W-S79°W	S61°W	31°	34°
	26	S10°E-N25°W	S82°W	31°	41°
	9	S35°E-N64°W	S16°W	29°	35°
	6	S78°E-S90°W	S04°W	31°	35°
302	6	S27°W-N49°W	S87°W	27°	34°
303	5	N64°W-S86°W	N78°W	25°	30°
	8	S00°W-S59°W	S23°W	25°	31°
	5	N50°W-N73°W	N63°W	32°	40°
304	9	S60°W-S90°W	S72°W	31°	33°
	9	N25°W-N67°W	N46°W	29°	33°
	6	S03°E-S23°E	S09°E	32°	36°
601	10	S09°W-S40°E	S13°E	32°	34°
	10	N03°E-N34°W	N16°W	28°	35°
602	3	N65°W-N59°W	N62°W	29°	32°
603	5	N25°W-N65°W	N53°W	29°	32°

A third explanation presumes a fault in the area of Kahana Bay. In this case the eastern margin of Kahana Bay would represent the upthrown block removed from the original stand of the sea. A geomorphic support for this hypothesis lies in the fact that the Kahuku Plain is well developed on the coast until it reaches the northwest margin of Kahana Bay. Across the bay on the southeast margin practically no coastal plain exists.

A fourth alternate explanation is the possibility that at the time of formation of the dune, the lava flows from the Koolau Range extended further seaward. Sand from the beach and reef area was then driven up the slopes of the flows by the wind and accumulated at the present day 330 foot level.

Kailua Area

Approximately 1800 feet south of Alala Point (location 201, fig. 8) is a small exposure of consolidated calcareous sand. The deposit is situated on the southwest edge of a gap formed between Puu Halo and Kaiwa Ridge. The sand body is about 200 feet long and 200 feet wide, although its boundaries are indistinct.

Directly below the clubhouse facilities of the Mid Pacific Country Club two sets of strata are exposed. Measurements of the major unit resulted in an average dip direction of N 66° W inclined at 28°. The minor set have an average dip direction of S 20° E at 30° (Table VI).

The relationship between these two sets of strata may be interpreted as a result of the effect of the topography on the prevailing winds. Deflections of the wind current as it passed through the gap would account for the wide angle of separation between the two units. Another obvious possibility is that this is a remnant of a longitudinal dune similar to those occurring in the Kahuku-Laie area.

Almost directly west of Puu Halo and extending some 1800 feet from its slopes, another sand dune deposit is present. The dune is about 600 feet across at its widest point and extends nearly 160 feet above sea level. The sand consists of fragments from shells and reef material. Foraminifera are present, but not abundant, comprising only 4% of total volume.

Measurements at locations 202 and 203 indicate that possibly 2 or 3 units of stratification exist. Because the readings have a small spread it is difficult to determine if each is a distinct set or if there is a transition from one to the other. Average dip directions for the two most diverging sets are only about 70° apart, with possibly a third set present which is intermediate between the two, Table VI. In general, these units all dip in a westerly direction.

Although the deposit is elongate generally east-west, no strata dipping north or south were observed. The absence of north and south dipping strata and the lack of a separation angle approaching 180° suggests that this dune is not a remnant of an elongate dune. Its position directly to the leeward of Puu Halo presents the possibility that this may be a dune form resembling a sand shadow.

Waimanalo-Bellows AFB Area

Southwest of Waimanalo Beach is a large elongated dune deposit. The trend of elongation is about N 45° W, nearly parallel to the present beach. The dune is well exposed around much of its margin. The deposit is almost 0.7 of a mile long, about 1200 feet wide at its widest point, with a maximum elevation of 162 feet (fig. 10).

Measurements were taken both perpendicular and parallel to the elongation of the dune. Average dip directions obtained are plotted on fig. 10 for four different areas of the dune. The data for these areas are summarized in Table VI. In general, the strata dip to the southwest approximately parallel to the prevailing winds and the dune is primarily elongate perpendicular to the wind direction. The structure and direction of elongation of the dune strongly suggest that this deposit is a remnant of a transverse dune form.

A similar feature is found on Bellows Air Force Base (location 303, fig. 10). As at Waimanalo, the deposit is approximately perpendicular to the prevailing wind direction. Two sets of stratification are revealed at this location. These are plotted on fig. 10. Generally, they are inclined in a westerly direction. Here, as at Waimanalo, this possibly represents a remnant of a transverse type dune.

