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Age and Origin of Late Quaternary Eolianite, Kaiehu Point (Moomomi), Molokai, Hawaii

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ABSTRACT

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A well-preserved, vertically stacked succession of two genetically distinct eolianites and associated caliche paleosol units, capped by modern and Holocene coastal dunes, occurs at Kaiehu Point, west Molokai, Hawaii. The Pleistocene eolianite facies comprise well-cemented, medium grained skeletal carbonate sand and their morphostratigraphic context implies formation at times of lower than present sea level. Amino acid racemization (AAR) evidence suggests eolianite formation late in marine Oxygen Isotope Stage (OIS) 5, but lacks the precision to uniquely define in which isotopic substage the deposits formed. Coupled with the AAR results, the morphostratigraphic evidence, would suggest that the Lower Eolianite formed in OIS 5c and the Middle Eolianite during 5a with their superposed caliche paleosols having formed in subsequent stadial stages. The unconsolidated coastal sand dunes of Holocene age contain reworked Late Pleistocene skeletal carbonate sand based on AAR evidence. The most likely source of the reworked carbonate is from the erosion of the eolianites at Kaiehu Point. The Pleistocene eolianite-caliche paleosol sediments reveal variable Mg-content, stable isotope ratios and petrological characteristics consistent with changing degrees of weathering intensity and meteoric diagenesis. These changes are attributed to orographic effects resulting from relative sea-level changes. Accordingly, a two-phase model is favored for the formation of the eolianite-paleosol successions at Kaiehu Point, west Molokai. Eolianite sedimentation is initiated at times of marginally lower sea levels promoting the landward migration of bioclastic sand to form extensive eolian sandsheets. This is followed by a more pronounced phase of pedogenesis associated with a further fall in sea level and concomitant increased rainfall due to enhanced orographic effects.

ADDITIONAL INDEX WORDS: *Hawaii, Late Quaternary, Molokai, eolianite, carbonate lithofacies, amino acid racemization, stable isotopes, limestone petrology, cliche paleosols, sea level.*

INTRODUCTION

Climate is a major influence on the formation of eolianites and carbonate paleosols, and the two lithofacies have long been interpreted as sedimentary records of Pleistocene and Holocene climate history (BRETZ, 1960; STEARNS, 1970; ESTEBAN and KLAPPA, 1983; HEARTY and VACHER, 1994). Calcareous eolianites and caliche paleosols develop in low-latitude coastal regions where the sediment source is represented by carbonate-secreting coralgal reefs. In vertical stratigraphic profiles, changes from calcareous eolianite to interbedded paleosols, reflect changes in sediment source tied to global sea-level changes (glacio-eustatic, ice-equivalent sea-level change) and climatic and environmental changes (BRETZ, 1960; HEARTY and VACHER, 1994; HEARTY and KINDLER, 1995).

In Hawaii, studies of carbonate eolianites and related paleosols were made by Harold Stearns on the island of Oahu (1970) and later at Kaiehu Point on Molokai (1973: Figure 1). In subsequent papers (STEARNS 1974, 1978; LUM and STEARNS, 1970), he refined his views of eolian deposition in light of changes in Hawaiian sea-level chronology. More recently, HEARTY *et al.,* (2000) surveyed last interglacial and Holocene carbonate deposits in Hawaii using amino acid racemization techniques and correlated eolian deposition with 'Marine Oxygen Isotope Substage 5e.

However, the Hawaiian model of eolianite deposition proposed by Stearns largely relies upon lower sea levels to initiate dune formation, whereas the Bermudan and Bahamian models (*e.g.* HEARTY and VACHER, 1994) is interpreted in the context of high sea-level stands. Because this difference calls into question important fundamental aspects of eolian deposition, the Hawaiian model is re-examined, based on a study of the exposures at Kaiehu Point, Molokai, to improve our understanding of Hawaiian carbonate dune sequences and their relation to Quaternary sea-level history.

In this work, the influence of relative sea-level changes on eolianite and caliche paleosol formation is assessed utilizing multiple, but integrated proxies for sediment source, age and post-depositional history. The degree of amino acid racemization (AAR) in carbonate fossils and bioclastic sediments is also examined to assign ages to the eolianite succession. Descriptive petrography to determine grain composition and cement characteristics, and magnesian carbonate and oxygen

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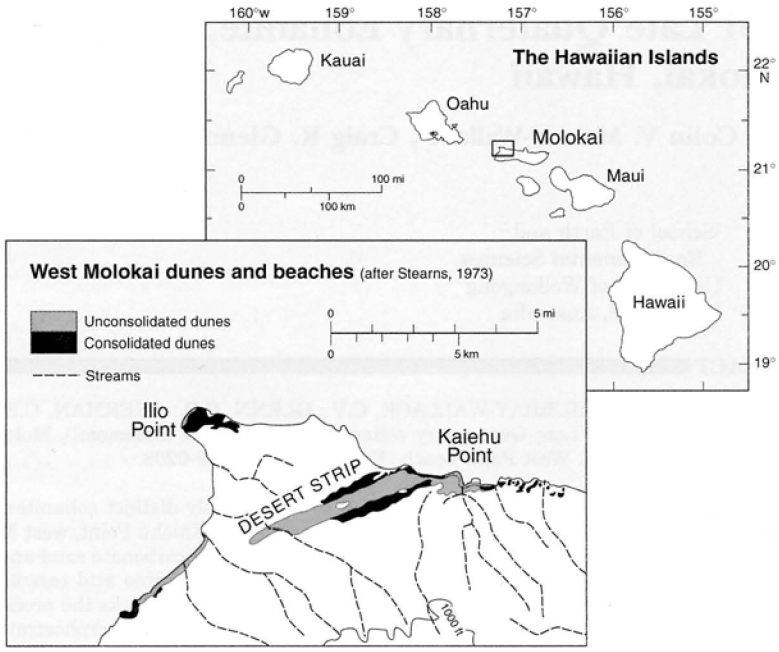


Figure 1. West Molokai dunes and beaches.

isotope indicators to assess post-depositional weathering and caliche paleosol formation were also undertaken.

MODELS OF EOLIANITE FORMATION

In view of the significant differences in the published origins of Hawaiian (STEARNS, 1970; 1974) and Bermudan/Bahamian (BRETZ, 1960; LAND *et al.*, 1967; VACHER and HARMON, 1987; HEARTY and KINDLER, 1995) eolianite/paleosol sequences, the contrasting depositional models are briefly reviewed here.

Hawaiian Eolianite Model

Five eolianite units have been identified on Oahu (Table 1). Stearns suggested that dune formation is enhanced during glacioeustatic low sea level stands, as greater quantities of sand are exposed on the inner shelf for dune building by the persistent NE trade winds than otherwise available at times of higher sea levels (STEARNS, 1970). He also acknowledged a complex origin for Hawaiian eolianites, and assigned two of the five major eolian units on Oahu to sea levels equal to or higher than present (Figures 2, 3 and Table 1). However, Stearns (1974) maintained that throughout the late Quaternary, periods of low sea level represented the time when most of the now lithified dunes were deposited.

According to the depositional model for Hawaiian eolianites, when sea level is high, sand from a source beach is blown inland by NE trade winds to form active sand dunes landward of the beach (Figure 3). As sea level falls at the end of a highstand, the once active dunes no longer receive sand from the beach, lithify, and develop soil profiles on their upper dune surfaces. A younger ridge of active dunes subsequently forms seaward of the relict dunes as the shoreline regresses. These post-highstand dunes are deposited on

Table 1. *Hawaiian eolian units defined by Stearns (Stearns, 1970, 1974, 1978).*

Name (OIS)	Stearns' Sea-Level History	Oxygen Isotope Stage
Unconsolidated "Holocene"	Transgression VI and present interglacial (0 to +1.5 m)	Stage 1
Laniloa Formation	Last glacial maximum, Regression VI *or* mid-Wisconsinan stadials (Reg. V)	Stage 2 (?) Stages 3/4 (?)
Kawella Soil	Mid-Wisconsinan stadials (Reg. V) *or* late-Sangamon Regression IV	Stage 3/4 (?) sub-Stage 5b/d(?)
Leahi Formation	Post-Waimanalo, Regression V ~115 ka (+0.6 m)	Stage 5 a/c (?)
Waialua/Hahaione dunes	Sangamon interglacial, Waimanalo highstand, ~125 ka (+6–12 m)	Stage 5e
Bellows Field Formation	Illinoian glaciation, Regression III, Waipio low stand, ~ (−107–110 m)	Stage 6

