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AGES OF DUNES ON OAHU, HAWAII[1]

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FIGURE 1.—Slab of Leahi II beach rock resting on ancient clay and emerged reef at edge of Kahuku runway, Kahuku, Oahu, February 22, 1968.

* Volume XXIV of the Occasional Papers is published in honor of Edwin H. Bryan, Jr., whose service to Bishop Museum began in 1919. He was for many years Curator of Collections, and at present is Manager of the Museum's Pacific Scientific Information Center. Many of the papers in this volume were read at a Symposium, held at the Museum on April 13, 1968, honoring Mr. Bryan on the occasion of his 70th birthday.

[1] The writer greatly appreciates the critical reading of the manuscript by Daniel Lum.

THE DUNES OF OAHU are separated into five different ages ranging from Holocene to Illinoian. A 2-foot stand, named herein Leahi I, a low stand named the Kawela, and a later stand at present sea level named the Leahi II, of Wisconsinan age, have not been recognized before. The Wisconsinan lithified dunes are herein named the Laniloa Formation, to distinguish them from the Illinoian eolianites of the Bellows Field Formation.

DUNE AGES

Five ages of dunes exist on Oahu. All consist of calcareous grains of sand, 0.50 to 2.00 mm. in diameter, blown inland from beaches and exposed reef flats. The sand consists of well-rounded grains of comminuted shells, coral, and skeletons of other marine organisms, including numerous foraminifers. The older dunes are partly or completely lithified into eolianite. The dunes are described below in order of increasing ages.

1. The youngest dunes are unconsolidated and occur chiefly along the shore. All accumulated during the Holocene. The highest dunes are on Mokapu Peninsula, where they reach a height of 93 feet. Elsewhere they seldom rise more than 20 feet above sea level (Stearns and Vaksvik, 1935, p. 56).

2. The next oldest dunes are those along the windward coast between Laie and Kahuku Point (Fig. 2). They accumulated chiefly during Regression V (Fig. 3) of the sea caused by the growth of the polar ice caps during one of the late stadials of the Wisconsinan. They are named the Laniloa Formation herein.

3. The third oldest are the lithified dunes formed at the time of the Leahi I stand of the sea. They make up the dune deposits of the Leahi I Formation and crop out chiefly on the south side of Diamond Head. They are weakly cemented compared with the older lithified dunes. The 2-foot stand, Leahi I, marks a halt in the fall of the sea near the beginning of Regression IV (Fig. 3). Some of the sand in the dunes probably blew inland also during the rest of Regression IV.

4. The fourth oldest are the small dunes capping ancient beach deposits near Waialua Mill and in Hahaione Valley (Stearns, 1935a, p. 1478). This sand accumulated during the 25-foot stand of the sea correlative with the last, or Sangamon, interglacial epoch. The dunes in Hahaione Valley were destroyed in 1967 to make house lots.

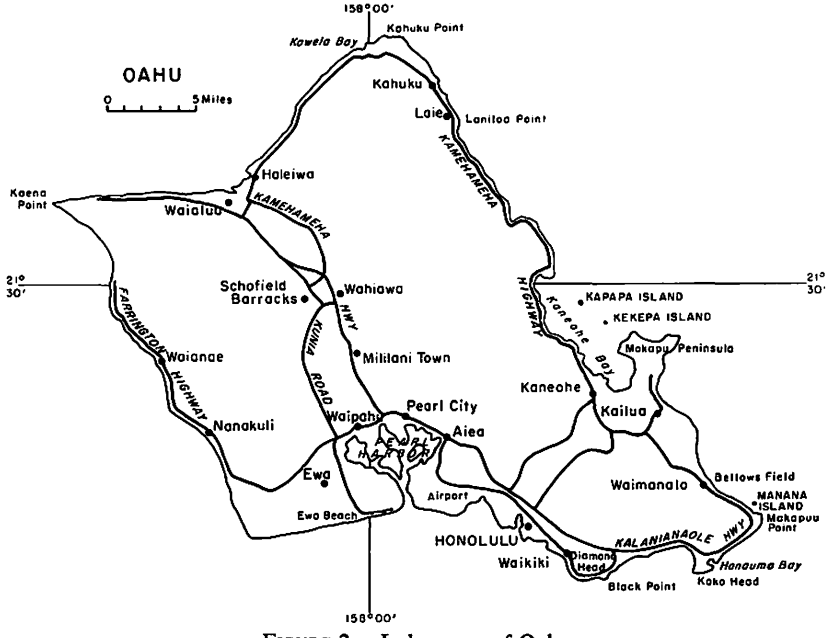

FIGURE 2.—Index map of Oahu.

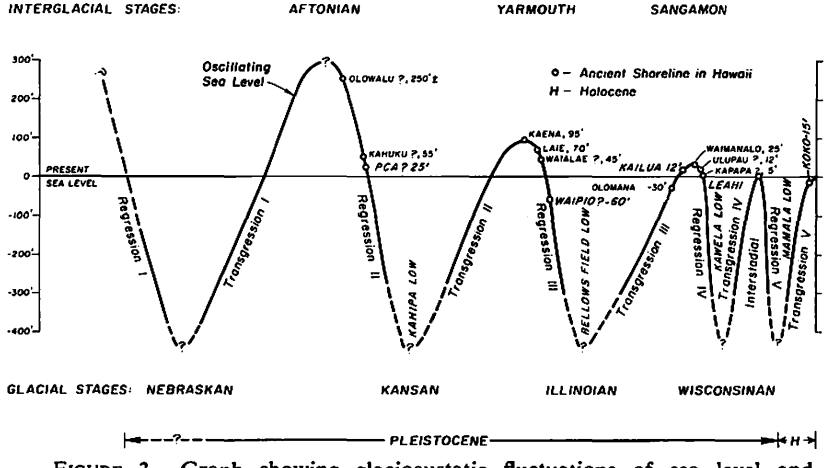

FIGURE 3.—Graph showing glacioeustatic fluctuations of sea level and Pleistocene Hawaiian shore lines. Question marks after shore-line names indicate that the order in time sequence is uncertain. The Penguin Bank —180±-foot shore line is omitted because of its uncertain age. Leahi I stand is just below the Kapapa stand and the Leahi II is at the top of Transgression IV. (After Lum and Stearns, in press.)