East of the town of Waimanalo (location 304, fig. 10), is another dune. Unlike the other dunes in this area, it is elongate parallel to the prevailing wind. Average dip directions for this dune are summarized in Table VI and plotted in fig. 10. The structure and elongation of this dune are strikingly similar to that seen at Laniloa Point in the Kahuku-Laie area. The obvious conclusion is that this dune represents a remnant of a longitudinal dune.

A difficulty on Bellows Field which hampered complete structural analysis of some of the dunes was military construction. Many of the

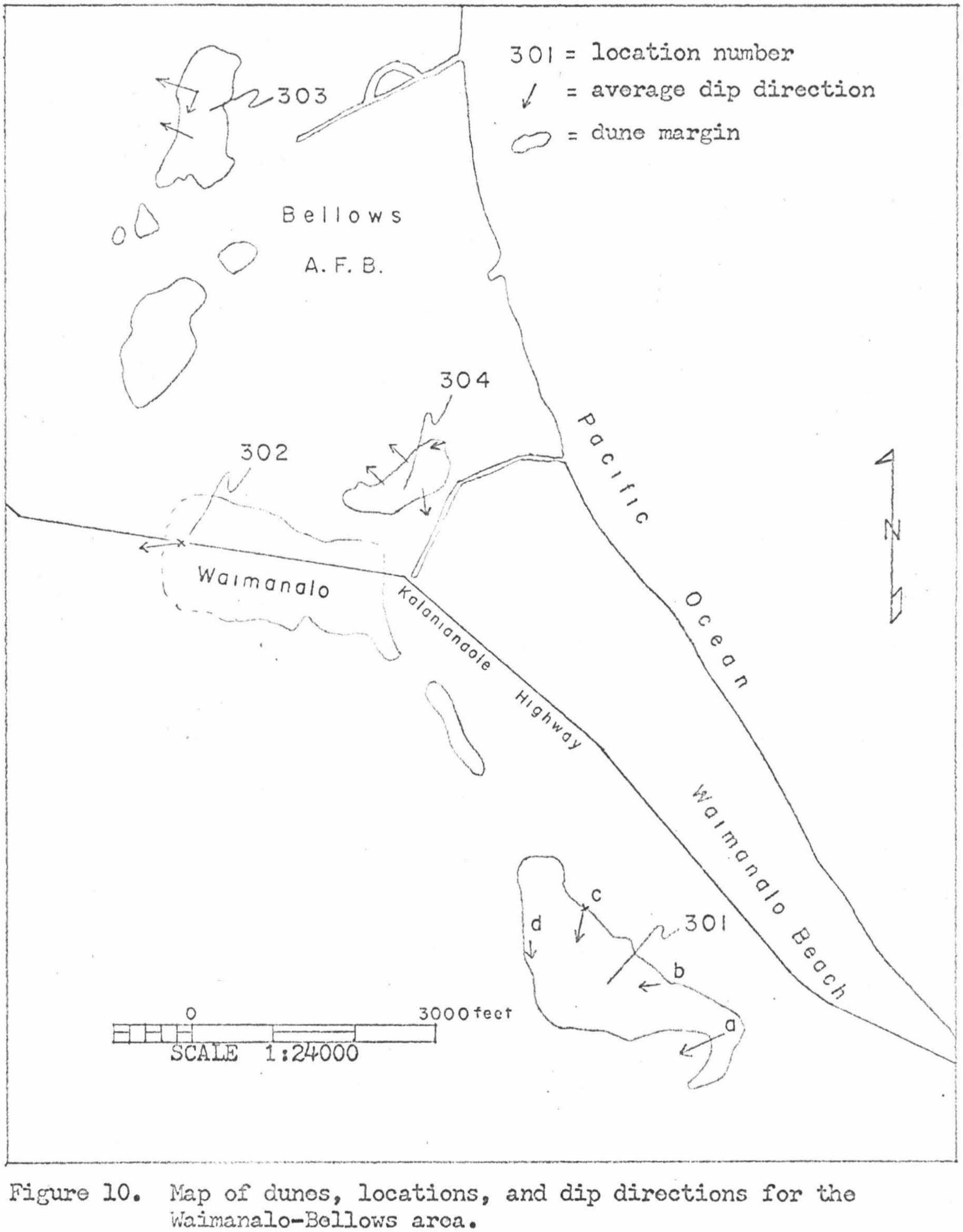


Figure 10. Map of dunes, locations, and dip directions for the Waimanalo-Bellows area.

dunes had been excavated for airplane hangers and the walls of the hangers had been cemented. This completely obscured any structure previously exposed in the excavations. In some cases, most of the dune was covered and analysis of the structure was impossible.

