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REPORT

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Age and composition of carbonate shoreface sediments, Kailua Bay, Oahu, Hawaii

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Abstract The origin, age, and dynamics of carbonate sediments in Kailua Bay on Oahu, Hawaii, are described. The shoreface (from shoreline to 4 km offshore) consists of a broad (5 km^2) fringing coral reef ecosystem bisected by a sinuous, shore-normal, sand-filled paleostream channel 200–300 m wide. The median grain diameter of surface sands is finest on the beach face (<0.3 mm) and increases offshore along the channel axis. Kailua sands are >90% biogenic carbonate, dominated by skeletal fragments of coralline algae (e.g. *Porolithon*, up to 50%) followed by the calcareous green alga *Halimeda* (up to 32%), coral fragments (1–24%), mollusc fragments (6–21%), and benthic foraminifera (1–10%). Sand composition and age across the shoreface are correlated to carbonate production. Corals and coralline algae, principal builders of the reef framework, are younger and more abundant in sands along the channel axis and in offshore reefal areas, while *Halimeda*, molluscs, and foraminifera are younger and more dominant in nearshore waters shoreward of the main region of framework building. Shoreface sediments are relatively old. Of 20 calibrated radiocarbon dates on skeletal constituents of sand, only three are younger than 500 years B.P.; six are 500–1000 years B.P.; six are 1000–2000 years B.P.; and five are 2000–5000 years B.P. Dated fine sands are older than medium to coarse sands and hence may constitute a reservoir of fossil carbonate that is distributed over the entire shoreface. Dominance of fossiliferous sand indicates long storage times for carbonate grains, which tend to decrease in size with age, such that the entire period of relative sea-level inundation (~5000 years) is represented in the sediment. Despite an apparently healthy modern coral ecosystem, the surficial sand pool of Kailua Bay is dominated by sand reflecting an antecedent system, possibly one that existed under a +1–2 m sea-level high stand during the mid- to late Holocene.

Key words Sediment · Carbonate · Radiocarbon · Hawaii · Holocene

Introduction

During the last decade, the composition of unconsolidated, shallow-marine carbonate sediments has been utilized to study depositional patterns and pathways (Gischler and Lomando 1999; Kench 1997), the zonation of reefal and lagoonal sediments (Chevillon 1996), and the sedimentological importance of *Halimeda* bioherms (Roberts et al. 1988). Although some compositional studies are concerned with the early diagenesis of sediments and include petrographic analysis of skeletal materials (e.g. Furukawa et al. 1997), most do not integrate detailed binocular, petrographic, mineralogic, and geochemical examination. Thus many aspects of carbonate sand origin, compositional diversity, and mineralogic diagenesis are poorly known.

Similarly, although radiocarbon age dating of consolidated, shallow-marine carbonates has proven to be a valuable tool in paleoenvironmental reconstructions and in studies of reef stratigraphy, contemporaneous unconsolidated carbonate sands have received less attention. Work with various aspects of carbonate sand and clast age in Pacific locales has contributed to our knowledge of Holocene sea levels and shoreline evolution (e.g. Athens and Ward 1991; Calhoun and Fletcher 1996; Fletcher and Jones 1996; Grossman and Fletcher 1998), sedimentation histories (e.g. Harris et al. 1990; Roy 1991; James et al. 1994), and the accumulation of *Halimeda* bioherms (e.g. Davies and Marshall 1985). Understanding the age of sand in various depositional

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environments aids in the interpretation of sediment production, transport, and residence time within diverse "shoreface" subenvironments (within the region of wave disturbance from shoreline to offshore). The purpose of this paper is to characterize carbonate sediment origin, age, and dynamics in a windward Hawaiian coral reef setting.

Study area

Kailua Bay is located on the northeast (windward) coast of Oahu (21°25′N, 157°43′W) in the Hawaiian Archipelago (Fig. 1, location map). Northeast trade winds blow onshore with wind speeds of between 10 and 25 knots for 90% of the summer months (April–September), generating waves that average 1–3 m in height with periods of 6–12 s. Ocean surface temperatures during these months are 25–28 °C. During winter months (October–March), storms in the North Pacific produce large swells on Oahu's north shore that occasionally refract into Kailua Bay as waves up to 4 m in height with periods of 10–20 s. During winter months, trade winds are more variable, and ocean surface temperatures range between 22 and 25 °C.

A georeferenced mosaic of airborne multispectral data collected over Kailua Bay (Isoun et al. 1999) illustrates the distribution and morphology of benthic substrates and reef environments in the study area (Fig. 1). Dark areas are consolidated substrate, living coral, and algae; light areas are typically sandy regions. The shoreline is rimmed by an arcuate, carbonate sand beach 3.5 km in length which grades seaward to a shallow (< 5 m depth), lithified limestone seafloor with a veneer of sand that is generally thin ("hardgrounds"). This nearshore region is dominated by sand, rubble, outcrops of fossil reef, meadows of calcareous *Halimeda* and fleshy algae (e.g. *Sargassum*), and by occasional coalesced colonies of the coral *Porites lobata*. In the central nearshore region, a large sand field exists in marked contrast to the generally sand-poor regions characterizing the shallow shoreface to the north and south. The 4 km^2 fringing reef platform is deeply bisected by a sinuous paleostream channel 200–300 m wide that originates in the nearshore sand field. The total length of the channel axis is nearly 2 km, and the area of sandy seafloor between its walls is $\sim 3 \times 10^5$ m^2.

Detailed bathymetry of the offshore region illustrates varied water depths over the broad fringing reef (5–20 m; Fig. 1). Aspects of coral morphology and community structure have been qualitatively observed over the broad reef platform by large-scale reconnaissance dives and tows. Values of live coral cover were based on visual estimates. The landward portion of the reef platform (5–8 m water depth) is largely composed of fossil reef with relatively low substrate relief (< 3 m) supporting ~25–50% living coral cover (typically encrusting *Porites lobata* and *Montipora* sp. or stoutly-branched *Pocillopora meandrina*). Large sand bodies and partially-buried outcrops of scoured limestone are also common. As the reef platform gradually slopes seaward to depths as great as 20 m, substrate relief (3–8 m) and percent living coral cover (50–75%) increase toward the fore-reef which lies nearly 3 km offshore. Branching *Porites compressa* and platy corals are abundant on the seaward portion of the reef platform. Portions of the reef slope support luxuriant growth and 100% living coral cover. The top of the fore-reef edge lies in ~15 m water depth and slopes steeply seaward (in some places as talus and elsewhere as continuous living coral cover) to abut a sand field in 25 m water depth. A detailed description of the fore-reef environment of Kailua is found in Hampton et al. (1998).

