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Submerged Shorelines and Shelves in the Hawaiian Islands and a Revision of Some of the Eustatic Emerged Shorelines

ABSTRACT

The paper presents new C^{14} and uranium series dates on Oahu and their bearing on the dating of fluctuations of sea level due to glacioeustatism during the Wisconsinan. The −60- and −120-ft shorelines are shown to be Wisconsinan. Scuba and submersible diving has made it possible to study the submerged shorelines. Some of the submerged shorelines are notches in vertical cliffs and were not previously found by detailed soundings. The −350-ft shelf, previously thought to be a drowned wave-cut platform, proved to be a drowned coral reef. Shorelines and drowned reefs indicate stillstands below sea level at 15, 30, 60, 80, 120, 150, 185, 205, 240±, 350, 1,200 to 1,800, and 3,000 to 3,600 ft. Those above −450 ft are thought to be glacioeustatic. Those below −450 ft are the result of subsidence. *Key words: Quaternary, dune limestone, geomorphology, geochronology.*

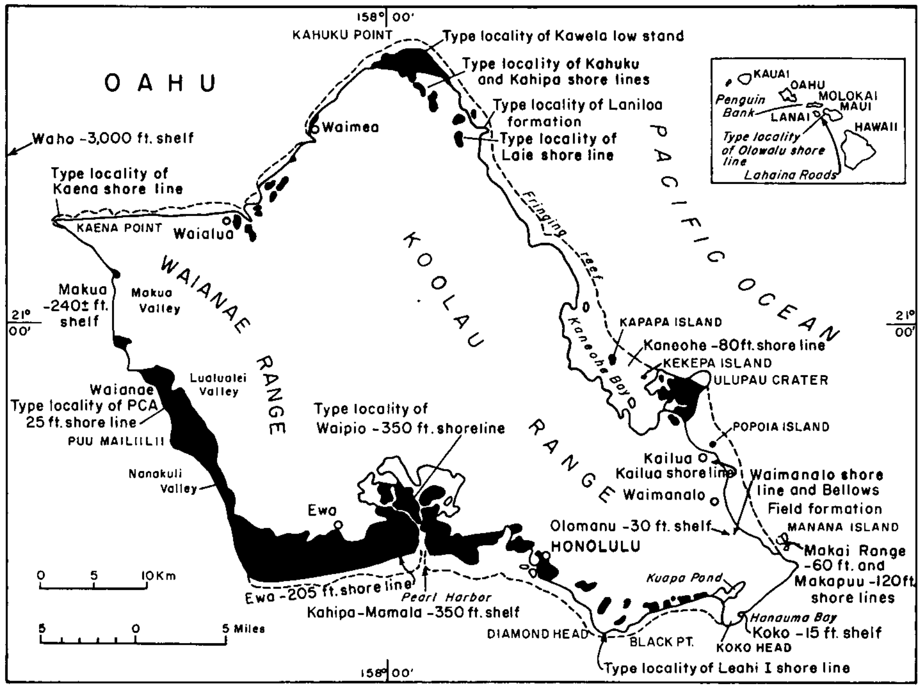

Figure 1. Map of Oahu showing areas of emerged reefs (solid black), fringing reef (dashed line), and type localities of emerged and submerged shorelines and shelves.

INTRODUCTION

All submerged shorelines described herein are either horizontal notches in rock or extensive narrow deposits of beachrock, indicating a stillstand of the sea in the past. The shelves are broad, flat features, apparently drowned coral reefs (Fig. 1).

The depth below sea level of the outer rim of a shelf, if a reef, is cited as sea level at the time the reef grew. The shoreward edge would give a more reliable elevation but is usually buried by talus. The rim of the fringing reef that lives around Oahu at the present time is about 1 ft below mean sea level. The sea did not stay long enough at any one level in Hawaii to plane extensive shelves or to cut high cliffs during the late Pleistocene. It did not stay in one place long enough during the last 15,000 yr for the growth of the present fringing reef; hence, the living corals must form a thin veneer on an older reef.

RELATION OF SHORELINES TO GLACIAL EUSTACY

It is assumed herein that all submerged shorelines and shelves above −450 ft were made when the sea was lower during the several glacial epochs. Two can be dated roughly from the K-Ar ages of the volcanic rocks they notch, but most await definite dating. All were made during the Pleistocene and are listed in Table 1 according to depth but not age. The shelves below −450 ft are older and may be as old as Miocene.

The names of the major glacial and interglacial epochs of the Pleistocene are given in Table 2. Dates have been generalized and should be considered approximate only. A list of the ancient shorelines, identified to date in the Hawaiian Islands, is given in Table 3.

REVISION OF THE GLACIOEUSTATIC CURVE

Regression VI and transgression VI were formerly regression V and transgression V (Lum and Stearns, 1970, Fig. 2) but have been increased one number because of the introduction of a new regression and transgression after transgression III. Apparently during the Wisconsinan three lows occurred instead of two (Figs. 2 and 3). C^{14} and uranium series dates recently obtained from emerged shoreline fossils are the basis for the revision of the glacioeustatic curve herein.

The Kapapa 5-ft stand is now considered to be Holocene or 3,500± yr B.P. Fossil corals from beach conglomerate 5 to 8 ft above mean sea level on a lava flow on Hanauma Bay bench, Oahu, have a C^{14} age of 3,485 ± 160 yr (Geochron Laboratory sample GX–2673). The bench of the present sea lies generally 0.5 to 1 ft below mean sea level on Oahu and is 10 to 30 ft wide where it is developed in limestone. The bench is easily identified by its smoothness and by the living algae on it. It was made chiefly by sea-water solution within a period of a few thousand years. The older Kapapa 5-ft bench, where developed in limestone, is always deeply pitted by solution and is being destroyed by storm waves. Where the Kapapa bench is cut in tuff, it is kept clear of talus by storm waves. It can be walked on readily during high tide but not during storms. Miles of cliffed headlands would be inaccessible on islands in the Pacific were it not for the 5-ft bench (Stearns, 1961, p. 8). Although the Kapapa 5-ft stand during the climatic optimum ~4,000 yr ago apparently does not exist along the Atlantic Coast of North America,

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evidence continues to accumulate for its presence in the Pacific. An emerged reef, whose top is nearly 5 ft above mean sea level on Midway Island, has a C^{14} age of 2,420 ± 1,230 yr B.P. A similar emerged reef on Kure Island has a C^{14} age of 1,480 ± 250 yr B.P. (Gross and others, 1969, p. 22). A notch 5 ft above mean sea level was found on Guam (Stearns, 1941, p. 779), and coral dated from this stand has a C^{14} age of 3,400 ± 250 yr (Tracey and others, 1964). In Japan, Fujii and Fuji (1967) found that the sea stood several meters above present level from 6,000 to 3,000 yr B.P. Most five-ft benches, especially if cut in lava rock, have a composite origin and were made by earlier stands at this height because the last 5-ft stand did not last long enough to make benches in durable nonsoluble rocks.

The youngest lithified dunes on Oahu belong to the Laniloa Formation and lie on a red to brown paleosol which is either windblown or washed onto the underlying rocks. The soil was derived from weathered basalt. The dunes apparently accumulated during the Mamala low stand of the sea that occurred during the last glacial stadial and which ended ~12,000 yr ago. The Mamala low stand reached a level 350 ft below present sea level. Age determinations of fossils from the soil, the overlying dunes, and the beach deposits just below the dunes are given in Table 4.

The C^{14} tests of shells from the beachrock from Leahi II(?) stand near Kahuku Point[1] and from Turban shells at the same horizon which bored into the Kawela soil indicate that the Leahi II(?) stand of the sea, if it exists, occurred ~21,000 yr ago (specimens 1 and 2, Table 4). The Kawela low occurred before that time. I took T. L. Ku of the University of Southern California to the Leahi II(?) stand to collect coral fragments for uranium series dating. Two different specimens of coral were collected that were embedded in the top of the soil ~3 ft above sea level and ~25 ft from where the Turban shells were collected. The coral was not waterworn and probably had been transported a short distance, but it was not torn from the underlying Waimanalo reef, which is massive and would not yield coral of this type. Ku's tests showed an age of 115,000 ± 6,000 yr (1972, written commun.). About 25 ft east from the coral specimens, he collected a coral in a position of growth from the Waimanalo reef 1 ft above sea level. It had a date of 137,000 ± 11,000 yr B.P. Veeh (1966), who collected coral from the reef about 100 yd to the west, got a uranium series date of 110,000 ± 20,000 yr. Veeh thought it came from reef of Waimanalo age.