In the town of Waimanalo (location 302, fig. 10), an average dip direction of S 87° W was obtained. This figure is based on only a few measurements taken on a very small outcrop (Table VI). No other outcrops were found on this dune, so interpretation of the dune form will not be attempted. The only statement possible is that the dip azimuth obtained at location 302 is in general agreement with measurements made on transverse dunes in the area.

Kahala Area

North of Kupikipikio Point, or Black Point, on the south shore of Oahu (fig. 11), is a dune which extends from the base of Diamond Head eastward approximately 0.7 of a mile. The margins of the dune are difficult to locate in many sections because of the recent residential development in the area. For this reason some of the margins of the dune had to be estimated and are dotted on fig. 11.

Here the general form of the dune appears to be elongate approximately parallel to the prevailing wind direction. Measurements of the dip directions of the bedding planes were difficult to obtain, as flower beds, gardens, vines, and rock walls obscure many outcrops. The average dip directions for the measurements taken are summarized in Table VI and plotted on fig. 11.

The relationship of the two sets of strata at location 601 suggests, as it did at Laniloa Point in the Kahuku-Laie area, that this dune might

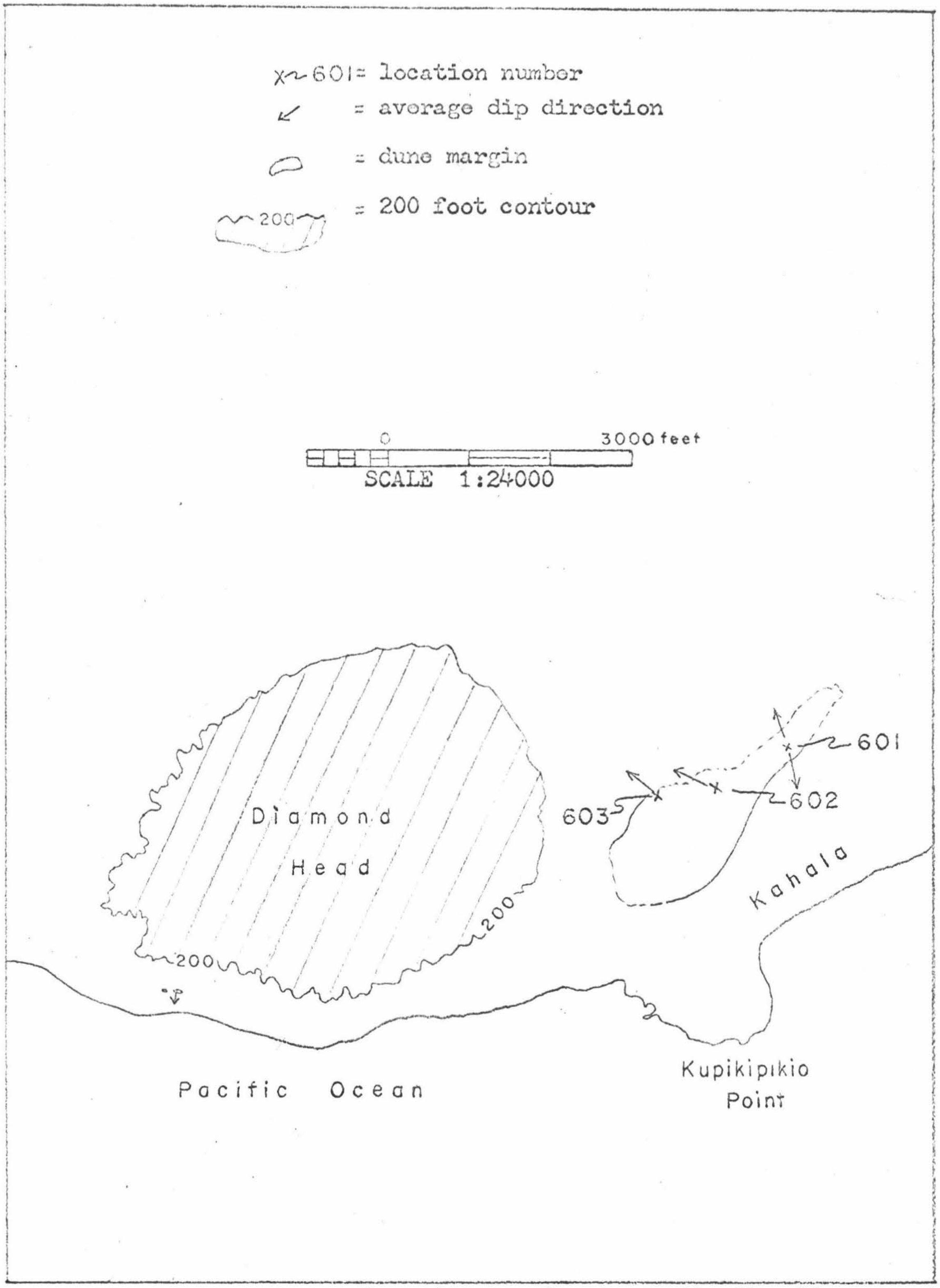


Figure 11. Map of dunes, locations, and average dip directions for the Kahala area.

represent a remnant of a longitudinal dune. The elongation of the dune generally parallel to the prevailing wind also supports this conclusion. The dip directions at localities 602 and 603 are possibly continuations of the northwesterly dipping set seen at location 601.