Materials and methods

Sample collection

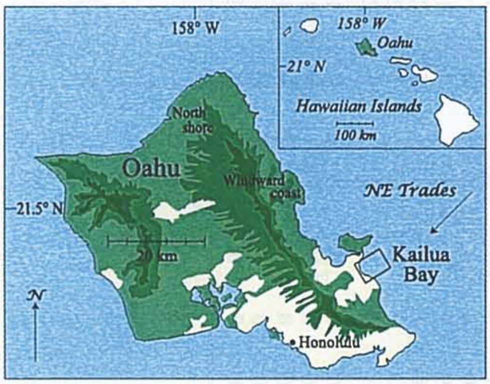
Sediment samples were collected in order to describe their composition, age, and geochemical properties. Samples were collected in Kailua Bay by divers pressing core jars (500 cm^3 volume) into unconsolidated sediment along a transect from the landward edge of the beach (B-series) in a shore-normal direction along the channel axis (C-series; Table 1). The location of samples collected from the beach face (B1–5) are shown in detail in Fig. 2. B1 was collected above sea level from an excavation pit ~1.8 m deep below B2 at the landward edge of the beach; B3 and B4 were surficial samples of the subaerial beach face at the high-tide line and in the swash zone (approximate mean sea level), respectively; B5 was collected from the turbulent surf zone in 1 m water depth. Offshore sampling continued just seaward of the breaking waves (C1, −2 m). The nearshore sand field was sampled in a broad region of small sand ripples (C2, −4 m), in a macroalgal shoal (C3, −3 m), and landward of the channel opening (C4, −4 m). The channel was sampled at its landward mouth (C5, −6 m), along its axis (C6, −11 m; C7, −13 m; C8, −17 m; C9, −20 m), and at its seaward mouth in the rippled fore-reef sand field (C10, −30 m).

Samples from sand bodies within the reef (R-series) in Kailua Bay were also collected for comparison with channel and beach sediments. Sample R1 was collected from the southern reef platform at 9 m water depth from a small depression 0.5 m wide. This slender sand body is flanked by spurs of 1 m in height covered by platy and encrusting *Montipora verrucosa*. Sample R2 was collected from the northern reef platform in 8 m water depth from a sand-filled depression 10 m wide. This sand body is flanked by talus and sloping walls covered by live coral rising 45° to the top of the reef platform at 5 m water depth. Sample R3 was collected on the south side of the channel mouth at 24 m water depth. This 8000 m^2 reef-top sand body is enclosed by steep spurs 8 m in relief covered with living coral. From the base of the reef spurs at this site, fossil pieces of the coral *Porites lobata* were sampled from the in situ framework for geochemical analysis. Shoreward of this site, around Popoia Island on the south side of the bay, sample R4 was collected from the sandy floor at 2 m water depth between fossil limestone outcrops. At this site, shallow mounds of fossil reef are topped by thickets of the branching coralline alga *Porolithon gardineri*; living specimens of the alga were collected for geochemical analysis. Sample R5 was collected north of the channel adjacent to an

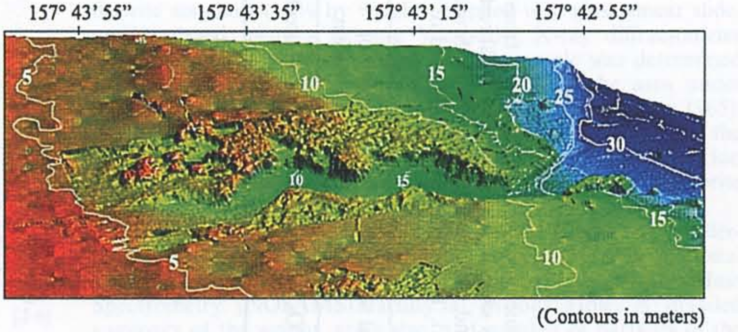
▶

Fig. 1 Location map, bathymetry, and reef environments of Kailua Bay, Oahu, Hawaii. Sample location and water depths (in m) are shown (see also Table 1). Exact locations of beach (B-series) samples (B1–5) are shown in Fig. 2. *Triangles* represent samples for which geochemical data are reported in this paper

