Pacific Science (1992), vol. 46, no. 3: 295–307

Hawaiian Quaternary Paleoenvironments: A Review of Geological, Pedological, and Botanical Evidence[1]

ROBERT T. GAVENDA[2]

ABSTRACT: Climates in Hawaii during glacial periods were relatively wetter and cooler than interglacial climates. Eolian deposits indicate that northeasterly trade winds predominated during glacial periods. Orographic rainfall patterns were probably similar to those of today except that they were shifted downward in response to lowered sea levels and a depressed inversion level. Botanical evidence indicates that some areas probably received more than double their current annual rainfall. Greater rainfall during glacial periods was probably responsible for the formation of highly weathered soils that are now in semiarid climates. More intense periglacial processes may have operated during glacial periods. Snowline on Mauna Kea was depressed about 900 m and glaciation may have occurred because of lower air temperature and greater cloudiness. Ocean temperature was probably also slightly cooler. At low elevations, interglacial climates were drier than glacial climates because of the influence higher sea levels had on orographic rainfall distribution. Trade winds still predominated but the inversion level was higher, which may have caused greater rainfall at high elevations. Pedological evidence indicates a highly erosive environment before the formation of the Kaena shoreline at about 650,000 yr ago. Climatic conditions at that time are not known. Subsequent environmental conditions have not been as conducive to erosion, and the past several hundred thousand years have witnessed relative landscape stability.

THE EVIDENCE FOR former climatic regimes on a worldwide scale is so compelling that Wright and Frey (1965) have considered climatic change to be the "dominating circumstance" of the Quaternary. Although paleoclimates of the middle and high latitudes and continental glaciation have been studied extensively, only recently have the various impacts of paleoclimates in the tropics received much attention (Street 1981).

The evidence of paleoenvironments in Hawaii includes geologic deposits and landforms, relict soils, and fossil plant remains. Some evidence indicates the direction and/or magnitude of climate change. Other geologic and pedologic features have poor time constraints or can be explained by conditions other than former climatic regimes.

Very little research has been conducted with the intent of elucidating former climatic regimes in Hawaii. The intent of this paper is to summarize the geological, pedological, and botanical research conducted in Hawaii that sheds light on former climatic regimes. This is not an in-depth review of each discipline but an attempt to pull together widely scattered information and to integrate the information on paleoclimatic regimes to the extent that the evidence permits.

Present Hawaiian Climate

Price (1983) characterized Hawaii's climate as the interaction of latitude, the surrounding ocean, the islands' terrain, and Hawaii's location relative to the storm tracks and the Pacific anticyclone. These factors produce a mild

---

[1] Manuscript accepted 27 August 1991.

[2] Department of Agronomy and Soil Science, University of Hawaii at Manoa, 1910 East-West Road, Honolulu, Hawaii 96822.

climate with moderate humidity at low elevations, persistent northeasterly trade winds, infrequent severe storms, and considerable variation in rainfall and temperature as influenced by topography. Using a modified Thornthwaite system, Jones and Bellaire (1937) identified a total of 15 climatic regimes on Kauai, Oahu, Maui, and Hawaii. All rainfall types except E (arid) and all temperature types except F′ (perpetual frost) are found on the island of Hawaii.

A nearly uniform daylength throughout the year is one factor that causes low seasonal variation in air temperature (Price 1983). In addition to supplying moisture to the air, the ocean moderates air temperatures in Hawaii. The seasonal extremes in sea surface temperature range from 22°C in March to 26°C in October. The extremes in average monthly means for air temperatures coincide with the extremes in sea surface temperature, indicating the overriding importance of the ocean in controlling air temperatures.

During the summer months the Pacific anticyclone dominates and produces the persistent northeasterly trade winds (Price 1983). As these winds rise in response to the topography, they cool and the moisture they carry precipitates, producing orographic rainfall patterns where rainfall increases rapidly from the coastlines to the mountaintops. On the low islands (below 1500 m elevation), the maximum rainfall occurs immediately to the lee of the mountain crests. The temperature inversion, which characterizes the trade wind periods, limits the highest convective clouds to about 2100 m. Mountains between 1500 and 2100 m elevation receive maximum rainfall near their summits. The mountains that rise above the inversion receive their maximum precipitation between 900 and 1300 m, whereas the mountaintops are semiarid. Isohyetal rainfall maps of Hawaii have been compiled by Giambelluca et al. (1986).

Similar rainfall patterns occur in the winter, but cyclonic storm rainfall occurs when the southerly portions of frontal systems pass over Hawaii (Leopold 1951). There is a marked correlation between winter precipitation and the latitude and speed of the jet stream (Yeh et al. 1951*a*). Under the current circulation patterns, winter precipitation is due as much to the increase and intensity of trade wind rain as it is to the increased frequency of cyclonic rain (Yeh et al. 1951*b*).

In summary, the present Hawaii climate is characterized by an orographic-convective cell that produces localized, intensive rainfall centers from trade winds near mountain summits that serve as focal points for rainfall activity regardless of wind direction (Ruhe 1964).

Geological Evidence of Paleoclimates

SEA LEVEL FLUCTUATIONS. Former climatic regimes have had the greatest impact on Hawaiian geology through glacio-eustatic fluctuations of sea level. These fluctuations were the result of global climatic changes that caused water either to be removed from the oceans and tied up in advancing glaciers or to be released into the oceans as retreating glaciers melted. Sea level fluctuations resulting from tectonic activity are without climatic significance other than how raising or lowering a landmass may influence weather patterns.

Numerous papers have documented emerged and submerged reef deposits in the Hawaiian Islands (Stearns and Vaksvik 1935, Stearns 1935, 1961, 1974, 1978, Ruhe et al. 1965*a*, Coulbourn et al. 1974). Stearns (1978) summarized the various relict shorelines in the Hawaiian Islands (Figure 1). The shorelines range in elevation from about −1100 to +365 m. Information on the principal shorelines is presented in Table 1.

