

$^{40}\text{Ar}/^{39}\text{Ar}$ age of a young rejuvenation basalt flow: implications for the duration of volcanism and the timing of carbonate platform development during the Quaternary on Kaua‘i, Hawaiian Islands

PAUL J. HEARTY

School of Earth and Environmental Sciences
University of Wollongong
Wollongong, NSW 2522, Australia
paulh@uow.edu.au

DANIEL B. KARNER

Department of Geology
Sonoma State University
1801 East Cotati Avenue
Rohnert Park, CA 94928, USA

PAUL R. RENNE

Berkeley Geochronology Center
2455 Ridge Road
Berkeley, CA 94985, USA
and
Department of Earth and Planetary Sciences
University of California
Berkeley, CA 94720, USA

STORRS L. OLSON

National Museum of Natural History
Smithsonian Institution
Washington DC, 20560, USA

SIOBHAN FLETCHER

School of Earth Sciences
James Cook University
Townsville, Queensland 4811, Australia

Abstract Remnants of an extensive carbonate platform crop out along the southeast coast of Kaua‘i, Hawaii. A basalt flow within this succession has a whole-rock $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating plateau age of 375 ± 4 ka. The plateau age, which we interpret as the eruption age, indicates that rejuvenation volcanism persisted on Kaua‘i for considerably longer (c. 200 000 yr) than previously thought, and also that published whole-rock K–Ar determinations may not accurately reflect eruption ages. The succession of younger sedimentary deposits and age of the basalt imply that the eruption occurred near the end of marine isotope stage (MIS) 11. Preservation of limestone dune assemblages and extensive paleosols above present-day sea level indicates that Kaua‘i underwent a period of emergence

during the early and middle Pleistocene, probably due to passage over the lithospheric arch or forebulge created by crustal loading of Maui Nui. The presence of at least eight major limestone-soil “couplets”, together with extrapolated ages from the $^{40}\text{Ar}/^{39}\text{Ar}$ dating, make this the oldest surficial record of limestone formation in the Hawaiian Islands. This work provides a framework for further interpretation of the stratigraphy and paleoecology of Kaua‘i and the tropical Hawaiian Islands.

Keywords lithospheric flexure; carbonate platform; bioclastic dunes (“eolianite”); argon dating; basalt flow; Quaternary; stratigraphy; Hawaiian Islands

INTRODUCTION

Studies of the carbonate platform development of the Hawaiian Islands have focused on O‘ahu and Maui Nui (Maui, Lana‘i, Moloka‘i, and Kaho‘olawe Islands) where uplift has prevailed in the geologically recent past and where coastal sedimentary outcrops are numerous (Stearns 1978; Jones 1993; Moore et al. 1994; Grigg & Jones 1997; Hearty et al. 2000). Geochronological studies of volcanism in the archipelago by K–Ar methods (summarised in McDougall (1979), MacDonald et al. (1983), and Clague & Dalrymple (1988)) provide broad age constraints for the timing of limestone development. By comparison, limestones on Kaua‘i have been inadequately studied due to tectonic subsidence and the absence of a chronostratigraphy. However, recent whole-rock aminostratigraphic studies have helped to clarify stratigraphic successions and estimate the ages of units on Kaua‘i and several Hawaiian islands (Hearty et al. 2000; Hearty 2002a). Studies by Blay & Longman (2001) attempted to construct a lithostratigraphy and define stratigraphic nomenclature, but recognised only four units, and failed to identify distinguishing characteristics among them. Their proposed time frame for the entire emergent succession was 315 000 yr, with the ages of the youngest two units defined on the basis of our amino acid racemisation (AAR) geochronology and radiocarbon (^{14}C) data (Hearty et al. 2000).

The Hawaiian Islands are a hotspot trace (Wilson 1963; Morgan 1972) caused by the WNW conveyance of the Pacific lithosphere over a near-stationary hotspot plume (Jackson et al. 1980). The island of Kaua‘i was constructed from extruded basalt from this plume between 5.7 and 3.9 Ma (McDougall 1964). Like Hawai‘i (the “Big Island”) is today, Kaua‘i was subject to subsidence for the first 2 m.y. of its post-shield forming history, but c. 2–1 m.y. ago, the WNW plate motion of c. 86 mm/yr (Jackson et al. 1980) transported the island across the lithospheric arch created by the crustal loading of the enlarging volcanic mass of Maui Nui (Moore 1970; McNutt & Menard 1978; Naughton et al. 1980). Kaua‘i was uplifted and its carbonate platform was greatly enlarged during this interval. Subsequent to the passage of Kaua‘i

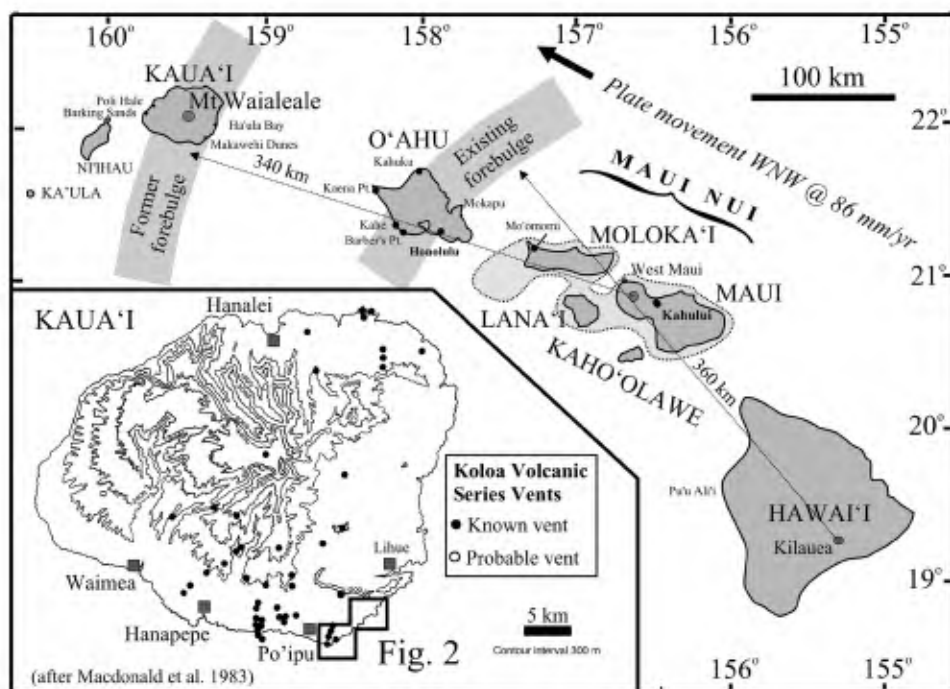


Fig. 1 Location map of the major Hawaiian Islands with Kaua'i at the western end of the chain. Arrows indicate the direction and distance to apparent lithospheric arch or forebulge (shaded line), existing and former.