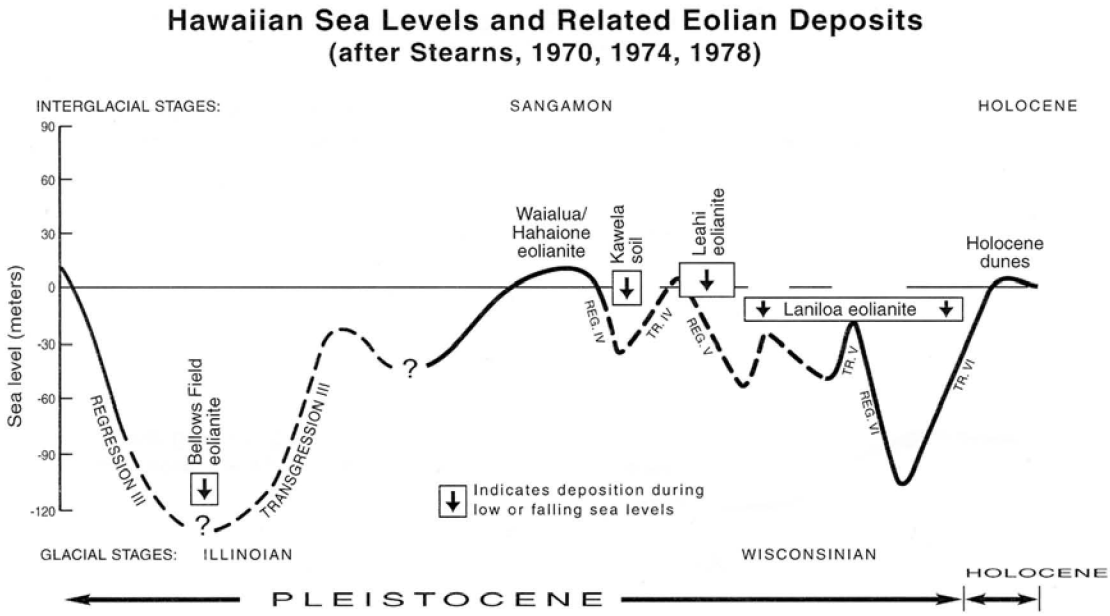


Figure 2. Hawaiian sea levels and related eollian deposits.

beachrock of the former highstand shoreline (Figure 3). The largest dunes form when sea level is low and the subaerially exposed reefs provide a ready supply of sand for dune formation (STEARNS, 1974). Dunes continue to form immediately landward of the beach by eolian deposition. A regressive sequence of lithified dunes on marine calcarenites (beachrock) occurs landward of the active dunes, and soils may form on surfaces of non-deposition or erosion.

Bermudan—Bahamian Eolianite Model

Knowledge of the eolianite-paleosol sequences of Bermuda and The Bahamas provide a conceptual framework to refine the understanding of similar successions in Hawaii (BRETZ, 1960; MACKENZIE, 1964; LAND *et al.,* 1967; VACHER and HARMON, 1987; HEARTY *et al.,* 1992 HEARTY and VACHER, 1994). The Bermuda model of dune deposition and soil formation, while somewhat modified today from the early work of the 1960s, consistently holds that eolianites form during, or immediately following, interglacial highstands of the sea. Central to this argument is the postulate that the paleosols accumulate when sea level falls and nearby carbonate sand is no longer available for deposition on dune ridges (Figure 4).

In the context of eolianite stratigraphy, BRETZ (1960) suggested that a complete record of a high sea level consists of (1) an eolianite, (2) a marine limestone, and (3) an eolianite. As interglacial high sea level retreats from the land, exposed sand is blown up into dune ridges that are immediately stabilized and do not migrate inland. Fixed sand dunes are then "abandoned" (no longer receiving new sand) as younger dunes form in succession associated with the retreating shoreline. BRETZ (1960) emphasized that permanent dunes only accumulated when sea level was at its highest level, and that throughout much of a glacial cycle, soil formation on "dormant" dunes would occur especially during glacial maxima.

VACHER and HARMON (1987) reassessed earlier models of eolianite-paleosol formation on Bermuda and concluded that although some eolianite deposition occurred during rising sea level, and during sea-level highstands, the majority of eolianite deposition occurred while sea level was falling. They attributed the widespread, lateral interdigitation of eolianites with marine calcarenites to marine regressions. The VACHER and HARMON (1987) model of eolianite-paleosol deposition actually brings the Bermuda model closer to that of Stearns in Hawaii, and serves to highlight the complex nature of eolianite formation. The greatest challenge to the application of the Bermudan-model of dune formation in Hawaii lies in the identification by LUM and STEARNS (1970) of the Bellows Field eolianites at elevations of 17 to 54 m below present sea level in cores at Waimanalo, and in the failure of Hawaiian workers to firmly tie paleosol genesis to glacioeustatic low stands of sea level.

STUDY AREA

One of the most extensive eolianite-caliche paleosol exposures on the Hawaiian Islands, occurs at Kaiehu Point, on the eastern (windward) forefront of the great Dune Strip of northwestern Molokai (Figure 1). The Dune Strip, an 8 km long eolian tract of both consolidated and unconsolidated sand ridges originates at Kawaaloa Beach, adjacent to Kaiehu Point, and rises to an elevation of 150 m while crossing the northwest corner of the island. STEARNS and MACDONALD (1947) suggested that most of the sand was derived from the adjacent inner shelf when it was subaerially exposed during the Waipio (Illinoian) sea-level lowstand, equivalent to ma-

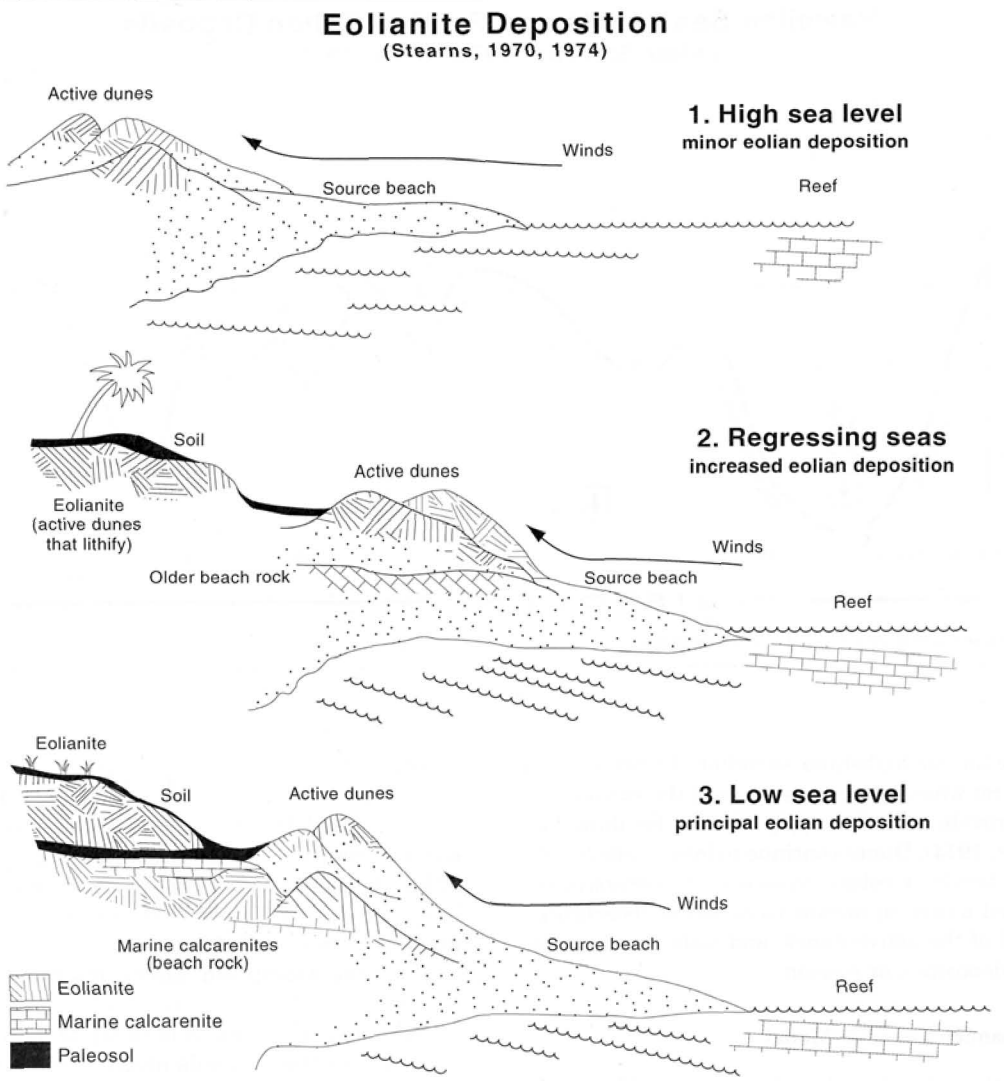


Figure 3. Eolianite deposition.