TABLE 1

SUMMARY OF ELEVATIONS AND AGES OF THE PRINCIPAL SHORELINES IN THE HAWAIIAN ISLANDS

SHORELINE	ELEVATION (m)	AGE*
Mamala	−106	12
Waimanalo	+7.5	125
Waipio	−106	Illinoian
Kaena	+30	650

Source: Stearns 1978.

* Thousands of years ago.

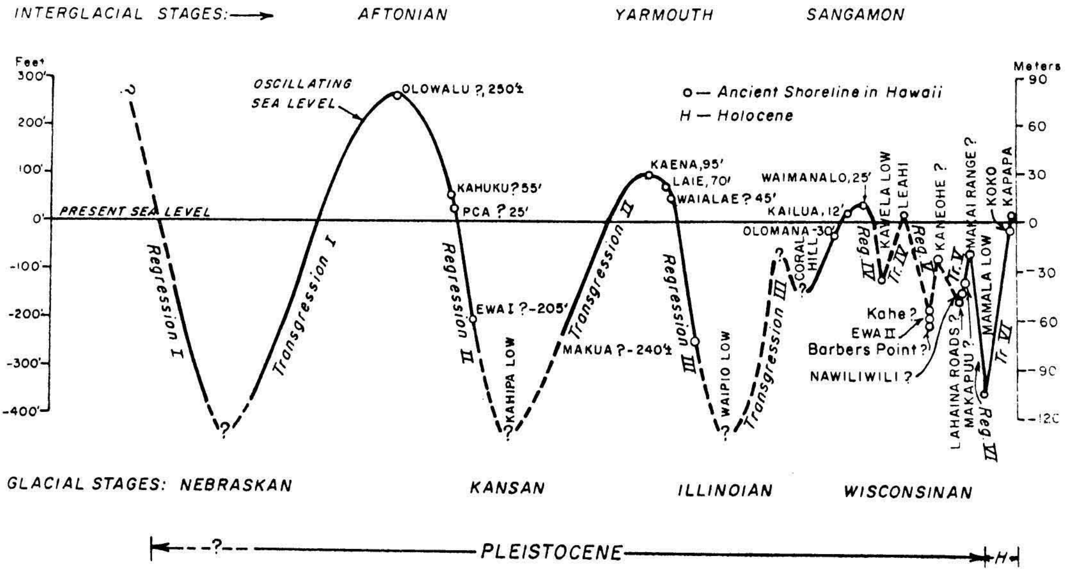

FIGURE 1. Graphic representation of glacio-eustatic sea level fluctuations and shorelines as proposed by Stearns (from Stearns 1978, fig. 1, reprinted by permission of Bishop Museum Press).

Glacio-eustatic level could be lowered by about 130 m during a glacial maximum and could be raised about 43 m if all existing glacial ice melted (Donn et al. 1962, Flint 1971). The alleged shorelines above 43 m are problematical because they lie above the theoretical sea level during an intense interglacial period. Because subsidence is the dominant tectonic activity in Hawaii (Moore 1987), it seems unlikely that tectonic uplift is responsible for shorelines above 43 m. Very large tsunamis due to debris avalanches could leave deposits that could be mistaken for shorelines (Moore and Moore 1984, Lipman et al. 1988, Moore et al. 1989). Ku et al. (1974) thought that shorelines between 7.6 m and current sea level could have been formed by storm waves or weathering unrelated to glacio-eustatic sea levels. The sequence of submarine terraces off Oahu is so complicated that Coulbourn et al. (1974) expressed doubts that the history of Hawaiian Quaternary sea levels can be unraveled. The picture is complicated by tectonic activity, which can alter the position of reefs (Moore and Fornari 1984).

Stream terraces along Kalalau Stream, Kauai, and Iao Stream, Maui, are examples of alluvial deposits that were graded to a high sea level (probably the Kaena +30 m) during an interglacial period and were subsequently eroded when sea level lowered. Waimea Valley on Oahu is an example of a stream that was incised during a low stand of the sea (probably −100 m) and was then filled with sediment as the sea rose to its present level. The lochs of Pearl Harbor are stream valleys that were cut when sea level was lower, then drowned as sea level rose (Stearns and Vaksvik 1935). Subsidence of the Pearl Harbor area was responsible for some changes in base level (Macdonald et al. 1983), but at least the last major cycle of alluviation and erosion was probably caused by glacio-eustatic sea level changes.

Regardless of the cause, sea level fluctuations around Hawaii have resulted in the relative raising or lowering of the existing topography relative to the orographic-convection cells produced by the trade winds (Ruhe 1964, 1965, 1975). Equations that quantitatively describe precipitation relative to elevation and distance from the summit on the leeward Koolau Range have been derived from meteorological statistics that character-