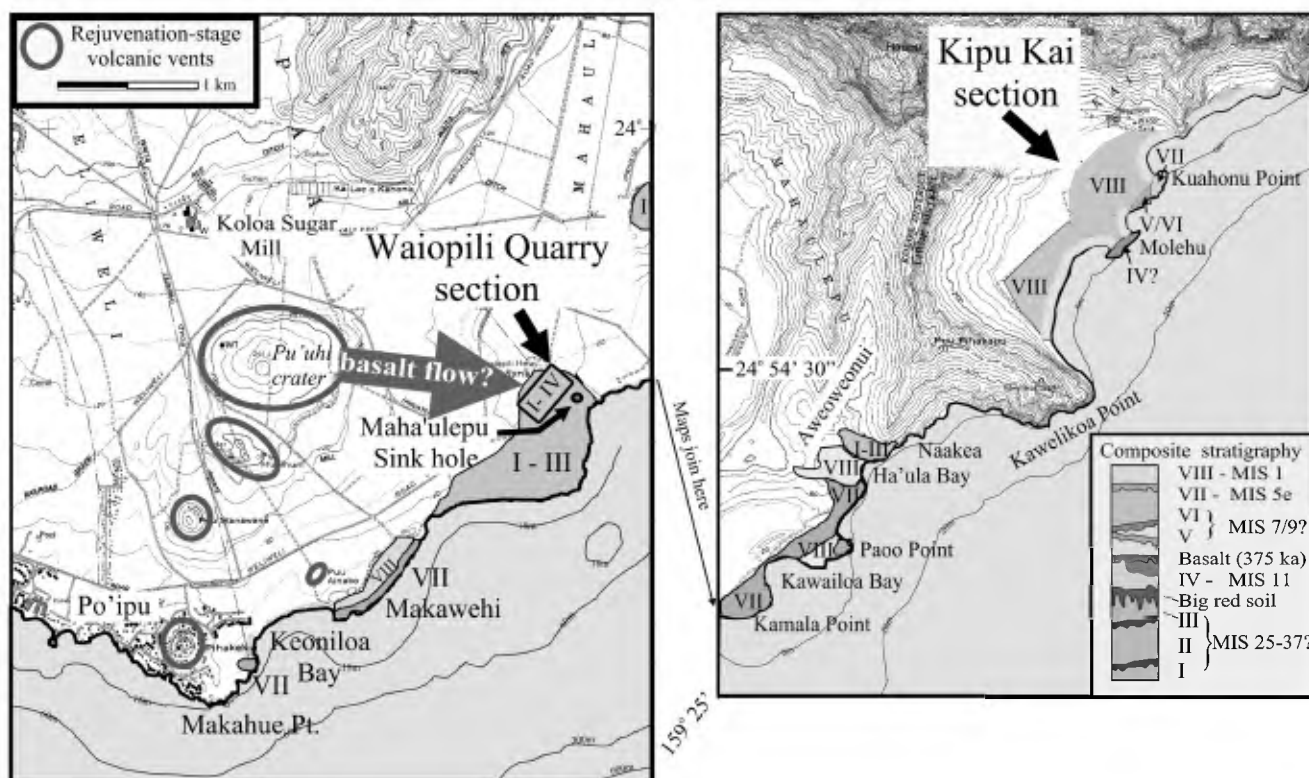


Fig. 2 Maps of coastline from Po'ipu to Kipu Kai showing location of rejuvenation-stage volcanic vents, Waipili Quarry, and Kipu Kai farther to the northeast. Locations of outcrops of several couplets are shown on the map.

over the lithospheric forebulge, the island began to subside (Parsons & Sclater 1977), and this subsidence continues to the present.

Thus, the geology of Kaua'i can be divided loosely into three main rock units: shield-building volcanic rocks, rejuvenation-stage volcanic rocks, and coastal sedimentary rocks; the latter are almost exclusively bioclastic limestone. Rejuvenation (post-erosional) volcanic rocks are common on several Hawaiian islands. On Kaua'i, these rocks were

reportedly extruded between 3.65 and 0.5 Ma (Clague & Dalrymple 1988), that is, 0.27–2.5 m.y. after completion of the major shield-building process. Rejuvenation volcanism is possibly due to structural warping and faulting of the islands as they travel over the lithospheric arch (Jackson et al. 1980; Clague & Dalrymple 1988). Clague & Dalrymple (1988) located more than 50 rejuvenation-stage cones and vents of the Koloa Volcanic Series (Fig. 1), one of which we date by $^{40}\text{Ar}/^{39}\text{Ar}$ methods in this study. Extensive

Fig. 3 Composite stratigraphic sections from Waiopili Quarry area (left) and Kipu Kai (right). Eight couplets are identified by Roman numerals while locations of samples analysed for thin-section petrography (Fig. 6, 7) are indicated (e.g., KUA3c). A tentative correlation with marine isotope stages (MIS) is offered in the centre column (see text for explanation).

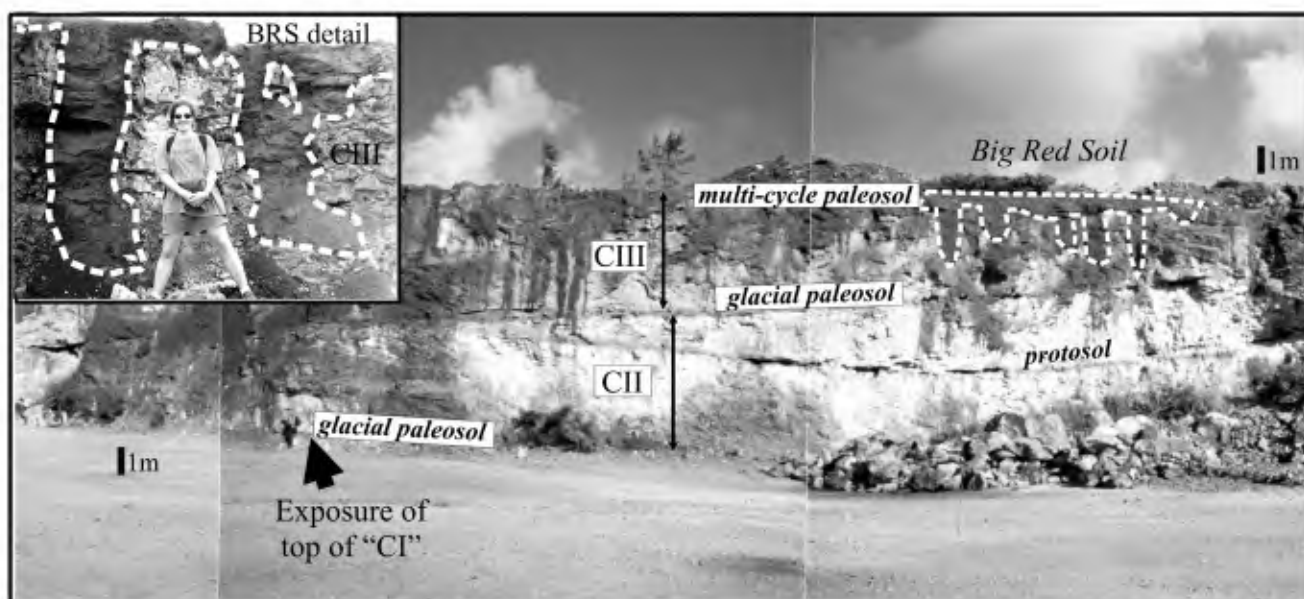
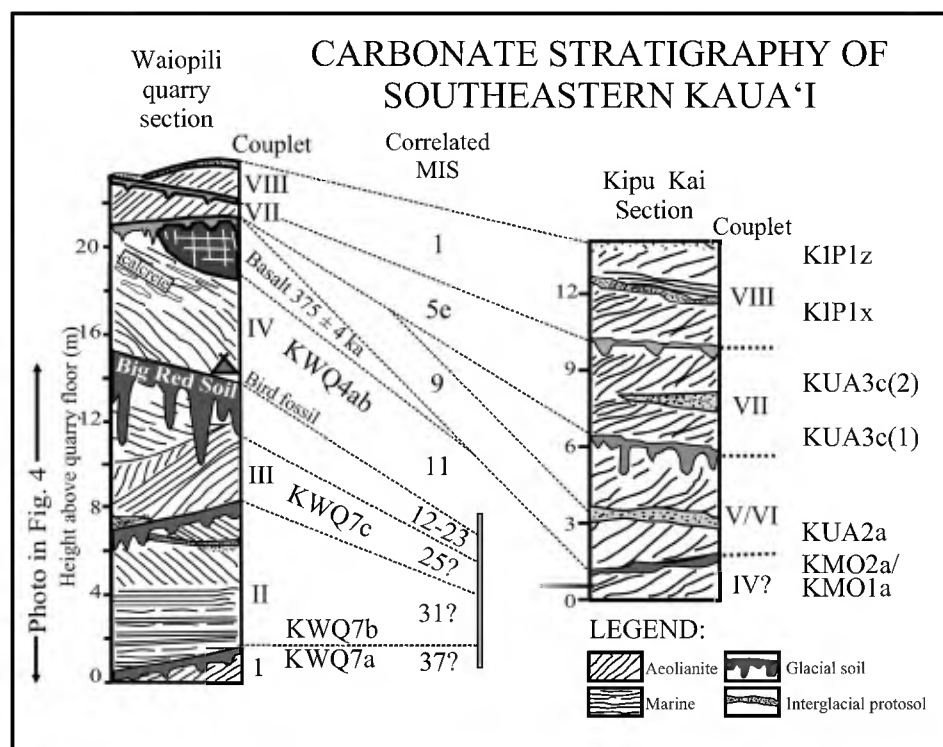


Fig. 4 Panoramic photo of the Waiopili Quarry (east wall) showing limestone-red-soil Couplets I–III and the capping BRS. The Big Red Soil (BRS) (dashed line and inset on upper left) is significantly better developed than other paleosols in the section.

remnants of carbonate platforms are generally upon these rejuvenation lavas, but rarely, as in this case, intercalated with them. These carbonate shoreline complexes extend both above and below sea level, and range between 40 and 150 m in thickness (Emery & Cox 1956; Inman et al. 1963).