[1] The locality is a point without a name on the U.S. Geological Survey Kahuku Quadrangle Map, 1.1 mi east of Kahuku Point north of the RCA Radio Station. In my notes, it is called RCA Point for convenience.

TABLE 1. LIST OF SUBMERGED SHORELINES AND SHELVES ACCORDING TO DEPTH BUT NOT CHRONOLOGICAL ORDER

Depth below mean sea level (ft)	Name	Island	Named by
-15	Koko	Oahu	Easton (1965)
-30	Olomana	Oahu	Lum and Stearns (1970)
-60	Makai Range	Oahu	Stearns (new name)
-80	Kaneohe	Oahu	Stearns (new name)
-120	Makapuu	Oahu	Stearns (new name)
-150	Lahaina Roads	Maui	Stearns (new name)
-185	Penguin Bank	Molokai	Stearns and Macdonald (1947)
-205	Ewa	Oahu	Stearns (new name)
-240±	Makua	Oahu	Stearns (new name)
-350	Kahipa-Mamala	Oahu	Stearns (1935b); Ruhe and others (1965)
-1,200 to -1,800	Lualualei	Oahu	Stearns (1935b)
-3,000 to -3,600	Waho	Oahu	Stearns (1966)

TABLE 2. MAJOR DIVISIONS OF THE QUATERNARY

Epoch	Yr B.P.*	Ocean level (end of epoch, ft)	Hawaiian name†
Holocene	12,000–0	0	Transgression VI, rising from Mamala low to Kapapa shoreline
4th glacial Wisconsinan			
Late stadial	25,000(?)–12,000	-350	Regression VI, falling to Kahipa-Mamala shelf (depostion of Laniloa Dune Formation)
Late interstadial	(?)–25,000(?)	0	Transgression V, rising to Leahi II(?) shoreline
Middle stadial	115,000–(?)	-(?)	Regression V, falling to the Kawela low stand (deposition of Kawela soil)
Early interstadial	120,000(?)–115,000	+5±	Transgression IV, rising to Leahi I shoreline (deposition of Leahi I beachrock and dunes)
Early stadial	125,000–120,000(?)	-(?)	Regression IV, (no deposits differentiated as yet in Hawaii for this period, but definite unconformity exists)
3rd interglacial Sangamon	400,000(?)–125,000	+27	Transgression III, rising to the Waimanalo shoreline (deposition of Waimanalo Formation)
3rd glacial Illinoian	450,000(?)–400,000(?)	-350±	Regression III, falling to the Waipio low (deposition of Bellows Field Dune Formation)
2nd interglacial Yarmouth	(?)–450,000(?)	+95	Transgression II, rising to the Kaena shoreline (deposition of Kaena Limestone)
2nd glacial Kansan	(?)	-350±	Regression II, falling to the Kahipa-Mamala shelf (deposition of reef limestone below sea level)
1st interglacial Aftonian	(?)	250±	Transgression I, rising to the Olowalu shoreline (deposition of Olowalu beachrock on Maui Island)
1st glacial Nebraskan	(?)	-350(?)	Regression I, not identified in Hawaii

Note: Dates added to table in Ages of Dunes on Oahu (Stearns, 1970).

** Another regression and transgression not reaching present sea level may have occurred in the Wisconsinan between regression V and transgression V ~80,000 yr B.P. The duration of the epochs to the end of the Sangamon are based on Th^{230} ages as determined by Broecker and Ku (1969), from marine fossils by Frericks (1968, p. 1457), and by new dates herein.*

† See Figures 2 and 3.

The extensive solution pitting in the top of the emerged Waimanalo reef under the Kawela soil would have required an emergence of ~5,000 to 10,000 yr. The sea must have receded below present level because the soil can be traced below sea level.

A C^{14} date of an algal nodule in the type locality of Leahi II shoreline at Diamond Head had a C^{14} age of 2,340 ± 110 yr (Stearns, 1972, p. 242), much too young to be correlative with the deposit near Kahuku Point. This means that the beachrock at the type locality is not Leahi II, and therefore Diamond Head must be discarded as a type locality for the Leahi II shoreline. The possibility that Diamond Head was not satisfactory for the type locality was suspected (Stearns, 1970, p. 71). If the deposits near Kahuku Point, previously identified as Leahi II deposits, are ~115,000 yr old, they

TABLE 3. ANCIENT SHORELINES IN THE HAWAIIAN ISLANDS

Approximate altitude (ft)	Shelf or terrace (name)	Age (yr B.P.)	Type locality (island)
0	Present	Present	..
5	Kapapa	4,000±	Oahu
-15	Koko	Late Holocene	Oahu
-350	Mamala	12,000	Oahu
-60	Makai Range	Late Wisconsinan	Oahu
-120*	Makapuu	Late Wisconsinan	Oahu
-150*	Lahaina Roads	Wisconsinan	Maui
-80*	Kaneohe	Wisconsinan	Oahu
-185†	Penguin Bank	Wisconsinan	Molokai
5±	Leahi I	115,000±	Oahu
-300(?)	Kawela	Early Wisconsinan	Oahu
25§	Waimanalo	125,000±	Oahu
12	Kailua	Late Sangamon	Oahu
-30	Olomanu	Sangamon	Oahu
-350(?)	Waipio	Illinoian	Oahu
-240±*	Makua	Illinoian(?)	Oahu
45	Waialae	Early Illinoian(?)	Oahu
70	Laie	Early Illinoian(?)	Oahu
95	Kaena	Yarmouth	Oahu
-350(?)	Kahipa	Kansan	Oahu
-205*	Ewa	Kansan	Oahu
25*	PCA	Kansan	Oahu
55*	Kahuku	Kansan	Oahu
250±*	Olowalu	Aftonian(?)	Maui
325±	..	..	Lanai
375±	..	..	Lanai
560	Manele	Early Pleistocene(?)	Lanai
625	Kaluakapo	Early Pleistocene	Lanai
1,200	Manele	Early Pleistocene	Lanai
-1,200 to -1,800	Lualualei	Late Pliocene(?)	Oahu
-3,000 to -3,600	Waho	Tertiary	Oahu

* *Position in sequence uncertain.*
† *Penguin Bank is too extensive to have been formed during this short-lived stand of the sea.*
§ *Two shorelines, 22 and 27 ft above mean sea level.*

are Leahi I deposits. The Kawela low occurred between the Waimanalo stand ~126,000 yr ago and the Leahi I stand ~115,000 yr ago. The Pleistocene sea-level curve, based on this dating, is shown in Figure 4.

Whether any stand of the sea near present sea level on Oahu occurred ~25,000 yr ago is now in doubt. The only known locality left to establish a stand at that time is the Makai Range Pier shown in Figure 8. Shells from 5 ft above present level at this place have a C^{14} age of 23,220 ± 1,200 yr (Table 4). T. L. Ku collected corals at the same outcrop but he found them to be too contaminated to yield an age determination by the uranium series method (1973, written commun.). Can one accept the C^{14} age for this locality or is the test in error, as were those near Kahuku Point? Proof of a Leahi II shoreline ~25,000 yr ago needs further confirmation. Emery and Milliman (1970, p. 8) published evidence for such a stand elsewhere.