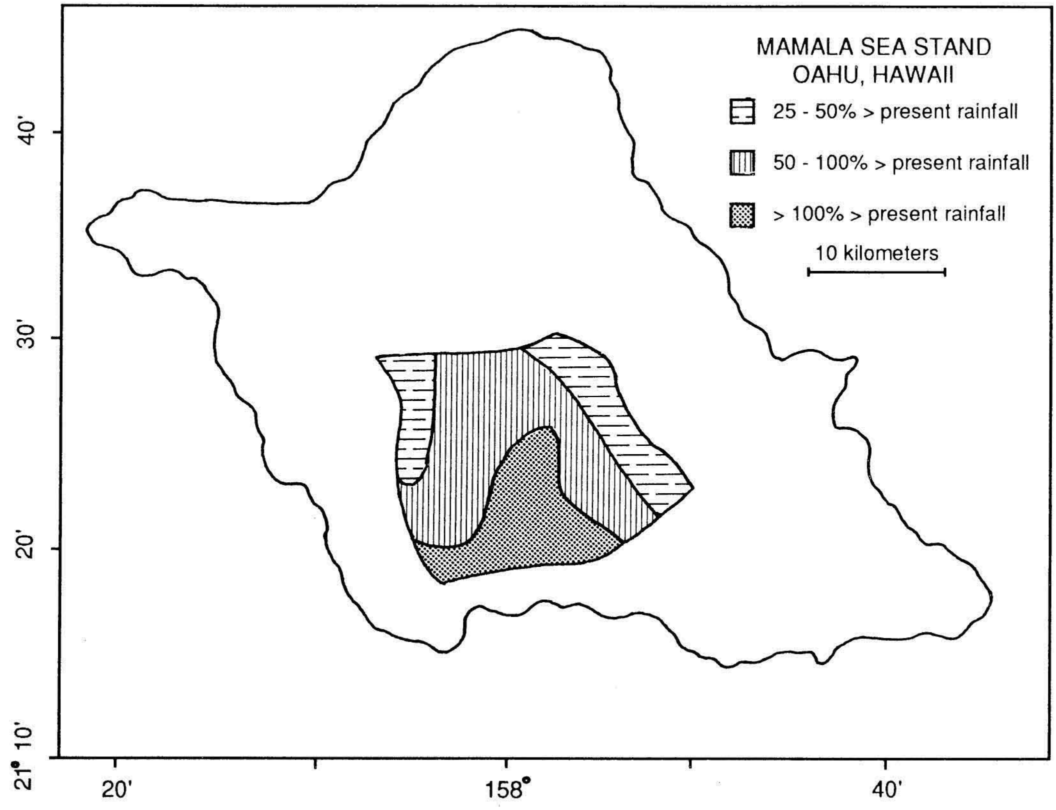

FIGURE 2. Estimated rainfall relative to present rainfall during the Mamala, −106 m, sea stand, Oahu, Hawaii (modified from Ruhe 1964, fig. 3. Reprinted by permission of American Journal of Science).

ize the present climate on Oahu (Ruhe 1964). These equations predict that a lowering of sea level by 100 m could have produced more than a 100% increase in rainfall (relative to present rainfall) in parts of the Wahiawa Basin (central Oahu) (Figure 2). A 30-m rise in sea level may have caused a 50% decrease in rainfall in some areas (Figure 3).

WIND DIRECTION DURING GLACIAL PERIODS. The main assumption underlying Ruhe's (1964) paleoclimate estimates is that the general circulation pattern during both glacial and interglacial periods basically resembled that of today. That is, precipitation related to trade winds is responsible for most rainfall. The orientation of lithified sand dunes and their occurrence below current sea level indicate that they formed during a glacial low stand of the sea and that northeasterly trade winds predominated at that time (Stearns 1940, 1947, Stearns and Macdonald 1942, 1947, Macdonald et al. 1960).

The persistence of northeasterly trade winds during glacial periods is also shown by the asymmetrical morphology of pyroclastic cones on Oahu. The southwestern rim of most of these cones is higher than the northeastern rim because trade winds carried the pyroclastics toward the southwest (Wentworth 1926). Ulupau Head (Kahipa stand) and Diamond Head (Waipio stand) (Winchell 1947) are two prominent examples of asymmetrical cones deposited during low sea levels. Orientation of sand dunes at the Mauna Kea–Mauna Loa saddle, and tephra plumes

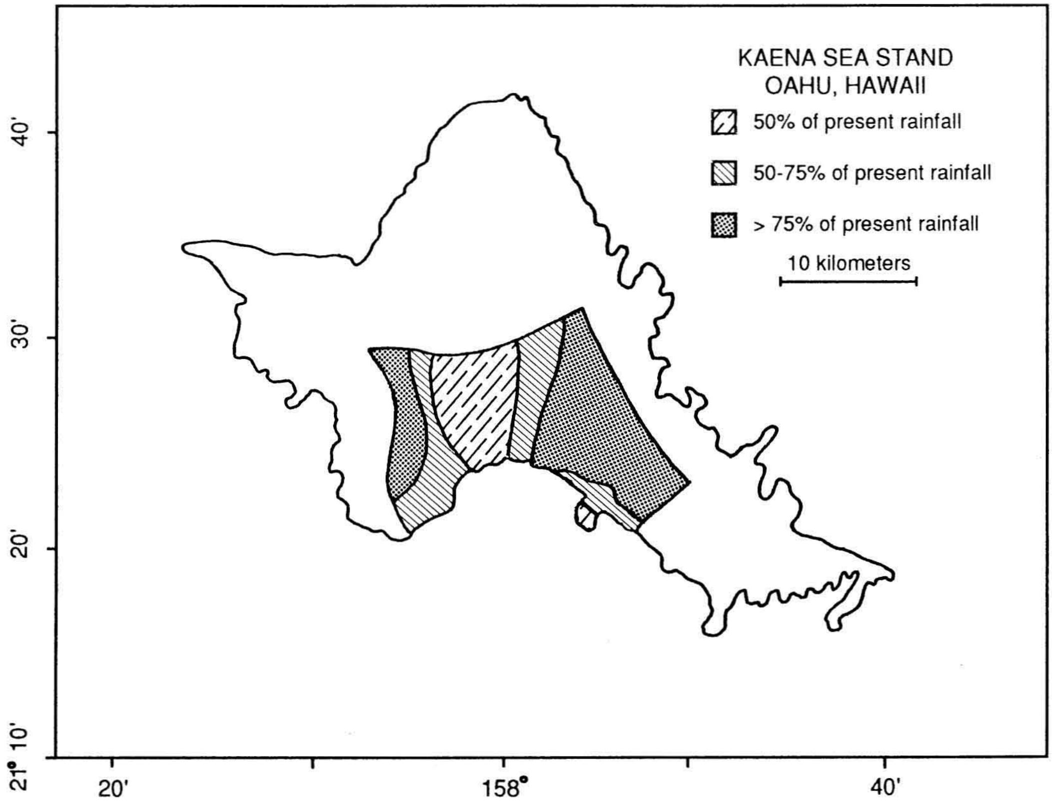

FIGURE 3. Estimated rainfall relative to present rainfall during the Kaena, +30 m, sea stand, Oahu, Hawaii (modified from Ruhe 1964, fig. 4. Reprinted by permission of American Journal of Science).

on Mauna Kea also indicate a northeasterly trade wind pattern during the middle of the last glacial period (Porter 1979).