5. The oldest are the very extensive dunes (Bellows Field Formation), mostly hard rock, which accumulated during the Illinoian glacial epoch (Regression III). These dunes have a volume greater than all the dunes of later age added together. Their volume seems to indicate stronger winds and/or a more abundant supply of sand at the time of deposition.

RELATION OF DUNES TO GLACIAL EUSTASY

Where are the sand dunes of the two still older glacial epochs? As times of low sea level were generally times of dune formation, the absence of older dunes correlative with older glacial epochs requires explanation. Possibly the winds did not blow hard enough to pile up dunes, or those formed in earlier periods may have been submerged or eroded away. Possibly a source of sand did not exist. Erosion may have been effective, as indicated by an outcrop of lithified dune on a saddle at the top of a basalt cliff 330 feet above sea level about 1,000 feet south of Mahie Point at Kahana Bay (Pottratz, 1968). The dune was probably formed during an early high stand of the sea and has been disconnected by erosion from its source beach. Two other dunes, which also have been disconnected from their source beaches, crop out on the ridge at a high elevation just south of the Makapuu Lighthouse (see "Geologic Map of Oahu," Stearns, 1939).

All Pleistocene dunes except those at Diamond Head lie along the same coasts where modern dunes have formed, indicating that they were formed by trade winds blowing during the glacial epochs from a northeasterly direction, as prevailing winds do now. Unlike dunes in Bermuda (Land, Mackenzie, and Gould, 1967) and in Australia (Fairbridge and Teichert, 1953), where they accumulated chiefly during high stands of the sea, most Hawaiian dunes accumulated during low stands.

The writer mapped all dunes on the "Geologic Map of Oahu." He recognized different degrees of cementation (1940) but differentiated only the consolidated from the unconsolidated on the map. The consolidated dunes were assumed to be chiefly sand blown inland from the ocean floor as the reefs were bared by Regression III (Fig. 3). They were assigned to the minus 60±-foot Waipio stand of the sea on the basis that some of the dunes, now islands in Kaneohe Bay, rose from a submarine platform at this depth.

Recent core borings at Waimanalo by the Hawaii State Department of Land and Natural Resources have shown that the lithified dunes there extend as much as 160 feet below sea level (Lum and Stearns, in press). Thus the sea must have been lower than 60 feet when some of these dunes were formed. Because the type locality of the 25-foot stand of the sea of Sangamon interglacial age was determined from notches made in the lithified dunes at Waimanalo, no doubt remains that those dunes accumulated prior to the 25-foot stand. Regression III, when the dunes accumulated, following the 95-foot stand and prior to the 25-foot stand, is correlated with the Illinoian glacial epoch. The depth to which the sea receded on Oahu during the Illinoian is not known exactly, but it probably fell to the minus 300- to 350-foot Kahipa-Mamala shelf off Pearl Harbor (Stearns, 1966a, p. 23). Good agreement exists among scientists today that the ice stored on the poles during each of the four major glacial epochs caused sea level to fall a minimum of 300 feet and probably as much as 450 feet.

Estimates range from 600,000 to 3,000,000 years for the duration of the Quaternary. The polar ice caps contain enough water, if melted, to raise the world's oceans about 200 feet. The graph (Fig. 3) shows the names and altitudes of the Pleistocene Hawaiian shore lines so far recognized and their time sequence. Doubtless many more existed in the past and it is known from submarine dives that several more exist below sea level (Brock and Chamberlain, 1968). The name "Bellows Field Low" is here given to the Illinoian Low (Regression III), recognized but not named before. It is named from Bellows airfield near Waimanalo where the Bellows Field Formation was traced 160 feet below sea level by core drilling (Lum and Stearns, in press). It is probable that the sea dropped 350 to 450 feet below the present during the Bellows Field Low.

The Kailua 12-foot stand is recognizable at Kailua, where it cut a bench and sea caves in Illinoian dunes prior to the Waimanalo 25-foot stand. The features of this Pleistocene shore line have been described by the writer (1935b, p. 1945), but this is the first time it has been named. The Penguin Bank stand at −180 feet has been omitted from the graph (Fig. 3), because its position in time is uncertain. It is too extensive to have been made during a Wisconsinan halt. A list of Hawaiian shore lines is given elsewhere (Stearns, 1966a, p. 23).

The names of the major glacial and interglacial epochs of the Pleistocene are given in Table 1.