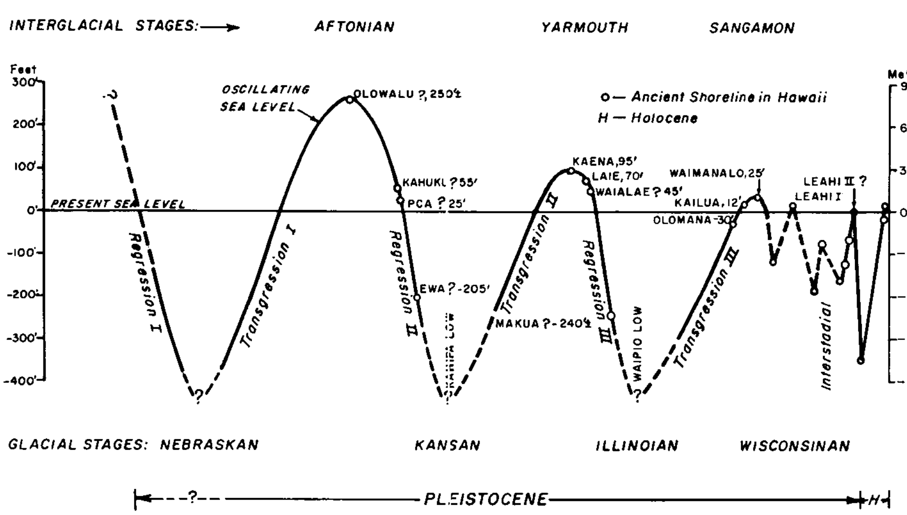

Figure 2. Graph showing glacioeustatic fluctuations of sea level and Hawaiian Pleistocene shorelines, using C^{14} dates in the Wisconsinan. See Figure 3 for details of the Wisconsinan. Question marks after shoreline names indicate that the order in time sequence is uncertain. (Modified after Lum and Stearns, 1970.)

The Leahi I stand 2 to 5 ft above mean sea level has been dated by two specimens collected at the Diamond Head type locality to be 120,000 ± 20,000 yr old (Kimmel and others, 1972, p. 182). A beach conglomerate 5 ft above mean sea level is well exposed along the shore of Black Point below Kaikoo Place. Kimmel and others tested three samples from this shoreline at Black Point but found them unsuitable for analysis. Subsequently, Veeh and I found a coral cobble in the conglomerate that showed no recrystallization. It had a uranium series age of 125,000 ± 10,000 yr (W. H. Veeh, 1972, written commun.). Apparently, the 5-ft shoreline deposits along Black Point were laid down during the Leahi I stand and not during the Kapapa stand. An erosional and solutional unconformity separates Leahi I deposits from the Waimanalo reef, which is ~125,000 yr old. This indicates not just a drop in sea level from 25 ft to 5 ft, but an intervening recession and transgression, as shown in Figure 3. The depth below present sea level that the sea fell is unknown for this low.

Figure 5 is a geologic section of a Leahi I beach deposit 4.5 mi southeast of Kaena Point, Oahu, covered by lithified dunes. The dunes are overlain by 50 ft of bedded talus. The important feature is the unconformity separating the massive reef typical of the Waimanalo Formation from the Leahi I beachrock.

The Ulupau 12-ft shoreline has been deleted from Table 3 and from the curve in Figure 2 because the deposits at the type locality (Wentworth and Hoffmeister, 1939, p. 1571) were found, during a recent examination, to have been laid down by a sea that was only ~5 ft, instead of 12 ft, above present sea level. The Ulupau weakly cemented beach deposit is 12 ft above sea level, as stated by Wentworth and Hoffmeister, and is overlain with 60 ft of talus breccia. However, the coast at Ulupau Head is reefless and is pounded by such high waves that the present sand beach there reaches 10 ft above sea level. Thus, the ancient beach deposits indicate a sea level of not more than 5 ft above the present sea when laid down. The emerged reef forming the Ulupau coast grew in the Waimanalo 25-ft sea and, after a considerable period of emergence and solution, was submerged. A bench ~5 ft above present sea level was made by the 5-ft Leahi I stand of the sea on this limestone after the sea rose again.

A specimen of limestone (No. 1) containing coral, *Conus*, and a pelecypod (*Cardium*) fragment was sent to Geochron Laboratory (GX-2945) from an outcrop of beach conglomerate cemented in a solution cavity in reef of Waimanalo age at the northeast end of the sand beach at the abandoned concrete Mokapu Landing on Mokapu Point. The outcrop is about 5 ft above mean sea level, is unconformable on the reef, and is obviously younger than the reef. It was dated as ≥37,000 C^{14} yr B.P. Another sample (No. 2; GX–2946) of water-worn shells from a weakly cemented beach sand about 12 ft above sea level, 1,000 ft southwest of Pukauloa Point on Ulupau Head, had an age >32,000 C^{14} yr B.P. The analysis was made on a complete *Conus*, a fragment of upper whorls of *Conus*, pelecypod *Cardium*, and a bryozoan-encrusted pelecypod fragment. The beach sand lies under 60 ft of very blocky talus from Ulupau tuff cone. The ancient beach lies landward of a solution-pitted bench cut on reef of Waimanalo age. Many of the pits are filled with later fossiliferous conglomerate. Some of the conglomerate is so weakly cemented that it may have been deposited by the Kapapa 5-ft stand of the sea. Fossils from these same localities were sent to Ku for uranium series dating. He found that specimen no. 1 has a Th^{230} age of 118,000 ± 9,000 yr and a Pa^{231} age of $105{,}000^{+15{,}000}_{-11{,}000}$ yr, which makes the deposit correlative with the Leahi I stand of the sea (T. L. Ku, 1973, written commun.).

The age of the Waimanalo 25-ft stand on Oahu is well established as being ~125,400 ± 22,200 yr ago, as shown in Table 5.

It is generally agreed that the 25-ft reef grew in the Sangamon interglacial epoch. Broecker and Ku (1969) think this epoch lasted from ~392,000 to 122,000 yr ago.

KOKO −15-FT SHELF

The Koko −15-ft shelf was first described and named by Easton (1965, p. 21). The type locality is in Hanauma Bay in the Koko Crater area on eastern Oahu (Fig. 1). The Koko Volcanics in this area have a K-Ar age of ~40,000 yr B.P. (Gramlich and others, 1971). The tuffs are subaerial and rest on soil-covered emerged reef of the Waimanalo 25-ft stand in an adjacent valley and in the sea cliff near Hanauma Bay (Stearns, 1935a, p. 1477). They were assigned to the very late Pleistocene (Stearns and Vaksvik, 1935), but Hay and Iijima stated that the tuffs are pre-Waimanalo or pre-Sangamon in age because they are subaerial and were laid down during a glacial low stand of the sea (Hay and Iijima, 1968, p. 344). My tabulation of eruptive events on Oahu (Stearns, 1966, p. 97) lists the Koko Volcanics as post-Waimanalo on the basis that they overlie soil-covered reef of the Waimanalo stand of the sea. It is true that the Koko Volcanics were erupted during a low stand of the sea but they were erupted during either the Kawela low or the Mamala low of the Wisconsinan, not during an earlier low. The K-Ar age of ~40,000 yr would place the eruption during the late Wisconsinan and the −15-ft shoreline probably was cut during a halt by the sea on the way up from the Mamala low. A detailed description of the −15-ft shelf was published recently (Easton, 1973). C^{14} dates of coral obtained in bore holes have an average age of 3,700 yr B.P. They indicate that the shelf is older than 3,700 yr B.P.

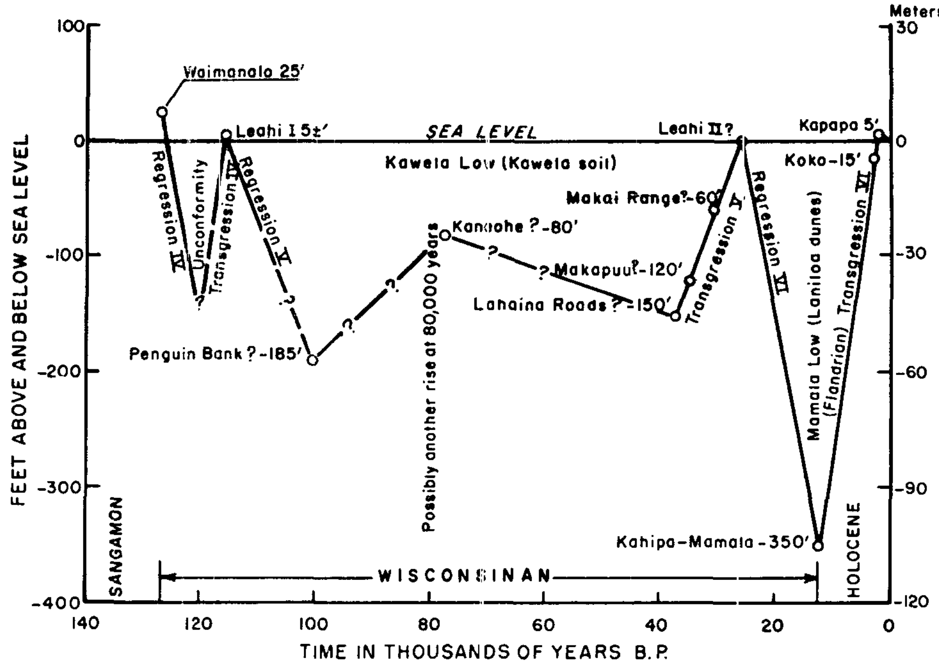

Figure 3. Graph showing an interpretation of the glacioeustatic fluctuations of sea level based on C^{14} dates during the Wisconsinan and Holocene and concurrent shorelines.