LOCATION MAP

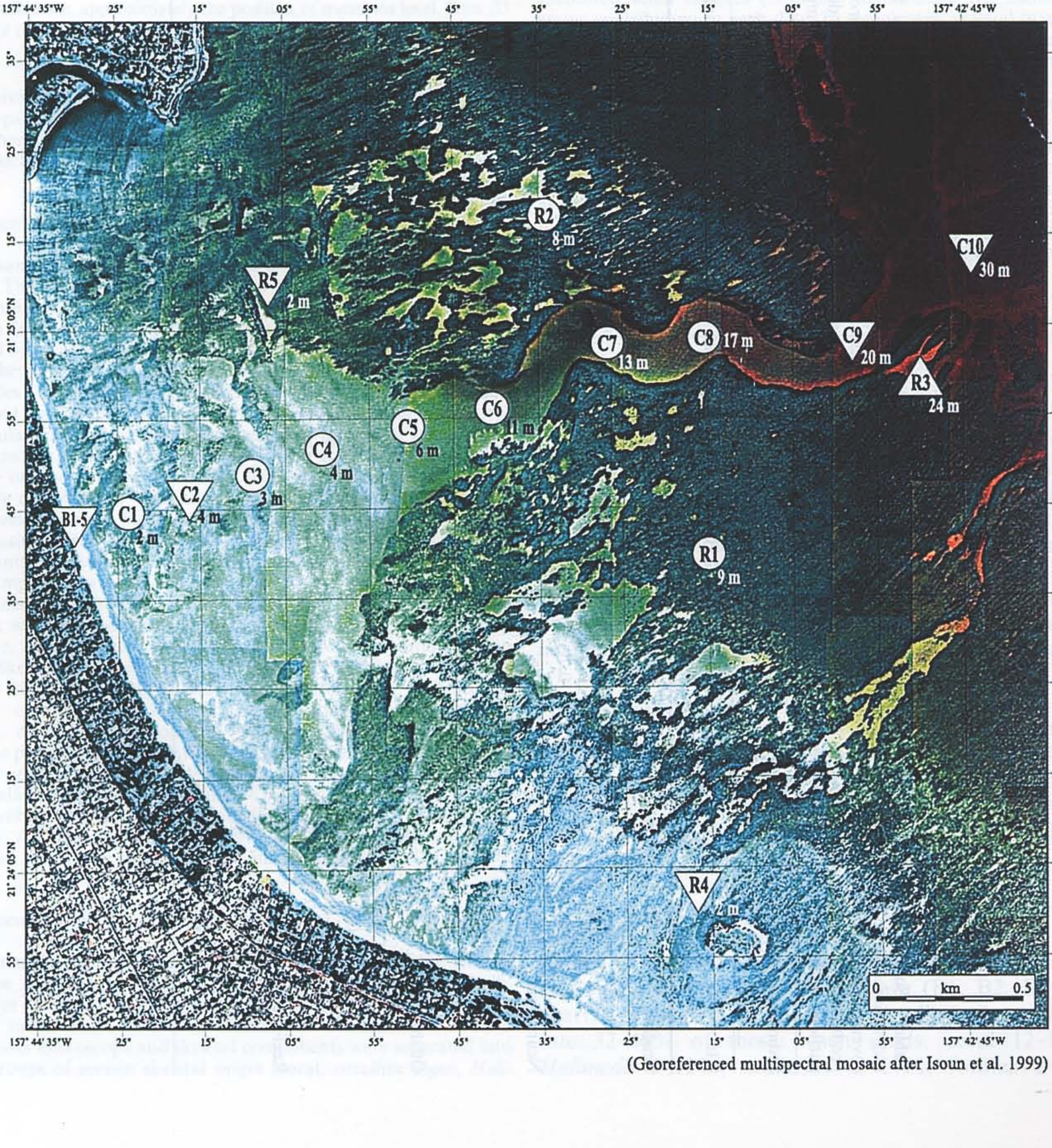


REEF PLATFORM AND CHANNEL BATHYMETRY



(Contours in meters)

REEF ENVIRONMENTS, KAILUA BAY



(Georeferenced multispectral mosaic after Isoun et al. 1999)

Table 1 Summary of mean sediment grain size (mm), sorting index (see text), and percent composition of samples in this study. Shoreface sites and elevations are listed from the beach excavation (*B1*) to the seaward mouth of the channel (*C10*-trough and *C10*-crest). Samples *R1*, *R2*, and *R3* are reef platform sands; *R4* is sand collected between fossil reef outcrops covered with coralline algae; *R5* is sand from a *Halimeda* meadow. Skeletal grains are separated as to origin: framework production and direct production. *Other* direct sediment producers are bryozoans and serpulids. Diagenetic (nonskeletal) grains are intraclasts and crystalline fragments (see text for descriptions). Total sediment is composed of carbonate particles, volcanic minerals, and unidentifiable grains. The last column summarizes the origin of carbonate grains in each sample

Sediment origin and abundance (%)					Framework derived		Directly-produced					Diagenetic (nonskeletal)		Total sediment			Summary of $CaCO_3$ origin		
Site		Elevation (m)	Size (mm)	Sorting	Coral	Coralline algae	*Hali-meda*	Mollusc	Foram	Ech-inoid	Other	Intra-clast	Crystalline clast	$CaCO_3$	Vol-canic	Unid.	Frame-work	Direct	Dia-genetic
Beach	B1	0	0.30	0.6	12	32	3	16	2	2	1	12	10	90	10	0	44	24	22
	B2	+2	0.30	0.6	12	40	12	16	5	2	0	2	8	97	3	0	52	35	10
	B3	+1.5	0.30	0.7	13	36	12	17	3	1	1	9	6	97	3	1	49	33	15
	B4	0	0.21	0.7	13	24	17	17	9	3	1	4	9	97	2	1	35	47	13
	B5	−1	0.12	0.7	6	18	30	21	6	2	1	0	10	94	6	0	24	60	10
Nearshore	C1	−2	0.12	0.6	3	16	31	11	7	5	1	2	17	94	4	2	19	55	19
	C2	−4	0.46	0.8	12	35	13	11	5	2	0	7	9	94	6	0	47	31	16
	C3	−3	0.40	0.7	13	28	16	12	8	3	4	7	6	97	1	2	41	43	13
	C4	−4	0.51	0.7	8	38	8	11	6	4	2	10	9	96	3	1	46	31	19
	C5	−6	0.45	1.1	12	36	2	9	4	1	3	14	9	90	7	3	48	19	23
Offshore	C6	−11	0.83	1.0	9	51	8	6	5	1	0	12	5	97	3	0	60	20	17
	C7	−13	1.26	1.1	10	39	32	8	1	1	2	6	1	100	0	0	49	44	7
	C8	−17	0.70	0.9	11	48	12	7	3	1	1	11	5	99	1	0	59	24	16
	C9	−20	0.68	0.8	9	44	10	10	4	1	0	16	4	98	1	1	53	25	20
	C10-T	−30	0.72	1.6	8	49	4	7	2	0	1	17	5	93	7	0	57	14	22
	C10-C	−30	0.57	0.8	2	41	16	6	10	3	0	5	15	98	2	0	43	35	20
Reef platform	R1	−9	1.05	0.6	18	42	4	10	6	2	1	16	1	100	0	0	60	23	17
	R2	−8	0.71	0.6	11	46	10	11	4	1	1	16	0	100	0	0	57	27	16
	R3	−20	0.85	1.1	24	33	14	6	3	1	0	16	3	100	0	0	57	24	19
	R4	−2	1.10	0.8	5	38	32	19	0	0	1	2	3	100	0	0	43	52	5
	R5	−2	0.60	0.9	1	25	31	13	5	1	2	15	5	98	2	0	26	52	20

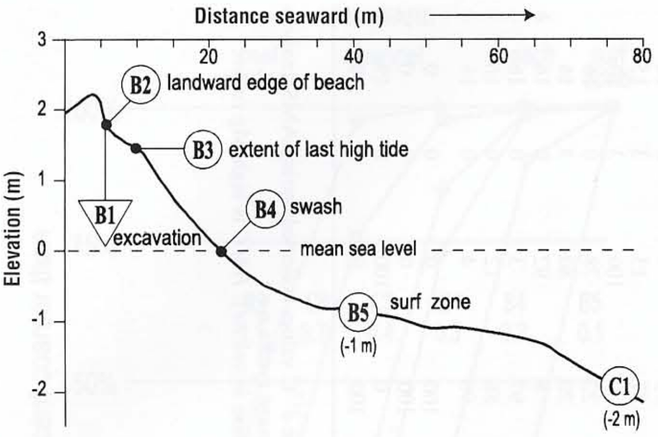


Fig. 2 Beach profile (distance seaward vs. elevation) of shoreline sites on sampling transect. Site *B1* is an excavation pit 1.8 m deep beneath *B2* at the landward edge of the beach. *B3* is the high tide line. *B4* is in the swash zone, approximately the position of mean sea level. Sites *B5* and *C1* are submarine (depths given in parentheses)

extensive nearshore meadow of living *Halimeda* growing along a shore-parallel ridge of fossil carbonate at 2 m water depth. Living specimens of the aragonitic green algae at this site were collected for geochemical analysis.