TABLE 1

MAJOR DIVISIONS OF THE QUATERNARY

EPOCH	NAME	HAWAIIAN SHORE LINE NAME	RELATION OF SEA TO PRESENT LEVEL
Postglacial	Holocene	Present	Rising from about 350 feet below
4th glacial	Wisconsinan	Mamala Low Leahi II Kawela Low	Falling to about 350 feet below twice and rising once to approximately present level
3rd interglacial	Sangamon	Waimanalo	Rising to 25 feet above
3rd glacial	Illinoian	Bellows Field Low	Falling to about 350 feet below
2nd interglacial	Yarmouth	Kaena	Rising to 95 feet above
2nd glacial	Kansan	Kahipa Low	Falling to about 350 feet below
1st interglacial	Aftonian	Olowalu	Rising to 250 (?) feet above
1st glacial	Nebraskan	No name	Falling to about 350 feet below
End of Pliocene	Pre-Nebraskan		Sea level unknown but probably higher than now

Carbon 14 dates indicate that the end of the Wisconsinan occurred approximately 11,000 years ago. The sea has risen at least 350 feet since then, or at an average rate of at least 3 feet per century. The rate of rise on Oahu is now only about 1 foot per century (Munk, 1966), and this may not be entirely glacioeustatic. Radiometric dates of corals from emerged reefs of Waimanalo age at Kahe Valley on Oahu average about 120,000 years before present (Veeh, 1966). On this basis, admittedly tentative, the Waimanalo 25-foot shore line of Sangamon age occurred at least 120,000 years ago. The end of the Illinoian glaciation, or the beginning of the Sangamon interglacial, has been dated elsewhere as about 320,000 years ago (Ku and Broecker, 1965). Thus the Kaena 95-foot stand of the sea, which represents the maximum height of the ocean on Oahu during Yarmouth interglacial time, occurred considerably more than 320,000

years ago. No radiometric dates are known for reefs on Oahu older than the Sangamon, although cores from deep holes on Oahu (Stearns and Chamberlain, 1967), and the existence of emerged high reefs on Maui and Lanai (Stearns, 1961), show clearly that the ocean was fluctuating widely during pre-Kaena time.

LANILOA FORMATION

The youngest lithified dunes are found only on the windward side of Oahu. The grains of sand ordinarily are held together by contact cementation but the interstices between the grains usually are not filled with calcite as in the older dunes. Some of the dunes are so weakly cemented that the sand can be removed with a shovel. This group of dunes has a well-developed nip, made by the present sea, but lacks any high cliffs, sea caves, or nips made by either the 5- or 25-foot sea. It is possible that the notch of the 5-foot sea has been destroyed but the notch of the 25-foot sea would be preserved if it had ever existed on the dunes.

These dunes are correlated with the Mamala Low in late Wisconsinan time and all dunes formed during Regression V are hereby named the "Laniloa Formation," from Laniloa Point at the seaward tip of the large lithified dune at Laie on windward Oahu. This dune is 45 feet thick and 3,500 feet long. A deep sinkhole full of water existed at its inland end until September, 1969, when the sinkhole was filled. The top of the sinkhole is about 3 feet above sea level. The dune there rests on 6 inches of reddish brown clay and a thick emerged coral reef. The sinkhole indicates solution of the reef by ground water when the sea stood lower. The dune still retains essentially its original whale-back form, with its axis trending a few degrees south of west, indicating that glacial winds were blowing easterly, as at present. Kukuihookua and Mokualai Islands, seaward of Laniloa Point, also are lithified dunes of similar age. The dunes rise from a platform at least 30 feet deep off the seaward side of these islands, according to the USGS Kahuku quadrangle map, indicating accumulation during a time when the sea was lower. Numerous rocks and islets to the north along the coast are lithified dunes of the Laniloa Formation also. From world-wide data the last Wisconsinan regression reached a low at least 350 feet below present sea level (Mamala Low, Fig. 3) 15,000 years ago (Milliman and Emery, 1968).

The Artex Concrete Company quarry, 1,200 feet west of the shore and 3,200 feet south of the town of Laie, exposes an unconformity between lithified dunes of two different ages. The contact is approximately 40 feet above sea level. Two to 6 inches of brown soil rests on 2 to 4 inches of hard caliche at the contact (Figs. 4, 5). The soil appears to be chiefly windblown dust from a weathered basalt terrane, but it contains abundant black mineral grains derived from basalt. They may be residual nonsoluble grains from the underlying dunes. The dune rock below the contact is full of solution cavities, many partly or completely filled with coarsely crystalline calcite. The dune rock above the contact is 40 feet thick and fairly well cemented, but less cemented than the lower dune rock. As a whole it is more cemented than most other Laniloa dunes. The lower dune belongs apparently to the Bellows Field Formation and the upper dune to the Laniloa Formation, but final assignment awaits radiogenic dating. This is the only known outcrop of soil interbedded with lithified dunes on Oahu, although soil is present between lithified dunes of different ages on Maui (Stearns, 1966b, p. 46), Molokai (Stearns and Macdonald, 1947), and Kauai (Stearns, 1935b), probably of correlative ages to those on Oahu.

FIGURE 4.—Horizontal break at base of cliff is caused by an ancient soil bed. Artex Quarry, near Laie. Photo by Dan Lum.

FIGURE 5.—Hammer rests on soil layer between two ages of dunes at Artex Quarry near Laie. Photo by Dan Lum.

DUNES AT DIAMOND HEAD

Leahi I Formation and 2-foot shore line.—At the foot of Beach Road on the south shore of Diamond Head is a very significant exposure of a Pleistocene shore line not described before. All the features and rocks exposed could be the deposits of the present sea level except for three important differences. (1) The landward end of the beach sand is transitional upward into a foreshore dune which is overlain with 50 feet of cemented slope-wash breccia derived from Diamond Head and cliffed by the present sea. (2) The sand in the ancient beach is essentially all calcareous whereas the modern beach sand has enough olivine present to give the beach a green

color. The olivine is derived from the attrition of the tuff fragments in the breccia. (3) The ancient dune is weakly to well cemented in most places (Fig. 6).