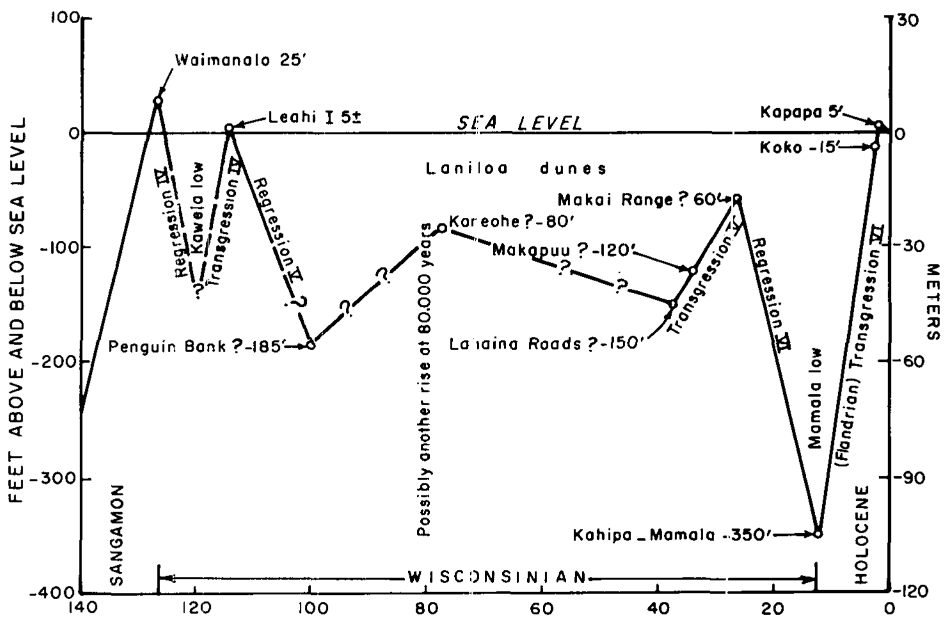

Figure 4. Graph showing an alternate interpretation of the glacioeustatic fluctuations of sea level during the last 140,000 yr based on the uranium series dates of corals from the Wisconsinan limestones. Question marks after shoreline names indicate that the order in the time sequence is uncertain.

OLOMANA −30-FT SHELF

The Olomana −30-ft shelf truncates Bellows Field Dune Limestone, which is of Illinoian age, for a horizontal distance of 650 ft. It is overlain by 5 ft of Waimanalo reef limestone of Sangamon age, as found in cores from holes drilled at Waimanalo, Oahu. The Olomana −30-ft shelf probably was cut by the sea on the rise from the Waipio low. If so, it is early Sangamon in

TABLE 4. C^{14} AGE IN YEARS B.P. OF CERTAIN FOSSILS IN HAWAII

Specimen no.	Locality	Formation	Fossils	Age	Elevation above mean sea level (ft)
1	Kahuku Point, *Oahu*	Leahi II(?) beachrock *on top of Kawela soil*	Marine shells	19,600 ± 1,500*	2
2	Kahuku Point, Oahu	Turban shells of Leahi II(?) age in top of Kawela soil	Marine shells	21,600 ± 80*	-1
3	Makai Range Pier, Oahu	Leahi II(?) beachrock under lithified dunes (Laniloa Formation)	Shells and coral†	23,220 ± 1,200*	5
4	Moomomi Beach, Molokai§	Lithified dune (Laniloa Formation?) on top of (Kawela?) soil	Land snails	25,150 ± 1,000#	8
5	Moomomi Beach, Molokai(?)§	Soil (Kawela?) between two ages of lithified dunes	Land snails	>27,000*	6
6**	Moomomi Beach, Molokai(?)§	Soil (kawela?) between two ages of lithified dunes§ (of sample 5)	Land snails	<28,000†	6

* *Determined by Geochron Laboratory. Sample from 1 is GX−1947; 2 is GX−1948; 3 is GX−2838; and 5 is GX−2672.*

† *T. L. Ku made a uranium series test on coral from this exposure and found that it was too contaminated to give a reliable age. Ku also determined an ionium date of <28,000 yr B.P. for sample 6 (1973, written commun.). Ku's work was supported by the Earth Science Section, National Science Foundation, NSF Grant GA−36182, also including specimens described in the text.*

§ *For the geologic setting of samples 4, 5 and 6, see Stearns, 1973.*

Determined by Robert Buddemeier, University of Hawaii. Sample HIG−35.

** *Specimen 6 is an ionium date.*

age. It is named from Olomana Peak near Waimanalo (Lum and Stearns, 1970, p. 13). It is doubtful whether evidence of this shelf can be found elsewhere except in drilled holes.

−60-FT SHORELINE

The −60-ft stillstand and the resulting shoreline notch and shelf are best recognized where the sea notched the Kaohikaipu basalt offshore of Sea Life Park on the eastern end of Oahu. The shoreline is typified by a submerged cliff 35 ft high, at the foot of which is a horizontal notch in places 6 ft deep and 8 ft high, fronted by a cobble and boulder beach. Numerous measurements by divers of Makai Range Inc. indicate that the notch is remarkably uniform in its depth at −60 ft and is cut into blue basalt.

The fact that the shoreline is cut into Kaohikaipu basalt means that the sea cut the cliff and notch during one of the transgressions or regressions in Wisconsinan time. It is tentatively shown as the peak of transgression V in Figure 4. This is the first time it has been possible to date, even approximately, the −60-ft stand. Unfortunately, no K-Ar age was determined for the Kaohikaipu basalt. However, the Kaupo basalt is ~33,000 yr old (Gramlich and others, 1971, p. 1401), and from its freshness, it is either later or about the same age as the Kaohikaipu eruption. Both lavas overlie the Manana Island tuff.

A drowned barrier reef lying about 1.5 mi off the westernmost shore of Kauai has a level top at −60 ft, which indicates that it reached this level during a stillstand. C^{14} dates of corals from this reef indicate it was alive ~8,000 yr ago (Inman and Veeh, 1966). The sea was rising so fast at that time that the dated corals must have come from a thin veneer on an older reef.

I named a low stand of the sea (the time at which most of the lithified dunes in the Hawaiian Islands were deposited) the Waipio low. Because extensive shelves were indicated by submarine contours on charts of Oahu, I placed it at −60 ft (Stearns, 1935b, p. 1941). Stratigraphically, on Waipio Peninsula, the Waipio low occurred prior to the Waimanalo 25-ft stand of Sangamon age; hence, it is Illinoian in age. It is shown in this paper for the first time that the −60-ft shoreline is Wisconsinan in age, or definitely much later than Illinoian. Thus, the recognition of the Waipio low as Illinoian in age was correct, but its assignment to a −60-ft halt of the sea was incorrect. This means that the Waipio low stand was not a halt on the way down in the Illinoian (Stearns, 1970, Fig. 3). The name Waipio is so widely used in the literature that it seems best to discard the name Bellows Field low (Stearns, 1970, p. 53) to represent the time the dunes formed during the Illinoian glaciation. The Waipio low probably was about −350 ft—certainly not −60 ft. The −60-ft shoreline observed offshore at Sea Life Park is hereby named Makai Range shoreline (from the Makai Range Pier near Sea Life Park) to avoid ambiguity. Since the Makai Range shoreline was cut long after the Waimanalo stand—~125,000 yr ago—it probably was cut either during transgression V or during regression VI (Fig. 3).