Sedimentology and composition

Sand samples were washed with deionized water over a 63-µm mesh sieve. The filtrate was collected in a 1-l graduated cylinder, stirred for several minutes, and sampled by pipette. A 20-ml aliquot was drawn from the slurry and dried; the weight of the residue (multiplied by a factor to bring the aliquot volume to that of the filtrate) was then used to calculate the total weight percent of silt-sized particles (< 63 µm) in the bulk sediment sample. The sand fraction retained by the sieve was oven-dried, weighed, examined under a binocular microscope, and described with respect to texture and composition. Subsamples were sieved into eight grain-size classes based on the Wentworth (1922) scale, and cumulative size-frequency distributions were assembled using the weight percent of each sieve fraction. Mean grain size and sorting index were calculated using both Folk and Ward (1957) formulae and the method of moments (cf. Tucker 1991), yielding similar results.

Sample splits were embedded in epoxy, thin-sectioned, and examined using a petrographic microscope. A minimum of 300 grains were point-counted to determine the composition of each sample, and replicate counts yielded compositional results within 2%. Skeletal particles were identified (after Johnson 1961; Majewske 1969; Tucker 1991; Adams et al. 1994) and classified by origin: coral, coralline algae, *Halimeda*, mollusc, benthic foraminifera, echinoderm, bryozoan, or worm tube. Nonskeletal carbonate particles included intraclasts (aggregates and micritic grains composed of microskeletal debris) and crystalline fragments. Crystalline fragments (generally < 0.7 mm in diameter) lacked discernible skeletal structure and displayed no clear evidence of origin. All noncarbonate sediments were classified as 'volcanic'. A small percentage of grains were unidentifiable.

Geochemical analyses

Geochemical analyses included X-ray diffraction, stable carbon isotope composition, and radiocarbon age dating. Two 'bulk' samples (from C2 and C9) consisted of undifferentiated sediment splits. In all other cases, clean subsamples were examined under a binocular microscope and skeletal components were separated into five groups of certain skeletal origin (coral, coralline algae, *Halimeda*, molluscs, and forams). Representative grains were chosen from these groups for analyses, and two samples were prepared for all materials. Samples for mineralogical analysis were ground to a fine powder with an agate mortar and pestle, mixed with an internal fluorite standard (10% by weight), applied to a glass smear slide, and analyzed using a Scintag V powder X-ray diffractometer (XRD). Mineralogic composition of each sample was determined from the resulting diffractogram by calculating the area under curves fitted to major aragonite and calcite peaks (Neumann 1965). The mole percentage of magnesian calcite was determined from the d-spacing offset of primary calcite peaks (caused by magnesium ion substitution in the crystal structure) using the internal fluorite standard (Bischoff et al. 1983).

Radiocarbon ages were obtained from the Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore National Laboratory and the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) facility at Woods Hole. A detailed summary of the weight, grain size, and number of particles of the materials submitted to each laboratory is listed in Table 2. Accelerator mass spectrometry (AMS) ^{14}C measurement techniques require only 0.5 mg of carbon (Pearson et al. 1998), and we generally submitted small samples (< 30 mg) to minimize the number of grains contributing to each date. In some cases, skeletal materials were analyzed in two different size classes from the same sample (e.g. coralline algae and *Halimeda* from C10). Other dated materials include two fossilized pieces of *Porites lobata* (removed from the reef framework at R3), living coralline algae (*Porolithon gardineri* from R4), and living *Halimeda* (from R5).

Both CAMS and NOSAMS provided a conventional radiocarbon age and 1σ error that included corrections for isotopic fractionation based on δ^{13}C values collected during AMS analysis of each sample. These ages were calibrated using Calib software version 3.0.3c (Stuiver and Reimer 1993) with a regional age correction (ΔR) of 117 ± 51 years for the Hawaiian Islands (Broecker and Olson 1961; Stuiver and Braziunas 1993).

Results

Sedimentology and composition

Grain-size distributions for representative sites given in Fig. 3 illustrate a general trend of decreasing mean grain size along the channel axis in the shoreward direction. The coarsest sands (mean 0.7–1.3 mm) are found on the reef platform and along the deeper channel axis (C6–C10). Shoreward of C5, sediments become increasingly finer in size (mean < 0.5 mm), presumably in response to nearshore wave abrasion. This is particularly evident at C1 and in the surf zone (B5), where grain size is at a minimum (0.12 mm). Sands collected at the high tide line (B3), at the edge of the beach (B2), and in the excavation pit (B1) all have mean diameters of 0.3 mm and identical size distributions, represented by one curve (B*) in Fig. 3. Additionally, sediments collected from the channel axis and reef platform are moderately to poorly sorted, while those shoreward of C5 are well-sorted.

The relative abundance of the primary constituents in sediments from the beach, channel, and reef-top sand bodies is depicted in Fig. 4. Sand from various morphologic features of the beach face (B1, B2, B3) are nearly identical in composition; coralline algae constitute 32–40% of these beach sands, coral 12–13%, *Halimeda* 3–12%, molluscs 16–17%, forams 2–5%,

Table 2 Summary of sediments analyzed and geochemical results. *Modern* indicates samples are post-1950 in age. Cannot be calibrated (refers to modern samples and marine materials when the radiocarbon age minus ΔR becomes less than 460 ^{14}C years B.P. (After Stuiver and Reimer 1993))