Furthermore, a specimen collected from a lens of beach conglomerate along the shore has a thorium age of 60,000±20,000 years (oral communication, William Easton, 1968). Thus these beach deposits, instead of being recent, are probably early Wisconsinan in age. The presence of Pleistocene shore deposits duplicating the present-day deposits makes it very difficult to be certain elsewhere along Oahu's shore which deposits are modern and which are Pleistocene.

The deposits at the foot of Beach Road shown in Figure 6 are here designated the Leahi I Formation, from the Hawaiian name of Diamond Head, and the place the type locality of the Pleistocene Leahi I shore line. The Leahi I stand of the sea was either at or slightly higher than the present sea level. For the convenience of separation from the present sea level and other Pleistocene shore lines it is herein designated as the 2-foot stand. Both the marine and dune deposits of this stand make up the Leahi I Formation. All are well cemented below high tide and poorly cemented above high tide.

Interbedded with the Leahi dune and beach deposits are layers a few inches to a foot thick of slope-wash breccia, indicating contemporaneity. One stretch of beach pavement about 50 feet long, awash at high tide, is firmly cemented breccia. The Leahi I Formation rests on clean wave-cut, steeply dipping Diamond Head tuff, in places bored by marine organisms. Fossil rills and grooves, filled with well-rounded cobble conglomerate, perpendicular to the shore and 2 feet deep, exist in the tuff.

About 550 feet east of the lighthouse but on the shore are two outcrops of Leahi boulder conglomerate 5 to 8 feet above sea level (Fig. 7). The easternmost one is overlain by 1 foot of beach sandstone which dips downward to high-tide level. The boulders and pebbles consist chiefly of basalt and reef limestone. Some well-worn coral boulders up to 18 inches across and one cobble of calcareous beach sandstone are exposed. Fossil shells are abundant and the matrix consists of calcareous sand and shell fragments. It was from these outcrops that Easton collected the dated specimen. Because the conglomerate occupies ancient grooves cut into the tuff by the Leahi sea, the ancient storm waves running up the grooves would have carried the boulders considerably above the sea level of that time. However, they terminate definitely higher than the rills of the

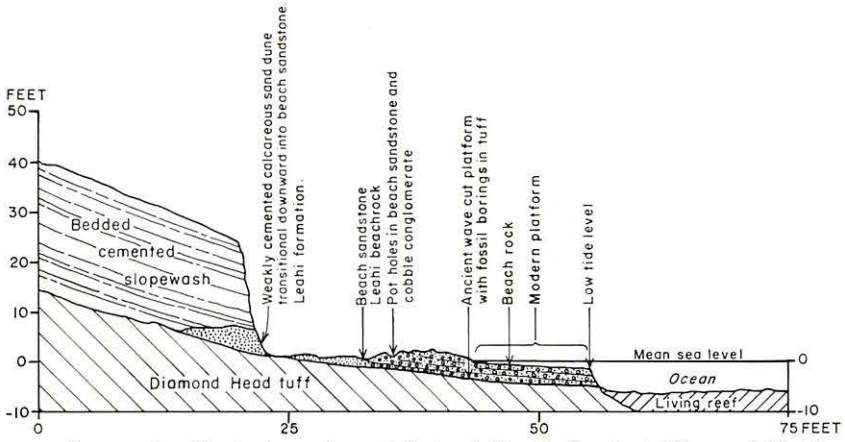

FIGURE 6.—Geologic section at foot of Beach Road at Diamond Head, Oahu, the type locality of the Leahi I shore line.

FIGURE 7.—Cobble conglomerate (Leahi I) 5 feet above sea level on Diamond Head tuff and overlain by 8 feet of eolianite and 20 feet of Diamond Head alluvium, 550 feet east of lighthouse. Oahu, Hawaii, March 8, 1968.

present sea and are the basis of placing the Leahi I stand 2 feet higher than the present.

The writer (1961) gave the name Manana to a 2-foot stand of the sea on the basis of a bench at this height on Manana Island. Lack of any definite stratigraphic data makes it difficult to assign this 2-foot stand in the shore line sequence except that it is of late age. Manana Island is a subaerial tuff and seems to have erupted during the Mamala Low after the Leahi II stand. Ash from this cone is known on Oahu nearby, lying on soil-covered reef of the 25-foot sea. It is, therefore, considered advisable to name the 2-foot stand at Diamond Head the Leahi I and later abandon the name Manana if it is found to be the same stand.

Leahi dunes.—Along Diamond Head Road west of the intersection with Beach Road are large exposures of weakly cemented dunes (see "Geologic Map of Oahu"). These dunes rest unconformably on eroded Diamond Head tuff and reach a height of about 90 feet above sea level. Near the upper end of one of the dunes fragments of lithified dune were found in the slope wash overlying the dune indicating that the dunes were cemented a long time ago.

Because these dunes on Diamond Head are so poorly cemented compared with those of Illinoian (?) age on the eastern slope and because they occupy the same stratigraphic position as the Leahi I dunes at the type locality nearby, all the dunes on the southwestern side are assigned tentatively to the Leahi I Formation. It is probable that part of the sand in the dunes accumulated as the sea fell from the Leahi I shore line during Regression IV (Fig. 3). Their age determination awaits geochemical dating.