Richard Grigg reports that the top of a dead reef at Sunset Beach, near Waimea, Oahu, lies at −50 ft and is terminated by a steep cliff which bottoms at −80 ft. A definite notch of the −60-ft shore is cut in the cliff. I found a break in slope at −60 ft in 7 of the 24 sonar profiles made by Robert Kinzie along the Waianae coast. Divers reported to the writer that the −60-ft notch is common around Raiatea and Tahiti in the Society Islands.

−80-FT KANEOHE SHORELINE

The −80-ft shoreline has never been described before. It was first noted during dives by Robert Dill in 1969 in Kaneohe Bay, from where it is hereby named. Richard Grigg observed the −80-ft shoreline all around Oahu during his many dives. In Kaneohe Bay, the sea made a notch ~8 ft high and 8 ft deep, with a prominent overhanging visor (Fig. 6). It ap-

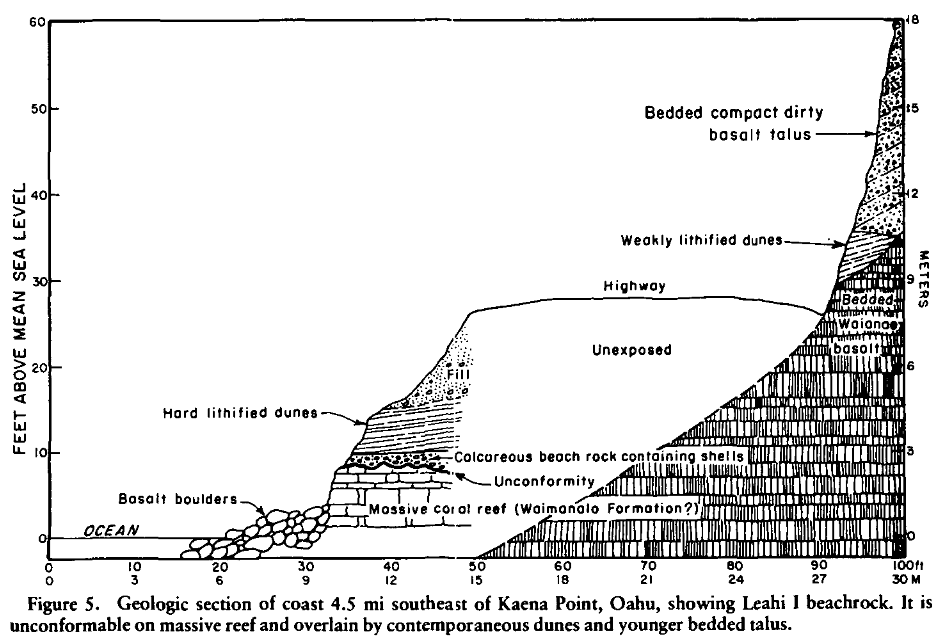

Figure 5. Geologic section of coast 4.5 mi southeast of Kaena Point, Oahu, showing Leahi I beachrock. It is unconformable on massive reef and overlain by contemporaneous dunes and younger bedded talus.

Figure 6. View of notch of the −80-ft shoreline with overhanging visor in dead coral reef in Kaneohe Bay, Oahu. Photo by Robert Dill. Published by permission of U.S. Navy.

pears to have been made during a stillstand in ancient reefs at many places. Because the notch does not occur in the Manana Island tuff, it must have formed during a glacial epoch prior to the Manana eruption. The rim of the dead reef above the notch in Kaneohe Bay is 45 ft below sea level, according to Deetsie Chave, who dived on the notch. She found the deepest part of the notch as measured by a lead sounding line is 78.5 ft below sea level. Living coral grows in scattered lumps and clusters on the dead reef, probably colonized in the last few thousand years when the sea again flooded the reef. The base of the cliff is at −92 ft. From that elevation, the ocean floor extends seaward as a nearly level shelf. Richard Grigg reports that the base of a cliff 30 ft high, terminating the dead reef off Sunset Beach, Oahu, is at −80 ft, apparently made during the −80-ft stillstand.

I found a break in slope at −80 to −90 ft in 5 of the 24 sonar profiles made by Robert Kinzie along the Waianae coast.

−120-FT MAKAPUU SHORELINE

Robert Bartko, in the submarine *Star II*, photographed an extensive notch 6 ft high and 6 to 10 ft deep cut into the base of a cliff of horizontally bedded subaerial Manana tuff near Manana Island at a depth of −120 ft. Most of the blocks torn from the cliff when the sea stood at this level are either not rounded or only slightly rounded. Potholes up to 3 ft across and up to 10 in. deep are common in the tuff. The cliff closely resembles those along the coast of Koko Head made by the present sea. The shoreline is herein named the Makapuu stillstand (from nearby Makapuu Point). Jack Ackerman, the diver who discovered black coral in Hawaii, described to me a shelf off Lahaina, Maui, at this same depth. It has also been studied there by Richard Grigg, who found it to be a dead reef.

A traverse of the coast near Manana Island was made to determine the age of the Manana Tuff in order to date the −120-ft shoreline. A geologic section 0.5 mi northwest along the coast from Makai Range Pier on the Pryor property is shown in Figure 7. There, Manana Island subaerial tuff overlies a thin, gray clayey soil. The soil lies on solution-pitted reef limestone, in places covered with 18 in. or less of hard, coarse calcareous sandstone. The solution pits penetrate both the sandstone and reef, indicating that both were exposed at the same time to subaerial solution. The reef limestone extends below sea level an unknown distance. It is full of circular heads of coral and coralline algae 2 to 3 ft in diameter, typical of the limestone of the Waimanalo Formation. The sandstone is entirely calcareous and typical coarse beach sand. It apparently lay in crevices and cavities in the reef prior to emergence. The solution pits were formed after the reef and sandstone emerged. The tree molds indicate that the reef and sandstone were emerged and the gray soil accumulated prior to the fall of the Manana Tuff. I originally placed the tuff in the Wisconsinan epoch, and present evidence confirms this age (Stearns and Vaksvik, 1935, p. 150).

A cesspool, near where Figure 7 was made, was excavated in August 1969 and exposed the deposits listed in Table 6.

A specimen of tuff from this cesspool was examined by Richard Hay, University of California, Berkeley, California. He reported that the glass has an index of refraction of 1.610 and contains olivine, nepheline, and probably melilite and is probably a melilite nephelinite ash definitely not from Koko Craters (Richard Hay, 1969, written commun.). Hay and Iijima (1968, p. 339) stated that Manana Island craters probably were active before the Waimanalo stand of the sea. However, they had not seen the outcrop in Figure 7, which shows that Manana Island erupted in Wisconsinan time—long after the Waimanalo stand.

Next to the northwestern side of Makai Range Pier, an outcrop 1 ft thick of fossiliferous, calcareous beachrock rests unconformably upon a partly weathered Koolau basalt bench 5 ft above sea level. The beachrock is overlain by 10 ft of lithified calcareous dune that extends about 15 ft above sea level and down to 2 ft above sea level. The dune was formerly more extensive and apparently was deposited when

TABLE 5. URANIUM SERIES AGES OF SPECIMENS FROM THE 25-FOOT STAND OF THE SEA

Locality	Age	Reference
Southeast coast	120,000 ± 20,000	Kimmel and others, 1972 (9 specimens)
Kahuku	137,000 ± 11,000	Ku, 1973, written commun.
Kahuku	110,000 ± 20,000	Veeh, 1966
Nanakuli	120,000 ± 30,000	Veeh, 1966
Haleiwa	140,000 ± 30,000	Veeh, 1966
Average	125,400 ± 22,200	