STRATIGRAPHY OF WAIOPILI QUARRY AND SOUTHEAST KAUA'I

Extensive sedimentary deposits crop out along the southeast coast of Kaua'i (Fig. 2). A composite stratigraphic section was

developed primarily from limestone outcrops in the Waiopili Quarry (Fig. 3, 4) and along the adjacent coastal cliffs (Fig. 2), which attain a thickness of over 25 m. Eolian sets are abundant, but marine facies are lacking in most outcrops. Conspicuous in the quarry is a thick, clayey, and highly developed paleosol (Fig. 3, 4) that fills deep solution holes and caps several of the older units. We refer to this important stratigraphic marker as the "Big Red Soil" or BRS. Stratigraphic couplets (Hearty & Kaufman 2000) consisting of limestone capped by yellow, brown, or red clay-rich paleosol and/or calcrete are each assumed to represent at least one interglacial (highstand) to glacial (lowstand) cycle (Hearty et al. 1992).

MIS Correlation	Amino- zone	Bermuda Site/Fmn (Hearty et al. 1992; Hearty 2002b)	Kaua'i Blay & Longman (2001)	Kaua'i This study	Hawai'i Terraces, O'ahu (Stearns 1978)	Hawai'i (Hearty et al. 2000; Hearty 2002a)
Modern Recent	A3	Modern beach	Eolian sand sheets	Modern beaches and dunes	Present (0m)	Modern beaches and dunes
Late I	A2		Pa'a Mbr	Couplet VIII (with sub- divisions)	Kapapa (+1.5m)	Ohiki Lolo, OA
Mid I	A1					Makawehi, KA; Mo'om, MO
5a	C	Southampton Fmn		Couplet VIIb	Leahi (+0.6m)	Kalani Pt, MO (+2m)
Late 5e	E2	Rocky Bay Fmn	Makawehi Mbr		Waimanalo (+7.5m)	Mokapu Barber's Pt. Kahe (+9m)
Mid- early 5e	E1	Grape Bay Mbr (new name)		Couplet VIIa	Kailua (+3.6m)	Mokapu Barber's Pt. Kahe (+5.5m)
7	F	colianitic	Pa'o'o Mbr	Couplet VI	"Unnamed" ("High")	Laniloa, OA
9/11	G	Upper Town Hill Fmn	Punahoa Mbr "315 ka"	Couplet V	Kaena (+30m) Laie (+21.5m)	Wai'anae Health (+28m) Kaena Pt. (+30m) Wai'anae Health (+13.5m)
11	H	Lower Town Hill Fmn		Basalt 374 ± 5 ka Couplet IV	PCA (+7.5m)	Wai'anae Health +6 m beach?
13-23?	BIG RED SOIL				Unit not recognised	
25?		Walsingham Fmn		Couplet III	Units not recognised	
31?		(with stratigraphic divisions)	Units not recognised	Couplet II	on O'ahu or other Hawaiian Islands	
37?				Couplet I		

HI = Hawai'i, M.Y. = Maui, OA = O'ahu, MO = Moloka'i, KA = Kaua'i.

Fig. 5 Provisional correlation of major known stratigraphic units in Bermuda, Kaua'i and O'ahu with marine isotope stages (MIS). With the exception of Stearns (1978), all correlations are based primarily on stratigraphic succession and age estimates by the respective authors. Arrows indicate inferred correlations on Kaua'i from this study.

Biological carbonate sediment is formed during highstands in warmer climates on nearshore platform areas and is moved by waves, currents, and tides to the foreshore. Eolian processes further transport the sediments into dunes. During sea-level lowstands, the carbonate sediment is cemented and the surface of the limestone is progressively weathered and further blanketed with atmospheric dust. The weathered sediments eventually become clayey soils that progress in the richness of hues (e.g., brown → yellow → red) with greater age (Folk 1976). Accordingly, we interpret the limestone-paleosol couplets to correspond to interglacial sea-level highstands and glacially generated sea-level lowstands, respectively. The past four or five glacial-interglacial fluctuations occur with a quasi-100 000 yr cyclicity (Shackleton et al. 1984), with the exception of the couplet containing the BRS.

Stratigraphic descriptions of the Kaua'i limestone couplets

Stratigraphic overview

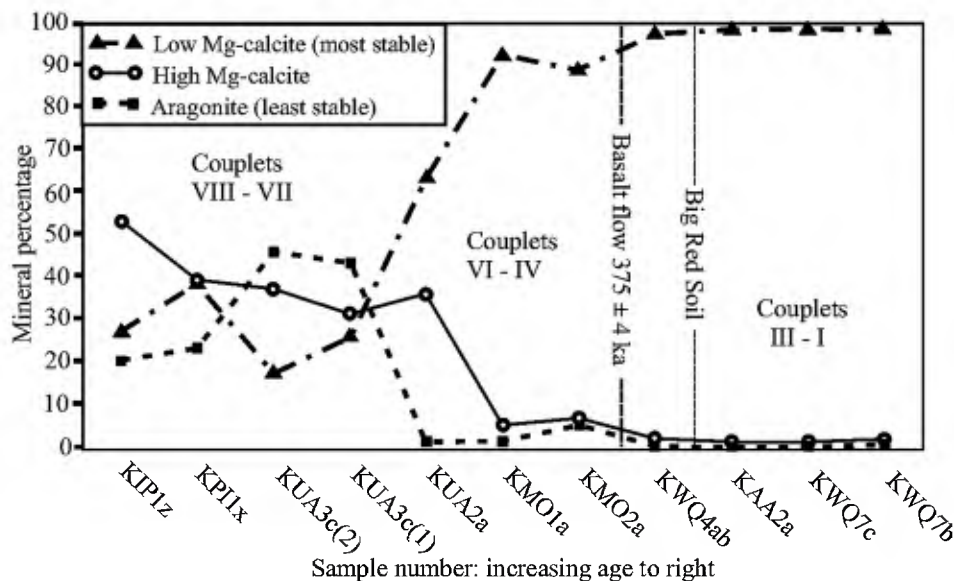
A succession of at least eight limestone-soil couplets occurs in southeastern Kaua'i. We suggest that the older units of this series are remnants of an extensive carbonate platform. The extent of morphological development of the platform offshore of our study area in southeastern Kaua'i is highlighted in USGS Pacific seafloor mapping images (<http://walrus.wr.usgs.gov/pacmaps>). We describe these couplets below,

and number them in ascending stratigraphic order (I–VIII). Considering the early stages of research on Kaua'i, unlike Blay & Longman (2001), we decline to introduce new names for these units to avoid further confounding the nomenclature. We summarise possible correlations between the respective records of various authors in Fig. 5.

The stratigraphic units can be distinguished on the basis of sedimentological, petrographical, mineralogical, pedological, and geochemical (AAR) criteria. The dominant grain types (>30–50%) in all limestone samples are red coralline algae and/or coral, with lesser amounts of foraminifera, molluscs, and bryozoans (Inman et al. 1963; Blay & Longman 2001; this study). The percentages of identifiable molluscs, corals, and foraminifera decrease slightly in older samples, due to their unstable aragonite mineralogy and loss of distinguishing biogenic structures through diagenesis. Limestones of the lowest three couplets I–III, overlain by the BRS (Fig. 4), show extensive visual signs of recrystallisation and vugginess. Younger units (couplets IV–VIII) above a major paleosol show higher percentages of aragonite and high Mg-calcite (Fig. 6).

From a field perspective, the relative degree of hardness (i.e., cementation; recrystallisation), reflected by the extent of diagenesis of the limestone units, can be assessed by hammer blows: couplets I–III are ringing hard; couplets IV and V are hard to punky; and couplets VI–VIII are broken easily with slight hammer blows or crushed by fingers. Further,

Fig. 6 Percent of three major carbonate minerals in the succession of limestone couplets in Kaua'i. The analyses indicate a near-equal mix of aragonite, low Mg-calcite, and high Mg-calcite in youngest couplets VII and VIII. Couplets IV–VI show greater loss of unstable minerals. Couplets I–III are composed of low Mg-calcite with only traces of unstable minerals. The increase of low Mg-calcite at the expense of the less stable minerals with age is one means of classification of the limestone couplets. The relative position of the basalt flow and the Big Red Soil is shown in the diagram.



this progression of diagenetic change over stratigraphic age is evident in thin-section petrography (Fig. 7). The oldest couplets I–III beneath the BRS (Fig. 3, 4) show advanced cementation and recrystallisation of >60% of the grains. These lower units are composed of c. 98% low Mg-calcite, with only traces of high-Mg calcite and aragonite (Fig. 6). Crystal size is greater than in younger samples, with crystal terminations crossing grain boundaries (Fig. 7). Intermediate couplets IV–V show greater percentages of sparry calcite filling voids between and around grains, with incipient recrystallisation apparent in some grains originally composed of aragonite (e.g., molluscs and corals). Youngest units (couplets VI–VIII) show sparry calcite cementation primarily at grain contacts. The grains themselves remain pristine and preserve internal biogenic structures without evidence of recrystallisation. Thus, the progression of diagenetic alteration (*vis-à-vis* Land et al. 1967) of stratigraphic units can be used as a means of classification of the units.