Along the southwest flank of Diamond Head at an elevation of approximately 50 feet to 80 feet is an outcrop of calcareous wind-blown sand. The strata dip generally in a southwest direction approximately parallel to the slopes of Diamond Head. Fragments of tuff from Diamond Head, as large as 10 cm in diameter are incorporated in this aeolian sand. The sand is resting on the tuff beds of Diamond Head and is overlain by talus breccia from the tuff deposits of the upper slopes.

The sand was probably originally transported up the flanks by southerly winds to form a sand drift deposit. Tuff debris from the upper slopes then moved downward and was deposited on the upper surface of the sand deposit. The calcareous sand and its included tuff debris was then partially covered by later debris from the upper portion of Diamond Head.

EVOLUTION OF DUNE FORMS

It has generally been agreed by those who have studied longitudinal dunes that cross winds are essential for the development of the longitudinal form (Bagnold, 1941, Madigan, 1946, McKee and Tibbitts, 1964). The angle between the cross winds determines the rate of extension and the massiveness of the ridge. If the angle is wide the dune ridge tends to be massive and built upward more rapidly than it is extended. The narrower the angle, the more effective the wind will be in extending the ridge forward at the expense of the bulk of the dune. Finally, as the angle becomes smaller and smaller and the wind approaches unidirection, the lateral winds become too weak to effectively concentrate sand along the ridges. This leads to the development of a transverse dune form.

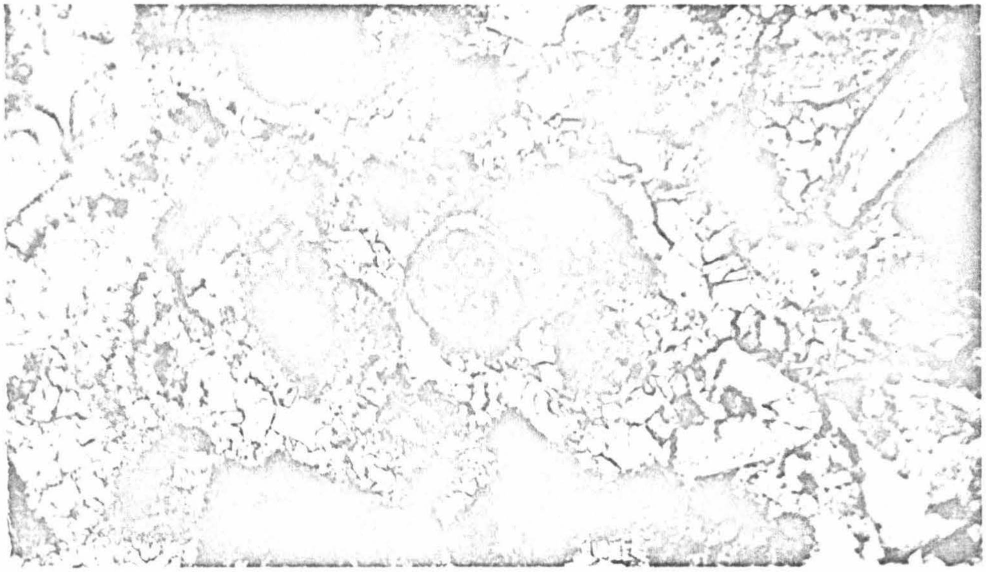
McBride (1962) has suggested that longitudinal dunes are end products of an evolutionary sequence beginning with a transverse ridge. Probably the beginning of the formation of a longitudinal dune is governed by more than cross winds alone. A sequence of events similar to those suggested by McBride seem justified on Oahu.