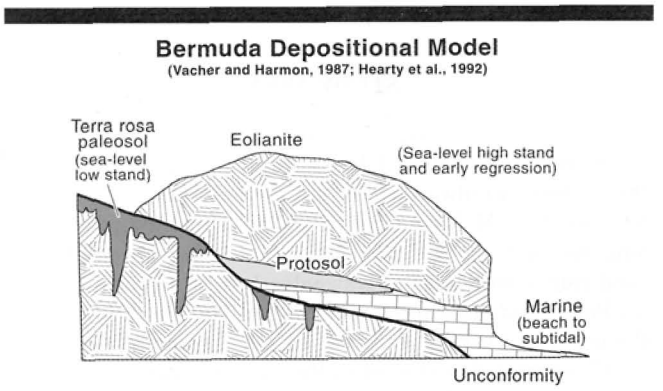


Figure 4. Bermuda depositional model.

rine Oxygen Isotope Stage 6. The inland extent of the modern (active) sand is a function of the strong trade winds, which blow directly onshore at Kaiehu Point for 75 per cent of the year.

METHODS

The eolianites at Kaiehu Point were mapped and physically sampled to identify the origin and age of the succession. Amino acid racemization (AAR), mineralogical, petrological, and stable isotopic analyses were undertaken to determine the origin of the sediments and the diagenetic processes that have modified them since deposition.

Amino Acid Racemization

The extent of amino acid racemization (AAR) was measured in specimens of the landsnail *Carelia sinclairi* and whole-rock sediment samples from the eolianite-caliche suc-

cession at Kaiehu Point, Molokai. The degree of AAR was also determined for fossil corals, mollusks, and whole-rock samples of eolianite and beachrock from several deposits from the Hawaiian islands of Molokai and Oahu as a framework to evaluate the results from Molokai. Several of the samples were selected because they have been previously dated by uranium-series disequilibrium and therefore provide a calibration for the racemization results. The extent of racemization (total acid hydrolysate) was determined for the enantiomeric amino acids valine (VAL), leucine (LEU), glutamic acid (GLU), and phenylalanine (PHE).

Fossil corals and molluscs were cleaned using a dental drill with a variety of tools, followed by a dilute acid etch to remove the outer weathered or recrystallized surfaces. The fossils were subsequently cleaned in a beaker of distilled water in an ultrasonic bath. The whole-rock samples were disaggregated and the cement removed in distilled water using an ultrasonic bath. The sediment was sieved to separate to 500 to 63 μm fractions. The potential soil organic residues were removed using H_2O_2 and the skeletal carbonate grains were subsequently etched in dilute HCl to remove the remaining cement and a portion of the grain surfaces; approximately 10% of the total carbonate was digested. AAR samples were hydrolysed for 22 hours at 110°C in 8 M HCl. Following cation exchange isolation of the amino acid residues, samples were freeze-dried and derivatized. Analyses of the N-pentafluoropropionyl D, L-amino acid 2-propyl esters were performed using a Hewlett-Packard 5890A Series II gas chromatograph with a flame ionization detector and a 25 m coiled, fused silica capillary column coated with the stationary phase Chirasil L-Val. Amino acid D/L ratios were determined based on peak area calculations and analytical precision is typically 3%. A detailed description of the analytical procedures is given elsewhere (MURRAY-WALLACE, 1993).

Mineralogy and Mg Content

To assess of the degree of sediment diagenesis at Kaiehu Point, X-ray diffraction analysis was undertaken. Percentages were quantified, based on peak area measurements for aragonite, low- and high-magnesian calcite, as well as additional mineralogical components, using a Scintag XRD following standard methods (SABINE, 1992). Although the relative percentages of calcite and aragonite are reported, in view of the very low concentration of accessory minerals, the relative percentages of the two major components are close to the total abundance in the sediment samples studied.

Petrology and Stable Isotopes

Petrologic and stable isotopic analyses were undertaken on samples from the section at Kaiehu Point. The isotopic composition of carbonate was determined by analysis of CO_2 evolved by reaction of powdered samples with phosphoric acid ($\rho > 1.89$ g cm^{-3}) at 50°C (MCCREA, 1950; WACHTER and HAYES, 1985). Analytical uncertainty for isotopic analyses is less ±0.1‰. Isotopic compositions are reported in the standard δ-notation relative to VPDB. Terminology for describing microfabrics follows that of REZAK and LAVOIE (1993).

RESULTS

Eolianite Stratigraphy

The stratigraphy of the eolianite succession at Kaiehu Point comprises two genetically distinct eolianite-caliche units, which in succession rest unconformably on beach rock and are capped by unconsolidated Holocene dunes. Upwards from the base of the exposure, occurs a basal calcarenite resembling beachrock (Figure 5). This is overlain by eolianite (c. 1–2 m thick) termed here the Lower Eolianite, which is in turn capped by a caliche (Lower Caliche: c. 1–2 m thick). The lower caliche is unconformably overlain by a lithified eolianite (c. 3 m thick), which is in turn capped by a caliche. A succession of Holocene dunes, some 2–8 m thick occur immediately above the upper caliche.

Lower Eolianite and Beach Rock

The Lower Eolianite, a 1.5–2 m thick, well-indurated eolianite unit occurs at the western end of Kaiehu Point headland. The eolianite is moderately cemented, of medium grain size, and contains rhizoliths and well-developed trough-cross bedding. STEARNS and MACDONALD (1947) noted that exposures of a lithologically similar, well-indurated eolianite occur at the base of remote Ilio Point, NW Molokai, and that the unit extends below sea level and preserve prominent benches by what has subsequently been interpreted as both the mid-Holocene Kapapa Stand (+1–2 m: FLETCHER and JONES, 1996; GROSSMAN and FLETCHER, 1998) and the last interglacial Waimanalo Stand (+2–6 m: MUHS and SZABO, 1994). STEARNS and MACDONALD (1947) assigned the eolianite unit to the Bellows Field Formation.

The calcrete and sand-rich facies of the lower caliche paleosol (below a laterally persistent brown silt) has aspects of an idealized caliche profile (ESTEBAN and KLAPPA, 1983: Figure 5). The paleosol can be divided into repetitive sediment packages. Each package comprises a basal, red, medium- to fine-grained sand displaying variable degrees of generally light cementation, overlain by a white nodular calcrete crust that may be relatively thick (c. 10–30 cm). Each sand/calcrete contact is gradational, suggesting that the crust represents a weathering surface developed on the host sands. However, the contact between the calcrete and the subsequent overlying sand/calcrete pair is unconformable, suggesting that sand deposition was relatively rapid, perhaps erosive, and was likely preceded by some period of nondeposition. This general sand-calcrete pattern is repeated four to six times within the paleosol below the middle eolianite (Figure 5).

Middle Eolianite and Paleosol

Unconformably overlying the lower caliche is a 3 m thick, trough cross-bedded eolianite (Middle Eolianite). The steeper cross-beds dip at 30 to 33°. Calcareous grains are well-sorted and typically 0.5–1.0 mm in diameter and are moderately to well-cemented. Rhizoliths appear in the lower half of the unit and may relate to dune migration over a previously vegetated landscape at the time of lower caliche development. An abrupt unconformity at the base of the unit is characterized by a 3–5 cm thick calcrete crust (or hardpan). This layer is

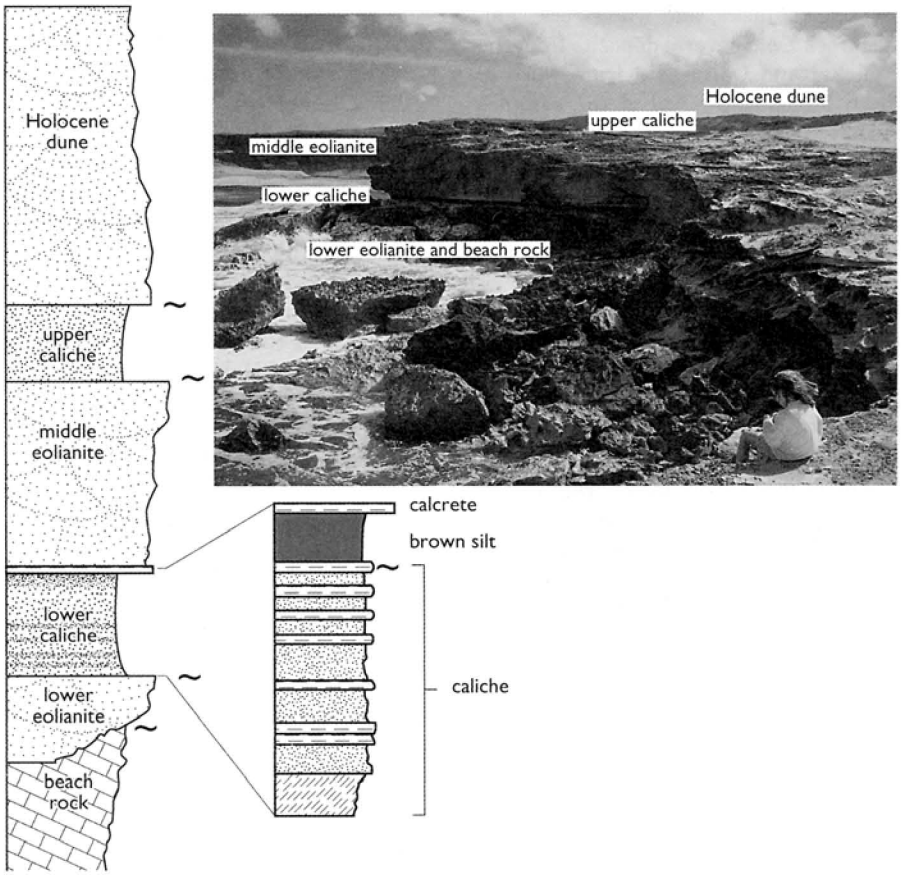


Figure 5. Eolianate succession at Kaiehu Point.

located along a horizontal contact where dune sands rest upon an underlying brown silt of terrigenous origin. The Middle Eolianite is overlain by a c. 1 m thick caliche paleosol that is exposed at the surface just seaward of the unconsolidated dune at Kaiehu Point. This paleosol contains portions of an idealized caliche profile, namely the platy, sheetlike calcrete crusts, and exhibits rhizoliths where it is exposed in contact with the underlying eolianite.