Molina-Cruz (1977) interpreted abundances of pelagic quartz, opal, and radiolarian assemblages as indicating increased trade wind velocity in the equatorial Pacific during glacial periods. The grain size of pelagic eolian sediments indicates greater variability in wind velocity in the central equatorial Pacific prior to 300,000 years ago (Chuey et al. 1987). A general correlation between glacial maxima and increased wind velocity is also indicated by these sediments.

GLACIAL CLIMATIC PATTERNS. Climate-sensitive marine sedimentary parameters indicate climatic fluctuations across the equatorial Pacific during the Quaternary (Valencia 1977). The CLIMAP Project members (1976) concluded that during the last glacial maximum polar frontal systems were displaced toward the equator, and the central gyre of the subtropical Pacific maintained nearly stable position and temperature. A computer simulation model of a tropical climate during a glacial period (Manabe and Hahn 1977) predicted that the zonal mean rate of precipitation over oceans at 5°–30° N latitude would be considerably greater as compared with the present climate. The model also predicted glacial period aridity in continental areas and this is supported by geological evidence (Damuth and Fairbridge 1970, Williams 1975, Street and Grove 1976).

OCEAN TEMPERATURE. CLIMAP Project members (1984) reported that the last interglacial sea surface temperature of about 125,000 yr ago was probably very similar to present sea surface temperature. Research on marine fauna by the CLIMAP Project members (1976) indicated that August sea surface temperatures near Hawaii during the last glacial maximum were about 1–2°C cooler than today. Fossiliferous strata of the Ewa coastal plain do not indicate that Pleistocene climatic fluctuations had any specific effect on reef and lagoonal microfauna (Resig 1969).

Gregory and Wentworth (1937) claimed that alternating cool and warm climates have left their mark on the floral and faunal composition of coral reefs, and they stated that various lines of evidence show that glacial ocean temperature around Hawaii was between 13°C and 20°C. They did not present supporting evidence for either assertion.

TOPOGRAPHY-INFLUENCED RAINFALL. East Molokai, which now receives about 3000 mm of rain annually, may have received over 12,000 mm of rainfall annually before subsidence of the island (Stearns and Macdonald 1947). Before the summit of the Koolau Range, Oahu, was lowered by erosion, the northwestern part of the range was more sheltered from trade wind rains than now (Stearns and Vaksvik 1935). The relatively youthful stream development stage in that part of the range, furthermore, may be relict from a time when the trade winds were more easterly than at present. Before its lowering by erosion and subsidence, the summit of the Koolau Range may have been about 1500 m high and it may have received double its present rainfall (Stearns and Vaksvik 1935). The large valleys of the leeward Koolau Range were incised during that period of higher rainfall.

INVERSION LEVEL. Stearns (in Stearns and Macdonald 1942), writing about the formation of Haleakala Crater, Maui, thought that the "erosion of the loosely knit cinder cones and lavas of the summit was probably accelerated by more precipitation there during the warm interglacial epochs than at present." The sum of the evidence reviewed in this paper indicates that glacial periods in Hawaii were probably wetter than interglacial periods (at least at low elevations), but the inversion level may have been higher during interglacial climates (cf. Selling 1948), which may have allowed more precipitation to reach the Haleakala summit.

MAUNA KEA GLACIATION. On Mauna Kea, the only summit in the tropical mid-Pacific Ocean Basin to show evidence of glaciation, there are four glacial drift sheets (Wentworth and Powers 1941, Porter 1979). The oldest and largest of these glaciations began about 280,000 yr ago and covered an area of nearly 150 km^2 (Porter 1979). Glaciation on Mauna Kea may have been due to an increase of winter snowfall and a decrease in ablation rates resulting from lower air temperatures and increased cloudiness.

Based on the extent and thickness of the most recent ice cap on Mauna Kea, Porter (1979) estimated the equilibrium line altitude (ELA) of the glacier under steady state conditions. The ELA marks the point on a glacier where the net mass balance is zero. This climate-sensitive parameter is dependent on various accumulative and ablation-related processes. When the ELAs for the four glaciations are corrected for the subsidence of the island, a picture of the relative drop in temperature for the four glacial periods emerges. A comparison of these ELAs with oxygen isotope ratios and eustatic sea level fluctuations shows a close correlation.

From the ELAs, Porter (1979) estimated that the snowline during the last glacial maximum was depressed about 935 m. If snowline depression was only due to a reduction of air temperature, and lapse rates were similar to those of today, then July temperatures near the summit of Mauna Kea would have been about 5°C lower during a glacial maximum. If mean air temperatures were only reduced 1–2°C (such as the change in ocean temperature) then an increase in precipitation would be required to account for glaciation on Mauna Kea. Other researchers (e.g., Krauss 1973) believe that a slight cooling of tropical surface waters amplifies the cooling of air at higher elevations. In a computer simulation of the effects of tropical deforestation (which might be analogous to the reduction of rainforest area during glacial periods), Potter et al. (1975) found that their model predicted a steepening of lower troposphere lapse rates. If this were the case, then there would be no need to invoke greater amounts of precipitation to explain the glaciations on Mauna Kea.

PERIGLACIAL FEATURES. Porter (1979) reported solifluction lobes covering a postglacial soil above 3300 m on Mauna Kea, which indicates a change to unstable slope conditions. Solifluction activity in association with an archeological site at 3790 m on Mauna Kea indicates that solifluction has been an active process for all or part of the past 800 yr. Gregory and Wentworth (1937) documented other periglacial features on Mauna Kea.

Noguchi et al. (1987) observed small stone stripes near the summit of Haleakala and attributed them to active periglacial processes. A former, more severe periglacial environment is suggested by even larger stone stripes and stone-banked terraces near the Haleakala summit (Noguchi et al. 1987).