Material description						Laboratory results				Calibrated Ages[c]		Mineralogy[d]			
Site		Sample	Grain size (mm)	Weight (mg)	No. grains	Lab ID[a]	Conv. age[b]		$\delta^{13}C$ (‰)	Best age (years B.P.)	2σ ranges (years B.P.)	Aragonite (%)	Calcite (%)	Mg (mol%)	
							(^{14}C years)	(±)						(LMC)	(HMC)
Beach	B1	Coralline algae[f]	0.25–0.50	11	93	OS16967	4400	40	0.97	4522	4380–4784	10	90	2	16
		Halimeda[f]	0.25–0.50	14	Many	OS16968	1420	60	3.44	943	782–1129	98	2	0	16
Nearshore	C2	Bulk	0.25–2.0	104	Bulk	OS14781	2230	30	1.93	1818	1683–1950	56	44	3	16
		Coral	< 0.5	12	Many	OS14776	1720	40	0.17	1267	1131–1382	88	12	< 1	15
		Coralline algae	0.4–1.5	13	25–30	OS14777	2020	35	2.09	1556	1415–1709	18	82	0	17
		Coralline algae	0.4–1.5	18	25–30	OS14789	2710	30	1.26	2354	2284–2633	18	82	0	16
		Halimeda	1.0–2.0	24	7	OS14780	730	25	3.90	353	273–463	97	3	0	16
		Halimeda	1.0–2.0	24	8	OS15028	455	50	3.88	...	< 250	98	2	0	16
		Mollusc	0.4–2.0	33	39	OS14778	605	25	2.29	259	72–361	98	2	0	13
		Foraminifera	0.4–2.0	33	124	OS14779	1100	25	0.86	649	548–735	0	100	3	13
Offshore	C9	Bulk	0.25–2.0	73	Bulk	LL42599	1040	50	1.41	1001	889–1174	77	23	3	16
		Coral	< 1.0	25	100	LL42601	930	50	−0.40	895	715–1009	80	20	3	16
		Coralline algae	0.75–1.5	26	5	LL42602	550	40	2.50	540	473–645	27	73	0	16
		Halimeda	1.0–2.0	29	2	LL42603	2920	40	4.40	3217	3038–3361	93	7	0	14
		Mollusc	0.25–2.0	26	50	LL42600	810	70	2.20	737	625–923	87	13	3	15
		Foraminifera	0.4–2.0	24	101	LL42604	1310	50	1.20	1270	1116–1402	0	100	3	13
	C10	Coralline algae[e]	1.0–2.0	14	3	OS16711	1000	25	2.33	558	502–651	22	78	0	16
		Coralline algae[f]	0.25–0.50	11	60	OS16712	3380	55	2.01	3236	3020–3394	20	80	3	16
		Coralline algae[g]	2.0	15	4	–	–	–	–	–	–	8	92	0	16
		Halimeda[e]	1.0–2.0	16	3	OS16713	2480	50	3.96	2114	1951–2299	97	3	0	16
		Halimeda[f]	0.25–0.50	9	Many	OS16714	2280	30	3.37	1870	1725–2003	88	12	0	16
		Halimeda[g]	4.0	12	2	–	–	–	–	–	–	96	4	0	16
Reef platform	R3	*Porites lobata*[h]	3.0	25	1	OS16929	640	55	−1.88	276	80–440	100	0	0	0
		Porites lobata[h]	3.0	25	1	OS16930	Modern	–	−0.53	...	...	100	0	0	0
	R4	*Porolithon*[i]	5.0	20	4	OS16969	Modern	–	−1.32	...	...	0	100	0	19
	R5	*Halimeda*[i]	5.0	20	4	OS16966	Modern	–	0.00	...	...	100	0	0	0

[a] Laboratory identifier and accession number (*OS* NOSAMS, *LL* CAMS)

[b] Conventional ages and errors reported by the laboratories in radiocarbon years, including corrections for isotopic fractionation using the $\delta^{13}C$ values collected during AMS analysis

[c] Best ages (intercepts) and 2σ error ranges (95.6% certainty) determined using Calib software, reported here in calendar year before present (years B.P.)

[d] Mineralogical composition in % aragonite and calcite determined by XRD (see text); *LMC* is low-Mg calcite (< 5 mol% Mg substitution in calcite); *HMC* is high-Mg calcite

[e] Skeletal materials selected from coarse fractions

[f] Skeletal materials selected from fine fractions

[g] Sample for XRD only

[h] Fossil coral samples removed from in situ framework

[i] Algal specimens that were living at the time of collection

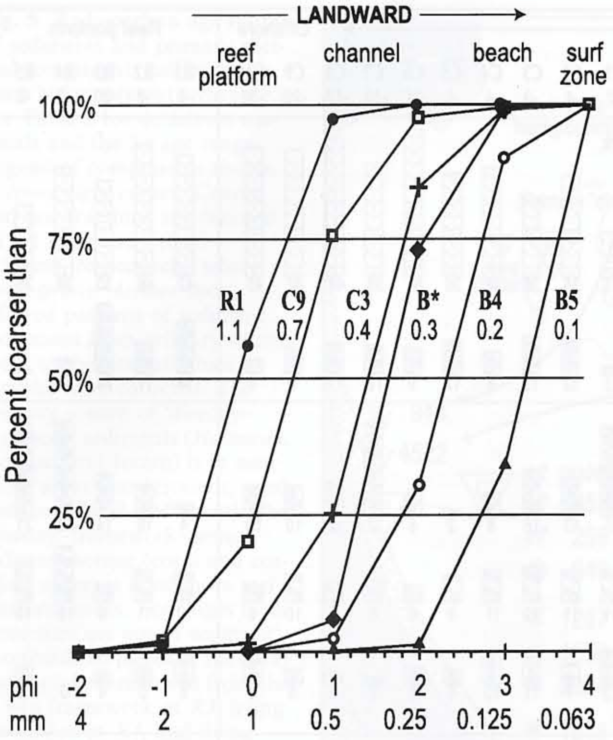


Fig. 3 Cumulative grain-size frequency distributions for representative sites. Line *B** represents three sites from the beach face (*B1*, *B2*, B3) with identical distributions. Mean grain size (given in mm beneath site ID) is greatest offshore and decreases in the landward direction

intraclasts 2–9%, and crystalline fragments 6–10%. In sand collected from high-energy zones near shore (sites B4, B5, C1), the relative abundance of coralline algae is 16–24%, corals 3–13%, *Halimeda* 17–31%, fine mollusc shell debris 11–21%, and forams 6–9%; crystalline fragments dominate (9–17%) over intraclasts (0–4%).

The abundance of coralline algae increases in the seaward direction along the channel axis, representing 28–38% of nearshore samples C2, C3, C4, and C5. Coral constitutes 8–13% of these samples, *Halimeda* 2–16%, molluscs 9–12%, forams 4–8%, intraclasts 7–14%, and crystalline fragments 6–9%. Offshore channel sands from sites C6, C7, C8, and C9 are dominated by coralline algae (39–51%); coral constitutes 9–11% of these sands, *Halimeda* 8–32%, molluscs 6–10%, forams 1–5%, intraclasts 6–16%, and crystalline fragments 1–5%.