Forty to 60 feet of cemented slope wash covers the dunes along the road. These coalesced fans of slope wash extend around the western side of Diamond Head along the inland edge of Kapiolani Park. The cemented slope wash there crops out in an abandoned marine cliff 20 to 30 feet high in which numerous caves exist. One cave, possibly an abandoned sea cave, is about 20 feet deep, 20 feet wide, and 10 feet high midway in the cliff face. Its floor is about 25 feet above sea level, according to the USGS Honolulu quadrangle. No wave-rounded pebbles were found along the cliff or in the cave, nor was wave smoothing observed anywhere nearby. Little doubt exists, however, that the cliff was made by the sea. If the cave is wave cut, then the cliff was possibly made by the sea when 25 feet higher than

now. Or the cliff may have been cut by the present sea and the land filled by late alluviation to a height of 20 feet at the base.

Age of Leahi I 2-foot shore line.—The assignment of the Leahi 2-foot stand in the sequence of Pleistocene Hawaiian shore lines is difficult. The overlying cemented slope wash with its interbedded silt layers required considerable time to accumulate. It was graded to a lower shore line farther seaward after the Leahi stand. Steep-sided gulches 50 to 100 feet deep have been cut into the slope wash since it was cemented. These are graded to the present sea. At no place in the gullies could marine borings or marine deposits of the 25-foot Waimanalo stand of the sea be found, yet we know from an exposure at Paikoo Place on the slope of Diamond Head at Black Point (Stearns, 1966a, p. 85) that Diamond Head erupted during the Regression III in Illinoian (?) time. Also the extensive lithified dunes of the Bellows Field Formation on the eastern slope of Diamond Head are deeply notched by the Waimanalo 25-foot stand of the sea. Furthermore, at Black Point marine conglomerate of the 25-foot stand overlies Black Point basalt and Diamond Head tuff.

Along the shore west of Black Point are excellent exposures of hard beach conglomerate, of a sea about 5 feet higher than the present, unconformable on reef of the Kaena 95-foot stand of the sea and overlain by 6 inches of red transported soil and the Black Point black ash. The black ash fills gullies cut in the cemented slope wash along Diamond Head Road east of the lighthouse. The source of the black ash is unknown (Stearns, 1940, p. 53). Until radiogenic dating is completed on specimens collected by Easton and the writer from the 5-foot conglomerate at Black Point, it is impossible to state whether that 5-foot conglomerate is of Leahi I age or of some different stand of the sea.

Within the framework of existing data it seems best to assign the Leahi I stand to a halt in Regression IV (Fig. 3). However, the writer cannot explain the removal of so much slope wash by the present sea and the accumulation of so much slope wash during Regression IV. Large volumes of slope wash must have been deposited in the long interval between the formation of Diamond Head during Regression III and Transgression III. Much of it may be buried beneath sea level and the rest may have been removed by the sea during Transgression III.

The stratigraphy at Kahuku Point described in this paper indicates that the Leahi II stand was preceded by the Kawela Low.

The geological events starting with the eruption of Diamond Head are:

1. Eruption of Diamond Head when the sea was lower during the Bellows Field low stand in Illinoian time, as shown by an outcrop at Paikoo Place (Stearns, 1966a, p. 85).

2. Lithification of the Diamond Head ash cone.

3. Eruption of Black Point lava.

4. Gullying of Diamond Head during storms and deposition of slope wash beyond present coast line and graded to a lower sea level (Bellows Field Low). Large quantities of calcareous sand blown inland to form the well-cemented dunes of the Bellows Field Formation on the east side of Diamond Head.

5. Rise of sea level during Transgression III (Fig. 3) to the 25-foot Waimanalo stand, making nips and caves in the dunes on the east side of Diamond Head. Growth of a narrow coral reef adjacent to these dunes.

6. Fall of sea level (Regression IV) with a halt at the 5-foot Kapapa shore line.

7. Fall of the sea to approximately the same level as at present, or Leahi I 2-foot stand, and deposition of beach deposits and dunes of the Leahi I Formation.

8. Partial cementation of Leahi I dunes and beach deposits as the sea fell to the Kawela Low 350± feet below present sea level. Concurrently the Leahi I deposits were buried by 50 feet of slope wash.

9. Rise of the sea to the Leahi II stand (Transgression IV).

10. Fall of the sea to the Mamala Low (Regression V).

11. Rise of the sea to present level. Gullying and cliffing of slope-wash deposits. Deposition of the Black Point black ash.

DUNES AT KAHUKU POINT

The stratigraphy at Kahuku Point, given in Table 2, is the key to several important events regarding the age of the dunes.

Figure 8 shows the areal relation of the Laniloa dunes near Kahuku Point to the older Bellows Field Formation and reef rock at the abandoned Kahuku quarry. Because of the small size of the

TABLE 2

STRATIGRAPHY AT KAHUKU POINT, OAHU

(Nos. 1-6 Exposed at the Coast; 7-13 in Kahuku Quarry Area)