Sand derived from existing beaches and newly exposed reef areas was blown inland by the wind. This sand would move forward and acquire a transverse-ridge form if there were nothing to hinder its advance. But the ridge probably encountered obstacles such as vegetation and topography which would create modifications in the dune pattern.

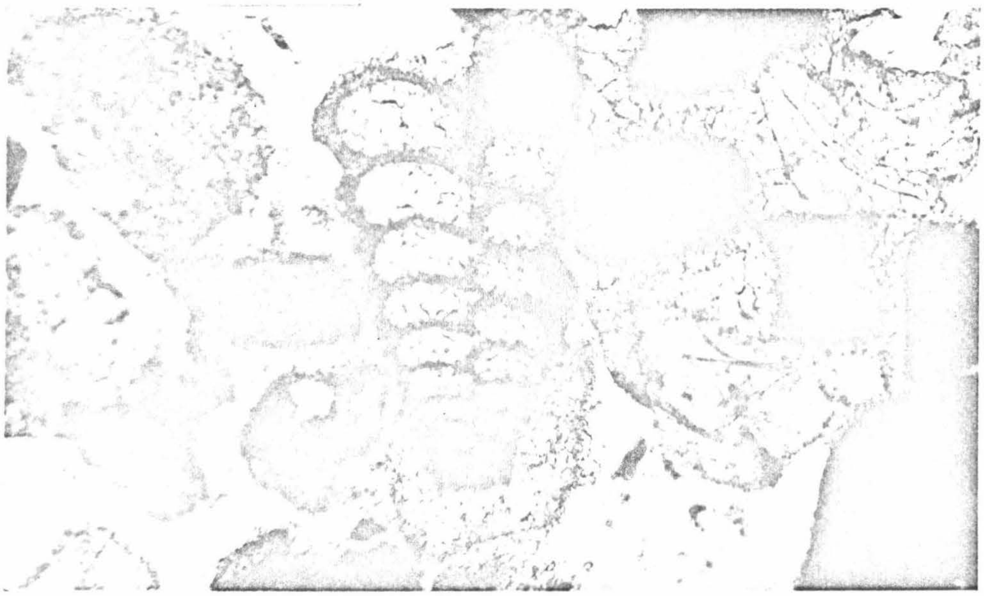
If vegetation in the form of trees were encountered, a depositional ridge, parallel to the seaward limit of the wooded area, would form. Deposition would not be uniform along the depositional ridge. Sand would accumulate in excess in different locations along the ridge because of irregularities in the wooded area. More rapid advance would be favored in portions where the ridge was low. The mound of lag sand would slowly be converted from a formless mound into an elongate ridge with its flanks open to the oblique impact of shifting winds.

Winds from the northeast would cause the mound of sand to develop a slip face to the southwest. Shifts in the wind to a southeasterly direction would favor the development of a slip face on the northwest facing side of the mound. The prevailing east-northeasterly trades extend the ridge inland while the cross winds concentrate sand along the ridge. At the extreme inland portion of the ridge a slip face would be formed approximately perpendicular to the prevailing wind direction due to oversteepening of the slope by the cross winds.

PLATE III



Photomicrograph of Soritidae X85.