Unconsolidated Dune and Paleosol

The unconsolidated dunes at Kaiehu Point are represented by a partially vegetated ridge of buff-colored calcareous sand. The lower portion of the sands is lightly cemented by exposure to meteoric precipitation.

Amino Acid Racemization Analyses

Amino acid racemization (AAR) results for samples from deposits on Oahu and at Kaiehu Point are given in Table 2. The extent of racemization of amino acids in fossil mollusk *Periglypta reticulata* from Barbers Point and Kapapa Island, Oahu, two deposits with independently well-established ages (SHERMAN *et al.* 1993; GROSSMAN and FLETCHER, 1998), provide an important geochronological framework to evaluate the AAR data from Kaiehu Point, Molokai. In addition, two submerged coral samples from Oahu and independently dated by the TIMS U-series method, and an electron spin resonance (ESR) age of 562±96 ka on a Middle Pleistocene coral from Barbers Point (SHERMAN *et al.* 1993) provide a further framework for the evaluation of the AAR data from Kaiehu Point (Figure 6).

The low extent of amino acid racemization in specimens of the mollusk *Periglypta reticulata* from Kapapa Island is consistent with their middle Holocene age determined on the basis of radiocarbon dating (GROSSMAN and FLETCHER, 1998), and by analogy with more extensive comparisons of Holocene AAR and radiocarbon ages (MURRAY-WALLACE, 1995). In contrast, a significantly higher extent of racemization is evident in P. reticulata from a coral rudstone unit at Barbers Point (Unit III of Sherman *et al.* 1993). This coral-rich deposit has been assigned a last interglacial age (OIS 5e) based on U-series and ESR dating of corals from sediments overlying and underlying this unit. A similar degree of racemization is evident in fossil mollusks from last interglacial coastal deposits in Australia with equivalent current mean annual temperatures (MURRAY-WALLACE, 1995). The three coral samples also independently dated by U-series and ESR (samples UWGA-490, 502 and 515: Table 2) show a consistent pattern of increasing degree of racemization with respect to age. Notwithstanding possible generic-effects on racemization rate be-

Table 2. *Extent of amino acid racemization (total acid hydrolysate) in fossil corals, mollusks, and eolianites, Hawaii*

Locality	Species	Laboratory Code	Amino acid D/L ratio				Age or Oxygen Isotope Stage
			VAL	LEU	PHE	GLU	
Oahu							
Kapapa Island	*Periglypta reticulata*	UWGA-420	0.057 ± 0.013	0.127 ± 0.034	0.154 ± 0.004	0.131 ± 0.001	1
	Periglypta reticulata	UWGA-421	0.063 ± 0.001	—	0.133 ± 0.036	0.227 ± 0.035	
	Periglypta reticulata	UWGA-419	0.103 ± 0.004	0.205 ± 0.017	—	—	
Barbers Point	*Periglypta reticulata*	UWGA-415a	0.572 ± 0.028	0.692 ± 0.054	0.544 ± 0.028	0.502 ± 0.016	115 ± 10 or 145 ± 15 ka*
	Periglypta reticulata	UWGA-415b	0.467 ± 0.006	0.611 ± 0.038	0.546	0.552 ± 0.009	
	Coral (Middle Pleistocene)	UWGA-515	0.778 ± 0.069	0.715 ± 0.017	0.771 ± 0.051	0.987 ± 0.022	562 ± 96 (ESR)*
	Coral (Middle Pleistocene)	UWGA-597	0.474 ± 0.012	0.311 ± 0.003	0.409 ± 0.012	0.781 ± 0.003	
	whole-rock	UWGA-599	0.379 ± 0.012	0.502 ± 0.010	0.610 ± 0.028	0.577 ± 0.004	115 ± 10 or 145 ± 15 ka*
Kaena Point, (overlies 5e) Submerged Corals	Upper Waimanalo Formation;	UWGA-485a	0.314 ± 0.014	0.391 ± 0.019	—	0.410 ± 0.014	
	whole-rock	UWGA-485b	0.311 ± 0.028	0.329 ± 0.010	0.801 ± 0.052	0.501 ± 0.006	
	Porites lobata (WAI10-S3)	UWGA-502	0.319 ± 0.047	0.524 ± 0.013	0.521 ± 0.029	0.539 ± 0.004	110 ± 7 ka
	Porites lobata (KAN1-S1A)	UWGA-490	0.610 ± 0.003	0.586 ± 0.004	0.664 ± 0.002	0.933 ± 0.003	294 ± 2 ka
Molokai							
Kaunakakai West,	whole-rock	UWGA-429b	0.125	0.357	0.262	0.395	
Eolianite	whole-rock	UWGA-429a	0.087	0.193 ± 0.009	0.302 ± 0.005	0.311 ± 0.008	
(radiocarbon)	whole-rock	Beta-60345					4570 ± 70 BP
		Beta-71518					5730 ± 80 BP
Kaiehu Point							
Holocene dune	*Nerita picea*	UWGA-430	0.067	–	—	—	1
"Holocene" dune	whole-rock	UWGA-422a	0.267 ± 0.001	0.359 ± 0.004	0.630 ± 0.051	0.436 ± 0.078	
Upper caliche	*Carelia sinclairi*	UWGA-423a	0.294 ± 0.001	0.510 ± 0.001	0.706 ± 0.013	0.599 ± 0.036	
Upper caliche	*Carelia sinclairi*	UWGA-423b	0.313 ± 0.002	0.623 ± 0.005	—	—	
Middle Eolianite	*Carelia sinclairi*	UWGA-424	0.308 ± 0.001	0.653 ± 0.026	—	—	
Middle Eolianite	whole-rock	UWGA-426	0.297 ± 0.001	0.410 ± 0.001	0.603 ± 0.009	0.385 ± 0.014	
Middle Eolianite	whole-rock	UWGA-425a	0.266 ± 0.009	0.359	0.426 ± 0.040	0.381 ± 0.032	5a-c?
Lower caliche	*Carelia sinclairi*	UWGA-427	0.290	0.583 ± 0.045	0.591 ± 0.040	0.554 ± 0.025	
	Carelia sinclairi	UWGA-428	0.298 ± 0.01	0.535 ± 0.001	0.731 ± 0.068	0.625 ± 0.048	

* Reported in Sherman *et al.*, 1993

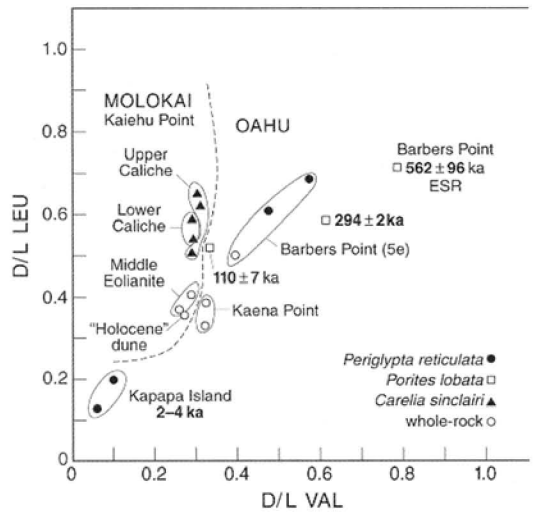


Figure 6. AAR results.

tween corals and molluscs, the amino acid data for the marine shell and coral provide an indication of the likely degree of racemization to be attained in fossiliferous materials with respect to age for the Hawaiian Islands. A relevant consideration in the interpretation of the AAR data reported here, is that the current mean annual air temperature is about 25°C, and that diagenetic temperatures are likely to have remained high and relatively stable, in contrast to more pronounced long-term temperature fluctuations apparent for higher latitudes.