NAME	NO.	DESCRIPTION	AGE	THICKNESS (FEET)	SYMBOL (FIG. 8)
Loose calcareous dune sand	1	Fine-grained, cross-bedded, cream-colored sand	Holocene	0 to 15 ±	Rd
Loose calcareous beach sand	2	Fine- and coarse-grained, cream-colored sand	Holocene	0 to 10 ±	Rs
Laniloa Formation Eolianite	3	Thin-bedded and cross-bedded lithified calcareous dunes	Pleistocene (Wisconsinan) Mamala low stand	0 to 15 ±	Pdl
Leahi II Formation Beach rock transitional upward to eolianite	4	Lithified cream-colored beach sand like present beach sand and overlying lithified dune capped with 2 inches of caliche and 2 to 4 inches of loesslike brown soil	Pleistocene (Wisconsinan) Leahi II stand	0 to 7	
Lithified clay	5	Brown fine-grained clay deposited during a regression of the sea	Pleistocene (Wisconsinan) Kawela low stand	0 to 1	
		Solutional unconformity			
Waimanalo Formation Reef limestone	6	Coral and nullipore reef with some clastic material Buried by Holocene brown alluvium (Ra) at inland edge, and truncated by a bench along the coast	Pleistocene The bench was apparently made by the Kapapa 5-foot stand but the reef is Waimanalo (Sangamon age)	5 +	Plsw
Waimanalo Formation Beach conglomerate partly contemporaneous with limestone above	7	Very coarse boulder conglomerate in road cuts on highway	Pleistocene (Sangamon age)	10 ±	Plswc
		Erosional unconformity			

TABLE 2 (Cont.)

NAME	NO.	DESCRIPTION	AGE	THICKNESS (FEET)	SYMBOL (FIG. 8)
Bellows Field Formation Eolianite	8	Very hard thin-bedded and cross-bedded lithified calcareous dunes	Pleistocene (Illinoian)	40 ±	Pdb
Brown alluvium	9	Clastic debris from a basaltic terrane	Pleistocene (Illinoian)	0.5 ±	
		Solutional and erosional unconformity			
Kaena Formation Reef limestone	10	Massive coral reef	Pleistocene (Yarmouth age)	20	Plsk
		Erosional unconformity			
Kahipa Formation Boulder alluvium	11	Basalt boulders in a matrix of brown sand and silt	Pleistocene (Kansan ? age)	12 ±	
		Erosional unconformity			
Kahuku Point Formation	12	Cream-colored, thin-bedded, lithified calcareous beach sand	Pleistocene (Aftonian ? age)	10	
		Great erosional unconformity			
Koolau basalt	13	Basalt flows deeply weathered and capped with residual soil	Pliocene	10 +	Tkb

outcrop of Leahi Formation it has not been separated from the Laniloa dunes in Figure 8. For a distance of about 1,000 feet between the inland edge of the exposed emerged reef limestone and the highway only recent brown alluvium is exposed. It is probable that the alluvial layer is thin and overlies limestone in this stretch. Figure 9 is a section drawn from the beach to the quarry along the north-south line AB shown in Figure 8. Part of the stratigraphy in the section is based upon old photos and upon stratigraphy of the rocks recorded by the writer prior to their removal by quarrying. The quarry is the type locality of the 55-foot Kahuku stand of the sea and the minus 300±-foot Kahipa stand of the sea, but all rocks of these ages have been removed by quarrying. Fortunately a photo and a stratigraphic table of the rocks before they were removed have been published (Stearns, 1935b).

The weathered Koolau basalt and soil, the reef of the Kaena stand of the sea, and the overlying lithified dunes are still well exposed in the abandoned quarry and the boulder beach conglomerate of the

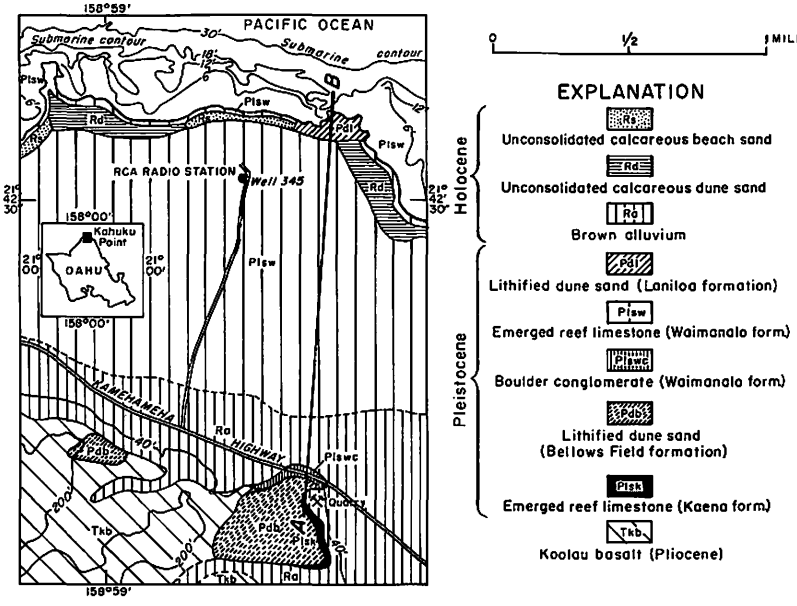

FIGURE 8.—Geologic map of Kahuku Point. R = Holocene; P and Pls = Pleistocene; and T = Tertiary in list of symbols.

25-foot stand of the sea is well exposed in the highway cuts nearby lying on weathered Koolau basalt. The boulders in the conglomerate consist of rounded basalt up to 18 inches across, eolianite boulders of the Bellows Field Formation up to 5 feet across, and a few older reef limestone cobbles. Directly above the outcrop is a sea cliff cut into reef of the Kaena stand of the sea. The Kaena reef extends up to 80 feet above sea level and is overlain unconformably by 40 feet of very hard lithified dunes of the Bellows Field Formation (Fig. 9). Six inches or more of brown alluvium lies between the reef and the dunes.