Pedological Evidence of Paleoclimates

BURIED SOILS. The occurrence of buried soils, especially between basalt flows, has been reported in the geologic literature of Hawaii. For example, Stearns (1947) described a highly weathered soil buried by lithified dunes of pre-Waimanalo age. In general, insufficient information is given in these geologic references to make paleoclimatic inferences. Beckmann (1963) attempted to deduce paleoclimatic conditions from buried soils in central Oahu but conceded that the main obstacle in his reconstructions was the problem of separating the effects of climate and time.

SOILS OF THE PEARL HARBOR AREA AND THE WAHIAWA BASIN. In the Pearl Harbor area, Oahu, formation of parent materials, changes in topography and vegetation, and duration of exposure to subaerial weathering were all affected by glacio-eustatic sea level fluctuations during the Quaternary (Ruhe 1965). The relative height of the Koolau Range, as influenced by sea level fluctuations, probably affected the amount of rainfall received and the distribution of vegetation (Ruhe 1964). The pattern of soils in the Pearl Harbor area reflects the complex interaction of these factors of soil formation.

The lower end of the Wahiawa Basin above Pearl Harbor is marked by a sea cliff formed during the Kaena +30 m stand of the sea of about 650,000 yr ago. The soils above this cliff are highly weathered and are classified as Oxisols (Foote et al. 1972). Below the cliff the soils are developed in alluvium and marine clay (Ruhe et al. 1965*b*) and are classified as Inceptisols, Mollisols, and Vertisols, indicating a less-weathered mineralogy. All of these soils now occur in a semiarid climate. Sherman and Alexander (1959) postulated that the highly porous nature of the basalt and/or volcanic ash parent material of the Oxisols allowed the formation of these soils under this semiarid climatic regime. Uehara and Sherman (1956) considered the possibility of an ash parent material, but they also postulated that the Oxisols may have formed under a wetter climate.

The apparently incongruous occurrence of Inceptisols, Mollisols, and Vertisols adjacent to Oxisols can be explained by the geologic and climatic history of the Pearl Harbor area. Whereas the Inceptisols and Mollisols developed in basaltic alluvium and the Vertisols developed in marine clay (Ruhe et al. 1965*b*), recent research (Gavenda 1989) has shown that soil derived from volcanic ash forms the upper portion of the highly weathered soils of the Wahiawa Basin. According to Ruhe et al. (1965*b*), the Oxisols are developed on pre-middle Pleistocene surfaces. The Vertisols are developed in marine clay deposited during Kaena time, and the Inceptisols and Mollisols are developed in alluvial deposits that are post-Kaena in age. The Oxisols were exposed for a longer duration and to more climates that were wetter than those that the other soils experienced.

The montmorillonitic mineralogy in the Vertisols of the Ewa coastal plain is inherited from basaltic detritus that underwent little diagenic alteration while in the marine environment (Ruhe et al. 1965*b*). Hussain and Swindale (1974) postulated that the high water table in these soils is promoting the formation of montmorillonite. The persistence and/or formation of montmorillonite during one glacial and two interglacial climates indicate that conditions conducive to the alteration of montmorillonite to kaolinite have not existed for any great period of time on the Ewa coastal plain since the transgression of the Kaena sea. Impeded drainage, however, rather than dry climates, may be responsible for the persistence of montmorillonitic mineralogy.

PALEOSOLS AND EROSION SURFACES. The soils of the Wahiawa Basin are composed of three distinct layers (Gavenda 1989). Below a layer of topsoil is a layer of volcanic ash–derived soil. The lowest layer is a truncated paleosol that contains an argillic horizon (i.e., a subsoil characterized by an accumulation of clay translocated from higher in the soil profile). Argillic horizon formation is promoted by alternating wet and dry soil conditions rather than continuously wet or dry conditions (Eswaran and Sys 1979). A seasonally wet and dry soil moisture regime occurs over much of central Oahu today. The ash-derived soil overlying the paleosol, however, has minimal expression of clay translocation, whereas clay translocation in the truncated paleoargillic horizon is strongly expressed, especially in the old Waianae alluvium.

The erosion surface (truncated paleosol) and the ash-derived soil predate the Kaena shoreline (650,000 yr ago) because neither the erosion surface nor the ash mantle is known to occur below it. There should have been sufficient time for an argillic horizon to form if conditions were favorable. Perhaps the climate since Kaena time has been too dry to produce much clay translocation. On the other hand, the minimal argillic expression in the ash-derived soil could be due to poor dispersion of the soil, which inhibits the translocation of the clay minerals.

The erosion surface that truncates the paleoargillic horizon in central Oahu appears to have been caused by a basin-wide event when stream channels on the leeward Koolau slopes were in their early stages of entrenchment (Gavenda 1989). An erosion surface has also been observed in soils on Molokai and Lanai (Gavenda, unpublished data) and has also been reported on Kauai, Maui, and Hawaii (R. V. Ruhe, unpublished data). Some of these surfaces may be contemporaneous, the result of a regional climatic regime conducive to erosion.

The botanical evidence (Lyon 1930) and paleoclimate models (Ruhe 1964, Manabe and Hahn 1977) indicate that glacial periods were wetter than interglacial period in the Salt Lake area, Oahu. Vegetative cover on the Wahiawa Basin was therefore probably more dense during glacial periods, which suggests that the erosion surface was created during a semiarid interglacial period when there was insufficient vegetative cover to reduce run-off.

The soils of the Wahiawa Basin record other erosional events that took place after the formation of the pre-Kaena erosion surface. In the soil exposure along Kunia Road north of Huliwai Gulch there are two ash deposits that rest on the pre-Kaena erosion surface (Figure 4). These deposits are separated by an erosional unconformity, and both deposits are truncated below the present topsoil, which formed in tropospheric dust (Gavenda 1989).

The topsoils in the Wahiawa Basin contain a considerable amount of tropospheric dust that originates from continental Asia (Rex et al. 1969, Jackson et al. 1971, Dymond et al. 1974). At an accumulation rate of about 1 mm per 1000 yr, 200 mm of topsoil consisting of relatively unmixed dust indicates that the geomorphic surfaces of the Wahiawa Basin have been accumulating dust, and have therefore been stable, for at least several hundred thousand years. There have been one or more glacial/interglacial cycles since the start of dust accumulation, but this series of climates did not produce the massive erosion that occurred in pre-Kaena time.