Mineralogy and Mg Content

The designation of calcite as either "high" or "low" magnesian is not clear-cut, and may be complicated by physical differences in the original carbonate mineralogy or rainwater chemistry. We abandon previous definitions of high- and low magnesian calcite and have established a scale specific to samples from Kaiehu point. Because modern beach sand provides the clearest indication of original mineralogy, we used the composition of beach sand at Kawaaloa Bay to discriminate low- from high magnesian. Low-magnesian calcite found in samples from Kaiehu Point, fall below 5 mol% Mg, while high-magnesian calcite had 10–15 mole% Mg. Five samples showed intermediate-magnesian calcite (5–10 mole % Mg) here termed "med- magnesian calcite" (Table 3 and Figure 7). With the exception of the brown silt (sample 103), all samples have at least partial carbonate mineralogy containing various amounts of aragonite and calcite (Table 3 and Figure 7 for sample locations).

PETROLOGY AND STABLE ISOTOPES

Lower Beachrock Lithofacies

The lower beachrock unit is a brecciated and conglomeratic facies that extends from about 0 to 3 m above the low tide mark. The bulk rock stable isotopic composition is identical to that of modern sand currently accumulating at nearby Ka-

Table 3. *Carbonate Mineralogy (Mg mol%) in stratigraphic order* at Kaiehu Point, Molokai*

Sample No.	Lithology	%high Mg	%med Mg	%low Mg	%total Calcite	%Arag.
11	beach sand	50	0	26	76	24
115	beach sand	47	3	25	74	26
116	active dune sand	40	3	27	70	30
5	weakly lithified sand	33	12	29	74	26
4	calcrete	0	100	0	84	16
7	lithified sand	39	0	41	80	20
114	lithified sand	33	0	41	74	26
101	lithified sand	47	0	26	73	27
6	lithified rhizolith	8	0	78	86	14
102	basal calcrete, contact of middle eolianite and brown silt	17	61	0	77	23
103	brown silt	0	0	0	0	0
1	calcrete under silt	23	56	0	79	21
3	calcrete	46	0	29	75	25
10	mixed calcrete/sand	37	0	29	65	35
104	red sand	9	13	49	71	29
105	calcrete	10	0	79	89	11
106	calcrete	0	0	100	100	0
107	red sand	22	0	56	78	22
108	calcrete (moist)	0	0	100	100	0
109	calcrete (moist)	0	0	100	100	0
110	calcrete (at lower contact with 111)	10	0	77	87	13
111	red sand	30	0	41	71	29
9	basal calcrete	0	0	100	100	0
112	lithified sand	45	0	32	77	23
113	beach rock	36	0	42	78	22

* See Figure 7 for sample locations

waaloa Beach (Table 4). The beds of this unit are calcarenites that contain, in order of decreasing abundance, fragments of abraded and well-rounded calcareous red algae, lime-mud intraclasts with traces of skeletal debris, benthic foraminifers (chiefly *Amphistogina lobifera, Amphisorus spp.* and *Miliolids*), and molluscs and echinoid fragments. Coral fragments are rare. Although well washed and lacking detrital micrite, these rocks are rather poorly sorted with particle sizes typically ranging from medium to very coarse-grained sand (0.23 to 1.3 mm).

The fabric of these rocks is largely cement-supported and the cements are dominated by three morphologies. One morphology is characterized by irregular coatings of micrite around grains that form meniscus cements and thin bridges of micrite between grains (Figure 8A-C). Another is characterized by bladed calcite cements (Figure 8D, E). The third cement morphology is characterized by a later void-filling drusy, sparry calcite that shows a coarsening of crystals towards the center of the pores, and that rounds pores but does not usually completely occlude them (Figure 8F). Aragonite needle cements are not present.

Eolianite Lithofacies

The eolianite cements generally display a wide range of crystal sizes and shapes including finely crystalline anhedral spar (Figure 9A), and coarse blocky spar (Figure 9B), as noted in eolian carbonates from other regions (*e.g.* Yucatan: McKee and Ward, 1983). Cementation of spar and microspar is patchy, and portions of the beds remain completely uncemented. Overgrowths on echinoderm fragments are partial and confined to areas with only small pores (where water was stuck due to capillary action: Figure 9C) and cements are generally best concentrated along small pore throats and within small primary intraskeletal pores such as within foraminifer apertures (Figure 9D). Occasional occurrences of vadose whisker crystals occur in the upper eolianite within voids of root molds (Figure 9E).

The eolianites are massive to cross-bedded calcarenites that display a similar skeletal assemblage to the underlying beach rock, with the exception that they contain greater proportions of disk-shaped *Amphisorus* foraminifers, possibly related to selective sedimentation due to their aerodynamic properties. The majority of the skeletal grains in the eolianites are highly abraded and, in contrast to the rounded and poorly sorted nature of the beachrock grains, have subangular to subrounded grains and are well sorted. Meniscus microspar and sparry cements typical of vadose cementation occur in these units and they display carbon and oxygen isotope ratios characteristic of modern skeletal sands.

Warren (1983) attributed the formation of micritic grain coats such as found in the Kaiehu Point caliche units to fluctuations in the volume and salinity of films of water on grains that occur after gravitational water has drained from the pores and evapotranspiration has not yet begun. Warren suggested that, relative to the dune mass, a greater abundance of micrite is deposited within pedogenic calcretes as these are sites associated with the soil moisture zone that is the zone of maximum pore waters and pCO_2 flux. Evaporation and soil suction in the uppermost zones of the sediment body (above the water table) causes precipitation of the micritic cements around the grain nuclei (Seisser, 1973). Above the middle eolianite, the calcretes are relatively pure and homogeneous micrite displaying vuggy porosity. There, rhizoliths are abundant in the eolianite and short, calcified double filaments interpreted as relict calcified root hair or fungi sheaths (cf. Klappa, 1979, 1980) are found in the upper paleosol (Figure 9h). These are found in greatest abundance in association with strings of voids that likely represent former root traces.

Calcrete and Caliche Paleosol Lithofacies

Three caliche intervals occur within the Kaiehu Point sequence. The thicker caliche paleosols within the two dune successions contain distinct, platey and laminar calcrete horizons. Interbedded calcretes and red, iron-rich and gypsiferous sands and soils form the lower caliche. These beds contain micritic and earthy iron-oxide coated grains indicative of vadose pedogenesis (Figure 9F,G). These are similar to "vadose micritic envelopes" of the Quaternary carbonate dune deposits of southern Australia (Warren, 1983), to "calcrete ooids" of Pleistocene dunes of western Australia (Read, 1974) and to "diagenetic ooids and intraclasts in calcretes" in calcretes on top of, or within, coastal eolianites of South Africa (Seisser, 1973). In some Kaiehu samples, the carbonate grains of the dune are first coated with micrite and secondly by iron oxides.

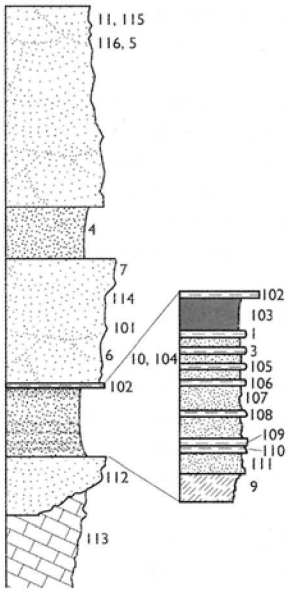
DISCUSSION

Age of the Eolianites

The AAR data for *Periglypta reticulata* appear to bracket the whole-rock data for the middle eolianite from Kaiehu Point, Molokai, suggesting a Late Pleistocene age for this unit (Figure 6).

The whole-rock AAR results for the middle eolianite at Kaiehu Point also yield a lower degree of racemization than for the whole-rock sample of last interglacial age from Barbers Point, Oahu. The whole-rock sample from Barbers Point is from a calcarenite (beachrock); Unit IV of Sherman *et al.* (1993) and based on relative stratigraphic relationships is of last interglacial age (OIS 5e). It is unlikely that contrasting racemization kinetics between the individual fossil mollusks and sediment samples accounts for the significant difference in degree of racemization in these materials. Thus, the middle eolianite at Kaiehu Point is most likely younger than the last interglacial maximum, and may correlate with a substage of marine Oxygen Isotope Stage 5 (OIS5a-d ca. 82–116 ka).