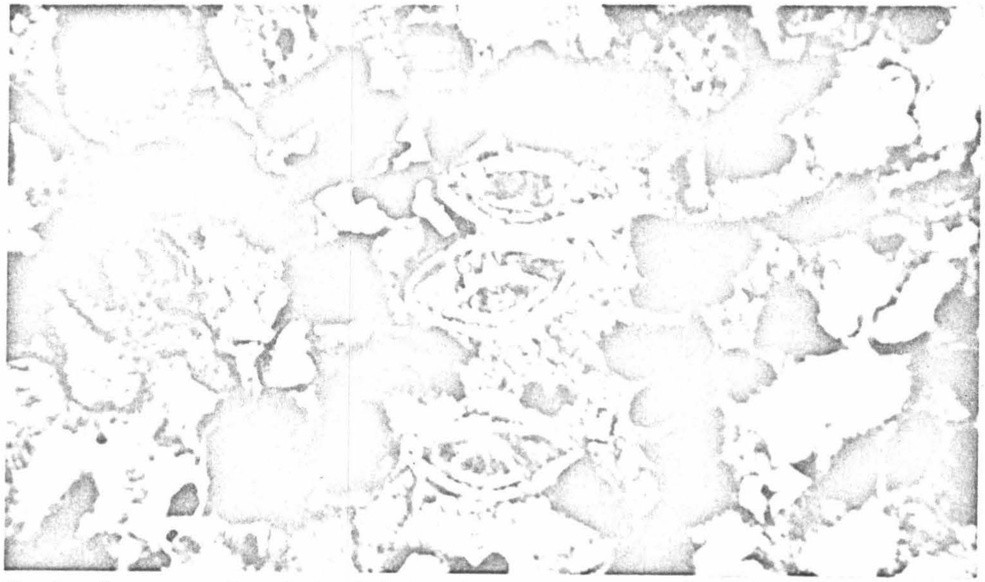
Photomicrograph of Textularia X80.

PLATE II

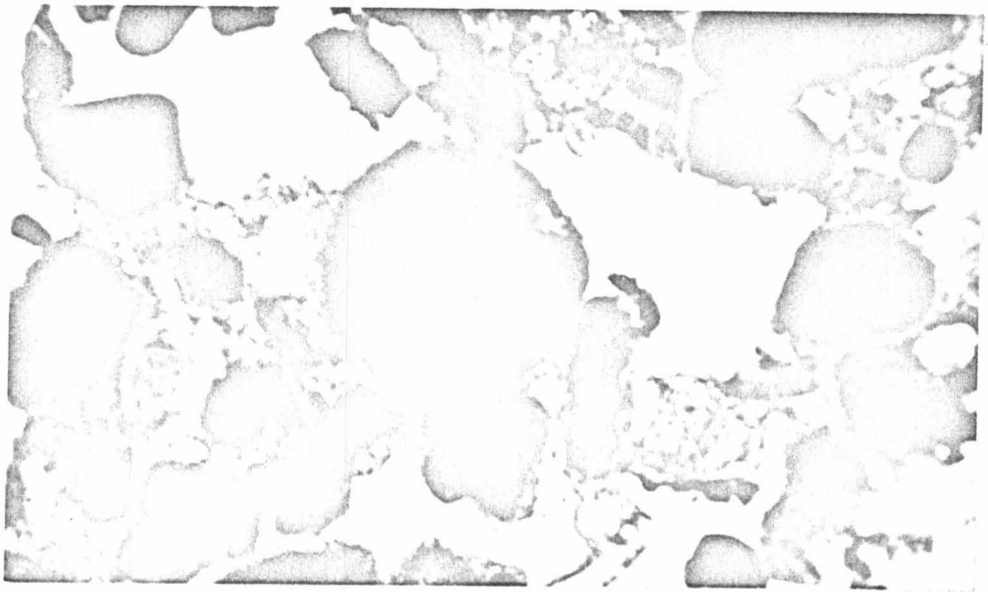
Photomicrograph of Miliolidae X75.

Photomicrograph of Cibicides lobatulus (Walker and Jacob) X100.

PLATE I



Photomicrograph of <u>Amphistegina</u> <u>madagascariensis</u> d'Orbigny X35.



Photomicrograph of <u>Marginopora</u> <u>vertebralis</u> Blainville X60. Imperforate foraminifer appear brownish in thin section.