Paleosols capping the oldest units are reddish brown to dark red in couplets I–III. Paleosols on younger couplets IV–VII vary from yellowish brown to strong brown using Munsell (1994) colour charts with minor overlap in mid succession (Fig. 8). The progression from yellowish brown to red is associated with evolution of the ferric minerals from limonite and goethite to hematite (Walker 1974). Red and/or reddish soils are not found in the younger couplets.

In the Hawaiian Islands, whole-rock AAR geochronology has been used as an independent measure of age of interglacial limestone deposits (Table 1) (Hearty et al. 2000; Hearty 2002a). The whole-rock approach uses D-alloisoleucine/L-isoleucine (or A/I) in the 250–850 μm grain-size fraction of gently milled limestone samples (Hearty et al. 1992). A/I ratios from the biogenic grains provide an index of the “average” relative ages of the deposits using A/I ratios, which are calibrated to absolute ages via independent radiometric or isotopic dating methods. The racemisation/epimerisation reaction is sensitive to climate, with warmer sites yielding increasingly higher ratios. The AAR results from Hawaii can be compared to other long AAR chronostratigraphic and lithostratigraphic records (Table 1) in Bermuda and Bahamas (Hearty et al. 1992, 1996; Hearty 1998, 2002a;

Hearty & Kaufman 2000). Independent age chronologies are available for several of the identified units at these sites (see references).

Fossil evidence

Almost all macrofossil remains from Kaua'i, with the exception of some terrestrial gastropod shells, are associated with the carbonate deposits on the southeast coast. Bird bones, terrestrial gastropod shells, and terrestrial crab shells were recovered from the loosely consolidated mid-Holocene age dunes (couplet VIII) at Makawehi (Olson & James 1982; Hearty et al. 2000). Remains of the large flightless waterfowl *Chelychelynechen* (Olson & James 1991) have been found in carbonate sediments of couplet VII (MIS 5) at Ha'ula Bay, and at the base of couplet IV at the contact with the BRS between Makawehi and Maha'ulepu. Based on the age of the basalt flow that we determine in this study, the fossils in couplet IV beneath the flow are among the oldest vertebrate remains yet found in the Hawaiian Islands, notwithstanding recent revelations from O'ahu (Hearty et al. 2005), and show structural differences from later fossils in the same lineage.

Description of lower couplets

Couplet I consists of pervasively recrystallised carbonate eolianite, with vuggy porosity, capped by a yellowish red paleosol (5YR 4/6) c. 15 cm thick. Couplet II is a fully recrystallised series of horizontal, graded beds of probable intertidal marine origin. These beds are succeeded by eolian foresets and a dark red (2.5YR 4/6), clay-rich paleosol (Fig. 8). Within the limestone unit is an extensive brown protosol, a weak sandy soil lacking a karst base (Vacher & Hearty 1989), capped by a second major eolianite. The protosol represents a pause in coastal deposition during which vegetation thrived during interglacials. Couplet III consists of strongly recrystallised eolian foreset beds, marked by a deep karst surface and mantled by the BRS (Fig. 3, 4, 8).

The Big Red Soil

The BRS is a dark to very dusky red (2.5YR 2.5/4), dense, clay-rich paleosol c. 0.5–1.5 m thick (Fig. 4). The BRS

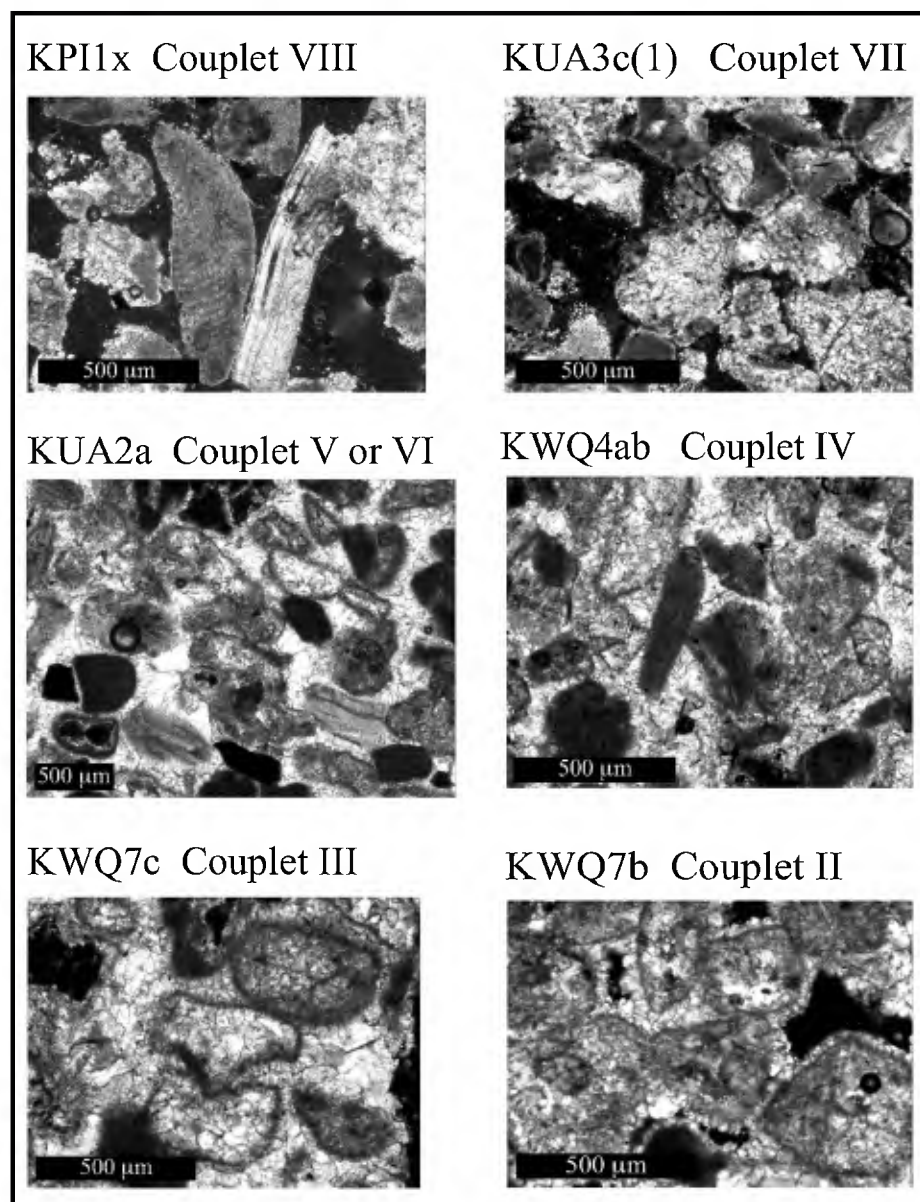


Fig. 7 Thin section petrography showing the progression of diagenetic characteristics through couplets II–VIII. The oldest samples (II and III) show extensive recrystallisation throughout both intergranular spaces and grains. Sparry calcite fills intergranular spaces and has altered some grain types (shells and coral grains) in intermediate samples (IV–VI). Grains remain unaltered in youngest samples (VII–VIII) and cements form only at grain contacts.