Individual grains in bed-form trough and crest samples collected from site C10 in the fore-reef sand field vary in preservation from relatively unaltered to extensively bored and pitted. Coralline algae constitutes nearly half the sand-sized sediment at this site, while coral is a minor component (8% in the trough, 2% in the crest). *Halimeda* flakes are less abundant in ripple trough sediment (C10-T, 4%) than in crest sediment (C10-C, 16%). The abundance of mollusc fragments is approximately the same in both samples (6–7%); foram tests constitute 2% of trough and 10% of crest sediment. Micritic intraclasts are more abundant in the trough (17 vs. 5% in crest), as are volcanic grains (7 vs. 2% in crest). The reverse is true for crystalline fragments (5 vs. 15% in crest). These observations are consistent with hydrodynamic sorting of bed-form sediment such that denser particles dominate trough sediments.

Samples collected from reef-top sand bodies in Kailua Bay differ markedly from those of the beach and channel. Reef platform sand at sites R1 and R2 are the coarsest of all samples and are dominated by coralline algae (42–46%). Corals (11–18%) and intraclasts (16%) are more dominant in these sands than are *Halimeda* (4–10%), molluscs (10–11%), and forams (4–6%); crystalline fragments are nearly absent (<1%). Sample R3 contains the greatest abundance of coral fragments of all samples (24%). Coralline algae constitutes one-third of this sand; *Halimeda* and intraclasts contribute 14 and 16%, respectively. Other constituents are minor contributors (forams 3%, molluscs 6%, crystalline fragments 3%). Sand collected from the shallow sea floor near Popoia Island (R4) is composed of 38% coralline algae, 5% corals, 32% *Halimeda*, 19% molluscs, and <3% each of intraclasts and crystalline particles; forams are absent. Nearly one-third of the sand from site R5 is *Halimeda*; 25% is contributed by coralline algae, 15% by intraclasts, and 13% by molluscs. Crystalline fragments are 5% of the sand; coral and echinoderms are rare (each <2%).

Mineralogy

The relative percentage of carbonate phases in samples of both living material and nonliving biogenic sediments are reported in Table 2. Two samples of in situ fossil coral (*Porites lobata*) collected from the base of the reef framework at site R3 are 100% aragonite, while coral grains analyzed from sediment samples C2 and C9 contain 12 and 20% high-Mg calcite (HMC), respectively. Low-Mg calcite (LMC) is also present in grains of coral from these sediments (<1 mol% Mg at C2, 3 mol% Mg at C9). Living coralline algae (R4, *Porolithon gardineri*) is composed entirely of high-Mg calcite (19 mol% Mg), but in the sediment there is up to 27% aragonite (B1, C2, C9, C10). Coralline algae grains in the 0.25–0.5 mm size fraction from B1 and C10 also contain low-Mg calcite (2–3 mol% Mg). Living *Halimeda* (R5) is 100% aragonite. Plates and fragments of the green algae in sediments contain 2–12% calcite with 14–16 mol% Mg content and lack a low-Mg calcite component (B1, C2, C9, C10). Molluscs exhibit a range of normal mixed aragonitic and calcitic mineralogies with varying Mg contents in sediments, as do bulk sand samples (C2, C9). Foram tests in sediments from these sites exhibit normal Mg-calcite mineralogies.

Radiocarbon age dating

Table 2 and Figs. 5 and 6 summarize the radiocarbon age results for samples dated across the shoreface. All