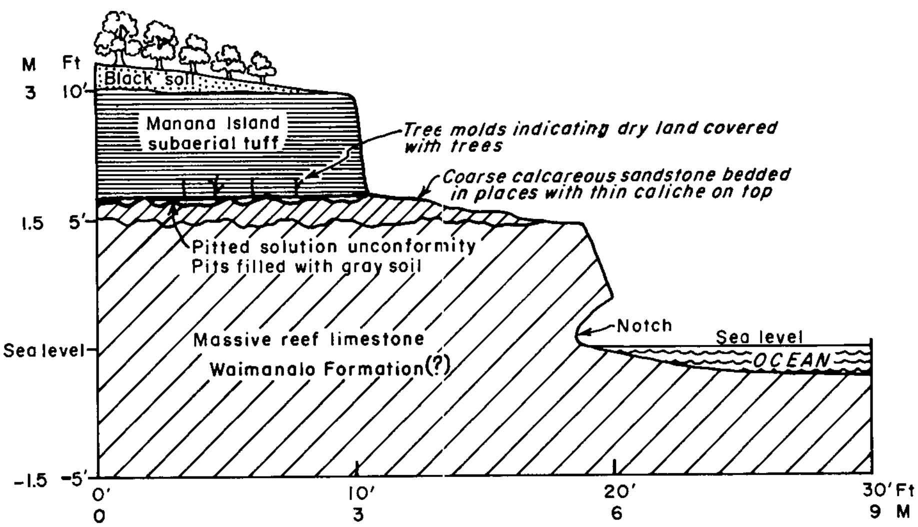

Figure 7. Geologic section 0.5 mi northwest of Makai Range Pier, near Sea Life Park, Oahu.

the sea was lower than it is today. It appears to belong to the Laniloa Formation. A geologic section is given in Figure 8. A mixed sample of coral and shells from the beachrock has a C^{14} age of 23,250 ± 1,200 yr old (Geochron Laboratory sample GX–2838). Because no Manana Tuff is present, the deposit appears to be later, if the writer's interpretation of the stiff brown clay in the test hole at the end of the pier is correct. This would mean that Manana Tuff is older than 23,250± yr on the basis of the C^{14} dating, but considerably younger than the Waimanalo reef, which is ~125,000 yr old.

I found a break in slope at −120 ft in 10 of the 24 sonar profiles made by Robert Kinzie along the Waianae coast.

A nearly vertical cliff 15 to 40 ft high rises above the −120 ft shoreline, indicating that the sea stood at that level for a considerable period. The cliff displays erosion too great for transgression VI. The Makapuu stand probably was cut during regression VI or transgression V. It is tentatively assigned to transgression V.

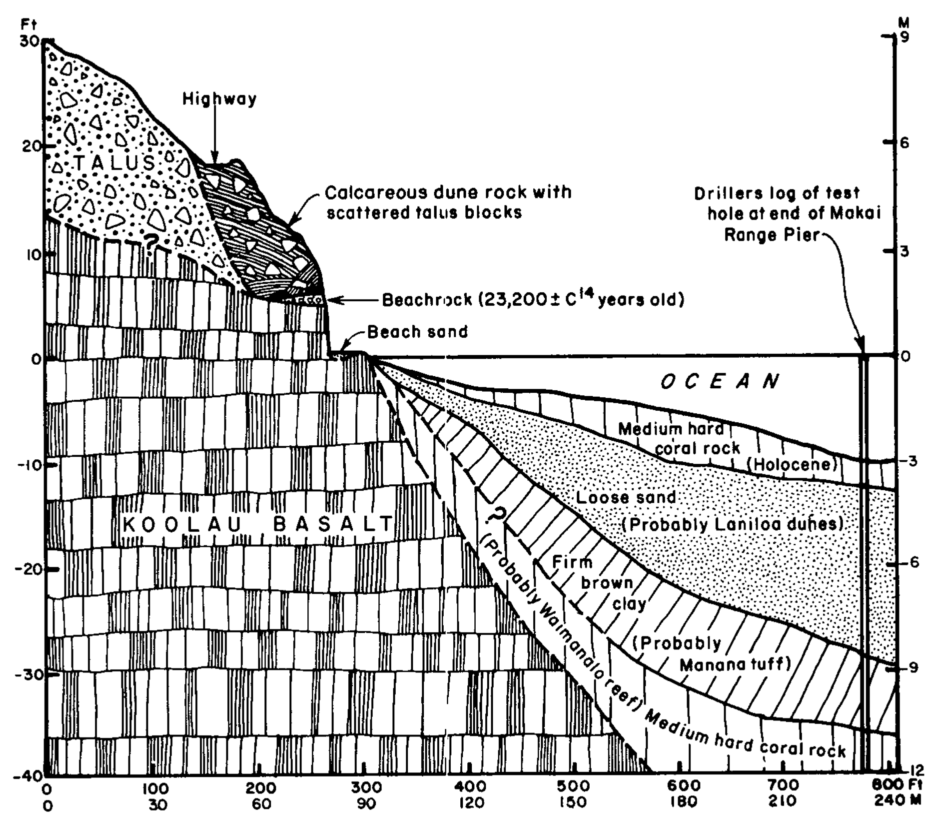

Figure 8. Geologic section at Makai Range Pier, near Sea Life Park, Oahu. Vertical exaggeration, × 10 horizontal. Author's interpretation in parentheses.

−150-FT LAHAINA ROADS SHORELINE

A well-developed notch cut into dead reef in the face of a vertical cliff 30 ft high was found by Richard Grigg to be −150 ft below mean sea level off Lahaina, Maui (Fig. 9). It is herein named the Lahaina Roads shoreline. The notch varies from 3 to 15 ft deep and from 6 to 8 ft high.

The notch lies 30 ft above the base of the cliff that forms the edge of the dead reef. The top of the cliff is the edge of an extensive shelf that lies 120 ft below sea level, possibly indicative of the −120-ft stillstand.

−185-FT PENGUIN BANK SHORELINE

The Penguin Bank −185-ft shoreline was named from the bank 27 mi across off the west end of Molokai Island (Stearns and Macdonald, 1947, p. 14). The bank is apparently an extensive drowned reef which caps a truncated ancient volcano (Stearns, 1946, p. 69). This shoreline and shelf indicate a long halt during one or more glacial epochs because of the vast area of the shelf (115 sq n mi). Observations from submarines indicate that glacial low stands did not bevel such wide platforms. Much black coral is recovered from a shelf at this level in Lahaina Roads. I collected a mollusk (*Acar hawaiiensis*), bryozoa, foraminifera, and a sponge from the base of a black coral "tree" from this shoreline. The tree had living red coralline algae coating it in places and a few living "hammerhead" oysters (*Pteria laciniata*) attached. Hammerhead oysters are reported by the divers to live only on coral trees, and these specimens are only the second ever found in Hawaii (Harry Ladd, 1964, written commun.). Sample W–185 of mixed dead and living coral and algae from the base of the tree had a C^{14} age of 3,570 ± 250 yr B.P., as determined by the U.S. Geological Survey.

Richard Grigg, who dived on the −185-ft shoreline near Lahaina, stated that a well-developed notch occurs in ancient reef at this depth and can be traced for miles undersea. The grade between the −185-ft notch and the −150-ft notch is about 15°. The slope below −190 ft is only about 5° and terminates in a flat at −225 ft. Grigg reported that the common depth of the flat is −240 ft and that there is a flat 3 mi across at this depth between Maui and Lanai and Molokai and Lanai.

The −185-ft shelf is very flat off Makua Valley, Oahu, as seen from a submarine (Brock and Chamberlain, 1968, p. 382). A reflection survey across Penguin Bank indicates that <100 ft of reef and sediments cover a flat basalt basement (Kroenke and Woollard, 1966, p. 13). The basalt basement is interpreted as a rift feature (Malahoff and Woollard, 1965). The stillstand is shown tentatively at the bottom of regression V in Figure 3. However, no evidence exists around Oahu that there was time enough during any of the low stands of the Pleistocene to truncate a volcano as large as Penguin Bank by wave erosion, and so the truncation of the basement apparently predates the Pleistocene. Its very steep southern side indicates faulting.

According to Grigg, the −185-ft shelf off Kaena Point, Oahu, drops off abruptly into deep water. I found the shelf in 7 of the 24 sonar profiles made by Robert Kinzie along the Waianae coast.

−205-FT EWA SHORELINE

Hard, sandy beachrock, which indicated a stillstand, was cored between −203 and −209 ft in Ewa test hole 1 (Stearns and Chamberlain, 1967, p. 158). It is herein named the Ewa shoreline (the hole is near Ewa, Oahu). A deposit consisting of basaltic pebbles and sand was cored between −204 and −208 ft in Ewa test hole 2, doubtless indicating the same stillstand. A beach conglomerate was found at this depth in holes 1 and 8 at Waimanalo, and there it appears to be pre-Yarmouth in age (Lum and Stearns, 1970, Fig. 7). A pronounced solution unconformity was found in the Midway cores at −200 ft, indicating a long exposure of Midway Island above sea level (Ladd and others, 1967, p. 1094). It is unlikely that this buried shoreline can be identified along the present coast.