Chapman (1946) published a detailed stratigraphy of the coastal rocks but did not recognize all of the events and incorrectly assigned the lithified dunes to the Waipio Low. The present writer subsequently reassigned them, also incorrectly, to a 5-foot stand of the sea (1961) estimated at 6,000 years ago by Fairbridge (1960). Many scientists now believe that the Atlantic Ocean did not rise higher than at present during Holocene time (Shepard, 1963), but some evidence exists that

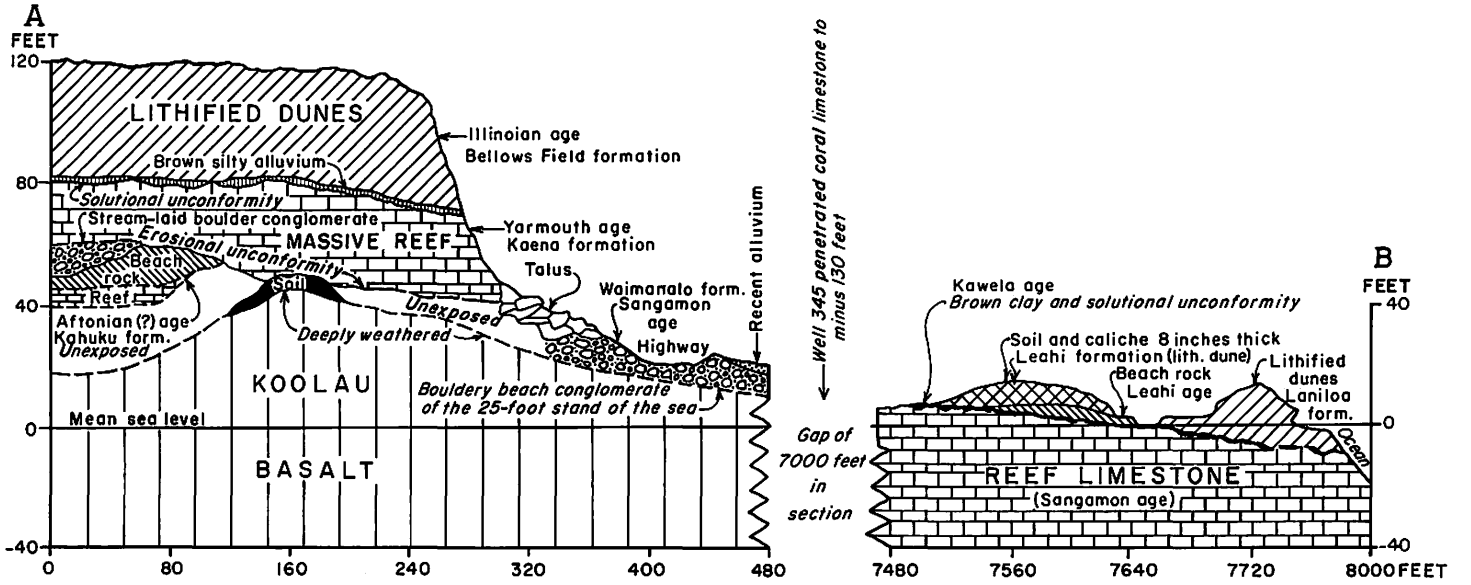

FIGURE 9.—Geologic section from Kahuku Quarry to the coast, along a north-south line AB in Figure 8. The Leahi Formation at this place was laid down by the Leahi II stand.

the Pacific Ocean may have been as much as 5 feet higher about 1,000 years ago, based on carbon 14 dates for the emerged reef rock at Midway and Kure Islands (Gross and Others, 1969).

Fossil land snails from the base of the lithified dunes of the Leahi II Formation at Kahuku Point are older than 34,000 years, based on a carbon 14 test reported by William Easton (oral communication, April, 1968). The dunes are probably middle to late Wisconsinan in age and correlative with an interstadial in the Wisconsinan. The lithified dunes on the shore are contemporaneous with the underlying beach rock and belong to the Leahi II Formation. Those that pass below sea level were blown inland as the sea regressed from the Leahi II stand to the Mamala Low and belong to the Laniloa Formation. The lithified dunes rest on clay and the pitted and rough surface of an extensive coral reef with its top about 5 feet above sea level (Fig. 8).

Kawela low stand of the sea.—The unconformity below the beach rock, which is indicated by the solution-pitted reef and lithified clay (Fig. 9) and which extends below sea level, is evidence of a low stand of the sea not heretofore named. It is hereby named the Kawela low stand after Kawela village two miles to the west. How far the sea fell during the Kawela Low is not yet known. The bench truncating the pitted reef may have been made by the Kapapa 5-foot stand (Fig. 8) and the beach rock above the reef and clay indicates the later Leahi II stand (Fig. 1). The Kapapa stand was separated from the Leahi II stand by the Kawela Low. Deposits of the Leahi II stand are found at Diamond Head also. The Leahi II stand was a maximum stand during one of the several interstadials of the Wisconsinan.