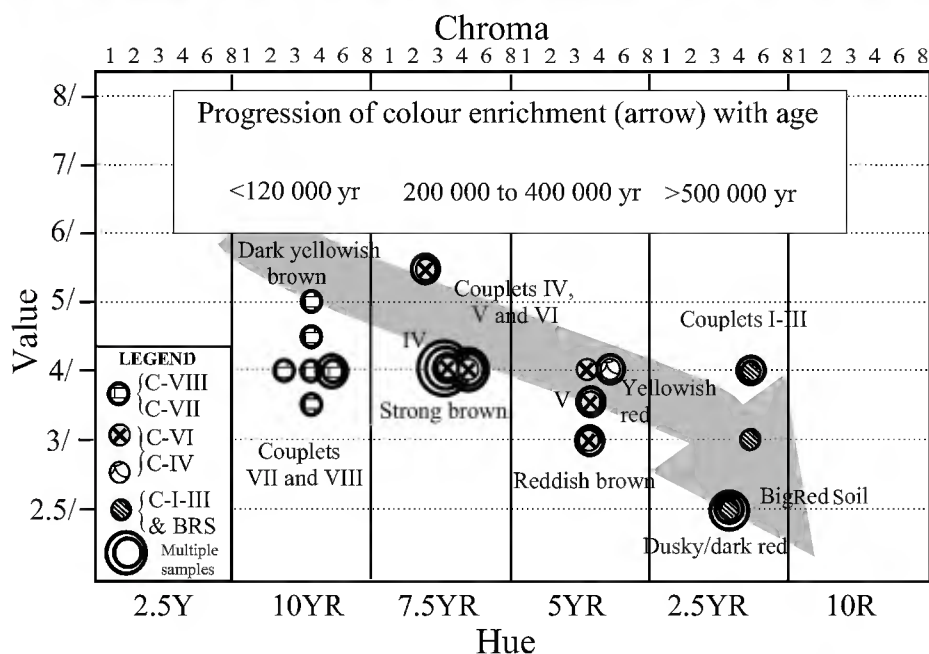


Fig. 8 Classification of paleosols of Kaua'i on the basis of wet Munsell (1994) colour. Stratigraphic position according to couplets is indicated in the legend. The large arrow shows the progression of hue with greater stratigraphic age. Dusky and dark red soils are only characteristic of the Big Red Soil and older Couplets I–III. Yellowish brown soils characterise Couplets VII and younger. Munsell soil colour, when combined with the carbonate mineralogy of the underlying limestone, can be used to distinguish the stratigraphic age in most cases.

fills karstic pipes up to 1 m in diameter and up to 4 m deep (Fig. 4, inset). When compared with the other soils in the Hawaiian Islands, the BRS is the thickest and most extensively developed paleosol on limestone. The degree of karstification is also more advanced than any other limestone surfaces in the Hawaiian Islands. Unlike other limestone paleosols, the BRS is probably the result of prolonged subaerial exposure, uninterrupted by shoreline deposition over several glacial/interglacial cycles. A BRS of similar development and stratigraphic position in Bermuda (Table 1) is constrained to >500 ka by a U/Th age of an overlying flowstone (Hearty unpubl.). In the Bermuda succession, the older couplets (I–III equivalents) are >700 ka and magnetically reversed (Hearty & Vacher 1994), while the younger couplets (IV–VIII) are younger than 415 ka based on U/Th ages (Hearty et al. 1999). The similar stratigraphy and whole-rock AAR ratios between Bermuda and Hawaii support this long-distance correlation.

Couplet IV and the Waiopili Basalt

At the Waiopili Quarry, couplet IV consists of a 7–9 m thick eolianite containing foreset beds. These foreset beds include decimeter-thick, strongly indurated calcrete lenses in the upper 2–3 m, overlain by a dark reddish brown (5YR 3/4) paleosol that mantles both a basalt flow and the limestone. The limestone of couplet IV, resting on the BRS, is significantly less recrystallised than the limestone from couplets I–III, as are all higher units in the succession (Fig. 6, 7). However, routine analyses detected amino acid concentrations no greater than background levels in couplet IV, perhaps reflecting intense heating. The indurated lenses and low concentration of amino acids in couplet IV suggests baking or local hydrothermal activity associated with the basalt flow, or otherwise greater vadose cementation due to increased meteoric precipitation.

A basalt flow, c. 1 m thick and 8–10 m wide, crops out along the western wall of the Waiopili Quarry (Fig. 9). The basalt is vesicular, dense, dark grey, and vertically jointed. It

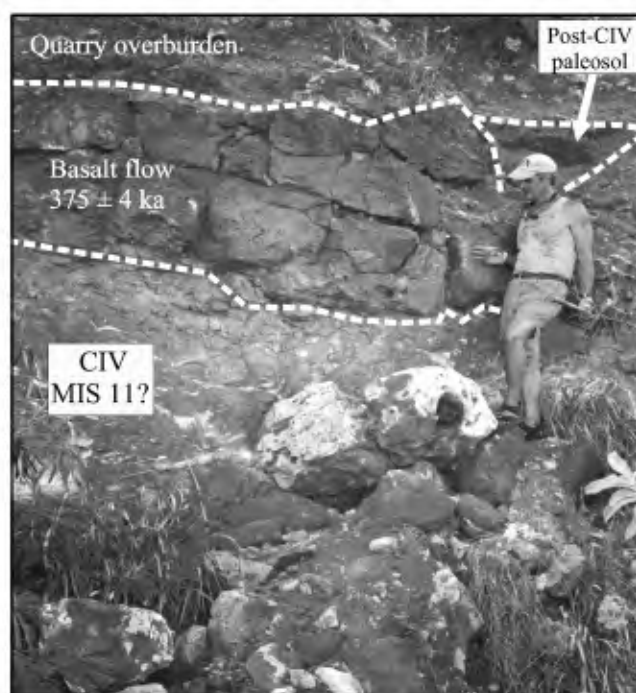


Fig. 9 Photo of alkalic basalt flow with $^{40}\text{Ar}/^{39}\text{Ar}$ age of 375 ± 4 ka in Waiopili Quarry. The basalt flow overlies couplet IV correlated on the basis of the argon age with MIS 11. Couplet IV contains multiple decimetre-thick calcrete lenses and is devoid of amino acids, perhaps due to baking and/or hydrothermal activity associated with the basalt flow.

was emplaced on limestone rubble in a small gully formed in couplet IV. The likely source of the basalt is the Pu'uhi Crater, directly up-slope 1.5 km to the west (Fig. 2). The presence of limestone rubble and the absence of a paleosol

Table 1 A comparison and proposed correlation of limestone-soil couplets and mean whole-rock D-alloisoleucine/L-isoleucine (A/I) ratios from Bermuda, Bahamas, and several Hawaiian islands. Warmer sites in the Bahamas and Hawaii produce higher A/I ratios for equal-age sites, in comparison to cooler Bermuda. Geochronological techniques (U/Th, ^{14}C , Ar/Ar) provide independent age calibration for several units (C-IV, C-VII, and C-VIII), reinforcing the AAR correlation. Refer to text and cited works (footnote) for additional details. Fewer units have been identified on the younger Hawaiian islands. A/I ratios are in the format 0.45 ± 0.02 (5) indicating mean, ± 1 σ , and number of samples analysed in parentheses.

Stratigraphic unit	Bermuda ¹	Bahamas ² (Eleuthera)	Kaua'i ³	O'ahu ³	Molokai ³
C-VIII	0.12 ± 0.01 (2)	0.05 ± 0.02 (3)	0.11 ± 0.03 (6)	0.10 (1)	not observed
C-VIIb	0.23 ± 0.03 (3)	0.10 ± 0.01 (2)	0.27 ± 0.02 (8)	0.22 (1)	0.27 ± 0.02 (7)
C-VIIa	0.29 ± 0.03 (12)	0.29 ± 0.03 (5)	not observed	not observed	0.34 ± 0.01 (6)
	c. 125 ka	c. 125 ka		0.45 ± 0.06 (17)	0.46 ± 0.06 (5)
				0.51 ± 0.03 (11)	
				c. 125 ka	
C-V/VI	0.49 ± 0.04 (11)	0.58 ± 0.01 (3)	Kipu Kai succession	0.64 (1)	0.66 (1)
C-IV	0.67 ± 0.03 (6) ⁵	0.67 ± 0.05 (16) ⁵	Basalt flow	0.81 ± 0.08 (6) ⁴	not observed
	405 \pm 5 ka	<550 ka	>375 \pm 4 ka	386–530 ka	
BRS	BIG	RED	SOIL	not observed	not observed
C-III	Reverse polarity in pre-BRS couplets	Reverse polarity in cores (Exuma Islands) ⁶	Three pre-BRS couplets	not observed	not observed
C-II				not observed	not observed
C-I	1.11 ± 0.02 (3)	ND	ND	not observed	not observed

ND = Sampled and analysed but levels of amino acids beyond detection.