A hole drilled at Waialua, Oahu, penetrated a peaty layer at −204 ft below sea level, apparently indicating a swamp at sea level during the Ewa stand of the sea. The log was made by Stephen Bowles, who examined the cores and cuttings during the drilling (Table 7). The hole proved that the dunes at this place were not laid down during the 25-ft stand of the sea. The dunes were apparently laid down during the Mamala glacial low when the Laniloa Formation was deposited. I previously stated that the dunes were deposited during the 25-ft stand (Stearns, 1970, p. 50). Beach sand deposits and discontinuities indicate the −60-, −150-, −185-, and −205-ft stands of the sea.

TABLE 6. LOG OF TAYLOR A. PRYOR CESSPOOL

Thickness (ft)	Formation
2	Black clay and slope wash
8	Thin-bedded brown palagonitized basaltic Manana Tuff
1	Friable thin-bedded black ashy Manana Tuff
1	Gray compact Manana Tuff containing tree molds
0 to 1	Subaerial weathered gray clay which fills solution pits in underlying reef limestone
0 to 1	Coarse, calcareous sandstone which fills cavity in underlying reef limestone
2	Reef limestone full of large, upright coral and algae heads in position of growth (extends below sea level)

Note: Top estimated to be 13.5 ft above mean sea level.

−240- ± 10-FT MAKUA SHELF

The −240- ± 10-ft shelf is a ubiquitous shelf in Hawaii and was first seen by Chamberlain (quoted in Stearns, 1966, p. 257) from a submarine along the Waianae coast between Kaena and Kepuhi Points, Oahu. It is hereby named the Makua shelf (from Makua Valley, which discharges in this area). The shelf was found, by seismic reflection profiling, to be present under marine sediments all around Oahu (Campbell and others, 1972, p. 135). The major stream valleys had cut across it before burial by sediments. Soundings on U.S. Coast and Geodetic Survey Chart no. 4139 indicate it is three mi across in Lahaina Roads between Maui and Lanai and between Molokai and Lanai. Grigg reports that it is the shelf below the −185-ft shoreline. The extensiveness of the shelf indicates that it was a reef which grew during a long halt in the Pleistocene. Its position is so uncertain that it is not shown in any of the figures. It may have been the level reached during the Waipio low. The shelf is assumed to be later than the Kaena stand because the reefs of that stand are so extensive they should have buried the −240 ± 10-ft shelf. The sonar profile made by Robert Kinzie off Pokai Bay at Waianae. Oahu, shows this shelf.

−350-FT KAHIPA-MAMALA SHELF

The −350-ft shelf is one of the most extensive undersea shelves in Hawaii (Fig. 10). This low stand of the sea was named the Kahipa of pre-Kaena or pre-Yarmouth age (Stearns, 1935b, p. 1933). Later, I pointed out that the same shelf was occupied by the sea during the Tazewell glacial substage of the Wisconsinan, but no new name was assigned to it for the substage occupancy (Stearns, 1961, p. 8). Much later, the same shelf was named the Mamala (from Mamala Bay near Pearl Harbor [Ruhe and others, 1965, p. 486]). Ruhe and others assumed it was cut by the sea during the last Wisconsinan low. They showed, by the study of 187 profiles of the sea bottom around Oahu, that the shelf is not tilted. There is not much doubt that the sea fell to that level during the Wisconsinan, but to avoid confusion, it was renamed the Kahipa-Mamala shelf (Stearns, 1966, p. 23). Actually, the shelf has a complex history and may have been at sea level during all the glacial epochs.

I examined the Kahipa-Mamala shelf from a submarine off Manana Island and found that it is a drowned reef — not a wave-cut feature—at that place. The submarine traversed the outer edge of the platform for 0.5 mi. It was remarkably uniform in depth and very rocky. Shell fragments and pebbles up to 2 in. across filled low places. No live coralpolyps were seen. The edge of this drowned reef has an overhang

TABLE 7. WAIALUA AGRICULTURAL COMPANY TEST BORING NEXT TO MILL

Depth (ft)	Elevation of bottom (ft)	Description*
0 - 33	8	Brown, sticky, plastic alluvial clay
33 - 59	-34	Cemented calcareous dune sand; moderate permeability; water struck at about 25 ft (goes 34 ft below sea level; hence, Laniloa Formation)
59 - 69	-44	Gray, marine clay, thin layer of organic material at 59 ft (−60-ft stand)
69 - 164	-139	Brown, alluvial clay
164 - 166	-141	Compact, unconsolidated, calcareous sand†
166 - 174	-149	Brown, alluvial clay
174 - 176	-151	Compact, unconsolidated, calcareous sand† (−150-ft stand?)
176 - 184	-159	Brown, alluvial clay
184 - 187	-162	Compact, unconsolidated calcareous sand†
187 - 194	-169	Brown alluvial clay, thin gravel lens at 192 ft
194 - 195	-170	Compact, unconsolidated, calcareous sand†
195 - 199	-174	Brown alluvial clay, thin gravel lens at 195 ft
199 - 204	-179	Compact, unconsolidated, calcareous sand† (−185-ft stand?)
204 - 229	-204	Brown alluvial clay; thin layer of organic material at -228 ft (−205-ft stand)
229 - 230	-205	Coarse conglomerate of basalt cobbles; matrix lime cemented; impermeable (just above basalt?)

Note: Mill elevation, approximately 25 ft. Log by Stephen Bowles, April 1972.
** Notes in parentheses by H. T. Stearns.*
† Not dune sand, according to Bowles.

of 8 to 10 ft; it then drops off to −450 ft with a slope of 20° to 60°. The base elevation at −450 ft has been assumed by some scientists as the maximum drop of sea level during the Pleistocene (Donn and others, 1962). The face is rough limestone and very cavernous. In one place, a narrow, deep ravine cuts the cliff. The shelf surface changes to a 10° slope below the cliff, flattens to 5° above the rim, and becomes covered with sediment inland. No evidence of wave-cutting, potholes, beach cobbles, or other features typical of the −60- and the −120-ft shorelines was seen. The reef may have died during each of the glacial highs, become recolonized with coral-polyps, and grown again during each of the glacial lows in spite of cooler temperatures.

−1,200- TO −1,800-FT LUALUALEI SHELF

The −1,200- to −1,800-ft shelf is thought to be a coral reef submerged to this depth by subsidence of Oahu. It was correlated with the long stillstand when the valleys were cut in the Waianae Range and named after Lualualei Valley (Stearns, 1935b, p. 1932). It forms a shelf 6 mi wide south of Diamond Head, Oahu, as shown in Figure 10.