Mattox, R. B., 1955, Eolian shape sorting: Jour. Sed. Pet., v. 25, p. 111-114

McBride, E. F., and Hayes, M. O., 1962, Dune cross-bedding on Mustang Island, Texas: Am. Assoc. Petroleum Geol. Bull., v. 46, p. 546-551

McCammon, R. B., 1962a, Efficiencies of percentile measures for describing the mean size and sorting of sedimentary particles: Jour. Geol., v. 70, p. 453-465

McKee, E. D., and Weir, G. W., 1953, Terminology for stratification and cross-stratification in sedimentary rocks: Geol. Soc. America Bull., v. 64, p. 381-399

McKee, E. D., 1957, Primary structures in some recent sediments: Am. Assoc. Petroleum Geol. Bull., v. 41, no. 8, p. 1704-1747

McKee, E. D., and Tibbitts, G. C., Jr., 1964, Primary structures of a seif dune and associated deposits in Libya: Jour. Sed. Pet., v. 34, no. 1, p. 5-17

McKee, E. D., 1966, Structures of dunes at White Sands National Monument, New Mexico (and a comparison with structures of dunes from other selected areas): Sedimentology, v. 7, no. 1, p. 1-69

Rosenfeld, M. A., Jacobson, L., and Ferm, J. C., 1953, A comparison of sieve and thin-section technique for size analysis: Jour. Geol., v. 61, p. 114-132

Shepard, F. P., and Young, R., 1961, Distinguishing between beach and dune sands: Jour. Sed. Pet., v. 31, no. 2, p. 196-214

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

Stearns, H. T., 1966, Geology of the State of Hawaii: Pacific Books, Palo Alto, California

Udden, J. A., 1914, Mechanical composition of clastic sediments: Geol. Soc. Am. Bull., v. 25, p. 655-744

Waskom, J. D., 1958, Roundness as an indicator of environment along the coast of Panhandle Florida: Jour. Sed. Pet., v. 28, no. 3, p. 351-360

Wentworth, C. K., 1922, A scale for grade and class terms for clastic sediments: Jour. Geol., v. 30, p. 377-392

REFERENCES CITED

Alder, H. L., and Roessler, E. B., 1962, Introduction to probability and statistics: W. H. Freeman and Co., San Francisco

Bagnold, R. A., 1933, A further journey through the Libyan desert, Jour. Geol., v. 82, p. 103-129

_____________, 1941, The physics of blown sand and desert dunes: Methuen & Co., Ltd., London, reprint Dover Company

Beal, M. A., and Shepard, F. P., 1956, A use of roundness to determine depositional environments: Jour. Sed. Pet., v. 26, p. 49-60

Folk, R. L., and Ward, W. C., 1957, Brazos River Bar: a study in the significance of grain-size parameters: Jour. Sed. Pet., v. 27, p. 3-26

Folk, R. L., 1966, A review of grain-size parameters: Sedimentology, v. 6, p. 73-93

Friedman, G. M., 1958, Determination of sieve-size distribution from thin-section data for sedimentary petrological studies: Jour. Geol., v. 66, p. 394-416

_____________, 1961, Distinction between dune, beach, and river sands from their textural characteristics: Jour. Sed. Pet., v. 31, no. 4, p. 514-529

_____________, 1962, Comparison of moment measures for sieving and thin-section data in sedimentary petrological studies: Jour. Sed. Pet., v. 32, p. 15-25

Hack, J. T., 1941, Dunes of the western Navajo country: Geog. Rev., v. 31, p. 240-263

Keller, W. D., 1945, Size distribution of sand in some dunes, beaches, and sandstones: American Assoc. Petroleum Geol. Bull., v. 29, p. 215-221

MacCarthy, G. R., 1935, Eolian sands, a comparison: Am. Jour. Sci., v. 30, no. 176, p. 81-95

Madigan, C. T., 1946, The sand formations, in the Simpson desert expedition, 1939: Scientific Reports, no. 6, Geology, Royal Soc. South Australia Trans., v. 70, p. 45-63

Mason, C. C., and Folk, R. L., 1958, Differentiation of beach, dune, and aeolian flat environments by size analysis, Mustang Island, Texas: Jour. Sed. Pet., v. 28, no. 2, p. 211-226

SUMMARY

The evidence presented suggests that the dune deposits on the coastal plains of Oahu represent portions of sequences from transverse ridges to longitudinal dunes. An additional type seen on Oahu is the pyramidal form. In some instances they develop at the extreme leeward edge of the coastal plain as a result of the complex wind conditions and loss of transporting ability due to vegetation, change of slope and increased rainfall at the contact with the Koolau Range. In other areas they occur just inland from the beach and may represent depositional ridges formed at the seaward margin of a previously vegetated area.

It has also been shown that 2 mm is a convenient grain diameter for distinguishing beachrock from lithified dunes in the field.