¹Hearty et al. (1992); ²Hearty (1998), Hearty & Kaufman (2000); ³Hearty et al. (2000); ⁴Hearty (2002a); ⁵Hearty et al. (1999); ⁶Hearty et al. (1996; unpubl.).

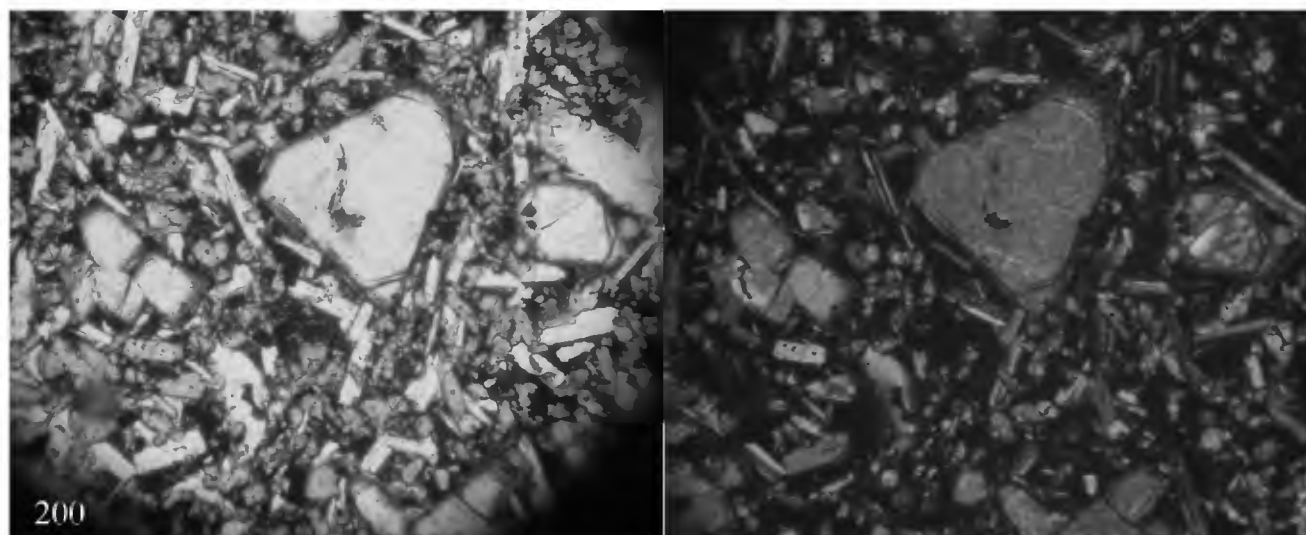


Fig. 10 Photomicrograph of Waiopili basalt. Phenocrysts of olivine have notable alteration rims when viewed in plain polarised light (left). Groundmass contains laths of plagioclase, plus olivine and magnetite. Voids (not in view) are filled with sparry calcite. Olivine is the only phase with discernible alteration rims, and so we interpret this sample to be minimally altered. The absence of nepheline in the groundmass (see cross-polars, right) indicates that this is an alkalic basalt in the classification system of Clague & Dalrymple (1988). Image width is 200 μm .

beneath hint that the basalt flowed down the gully a short time after initial induration and erosion of the limestone of couplet IV. Lava flowing down a local drainage might create hydrothermal conditions which could account for the unusual calcrete cementation in the underlying limestone of couplet IV.

Characteristics of upper couplets

While not present at the Waiopili Quarry, a carbonate sequence nearby at Kipu Kai (Fig. 2) is stratigraphically and diagenetically intermediate between sets of couplets I–IV, described above, and younger couplets VII and VIII, which we describe below. We designate these Kipu Kai sequences at Molehu and Kuahonu headlands to be couplets V and VI (Fig. 3). The units have mixed diagenetic characteristics (Fig. 6), and have reddish brown (c. 5YR 4/4) capping paleosols with significantly stronger hues than yellowish brown post-MIS 5e soils (c. 10YR–7.5YR 4/4). Probable stratigraphic equivalents of couplets V and VI may also be recognised on O‘ahu (PCA, Laie, Waialae, and Kailua of Stearns 1978) and Mo‘omomi, Molokai (Fig. 5), and have produced whole-rock A/I ratios averaging 0.65, indicating an age intermediate between MIS 5e and 11 (Hearty et al. 2000; Hearty 2002a) (Table 1).

Couplets VII and VIII are found near the Waiopili Quarry (Fig. 2) and locally around Kaua‘i. These units are correlated with MIS 5e and 1, respectively, based on comparisons with dated sections on Kaua‘i and other Hawaiian islands (Hearty et al. 2000). A younger MIS 5a eolianite (couplet VIIb, Table 1) was also described from Mo‘omomi, Molokai (Hearty et al. 2000), but has not been identified in Kaua‘i. Couplet VII consists of semi-indurated eolianite, ranging diagenetically from nearly pristine to nominally altered, and capped by a distinctively yellowish brown (10YR 4/4) paleosol. Although Blay & Longman (2001) described capping soils on this unit as “red and reddish”, they did not provide Munsell colours,

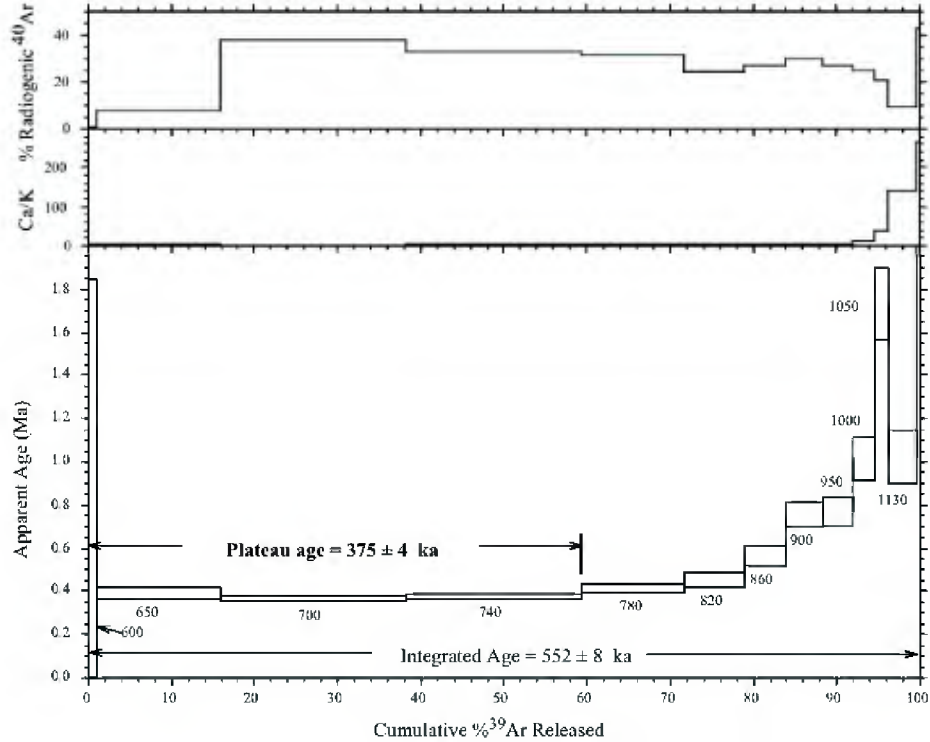
and we have not observed red soil on couplet VII in Kaua‘i. Unlike the Waimanalo Formation of O‘ahu (Stearns 1978), dated at 125 ka (Muhs & Szabo 1994; Szabo et al. 1994), no marine deposits (only eolianites) are associated with equivalent couplet VII in Kaua‘i. Couplet VIII consists of eolian facies on the southeastern side of Kaua‘i. These Holocene dunes are capped with pale brown (c. 10YR 6/3) sandy soils.

$^{40}\text{Ar}/^{39}\text{Ar}$ AGE OF THE WAIOPILI BASALT

To provide an independent age within the succession of eight limestone-soil couplets, a visually unaltered basalt sample from the western Waiopili Quarry wall was analysed for $^{40}\text{Ar}/^{39}\text{Ar}$. The sample (Fig. 10) consists of c. 30% by volume olivine phenocrysts, in a groundmass of plagioclase (40% vol.), olivine (20% vol.), and metal oxides (10% vol.). Under the Clague & Dalrymple (1988) basalt classification system, the Waiopili basalt is alkalic in composition. Olivine rims in phenocrysts show evidence of minor alteration in thin section (Fig. 10), but there is no similar evidence among the other mineral phases. Given this low degree of post-eruption alteration, we conclude that the Ar isotope systematics of this sample are unlikely to have been significantly affected by diagenesis since deposition.