A reflection survey across the shelf shows

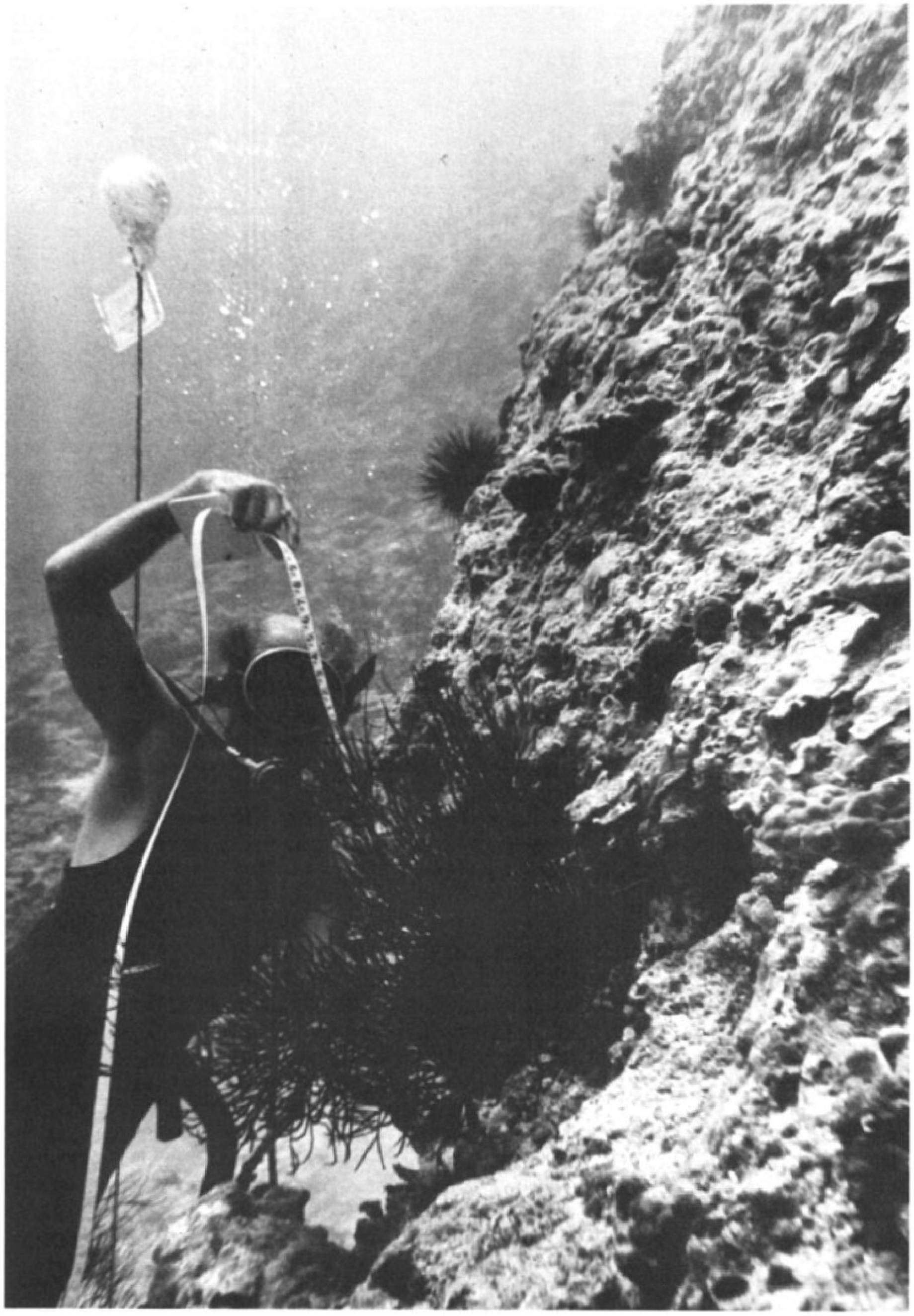

Figure 9. View of black coral "tree" in notch in dead reef made by the −150-ft stillstand in Lahaina Roads off the coast of Maui. Photo by Richard Grigg.

that it has 250 to 350 ft of sediment capping an extensive flat basement of volcanic rock (Kroenke and Woollard, 1966, p. 11). Kroenke and Woollard's description follows:

The reflection records reveal a typical barrier-reef profile with long gently rising slopes to the crest at the southern margin and steeply dipping fore-reef slopes seaward to the south. Back-reef deposits appear locally to be highly stratified. An extensive "lagoonal" facies contains many coherent reflecting horizons and probably represents an admixture of reef detritus, marls, and sediments derived from Penguin Bank, Molokai, and from Oahu. Locally, structures interpreted as large patch reefs are found interrupting the stratigraphic continuity close to Oahu.

Fossil shallow-water coral specimens dredged from the terrace south of Pearl Harbor were thought to support an age not younger than late Miocene (Tertiary g) (Menard and others, 1962, p. 896). However, E. C. Allison, a joint author, in a letter to me (dated March 9, 1964), questioned his assignment of the fossil coral to the Miocene. Ralph Moberly (1973, oral commun.) stated that none of the fossils he has dredged from this shelf are Miocene. The commercially valuable pink, gold, and bamboo coralpolyps live on the −1,200-ft shelf. The shelf has been examined many times by Richard Grigg in a submersible. According to Grigg, it appears to have a karst topography off Hanauma Bay. If we accept McDougall's (1964) K-Ar dates for the Waianae lavas, all the Waianae volcanic rocks are Pliocene. Because Lualualei Valley is cut deeply into the Waianae lava, it must have been cut in late Pliocene prior to later deep submergence. Lualualei Valley cannot be traced offshore as a submarine valley across the Lualualei shelf; hence, the Lualualei shelf, which is a submerged reef, must have grown later than the submerged valley or in late Pliocene.

Macdonald and Abbott (1970, p. 209) did not recognize this sequence when they guessed that Lualualei Valley had been cut to a depth of −1,300 ft. They named a hypothetical shoreline the Waianae stand. Because ancient shorelines must be identified by beach conglomerate in place or by definite horizontal notches, the −1,300-ft shoreline is omitted here as a valid stand of the sea. Furthermore, Lualualei Valley must have been cut to a sea level much lower than −1,300 ft. It must have been cut at least as low as the Waho Shelf at −3,000 to −3,600 ft (Stearns, 1966, p. 23) and, doubtless, even deeper.

Ruhe and others (1965, p. 489) proposed possible tilting of the Lualualei shelf. However, different amounts of sedimentation on the shelf may account for its variation in depth (Brock and Chamberlain, 1968, p. 381). Brock and Chamberlain, who worked in a submarine, said, ". . . it would be almost impossible to fix the depth of the inshore edge of the Lualualei shelf by means of echo soundings: the sand and talus deposits are probably tens of feet in thickness and completely bury the inner portion of the shelf."

−3,000- TO −3,600-FT WAHO SHELF

The most striking feature on the ocean floor in the Hawaiian Islands is the broad shelf between −3,000 and −3,600 ft. I named it after the last two syllables of Kaieiewaho Channel. The channel crosses the shelf off the western tip of Oahu where the shelf is 40 mi across (Stearns, 1966, p. 17). Waves cannot cut platforms this wide in hard lava rock unless the sea level is fluctuating over many millions of years within the range of the bench level. Sedimentation or very slow sinking of the islands and concurrent sedimentation and marine abrasion are the most likely causes for its flatness.

Drilling into coral atolls in the central Pacific showed the presence of extensive flat banks of Miocene marine sediments. Midway Island has Miocene sediments at a depth of 462 ft (Ladd and others, 1967, p. 1093) and Schreiber (1969, p. 2601) showed that the Hawaiian chain was above sea level as long ago as the Eocene. A hole should be drilled into the shelf to determine its geologic structure. The shelf is the site of large deposits of manganese nodules (Andrews, 1972).

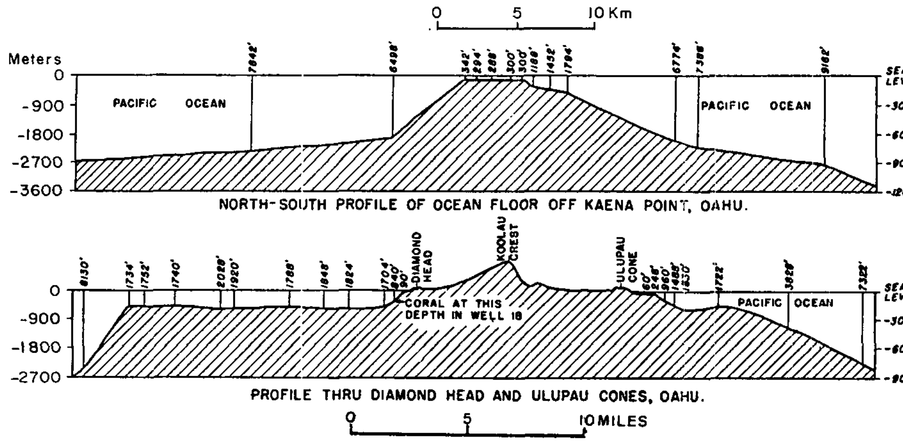

Figure 10. Profiles showing the 300±- and 1,800±-ft submarine shelves off Oahu.

CONCLUSION

Submarine shorelines below sea level left by stillstands during the Pleistocene regressions and transgressions are well preserved. Those at −60, −80, −120, −150, −185, −240±, and −350 ft are glacioeustatic stillstands. The −30-ft shelf and −205-ft beach conglomerate were found in drill holes. Data are given to show that the −60- and −120-ft shelves are Wisconsinan in age. None are tilted. Shelves at −1,200 to −1,800 and −3,000 to −3,600 ft are Pliocene and Miocene(?) drowned reefs that cap truncated basalt platforms.

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