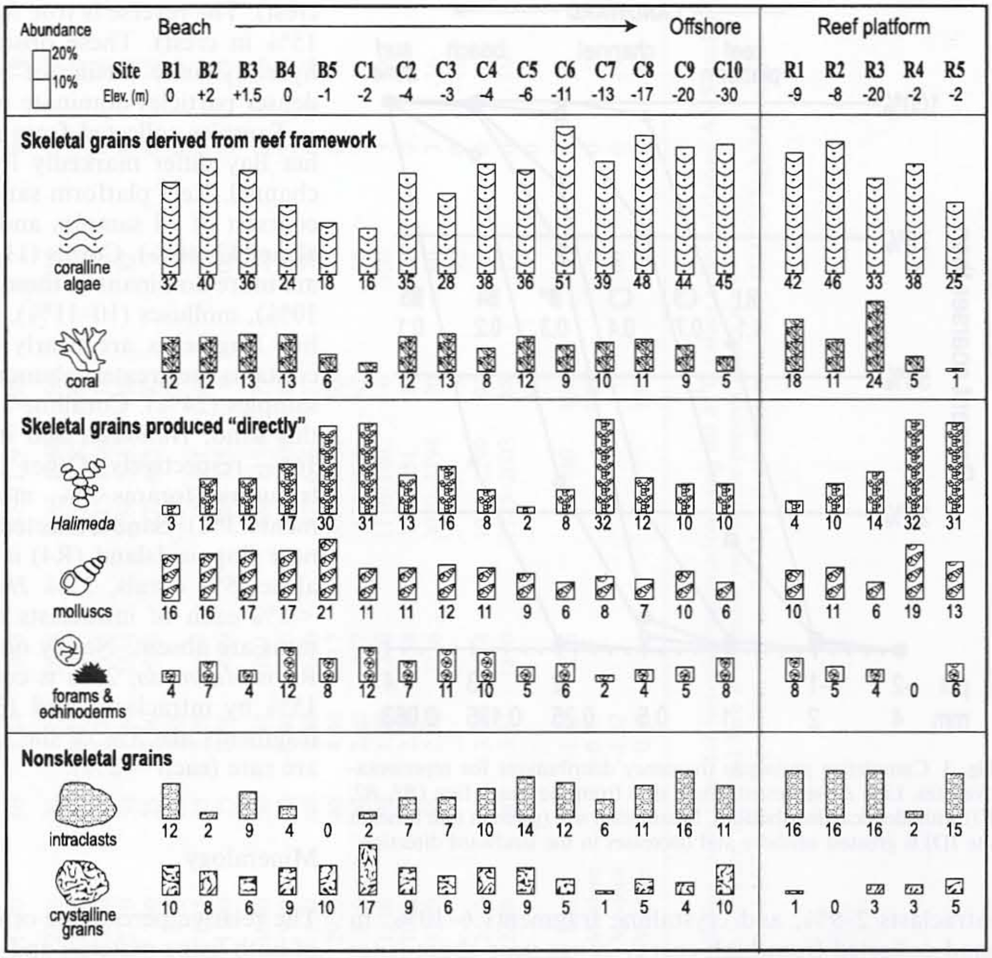


Fig. 4 Composition of carbonate sediments of Kailua, Oahu. Shoreface transect sites begin at the beach (*B1*) and continue in the offshore direction to the seaward mouth of the channel (*C-series*). Elevation of each site is given in meters beneath the sample ID. Refer to Fig. 1 for exact site locations. The composition of sediments collected from other sand bodies is shown for comparison: *R1*, *R2*, and *R3* (reef series) are from reef-top sand fields; *R4* is from the seafloor between fossil reef outcrops near Popoia Island; *R5* is from a nearshore *Halimeda* meadow. Components are grouped in terms of their origin (reef framework, direct production, and diagenetic products). The percent abundance of each constituent at each site is given beneath the vertical histogram bars. *C10* is the average of *C10-T* (ripple trough) and *C10-C* (ripple crest). The abundance of foraminifera and echinoderms are combined for this figure. The volcanic component is not shown. Refer to Table 1 for detailed compositional results

ages are reported in calendar years before present (1950) and are hereafter abbreviated "years B.P." Of two in situ samples of nonliving coral (*Porites lobata*) removed from the base of the seaward reef platform at 18 m water depth (R3), one yields a 'modern' (post-1950) age, and one is 276 years B.P. Coral grains in sediment of the adjacent channel are 895 years B.P. (C9, −20 m). Coral grains in nearshore sediment are 1267 years B.P. (C2, −4 m).

The ages of living specimens of *Porolithon* (a coralline red alga, R4) and *Halimeda* (a calcareous green alga, R5) are modern. Coralline algae in shoreface sediments exhibit a wide range of ages. Like coral, it is younger in offshore sediments (540 years B.P. at C9, 558 years B.P. at C10) than in nearshore sediments (1556 years B.P. and 2354 years B.P. at C2) of similar size classes. Coralline algae in fine-grained beach sand (0.25–0.5 mm diameter range) are 4522 years B.P. (B1). Similarly, in this size fraction of sand from offshore, it is 3236 years B.P. (C10).

Medium-grained and coarse fragments (1–2 mm) of *Halimeda* in sediment from the nearshore site C2 (−4 m) are the youngest found (<250 and 353 years B.P.), while offshore at C9 and C10, *Halimeda* fragments of similar size are aged 3217 years B.P. and 2114 years B.P., respectively. In the fine-grained size fraction (0.25–0.5 mm), *Halimeda* is 943 years B.P. on the beach (B1) but twice as old offshore (1870 years B.P. at C10). Mollusc debris is also younger in nearshore sediment (259 years B.P. at C2) than in offshore sediment (737 years B.P. at C9); the same is true for benthic forams (649 years B.P. at C2, 1270 years B.P. at C9). Bulk sediment is older nearshore (1818 years B.P. at C2) than offshore (1001 years B.P. at C9).

Discussion

Origin of carbonate sediments

Shoreface sediments of Kailua Bay are almost entirely composed of the skeletal remains of marine organisms, particularly those of coralline (red) algae, which constitute one-quarter to one-half of beach, channel, and reef top sediment assemblages. Its abundance drops below 20% at only two sites in the nearshore zone (<2 m depth). The benthic topography, relief, and vigorous circulation in Kailua Bay provide ideal habitats for these rhodophytes. In situ growth-rate measurements of articulated *Porolithon gardineri* living in waters

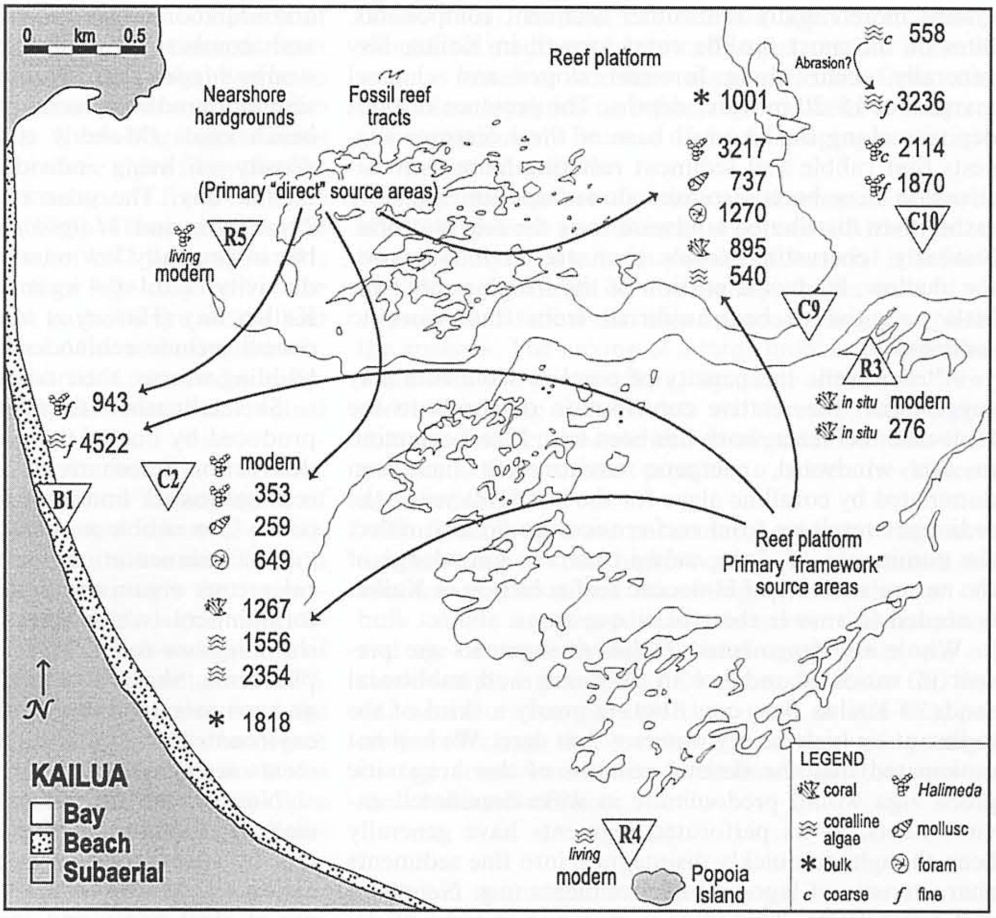


Fig. 5 Radiocarbon age results of sediments and primary skeletal constituents calibrated to years before present (years B.P.). See Table 2 for details on materials and the 2σ age range. Legend of components shown in *lower right corner*. Coarse and fine fractions are denoted c (1–2 mm) and f (0.25–0.5 mm), respectively, where appropriate. *Arrows* show inferred patterns of sediment movement from primary source areas to the sites at which samples were collected. The primary source of 'directly-produced' sediments (*Halimeda*, mollusc, and foram) is in nearshore areas (hardgrounds, sand flats, and fossil reef tracts). The primary 'framework-derived' sediment source (coral and coralline algae) is in offshore reef platform areas. Four ages from three sites are not of sediment: two fossilized pieces of the coral *Porites lobata* removed from the in situ framework at *R3*, living *Porolithon* at *R4*, and living *Halimeda* at *R5*. 'Modern' indicates a post-1950 (modern) age