SOIL STRIPPING. Stearns attributes "soil stripping" at relatively high (>75 m) elevations on Molokai, Lanai, Kahoolawe, and Maui to marine erosion during high stands of the sea (Stearns 1940, 1947, Stearns and Macdonald 1942, 1947). As discussed earlier, it is highly unlikely that high interglacial seas exceeded about 40 m elevation. The erosion

FIGURE 4. Exposure of soil along Kunia Road north of Huliwai Gulch, Oahu. The truncated paleosol developed in old Waianae alluvium is at a depth of about 1 m. The paleosol is overlain by two ash deposits, which are separated by an erosional unconformity. Both of these ash deposits were truncated and are mantled by aerosolic dust from continental Asia.

that Stearns described can be accounted for by giant tsunamis, exceptional subaerial erosion under former climatic regimes, or orographic climate/vegetation patterns similar to those under persistent northeasterly trade winds.

Botanical Evidence of Paleoclimates

FOSSIL POLLEN. Palynological evidence from Africa, South America, and New Guinea demonstrates that equatorial vegetation has not been immune to the climatic fluctuations of the Quaternary (Flenley 1979). In Hawaii, Selling (1948) examined the pollen found in the mountain mires of Kauai, Molokai, and Maui. The pollen represents only mountain vegetation because pollen of lowland species does not appear in the montane peat. The bogs and swamps that contain the pollen range in elevation from 1200 to 1765 m and currently receive high precipitation (ca. 5000 mm/yr). Selling recognized three major pollen zones (Figure 5).

Zone I pollen accumulated during the last glacial period and is characterized by a dominance of xerophytic subalpine species, with rainforest vegetation being more restricted than at present. Selling interpreted this distribution of plants as indicating the depression of the inversion layer. This interpretation basically agrees with Porter's (1979) estimate of treeline depression on Mauna Kea to an altitude of 2000 m during that time.

Selling's Zone II pollen reflects the dominance of rainforest vegetation. Zone II pollen was interpreted as representing the period of maximum postglacial warmth when rainforest vegetation and the inversion level probably extended several hundred meters higher than today. Zone II was also interpreted to be a time of pronounced trade wind rains and possibly high rainfall.

Zone III represents the change in vegetation to its present composition. Rainforest vegetation is not well represented, but conditions are not as dry as conditions represented by Zone I pollen. Selling's interpretation is that

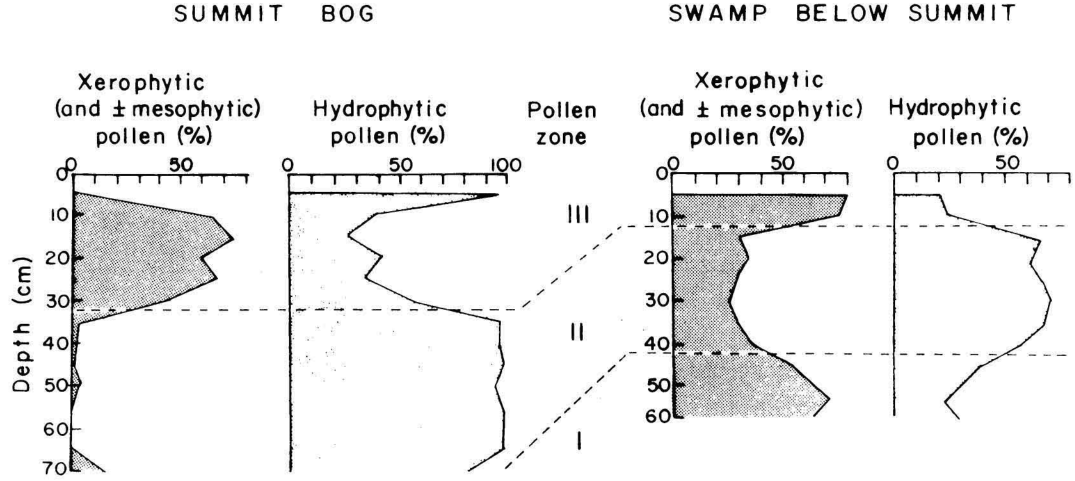

FIGURE 5. Pollen diagrams and zones from bog sediments at about 1700 m on West Maui volcano (from Porter 1979, fig. 15; data from Selling 1948, pl. 24 and 25. Reprinted by permission of the author, Bishop Museum Press, and Academic Press).

the inversion layer is lower than it was during Zone II, and the vegetation displacement may be due to increased trade wind rains. The more xerophytic vegetation representing Zones I and III may indicate the decreased influence of the North Pacific high-pressure area.

Bennett (1985) examined the fossil pollen preserved in nearshore marine sediments on the Ewa coastal plain but did not attempt a paleoecological reconstruction because of uncertainty regarding the source area of the pollen.

BURIED PLANT REMAINS. The Salt Lake Tuff was deposited during the Waipio (350,000 yr ago) low stand of the sea (Hay and Iijima 1968). The tuff contains many fossil plants found in an upright position, which indicates that they were not transported there by stream action. A total of fifteen species including koa, ohia, and loulu palm has been identified (Lyon 1930). These trees, which are found in high rainfall areas today, were collected from an area that now receives 500 mm of rain annually. Based on paleoclimatic estimates of Ruhe (1964), rainfall in the Salt Lake area at the time of tuff deposition could have been 1000 to 1750 mm annually.

Easton (1987) reported that lava intercalated with and immediately overlying Pahala ash and Pohakaa ash on Kilauea Volcano contains molds of tree ferns. He stated that an annual rainfall of 2000 mm is needed for fern forests, but this area now receives only 500 mm per year. This indicates that the climate was wetter at the time of ash deposition. Because the bulk of Pahala ash was deposited between 24,000 and 10,000 yr ago, this may also indicate that glacial climates in Hawaii were wetter than interglacial climates.