DUNES IN KANEOHE BAY

Kapapa and Kekepa Islands are hard, lithified dunes lying in the line of breakers in Kaneohe Bay. Their alignment indicates that their sands blew inland from a shore line now below sea level, then parallel and not far seaward of the present reef edge. Possibly the living reef in the breaker zone is a thin veneer on beveled-off dunes. Old charts indicate that the islands rose from a platform 60 feet below sea level, but new charts show that they stand in 12 feet of water. The fact that they do not rise from a minus 60-foot shelf casts doubt on the original assignment of these dunes to the Waipio stand in the Illinoian

epoch. It is probable, however, that the rock in the islands belongs to the Bellows Field Formation because it is so well cemented. Reliable age assignment awaits geochemical dating. Kapapa Island carries a well-defined bench 5 feet above sea level and is the type locality of the 5-foot stand of the sea. It is probable that the bench postdates the Kawela Low and is the same age as the 5-foot bench in Hanauma Bay. If so, two 5-foot stands of the sea occurred, one before the Kawela Low and one later, contemporary with the emerged 5-foot reef on Midway Island.

DUNES NEAR KAENA POINT

Along the new highway to Kaena Point, 1½ miles northwest of Makua Cave, partly lithified dunes are exposed about 35 feet above mean sea level, buried by 50 feet or more of compact basalt talus. The dunes are transitional downward into 1 foot of beach rock unconformable on a massive coral reef with the top of the reef about 5 feet above mean sea level. The dunes and beach rock appear to have been laid down as the sea receded from the 25-foot Waimanalo stand of the sea.

BELLOWS FIELD FORMATION

Different ages of lithified dunes on Oahu can be distinguished in most outcrops by the degree of cementation. The Illinoian dunes are sufficiently hard rock, in most places, to be crushed for road metal and for concrete aggregate. Interstices between sand grains are filled with calcite cement. Most Illinoian lithified dunes carry well-defined nips at 22 and 27 feet, two levels of the Waimanalo stand of the sea. Solution cavities along bedding planes and calcite veins are also common in them. Because this eolianite makes a mappable lithologic unit of definite geological age, it has been named the "Bellows Field Formation" (Lum and Stearns, in press). The rock at the type locality, in the Pacific Concrete and Rock Company quarry at Waimanalo, is a creamy yellow eolianite with calcite cement filling the interstices between the well-rounded calcareous sand grains. The lithified dunes extend a horizontal distance of 3 miles with their highest point 160 feet above sea level and their bottom 160 feet below sea level. Typical dune cross-bedding is everywhere apparent. The grains are uniformly fine and the rock does not contain large fragments of shells and coral, such as typify beach rock, and fossil land

snails occur in places. Grains of minerals derived from basalt are scarce.

All the lithified dunes shown on the "Geologic Map of Oahu" near Kailua also belong to the Bellows Field Formation. The formation extends in a belt about ¼ mile wide and 1¼ miles long on the east side of Diamond Head (see "Geologic Map of Oahu," Stearns, 1939). The great bulk of the dunes is hard rock with large notches and caves made by the 25-foot sea. Large volumes of sand accumulated during the Illinoian glacial epoch, as shown by the extensiveness of these dunes in comparison to later dunes. Solution pits, a thick crust of caliche, and patches of brown soil, commonly filling solution pits, are present on the weathered dune surfaces. The Waipio submarine shelf at minus 40 to 60 feet apparently was a halt during the recession of the sea in Illinoian time (Regression III, Fig. 3). Thus the older lithified dunes, mapped previously by the writer as of only Waipio age on the "Geologic Map of Oahu," accumulated as dunes not just when the sea halted at the minus 60±-foot level, but during the entire Regression III.

CONCLUSIONS

Four ages of lithified dunes which shed light on glacioeustatic changes of sea level can be differentiated on Oahu. The oldest are those of Illinoian age. They are hard eolianites used for road metal and are the Bellows Field Formation. They are voluminous and indicate that the wind blew from the same direction at the time of deposition as at present. The next youngest dunes, a part of the Waimanalo Formation, cover only a few acres and cap ancient beaches of the 25-foot Waimanalo shore line of Sangamon age. The next youngest lithified dunes are poorly cemented in most places and were laid down during the Leahi I stand of the sea and while the sea was retreating to the Kawela Low. They comprise the Leahi I Formation. Mapping them has revealed the presence of a previously unrecorded stand of the sea lower than the present, herein named Kawela. Next youngest are the dunes of the Laniloa Formation which were formed as the sea receded from the Leahi II shore. If the fairly well-preserved Bellows Field dunes are Illinoian in age, and the Illinoian occurred 325,000 years ago, then erosion and weathering in 325,000 years have been slight on Oahu.

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ADDENDUM

A second Leahi shore line (Leahi II) was found on the south side of Diamond Head after this paper had reached page proof. The older is an early Wisconsinan 2-foot stand named herein Leahi I and the second is a middle to late Wisconsinan stand at present sea level, herein named Leahi II. Leahi I, apparently, was a halt as the sea receded from the 25-foot Waimanalo stand.

Along the shore below Diamond Head Lighthouse Leahi II beach rock is separated from Leahi I deposits by an erosional unconformity. In some places the beach rock crops out only as thin veneering remnants on the Leahi I beach rock. Leahi II beach rock has a maximum thickness of 2 feet and consists of numerous Diamond Head tuff fragments in a matrix of calcareous sand and a few thin layers of hard, dark-colored calcareous beach sandstone. The presence of abundant volcanic detritus differentiates it from Leahi I deposits. The Leahi II deposits might be classed as Recent except they occur also as beach rock and weakly lithified dunes lying on top of the clay near Kahuku Point shown in Figures 1 and 9. Only in the

Kahuku Point area can the Leahi II deposits be proven stratigraphically later than the Kawela low stand and at the end of Transgression IV. Their positive age determination awaits geochemical dating.

The writer acknowledges valuable help from Dan Lum in differentiating the Leahi II from the Leahi I deposits at Diamond Head.