The middle eolianite at Kaiehu Point, Molokai, also displays a similar extent of racemization to an eolianite at Kaena Point, Oahu, which directly overlies a last interglacial reef. Although some of the coralline bioclasts from the gravels overlying the *in situ* reef at Kaena Point have been dated as last interglacial (Muhs and Szabo, 1994), it is likely that a significant component of the eolianite sediment at Kaena Point is actually younger than the last interglacial maximum. The degree of racemization in the sediments from Kaena



Sample	Description	Calcite			Aragonite	Halite	Kaolinite	Gypsum	Hematite
		Mg mol% 10–up high	5–9.99 med	0–4.99 low					
11	beach sand	•••		•	•		•	•	•
115	beach sand	•••	•	•	•				
116	dune sand	•••	•	•	•	•			
5	dune sand	•••	•	•	•	•			•
4	calcrete		•••		•	•			•
7	eolianite	•		•••	•				
114	eolianite	•		•••	•	•			
101	eolianite	•••		•	•	•	•	•	•
6	rhizolith	•		•	•	•		•••	
102	clacrete	•	•••		•			•	•
103	brown silt					•••	•	•	•
1	calcrete	•	•••		•	•	•		•
3	calcrete	•••		•	•	•			•
10	calcrete/sand	•••		•	•	•			•
104	red sand	•	•	•••	•	•			
105	calcrete	•		•••	•	•			
106	calcrete			•••		•			
107	red sand	•		•••	•	•			
108	calcrete			•••		•			
109	calcrete			•••		•			
110	calcrete	•		•••	•	•			
111	red sand	•		•••	•	•			
9	calcrete			•••		•			
112	eolianite	•••		•	•				
113	beach rock	•		•••	•	•	•		•

Figure 7. Sample locations.

Point is significantly lower to that observed for the last interglacial (OIS 5e) sediment at Barbers Point, and implies a younger age for the former succession.

The degree of racemization of amino acids in specimens of the gastropod *Carelia sinclairi* from the upper and lower caliches from the eolianite succession at Kaiehu Point are not significantly different. This may indicate that the two eolianite-caliche successions are similar in age. Although the amino acid racemization method lacks the age resolving power to discriminate at the substage level within OIS 5, the results preclude the upper and lower caliches having formed in substantially different intervals of time of the Late Pleistocene. The degree of racemization in the fossil *Carelia* is significantly higher than in the whole-rock samples from the middle eolianite. As the shells were not deeply buried, the significantly higher degree of racemization may relate to the disproportionate effect of temperature on racemization rate in the shallow burial environment. It is also noted that *Carelia* sp. produces a thin shell and the possibility of introduction of non-indigenous amino acids, or the diffusive loss of amino acids from the shells requires further evaluation. Another possible explanation is that amino acids bound within *Carelia* sinclairi undergo fast rates of racemization as noted for some mollusk species (MILLER and BRIGHAM-GRETTE, 1989).

Table 4. *Stable isotopic composition of eolianite and paleosol sediments at Kaiehu Point, Molokai.*

Elevation (m)	Sample No.	Description	$\delta^{13}C$ (PDB)	$\delta^{18}O$ (PDB)
0.00	11	Beach Sand	0.89	−1.41
0.00	115	Beach Sand	0.97	−1.32
13.50	116	Dune Sand (active)	0.99	−1.40
12.00	5	Dune Sand (lithified)	1.19	−0.44
7.50	4	Paleosol	−1.43	−2.83
7.10	7	Eolianite	0.90	−1.38
5.10	101	Eolianite	1.38	−0.57
4.20	6	Rhizolith (calcrete)	−2.12	−3.33
3.80	102	Hardpan	−0.93	−2.10
3.20	1	Calcrete	−1.10	−1.79
3.00	3	Calcrete	1.03	−0.40
2.95	10	Calcrete/Sand	0.92	−1.34
2.94	104	Red Sand	−0.57	−2.06
2.80	105	Calcrete	−3.25	−3.02
2.70	106	Calcrete	−5.49	−4.00
2.60	107	Red Sand	−0.73	−2.07
2.50	108	Calcrete	−6.32	−4.08
2.30	109	Calcrete	−7.12	−5.05
2.20	110	Calcrete	−2.63	−2.96
2.00	111	Red Sand	0.31	−1.62
1.80	9	Calcrete	−5.92	−3.84
1.20	112	Eolianite	1.08	−0.99
0.00	113	Beachrock	0.78	−1.51

The extent of valine racemization in the specimen of *Nerita picea* (UWGA-430) from the unconsolidated sand dune at Kaiehu Point is consistent with a mid-Holocene age, and although a result is only available for the amino acid valine for this specimen, the degree of racemization is comparable with that found in the Holocene molluscs from Kapapa Island (Table 2). In contrast, the unconsolidated skeletal carbonate sand representing the host to this fossil mollusk (UWGA-422a) shows a significantly higher degree of racemization and is comparable to the degree of racemization measured in the sand from the middle eolianite, as well as the calcarenite facies that overlies last interglacial corals at Kaena Point. The higher degree of racemization in this skeletal carbonate sand is likely due to local erosion and reworking of the Late Pleistocene sediments and redeposition during the Holocene. The degree of racemization in this sample far exceeds that for any known material of Holocene age (MURRAY-WALLACE, 2000), and thus precludes a Holocene age for the unconsolidated eo-

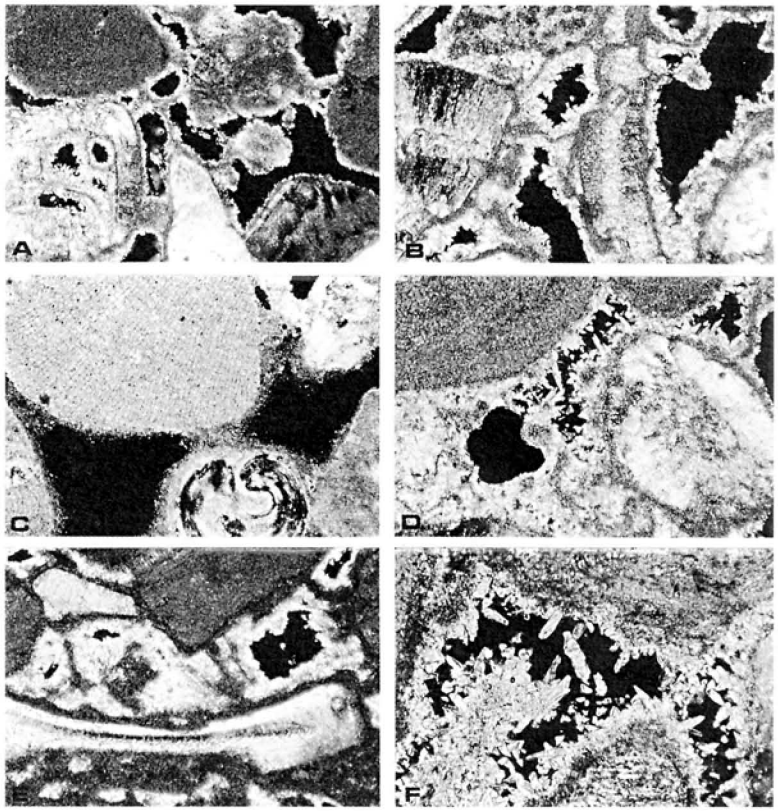


Figure 8. Morphology of rocks. A–C. Irregular coatings of micrite. D–E. Bladed calcite cements. F. Drusy, sparry calcite.

lian sand. A similar pattern of sediment reworking from erosion of Late Pleistocene eolianite was identified in the Coorong Coastal Plain of South Australia (MURRAY-WALLACE *et al.* 2001). In this region, it was found that reworking of skeletal carbonate sand accompanied each interglacial highstand, such that the residence time of skeletal carbonate sediment was on average 100 ka, a trend evident at least since the Early-Middle Pleistocene boundary.

Weathering Intensity

In the Kaiehu Point samples that contain high amounts of calcite and aragonite, some magnesium form of calcite always dominates over aragonite, and so the outcrop is likely to have experienced periods of meteoric exposure and weathering that caused a relative loss of aragonite (SCOFFIN and STODDART, 1987). Beach sands adjacent to Kaiehu Point consist of the foraminifer *Amphisorus hemprechii* and *Amphistegina lobifera* and the calcareous red algae *Goniolithon* sp., all of which have variable magnesium contents. Hence, magnesium content should not be used as the sole indicator of weathering history.

With the exception of sample 110 aragonite is missing entirely in the four lowermost calcrete horizons (samples 106, 108, 109 and 109: Figure 7), and in the rhizolith (sample 6) and brown soil (sample 103), gypsum and halite are the most abundant minerals. The high-gypsum content of the rhizolith at the base of the middle eolianite indicates that the sediment formed and stabilized under changing climatic conditions; climate was humid enough to support plant growth in the dune, and then became sufficiently dry to promote gypsum precipitation (MCKEE and WARD, 1983).

The relative amounts of magnesian calcite determined in 16 of the Kaiehu Point samples show a diagenetic trend. Generally, beach and unconsolidated dune sands have a greater percentage of high-magnesian calcite over low-magnesian calcite, while soils and eolianites contain higher percentages of low-magnesian calcite. Soil samples 105, 106, 107 and 108 have relatively high percentages of low-magnesian calcite, an indication that aragonite and high-magnesian calcite has reprecipitated to low-magnesian calcite during meteoric diagenesis (FRIEDMAN, 1964).