The basalt sample was crushed and sieved, and the 40–60 mesh (250–420 μm) fraction was used for whole rock $^{40}\text{Ar}/^{39}\text{Ar}$ age analysis. Before irradiation, the sample was placed in a 10% hydrochloric acid bath for 10 min, followed by a 5 min rinse in distilled water. Then, the feldspar-rich groundmass was concentrated by removing olivine phenocrysts by hand. Two separates each weighing c. 200 mg were wrapped in copper foil and placed in aluminium disks along with the Alder Creek Tuff sanidine standard (ACs, 1.194 Ma, Renne et al. 1998), and irradiated at the TRIGA reactor at Oregon State University for c. 30 min, where cadmium shielding is

Fig. 11 $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating spectrum. The plateau age is calculated by inverse variance weighting all steps on the plateau, and reported with 1σ uncertainty. Individual steps are shown with temperature in $^{\circ}\text{C}$ and with 2σ error bars. Higher temperature release steps show significantly older apparent ages and higher ratios of Ca:K, indicating that a calcium-rich mineral phase with $^{40}\text{Ar}_{\text{excess}}$ exists in this sample. The integrated age, which includes Ar released from all heating steps, is equivalent to a K-Ar age of 552 ± 8 ka.



employed to minimise the $^{40}\text{K}(\text{n,p})^{40}\text{Ar}$ reaction caused by thermal neutrons (Tetley et al. 1980).

Argon extraction was done at the Berkeley Geochronology Center, using a fully automated microextraction-mass spectrometer system following procedures similar to those in Karner & Renne (1998). The step-heating analysis was done using a double vacuum electrical resistance furnace and a MAP215-50, 90° sector extended-geometry mass spectrometer with electrostatic analyser. Details of furnace blanks and other

features of this system are given by Renne et al. (1999) and references therein. Released gases were scrubbed of reactive species using a two-stage clean-up system that employed Zr-Fe-V, and Zr-Al alloy getters (reaction times were 900 and 600 s, respectively). The remaining gases were then admitted into the mass spectrometer, where the Ar ion beam currents were measured on an electron multiplier.

The sample was heated from 600 to 1200°C in 13 increments. Data are reported in Table 2. The four lowest

Table 2 $^{40}\text{Ar}/^{39}\text{Ar}$ isotopic data.

Lab. no.	$T (^{\circ}\text{C})$	$^{36}\text{Ar}/^{39}\text{Ar}$	$^{37}\text{Ar}/^{39}\text{Ar}$	$^{38}\text{Ar}/^{39}\text{Ar}$	$^{40}\text{Ar}/^{39}\text{Ar}$	^{40}Ar moles ($\times 10^{-13}$)	$\%^{40}\text{Ar}^*$	$^{40}\text{Ar}^*/^{39}\text{Ar}$	Age (ka)	$\pm 1\sigma$
11312-01A	600	1.19802	1.73846	0.24442	356.92630	5.16	0.9	3.05091	683	581
11312-01B	650	0.07123	1.25992	0.02610	22.70387	5.19	7.7	1.75583	393	14
11312-01C	700	0.00948	1.09291	0.01360	4.37113	1.49	37.8	1.65545	371	6
11312-01E	740	0.01200	1.49532	0.01390	5.10841	1.66	32.8	1.67951	376	7
11312-01F	780	0.01410	1.48617	0.01440	5.88570	1.13	31.2	1.84005	412	10
11312-01G	820	0.02140	1.33303	0.01570	8.24057	0.92	24.5	2.02462	454	18
11312-01H	860	0.02340	1.44825	0.01720	9.33835	0.73	27.0	2.52503	566	25
11312-01I	900	0.02720	1.66863	0.01800	11.28575	0.78	29.8	3.36874	755	28
11312-01J	950	0.03207	2.40181	0.01880	12.73550	0.74	27.1	3.45180	773	33
11312-01K	1000	0.04750	5.66183	0.02140	18.11588	0.72	24.9	4.52992	1015	50
11312-01L	1050	0.10567	19.75323	0.03610	37.31317	0.98	20.4	7.73676	1733	82
11312-01M	1130	0.15833	72.83752	0.04250	45.44386	2.49	9.5	4.57172	1024	62
11312-01N	1200	0.32800	136.22330	0.07330	150.10330	1.00	42.5	70.57176	15744	419

Mass discrimination = 1.00805 ± 0.00004 per amu (based on a power-law correction) determined by analysis of air argon by gas pipettes.

Constants: $^{40}\text{K}/\text{K} = 1.167 \times 10^{-4}$ mol/mol and ^{40}K decay constants $\lambda_c = 0.581 \times 10^{-10} \text{ yr}^{-1}$ and $\lambda_b = 4.962 \times 10^{-10} \text{ yr}^{-1}$ (Steiger & Jäger 1977). Atmospheric $^{40}\text{Ar}/^{36}\text{Ar}$ ratio used was 295.5 (Nier 1950).

Irradiation parameter “J” = $1.242 (\pm 0.002) \times 10^{-4}$.

Corrections for interfering neutron reactions: $^{36}\text{Ar}/^{37}\text{Ar}$ (Ca) = $2.64 (\pm 0.02) \times 10^{-6}$, $^{39}\text{Ar}/^{37}\text{Ar}$ (Ca) = $7.04 (\pm 0.06) \times 10^{-6}$, $^{40}\text{Ar}/^{39}\text{Ar}$ (K) = $7 (\pm 3) \times 10^{-4}$.

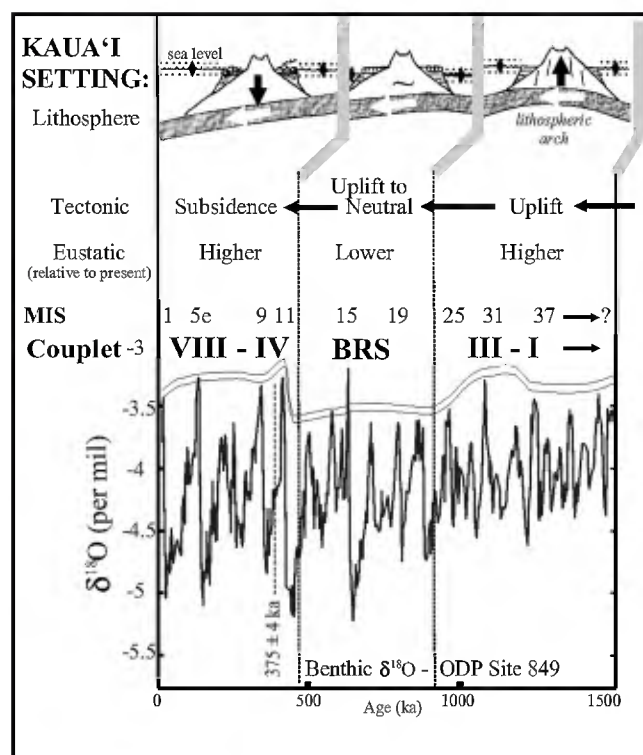


Fig. 12 A summary of the tectonic setting and inferred sea-level history of Kaua'i over the past 1.5 m.y. A benthic $\delta^{18}\text{O}$ curve (Mix et al. 1995) is provided for reference. Generally, three c. 0.5 m.y. intervals are interpreted from the geology: (1) tectonic uplift combined with relatively higher sea levels (1.5–1.0 m.y.); (2) tectonic uplift or neutrality combined with relatively lower than present sea levels (1.0–0.5 m.y.); and (3) tectonic subsidence combined with relatively higher eustatic sea levels (0.5 m.y.–present).

temperature steps in the step-heating spectrum (Fig. 11) produce a plateau age of 375 ± 4 ka (calculated from the error weighted mean $^{40}\text{Ar}/^{39}\text{Ar}$ ratio and presented with 1σ analytical errors) from 59.3% of the cumulative ^{39}Ar gas yield. An isotope correlation diagram of these plateau steps yields an age of 370 ± 5 ka, with a mean square weighted deviation (MSWD) of 0.15 (probability of 0.86), and an $^{40}\text{Ar}/^{36}\text{Ar}$ intercept of 296.9 ± 1.0 . Thus, the initial trapped argon gas associated with these heating steps is consistent with the atmospheric $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 295.5 (Nier 1950) at 95% confidence. Based on these results, we conclude that the plateau steps yield a reliable age for this sample of 375 ± 4 ka. In contrast, the integrated age of the sample, which is equivalent to its K-Ar age, is 552 ± 8 ka, based on the cumulative ^{39}Ar release. The higher temperature steps yielded older ages than did the plateau steps, and also contained higher ratios of Ca/K (Fig. 11). This release pattern indicates incomplete degassing of mantle-derived ^{40}Ar in a Ca-rich, K-poor mineral phase, which we interpret to be plagioclase, or possibly microcrysts of clinopyroxene.