LITERATURE CITED

BECKMANN, G. G. 1963. The genesis of certain Hawaiian palaeosols and their alteration following burial. Ph.D. diss. University of Hawaii at Manoa, Honolulu.

BENNETT, T. M. 1985. Palynology of selected horizons from the Ewa coastal plain, Oahu, Hawaii. M.S. thesis. University of Hawaii at Manoa, Honolulu.

CHUEY, J., D. REA, and N. PISIAS. 1987. Late Pleistocene paleoclimatology of the central equatorial Pacific: A quantitative record of eolian and carbonate deposition. Quat. Res. 28:323–339.

CLIMAP PROJECT MEMBERS. 1976. The surface of the ice-age Earth. Science (Wash., D.C.) 191:1131–1144.

———. 1984. The last interglacial ocean. Quat. Res. 21:123–224.

COULBOURN, W. T., J. F. CAMPBELL, and R. MOBERLY. 1974. Hawaiian submarine terraces, canyons, and Quaternary history evaluated by seismic-reflection profiling. Mar. Geol. 17:215–234.

DAMUTH, J. F., and R. W. FAIRBRIDGE. 1970. Equatorial Atlantic deep-sea arkosic sands and ice-age aridity in tropical South America. Geol. Soc. Am. Bull. 81:189–206.

DONN, W. L., W. R. FARRAND, and M. EWING. 1962. Pleistocene ice volumes and sea level lowering. J. Geol. 70:206–214.

DYMOND, J., P. E. BISCAYE, and R. W. REX. 1974. Eolian origin of mica in Hawaiian soils. Geol. Soc. Am. Bull. 85:37–40.

EASTON, R. M. 1987. Volcanism in Hawaii. Stratigraphy of Kilauea Volcano. U.S. Geol. Surv. Prof. Pap. 1350:243–260.

ESWARAN, H., and C. SYS. 1979. Argillic horizon in LAC (low activity clay) soils. Formation and significance to classification. Pedologie 29:175–190.

FLENLEY, J. R. 1979. The late Quaternary vegetational history of the equatorial mountains. Prog. Phys. Geogr. 3:488–509.

FLINT, R. F. 1971. Glacial and Quaternary geology. J. Wiley and Sons, New York.

FOOTE, D., E. HILL, S. NAKAMURA, and F. STEPHENS. 1972. Soil survey of the islands of Kauai, Oahu, Maui, Molokai, and Lanai. State of Hawaii. U.S. Department of Agriculture. Soil Conservation Service. U.S. Government Printing Office, Washington, D.C.

GAVENDA, R. T. 1989. Soil genesis and landscape evolution in central Oahu, Hawaii. Ph.D. diss. University of Hawaii at Manoa, Honolulu.

GIAMBELLUCA, T. W., M. A. NULLET, and T. A. SCHROEDER. 1986. Rainfall atlas of Hawai'i. Report R76. State of Hawaii. Department of Land and Natural Resources. Honolulu, Hawaii.

GREGORY, H. E., and C. K. WENTWORTH. 1937. General features and glacial geology of Mauna Kea, Hawaii. Geol. Soc. Am. Bull. 48:1719–1742.

HAY, R. L., and A. IIJIMA. 1968. Nature and origin of palagonite tuffs of the Honolulu Group on Oahu, Hawaii. Geol. Soc. Am. Mem. 116:331–376.

HUSSAIN, M., and L. SWINDALE. 1974. The physical and chemical properties of the Gray Hydromorphic soils of the Hawaiian Islands. Soil Sci. Soc. Am. Proc. 38:935–941.

JACKSON, M. L., T. W. M. LEVELT, J. K. SYERS, R. W. REX, R. N. CLAYTON, G. D. SHERMAN, and G. UEHARA. 1971. Geomorphological relationships of tropospherically derived quartz in the soils of the Hawaiian Islands. Soil Sci. Soc. Am. Proc. 35: 515–525.

JONES, S. B., and R. BELLAIRE. 1937. The classification of Hawaiian climates. A comparison of the Koppen and Thornthwaite systems. Geogr. Rev. 27:112–119.

KRAUSS, E. 1973. Comparison between ice age and present general circulations. Nature (Lond.) 245:129–133.

KU, T. L., M. A. KIMMEL, W. H. EASTON, and T. J. O'NEIL. 1974. Eustatic sea level 120,000 years ago on Oahu, Hawaii. Science (Wash., D.C.) 183:959–962.

LEOPOLD, L. B. 1951. Hawaiian climate—its relation to human and plant geography. Meteorol. Monogr. 1(3): 1–6.

LIPMAN, P. W., W. R. NORMARK, J. G. MOORE, J. B. WILSON, and C. E. GUTMACHER. 1988. The giant Alika debris slide, Mauna Loa, Hawaii. J. Geophys. Res. 93:4279–4299.

LYON, H. L. 1930. The flora of Moanalua 100,000 years ago (abstract). Pages 6–7 *in* Proc. Hawaii. Acad. Sci. Fifth Annual Meeting. Bernice P. Bishop Mus. Spec. Publ. 16.

MACDONALD, G. A., D. A. DAVIS, and D. C. COX. 1960. Geology and ground-water resources of the island of Kauai, Hawaii. Hawaii Div. Hydrogr. Bull. 13.

MACDONALD, G. A., A. T. ABBOTT, and F. L. PETERSON. 1983. Volcanoes in the sea, 2d ed. University of Hawaii Press, Honolulu.

MANABE, S., and D. G. HAHN. 1977. Simulation of the tropical climate of an ice age. J. Geophys. Res. 82:3889–3911.

MOLINA-CRUZ, A. 1977. The relation of the southern trade winds to upwelling processes during the last 75,000 years. Quat. Res. 8:324–338.

MOORE, J. G. 1987. Volcanism in Hawaii. Subsidence of the Hawaiian Ridge. U.S. Geol. Surv. Prof. Pap. 1350:85–100.

MOORE, J. G., and D. J. FORNARI. 1984. Drowned reefs as indicators of the rate of subsidence of the island of Hawaii. J. Geol. 92:752–759.