Medium-magnesian calcite is more abundant in the carbonates in the middle of the stratigraphic section than in the older or younger carbonates. Sample 4 has a medium-magnesian calcite composition. Evidently, intense weathering of the exposed middle eolianite altered its aragonite and high-magnesian calcite to a medium-magnesian calcite soil, which characterizes the calcrete paleosol.

The basal beachrock unit, the lowermost eolianite, and its overlying paleosol all contain surprisingly high amounts of

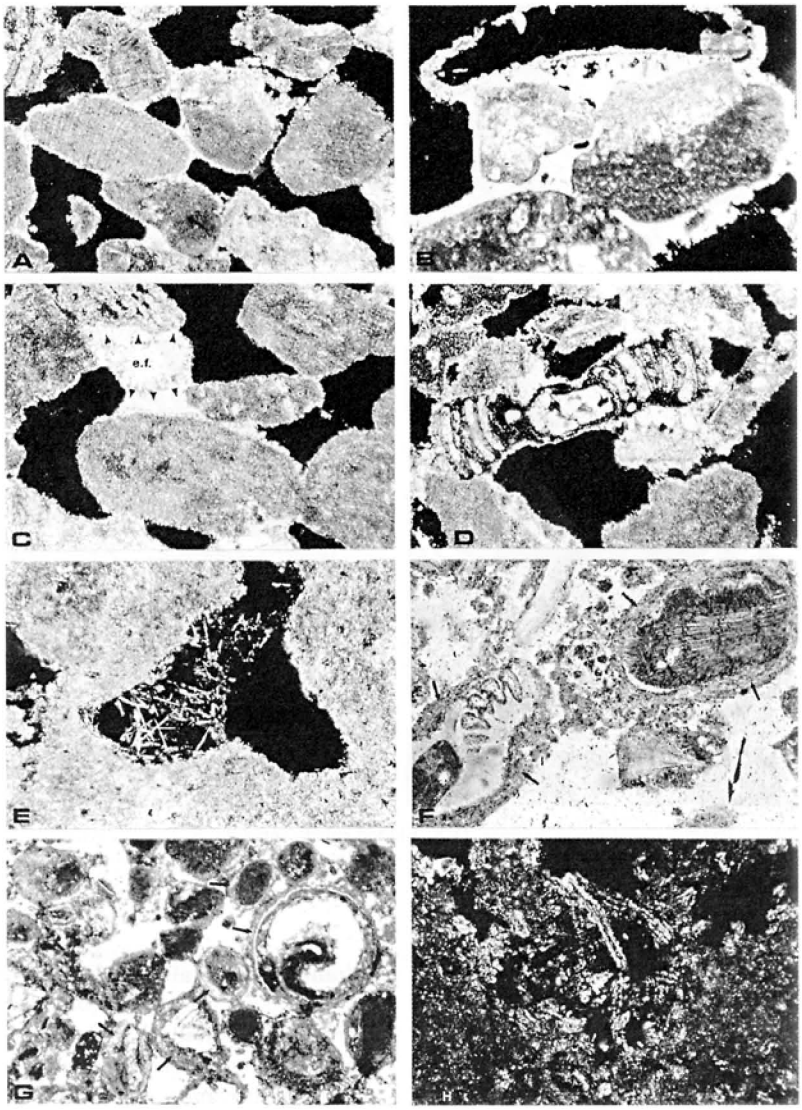


Figure 9. A. Anhedral spar. B. Blocky spar. C. Echinoderm fragments. D. Foraminiferal apertures. E. Root molds. F–H. Vadose pedogenesis.

aragonite and high-magnesian calcite, considering the probable duration over which they have experienced subaerial weathering. FRIEDMAN (1964) suggested that rocks that have already been altered to low-magnesian calcite might reincorporate the magnesium under marine conditions and become slightly more magnesian again. The lower portion of the Kaiehu Point outcrops are in the ocean spray zone and receive a seawater influence daily. As aragonite and high-magnesian calcite are both relatively stable in marine waters, the partial cements will remain aragonitic and high magnesian with marine water inundation (FRIEDMAN, 1964). Thus, the history of these rocks based on alteration extent and magnesian content will be significantly influenced by the chemistry of the local seawater.

Given that the lower samples from the Kaiehu Point succession are located in and affected by sea spray, their position potentially complicates any attempt to classify weathering stages to these sediments. However, calcrete horizons 106 and 108, and possibly 105 have advanced cementation; all aragonite has been altered to low-magnesian calcite (0.45 and 1.98 mole% respectively). The remaining samples appear to fall into intermediate stages of cementation. Taken collectively, the interbedded calcretes and red sands constituting the paleosol immediately below the middle eolianite exhibits significantly higher levels of weathering than the other units.

Depositional and Diagenetic Histories

The meniscus cements and bladed calcite spar in the beachrock sample represent features having formed close to the time of deposition. They most likely precipitated along a clean sandy beach as a result of evaporation of seawater (raising the ionic concentration of the waters) and/or CO_2 degassing (MOORE, 1973, 1977; HANOR, 1978; SCOFFIN and STOD-

DART, 1987). The micritic cements are dark brown, are not pelleted and sometimes contain minute (10–20 μm) inclusions of iron oxides. These micrite cements are very similar to high magnesian calcites described for modern beach rocks of the West Indies (MOORE, 1973) and Maui (MEYERS, 1987), exposed beach rocks at Kaena Point on Oahu (SHERMAN, 1992; SHERMAN, *et al.,* 1999), and elsewhere (see reviews of SCOFFIN and STODDART, 1987). As suggested by MEYERS (1987) for hollow-rim cements of Maui, the origin of some of the bridging micrite cements in these rocks may be related to precipitation of magnesian calcite around the periphery of bubbles or bubble trains. The cement-supported fabric of the beachrock indicates that cementation was rapid and perhaps grain displacive, although such fabric may result from infiltration of fine particles into pores where they are trapped by expanding surfaces of micritic cement (MOORE, 1973).

Sparry calcite cements and caliche veins that cross-cut the beachrock are indicative of precipitation from fresh waters that likely entered during subsequent deposition and exposure of the overlying eolian sand. A caliche horizon within the upper portion of the beachrock occurs as a thin layer of vuggy, laminated calcite above which lays a thin slightly iron-stained grainstone layer containing beachrock cements (uneven micritic coatings and bridges). Light stable isotopic results, which show substantial lightening of bulk $\delta^{13}C$ and $\delta^{18}O$ relative to the beach rock below, confirms that this alteration is due to incursion of fresh waters. Calcite spar has also replaced portions of the skeletal fragments in the beach rocks and incomplete syntaxial overgrowths of calcite, suggestive of vadose cementation (LONGMAN, 1980), occur on altered echinoderm plates. As reported for Bahamian cements (WHITTLE *et al.,* 1993), the later-generation of equant spars within these rocks appear to be most spatially related to the bladed cements, and the latter may have become locally recrystallized to the former.

Orography and Climatic Change on the Islands

Although glacial periods represent times of enhanced global aridity, lower sea levels have indirectly increased rainfall on the Hawaiian Islands, owing to the orographic effect. When moist northeasterly tradewinds approach the high islands, the air is forced to rise and cool. Clouds form and create a rainy environment on the slopes below. GAVENDA (1992) proposed that lowering sea level by 100 m could potentially double the rainfall on Molokai. When sea level attains present levels, the orographic effect on the west Molokai Plateau is slight and the microclimate remains. The $\delta^{18}O$ of groundwater in Hawaii is largely a function of the orographic effect and to a lesser extent the intensity of the tradewinds and storms (SCHOLL *et al.,* 1996). Enhanced weathering during rainy periods associated with lower sea levels is reflected in the significantly lower $\delta^{18}O$ values of the caliche paleosols at Kaiehu Point. The enhanced orographic effect established during periods of lower sea level produced more fractionated meteoric water as revealed in the lower $\delta^{18}O$ signature of cements. Given the last interglacial age (sensu lato) of the Kaiehu Point succession, these conditions are most prevalent during post 5e episodes of lower sea level (*e.g.* OIS 5b and 5d).

The sea level-controlled orographic climates on the Hawaiian Islands, which may influence dune building and soil production, are unique to the region and make comparisons with global processes more complex.

HISTORY OF KAIEHU POINT HEADLAND

Basal Regressive Sequence (Beachrock, Lower Eolianite, and Lower Caliche)

Both regressive and transgressive sedimentary successions are preserved at Kaiehu Point. Beachrock at the base of the succession lithified when relative sea level was near present level. A significant and rapid fall in sea level is inferred (NEUMANN and HEARTY, 1996) associated with the formation of the succession of beachrock—eolianite—and lower caliche paleosol. Based on the similar degree of amino acid racemization within *Carelia sinclairi* from the upper caliche, middle eolianite and lower caliche, the entire succession of lithified units at Kaiehu Point, excluding the unconsolidated Holocene sands, were deposited within a narrow range of time, and possibly during the last interglacial *sensu lato* (OIS 5a-d). STIRLING *et al.* (1998) placed sea level during OIS 5d and 5b between −25 and −55 m, for locations in Bermuda, the Bahamas and Western Australia. Importantly, the insular shelf of Molokai (and Oahu) is composed of OIS 7 paleoreef complex (SHERMAN *et al.,* 1999) with a sharp increase in slope, a seaward facing wall (FLETCHER and SHERMAN, 1995) that begins at approximately −20 m. If sea level drops below the lip of this feature, it would constitute a significant interruption in the carbonate sediment availability to landward calcarenites. The dune field at Kaiehu Point would consequently become sediment starved, and weathering and lithification would ensue under an accelerated pace associated with the enhanced orographic circulation.