DISCUSSION

Interpreted age of the Kaua'i limestone sequence

The 375 ± 4 ka plateau age of the basalt is the youngest age reported for rejuvenation lavas from Kaua'i by nearly

200 000 yr. Clague & Dalrymple (1988, 1989) determined several K-Ar ages of 500–600 ka for several basalt flows on southeast Kaua'i. These K-Ar ages are consistent with our integrated $^{40}\text{Ar}/^{39}\text{Ar}$ age of 552 ± 8 ka. This indicates that the lack of step-heating measurements precluded those authors from identifying radiogenic versus non-radiogenic argon sources. As such, the K-Ar ages for rejuvenation lavas should be viewed as maximum age limits; the eruption ages could be substantially younger.

With the basalt age as one of several temporal benchmarks, the succession of limestone-soil couplets in Kaua'i appears to correlate well with the general ice volume trends revealed in deep-sea oxygen isotope records. In the Hawaiian Islands, the correlation of reef and limestone platforms and interglacial highstands with negatively numbered isotope stages is confirmed in U/Th dating of corals (e.g., Muhs & Szabo 1994; Szabo et al. 1994; Sherman et al. 1999). The Holocene/modern analog and the presence of coarse and moderately sorted particles in most units, indicating the proximity of the source deposits, further support the limestone/interglacial correlation.

Thus, accepting that the limestones correlate with interglaciations, and lacking evidence for significant lacunae, we infer that couple IV, directly beneath the 375 ± 4 ka basalt flow, correlates with the next older interglaciation, MIS 11 (c. 415 ka). From a global perspective, $\delta^{18}\text{O}$ in benthic foraminifera during MIS 11 is isotopically light, suggesting that more glacial ice melted during this interglacial period than during any other interglacial period in the middle or late Pleistocene. Examination of the benthic $\delta^{18}\text{O}$ record from ODP Site 849 (Mix et al. 1995) (Fig. 12) as well as many other benthic records (see Karner et al. 2002 for review) supports the notion of an unusually high sea level during MIS 11. On the tectonically stable Bermuda and the Bahamas (Hearty et al. 1999), changing high sea levels (up to +20 m) over the very long interglaciation of MIS 11 were responsible for the extensive and voluminous deposits relative to other interglaciations. Similarly on O'ahu, the Kaena highstand, correlated with MIS 11 (Hearty 2002a), preserved extensive evidence of a late Quaternary highstand (to +30 m including c. 10 m of uplift). We thus correlate couplet IV eolianite with the Kaena Highstand; however, lacking the marine facies.

Generally lower sea levels occurred during several interglacial cycles preceding MIS 11 (i.e., MIS 13 and 21; c. 500–900 ka). Deep-sea oxygen isotope records suggest that global temperatures then were significantly cooler than the modern datum (Shackleton et al. 1984, 1990; Oppo et al. 1990; Raymo et al. 1990) (Fig. 12). With lower sea levels, carbonate shoreline sedimentation would generally extend only over the seaward margin of the carbonate platform. Thus, prolonged exposure of the platform over several interglacial cycles would explain the greater degree of development of the BRS. The oldest units are characterised by extensive shoreline development of massive eolianite and possible marine facies in couplet II.

The Kaua'i succession and sedimentary development parallels well-documented carbonate platform settings on Bermuda (Hearty & Vacher 1994), Italy (Hearty et al. 1986; Karner & Renne 1998), and the Bahamas (Hearty et al. 1996) (Fig. 5, Table 1). These sequences of coastal development generally agree with the relative magnitude of ice volume changes and duration of interglaciations over the past

1.5 m.y. indicated by oxygen isotope records (e.g., Shackleton et al. 1984).

On this basis, we can constrain the minimum age of the Kaua'i carbonate platform deposits. If we assume that: (1) couplet IV equates with MIS 11 or older (≥ 415 ka); (2) no additional couplets of 100 000 yr cyclicity are missing between the oldest couplets I through IV; and (3) the BRS formed over at least one interglacial cycle (100 ka), then we can infer that the collective age of the sequence comprises a minimum of 800 000 yr. Because coastal carbonates are by their nature spatially discontinuous, assumption (2) is improbable. The greater degree of development of the BRS, compared to all other known soils from the Hawaiian Islands, endorses a reasonable conclusion that more than one eustatic cycle was required for its formation. If both (2) and (3) are invalid, as we suggest, the total sequence must be well over 800 000 yr old (Fig. 12). Indeed, we interpret all couplets preceding the BRS (I–III) to fall within the early Pleistocene (>0.78 m.y.) as in the Bermuda example. As we are proposing a record of 0.8 to possibly >1.5 m.y., we find Blay & Longman's (2001) proposed duration of c. 315 000 yr for the entire Kaua'i sequence to be an unlikely representation of the age of this limestone succession.

Tectonic and sea-level history inferred from the Kaua'i successions

The identification of extensive early Pleistocene carbonate platform deposits on Kaua'i above present-day sea level is somewhat unexpected. Had Kaua'i simply subsided at typical rates following its construction over the Hawaiian hotspot, these deposits should now be far below sea level. Therefore, Kaua'i must have undergone an early period of emergence during its platform formation. Couplets I–III exhibit predominantly terrestrial eolianite and paleosol facies. The BRS also must have been formed during this extended period of emergence as the product of upward tectonic motion and a prolonged interval of relatively lower sea-level highstands.

This emergent trend apparently reversed over the past four or five interglaciations, based on our field assessment of the MIS 11 and couplet IV interglacial deposits. Using the sea-level maxima of +20 m and +6 m for MIS 11 and 5e, respectively (Hearty et al. 1999; Hearty & Kaufman 2000; Hearty 2002a), the present elevations of couplets IV and VII indicate that average subsidence rates must have exceeded 0.05 m/ka to inundate their respective subtidal facies, which, despite extensive searches, have not been located on Kaua'i. Thus, couplets IV through VIII appear to show evidence of eustatic sea-level changes superimposed on a general trend of tectonic subsidence.

Today, O'ahu is passing over the lithospheric arch created by crustal loading at Kilauea, Hawaii, located 360 km ESE of O'ahu, providing a modern analog for Kaua'i over 1 m.y. ago. Kaua'i is situated c. 340 km WNW of the weighted centre of Maui Nui (near West Maui) (Fig. 1), a distance similar to that between O'ahu and Kilauea. Maui Nui underwent its major shield-building phase and crustal loading between 2 and 1 m.y. ago (McDougall 1964; Naughton et al. 1980). Presumably, at that time, Kaua'i was astride the Maui Nui lithospheric arch (Fig. 12). Given an approximate width of 100 km for the forebulge (Grigg & Jones 1997) and a plate velocity of 86 mm/yr, Kaua'i would have crossed the Maui Nui forebulge

over a period of c. 0.9 m.y. Emergence of Kaua'i would have thus continued between c. 1.5 and 0.5 m.y. ago. Since 0.5 m.y. ago, after passing over the forebulge, Kaua'i has experienced, and will continue to experience, tectonic subsidence.

CONCLUSIONS

The carbonate deposits on Kaua'i preserve a history of glacial-interglacial sea-level change superimposed on upward and downward lithospheric warping. The $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating plateau age of 375 ± 4 ka for the Waiopili Quarry basalt flow provides an important age landmark for the timing of limestone formation on Kaua'i. Our evidence suggests that Kaua'i experienced a period of emergence during the early Pleistocene caused by passage of the island over the lithospheric arch created by Maui Nui. The $^{40}\text{Ar}/^{39}\text{Ar}$ age also reveals that the rejuvenation volcanism on Kaua'i is younger than determined previously by K-Ar methods. Apparent from our data and interpretations, Kaua'i exposes the oldest subareal limestone succession, as well as some of the oldest vertebrate fossils in the Hawaiian Islands. Paleomagnetic analyses of limestone couplets I–III are warranted to confirm our inference that limestone couplets I–III extend into the Matuyama geomagnetic chron (>0.78 Ma).

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