MOORE, J. G., and G. W. MOORE. 1984. Deposit from a giant wave on the island of Lanai, Hawaii. Science (Wash., D.C.) 226: 1312–1315.

MOORE, J. G., D. A. CLAGUE, R. T. HOLCOMB, P. W. LIPMAN, W. R. NORMARK, and M. E. TORRESAN. 1989. Prodigious submarine landslides on the Hawaiian Ridge. J. Geophys. Res. 94:17, 465–17, 484.

NOGUCHI, Y., H. TABUCHI, and H. HASEGAWA. 1987. Physical factors controlling the formation of patterned ground on Haleakala, Maui. Geogr. Ann. 69A:329–342.

PORTER, S. C. 1979. Hawaiian glacial ages. Quat. Res. 12:161–187.

POTTER, G. L., H. W. ELLSAESSER, M. C. MACCRACKEN, and F. M. LUTHER. 1975. Possible climatic impact of tropical deforestation. Nature (Lond.) 258:697–698.

PRICE, S. 1983. Climate. Pages 59–66 *in* R. W. Armstrong, ed. Atlas of Hawaii, 2d ed. University of Hawaii Press, Honolulu.

RESIG, J. M. 1969. Paleontological investigations of deep borings on the Ewa Plain, Oahu, Hawaii. Hawaii Inst. Geophys. Rep. HIG-69-2.

REX, R. W., J. K. SYERS, M. L. JACKSON, and R. N. CLAYTON. 1969. Eolian origin of quartz in soils of the Hawaiian Islands and in Pacific pelagic sediments. Science (Wash., D.C.) 163:277–279.

RUHE, R. V. 1964. An estimate of paleoclimate in Oahu, Hawaii. Am. J. Sci. 262: 1098–1115.

———. 1965. Relation of fluctuations of sea level to soil genesis in the Quaternary. Soil Sci. 99:23–29.

———. 1975. Geomorphology. Houghton Mifflin Co., Boston.

RUHE, R. V., J. M. WILLIAMS, and E. L. HILL. 1965*a*. Shorelines and submarine shelves, Oahu, Hawaii. J. Geol. 73:485–497.

RUHE, R. V., J. M. WILLIAMS, R. C. SHUMAN, and E. L. HILL. 1965*b*. Nature of soil parent material in Ewa-Waipahu area, Oahu, Hawaii. Soil Sci. Soc. Am. Proc. 29:282–287.

SELLING, O. H. 1948. Studies in Hawaiian pollen statistics. Part III. On the late Quaternary history of the Hawaiian vegetation. Bernice P. Bishop Mus. Spec. Publ. 39.

SHERMAN, G. D., and L. T. ALEXANDER. 1959. Characteristics and genesis of Low Humic Latosols. Soil Sci. Soc. Am. Proc. 23:168–170.

STEARNS, H. T. 1935. Pleistocene shorelines on the islands of Oahu and Maui, Hawaii. Geol. Soc. Am. Bull. 46:1927–1956.

———. 1940. Geology and ground-water resources of the islands of Lanai and Kahoolawe, Hawaii. Hawaii Div. Hydrogr. Bull. 6.

———. 1947. Geology and ground-water resources of the island of Niihau, Hawaii. Hawaii Div. Hydrogr. Bull. 12.

———. 1961. Eustatic shorelines on Pacific islands. Z. Geomorphol. Suppl. 3:3–16.

———. 1974. Correlation of Pleistocene shorelines in Gippsland, Australia, and Oahu, Hawaii: Discussion. Geol. Soc. Am. Bull. 86:1189.

———. 1978. Quaternary shorelines in the Hawaiian Islands. Bernice P. Bishop Mus. Bull. 237.

STEARNS, H. T., and G. A. MACDONALD. 1942. Geology and ground-water resources of the island of Maui, Hawaii. Hawaii Div. Hydrogr. Bull. 7.

———. 1947. Geology and ground-water resources of the island of Molokai, Hawaii. Hawaii Div. Hydrogr. Bull. 11.

STEARNS, H. T., and K. N. VAKSVIK. 1935. Geology and groundwater resources of the island of Oahu, Hawaii. Hawaii Div. Hydrogr. Bull. 1.

STREET, F. A. 1981. Tropical paleoenvironments. Prog. Phys. Geogr. 5:157–185.

STREET, F. A., and A. T. Grove. 1976. Environmental and climatic implications of late Quaternary lake-level fluctuations in Africa. Nature (Lond.) 261:385–390.

UEHARA, G., and G. D. SHERMAN. 1956. The nature and properties of the soils of the red and black complex of the Hawaiian Islands. Hawaii Agric. Exp. Stn. Tech. Bull. 32.

VALENCIA, M. J. 1977. Pacific Pleistocene paleoclimatic stratigraphies: A comparative analysis of results. Quat. Res. 8:339–354.

WENTWORTH, C. K. 1926. Pyroclastic geology of Oahu. Bernice P. Bishop Mus. Bull. 30.

WENTWORTH, C. K., and W. E. POWERS. 1941. Multiple glaciation of Mauna Kea, Hawaii. Geol. Soc. Am. Bull. 52:1193–1218.

WILLIAMS, M. A. J. 1975. Late Pleistocene tropical aridity synchronous in both hemispheres? Nature (Lond.) 253:617–618.

WINCHELL, H. 1947. Honolulu Series, Oahu, Hawaii. Geol. Soc. Am. Bull. 58:1–48.

WRIGHT, H. E., and D. G. FREY. 1965. Preface. *In* H. E. Wright and D. G. Frey, eds. The Quaternary of the United States. Princeton University Press, Princeton.

YEH, T. C., J. E. CARSON, and J. J. MARCIANO. 1951*a*. On the relation between the circumpolar westerly current and rainfall over the Hawaiian Islands. Meteorol. Monogr. 1(3): 47–55.

YEH, T. C., C. C. WALLEN, and J. E. CARSON. 1951*b*. A study of rainfall over Oahu. Meteorol. Monogr. 1(3): 34–46.