As seas regressed following the deposition of the beachrock, dune formation continued landward of the retreating beach, eventually burying the marine calcarenite (and brecciated facies) and creating the contact between the lowest eolianite and the basal beachrock. A similar marine-eolian sequence has been reported from Bermuda (BRETZ, 1960; LAND *et al.,* 1967). The brecciated facies in the beachrock at Kaiehu Point, consistent with deposition in a high energy, intertidal environment, also shows characteristics similar to the Bermudan record.

Erosion responsible for the unconformity between the lowermost eolianite and the overlying caliche is attributed to higher weathering rates associated with the wetter climate during last interglacial (*sensu lato*) low sea-levels (-25 to −55 m) and decreased sediment availability due to the bathymetric barrier at −20 m.

Intense weathering conditions due to the enhanced orographic effect resulting from lower sea levels is evidenced by the significantly lower δ 18O values of the caliche profiles. The lower caliche at Kaiehu Point is characterized by a series of four to six sedimentary packages each including a lower red sand unit grading into an upper calcrete layer(s). These packages are interpreted as representing renewed, but temporary, sand deposition associated with intermittent sand source availability due to either fluctuating sea levels and/or

active dune migration during the OIS 5a-d period. The present day transport of sand from active dunes to stable ridges well inland of the beach, and the existence of the Desert Strip near Kaiehu Point both suggest that dunes on Molokai have been migratory, unlike those on Bermuda that are stable (BRETZ, 1960). This ultimately makes a direct comparison of Bermuda and Hawaii dune and soil formation less practical.

Laterally persistent fluvial silt unconformably overlies the uppermost red sand of the caliche. It is fine-grained, contains some iron in the form of hematite, and has considerable amounts of halite, kaolinite, and gypsum. Hematite is derived from basalt weathering, kaolinite, a product of intense chemical weathering and gypsum of evaporitic origin during dry conditions (SCHOLLE *et al.,* 1983). This mineralogical suite suggests that the silt (or possibly the materials from which it was derived) may have experienced a slow, but significant climate change following deposition, from a humid regime needed for deep hematite weathering and kaolinite accumulation to an arid period necessary for gypsum and halite precipitation. Toward the end of silt deposition, then, the seas were rising again and the climate was becoming increasingly arid. A terrigenous origin for the silt is favored based on the complete absence of marine skeletal fragments and its similar lithological properties to fluvial silt deposits in the immediate watershed.

Middle Eolianite, Upper Caliche, and Unconsolidated Dunes

With higher sea levels associated with OIS 5a-c, dune deposition at Kaiehu Point once again became active. The high-gypsum rhizoliths within the middle eolianite indicate that the dunes must have stabilized and supported plant growth, consistent with a sea level that was relatively low, but in the process of rising. The middle eolianite may have initially formed in a source-distal position, again suggesting that some Molokai dunes did migrate inland before stabilizing.

The upper caliche is interpreted as having formed in a temperate and moist climate associated with the last glacial period. This paleosol unit lacks the red sand characteristic of the lower caliche because sea levels were distinctly lower in OIS 4–2. This effectively shut off the carbonate sand source and all eolian deposition ceased. Dune deposition associated with the present interglacial began once sea level rose above the −20 m barrier. The "Holocene" dune was deposited on the upper caliche paleosol, apparently through the partial, or perhaps total reworking of antecedent sands derived from the middle eolianite. The recycling of carbonate sand within "Holocene" dunes, in part, derives from the remobilization of the shelf sand bodies associated with Holocene sea-level rise. An additional source for these grains is the weathering and erosion of the Late Pleistocene succession at Kaiehu Point.

Stearn's Eolianite Nomenclature and The Island of Molokai: a Reassessment

The eolianite nomenclature formulated by STEARNS (1970) for Oahu provides a stratigraphic framework for all eolianite successions in Hawaii. Thus far, however, the only attempt to apply the stratigraphic nomenclature to neighboring islands was by Stearns himself, where he attempted to name the stratigraphy at Kaiehu Point (STEARNS, 1973).

There is no reason to believe that the unconformities at Kaiehu Point represent the erosional loss of entire eolian episodes. Rather, these appear for the most part to be diastems, surfaces of nondeposition characterized by weathering and *in situ* caliche formation. Indeed, the stratigraphy of the lower caliche supports the concept that some eolian deposition continued throughout the period of paleosol formation. It seems likely then, that a reasonable chronology of eolianite deposition can be proposed based on the amino acid racemization data.

STEARNS (1973) identified the basal eolianite unit at Kaiehu Point as the Bellows Field Formation and suggested that these sands extend below sea level. He did not recognize, however, the beachrock and breccia facies as it was below high tide at the time of his visit. Stearns assigned an Illinoian age of about 320 ka to this oldest eolian unit, and proposed that it was deposited when the sea was some 106 m below present level. The lower caliche was correlated with the Kawela Soil of presumed Wisconsinan age, and he suggested that it was composed of windblown dust derived from a weathered basaltic terrane. Stearns suggested the paleosol represented a period of significant climatic change, characterized by prevailing antitrades blowing from a southerly direction. The overlying middle eolianite was tentatively correlated with the Laniloa Formation of Oahu, and also blew inland when the sea was lower than present. The upper caliche is not mentioned, and the unconsolidated dunes were regarded as recent. On Oahu, STEARNS (1970) identified the Laniloa Formation, a thick ridge of dunes appearing at Kahuku Point on Oahu. Stearns dated Laniloa rocks from the middle Wisconsinan and associated their formation with OIS 4/3.

Within the context of the Bermuda model, the large volume of the middle eolianite indicates formation at a time when sea level was close to present level, but regressing in order to provide the necessary sand for deposition. This is consistent with the amino acid racemization evidence suggesting a late stage 5 age for the succession. Stearns suggested that the Laniloa dunes formed as sea level fell for the last time in the Wisconsinan to the glacioeustatic lowstand in OIS 4–2. Based on the evidence presented in this work, we favor the view that the entire succession at Kaiehu Point formed earlier, and during the fluctuating sea levels during OIS 5a-d, but are unable to discriminate at the substage level.

The amino acid racemization results reported here, point to a less complicated interpretation of the lithostratigraphy at Kaiehu Point, than originally proposed by STEARNS (1970). The amino acid racemization data for both whole-rock and gastropod samples suggest minimal age differences within the succession, implying that the sediments were deposited during a single isotope stage. The degree of racemization in the gastropod *Carelia sinclairi* from the Lower Caliche precludes a Bellows Field age for the deposits at Kaiehu Point. On Oahu and also at Ilio Point, Molokai, STEARNS and MACDONALD (1947) characterize the Bellows Field as a considerable sand deposit, heavily cemented and situated near present sea level (STEARNS, 1970). LUM and STEARNS (1970) present borehole data that the Bellows Field Formation ex-

tends significantly below present sea level. These features are all consistent with our observations at Kaiehu, with the exception of the basal beach rock unit. Nonetheless, if the beach rock truly represents a sustained interval of near present sea level, then the rocks at Kaiehu Point may correlate with the Leahi age, correlative to OIS 5a-c. STEARNS (1970) describes the Leahi eolianites on Oahu as resting on beachrock and representing a regressive sequence, much like the lowest eolianite at Kaiehu Point.

CONCLUSIONS

A well preserved, vertically stacked succession of two genetically distinct eolianites with associated caliche paleosol units at Kaiehu Point, west Molokai, is concluded to have formed during the later stages of OIS 5 based on AAR evidence. Although the AAR method lacks the age resolving ability to definitively conclude in which substage each of the eolianite deposits formed, morphostratigraphic evidence would favor the Lower Eolianite having formed in OIS 5c and the Middle Eolianite during 5a with the superposed caliche paleosols for each unit having formed in subsequent stadial stages. This interpretation is favored in view of the thick and advanced stages of caliche paleosol development on each of the eolianite units, each representing several thousands of year's pedogenesis. Accordingly, the eolianite—caliche paleosol succession at Kaiehu Point, west Molokai, is a function of glacio-eustatic sea-level changes, and local climatic changes enhanced by relative sea-level changes (i.e. enhanced pedogenesis associated with a further fall in sea level and concomitant increased rainfall due to enhanced orographic effects).

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