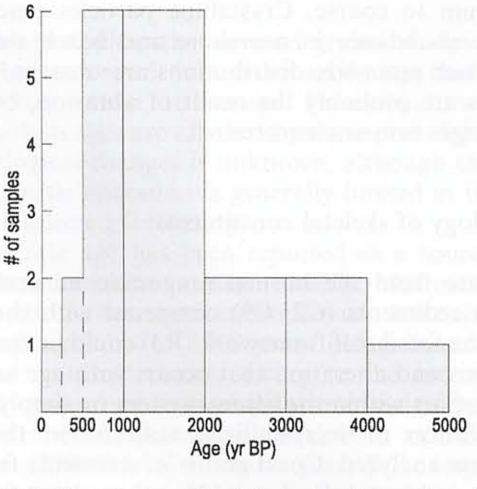


Fig. 6 Distribution of ages collected on shoreface sediments in this study (in calendar years B.P.). Twelve of 20 calibrated ages fall between 500 and 2000 years B.P.; five are between 2000 and 5000 years B.P., indicating that long storage times dominate the contemporary signature of the present benthic community

around Oahu correspond to a carbonate production rate of ~20 kg m^{-2} year^{-1} (Agegian 1985). Estimates of carbonate production by crustose *Porolithon onkodes* are lower (e.g. 3.6 kg m^{-2} year^{-1}, Soegiarto 1972; ~2.1 kg m^{-2} year^{-1}, Agegian et al. 1988), but these forms occupy a greater range of depths (subtidal to 100 m) and colonize a variety of substrates including patch reefs, fossil limestone outcrops, coral skeletons, mollusc shells, loose rubble debris (forming rhodoliths), and even individual sand grains. These levels of productivity are consistent with our observations of the dominance of coralline algae in nearly all beach and submarine sediments.

'Coral sand' is a misnomer commonly used to describe the white carbonate sediments of volcanic islands and atolls, where more often coral fragments are a minor constituent (cf. Chevillon 1996). Such is the case in Kailua, where coral contributes <15% of sediments analyzed from the shoreface transect. However, in sediments collected from on or near the reef platform at sites R1 and R3, grains of coral constitute one-fifth of the sediment assemblage. This preservation of coral grains in close proximity to the source framework probably reflects negligible transport following deposition.

Compared with their abundance in the modern benthic community, corals are under-represented in shoreface sediments. If coral has made a significant contribution to the Holocene reef framework but not to the surficial sediment pool, taphonomic processes may be primarily responsible for this observation. Coral fragments may be eroded or otherwise removed from the system more rapidly than other sediment components. Sites of the most prolific coral growth in Kailua Bay generally occur along fore-reef slopes and channel margins at 15–20 m water depths. The presence of talus deposits along the seaward base of these features suggests that rubble and sediment resulting from their destruction may be transported downslope and offshore rather than distributed landward over the reef platform. Similarly, encrusting corals that are abundant over the shallow, landward portion of the fringing reef have little potential to be transferred from framework to sediments.

Alternatively, the paucity of coral in sediments may suggest that the relative contribution of corals to the Holocene reef framework has been low. If reef accretion in this windward, energetic environment has been dominated by coralline algae for the last 5000 years, the sediments resulting from reef erosion would also reflect the dominance of algae, as we observe. Knowledge of the nature and rate of Holocene reef accretion in Kailua is needed to answer these basic questions.

Whole and fragmented *Halimeda* segments are present in varied abundance in all beach and sublittoral sands of Kailua Bay, contributing nearly a third of the sediments in high energy waters < 2 m deep. We had not anticipated that the skeletal remains of this aragonitic green alga would predominate in wave-dominated environments, as its perforated segments have generally been thought to quickly disintegrate into fine sediments characteristic of lagoonal environments (e.g. Neumann and Land 1975). This view is changing in light of detailed studies of extensive *Halimeda* banks and associated sediments of the Great Barrier Reef (e.g. Davies and Marshall 1985; Phipps et al. 1985) and of biomineralization in this and other calcareous algae (Macintyre and Reid 1992, 1995; Reid and Macintyre 1998). *Halimeda* exhibits a wide range of growth forms and is no longer considered to be a predominantly lagoonal alga (Hillis 1997). When living, the plant bodies ('thalli' composed of consecutive, branching, calcified segments connected by longitudinal coenocytic filaments) may grow attached to hard substrates by a meshwork of filaments or anchored in unconsolidated sediments by a single, buried holdfast (Hillis 1991). In nearshore Kailua Bay, we have found dense, sandy meadows and extensive epilithic mats of *Halimeda* flourishing at 2–10 m water depths. Clumps of the alga are abundant in well-lit areas landward of the reef platform but are generally rare to absent within the reef tracts offshore. Death and the natural process of senescence shed aragonitic segments to the surrounding seafloor, where they are then subjected to sedimentary and taphonomic processes. Estimates of *Halimeda* production in subtropical populations around the world are on the order of 2 kg $CaCO_3$ m^{-2} $year^{-1}$ (Hillis 1997), attesting to the significance of this green alga as a sediment producer.

Mollusc shells are common constituents of most sediments in Kailua Bay. Shell hash, intact helices, and fragmented valves are most concentrated in beach sands and nearshore areas and reflect the great diversity in size and number of molluscs in Hawaiian waters. Past studies suggest that benthic foraminifera would occur in similar abundance, having been observed to dominate in beach sands (Moberly et al. 1965) and having a high density of living individuals on reefal substrates in Kailua Bay. The genera *Amphistegina*, *Heterostegina*, *Peneroplis*, and *Marginopora* are present in sediments but in generally low numbers, despite their annual productivity of 0.1–0.4 kg m^{-2} at reefal depths (<10 m) in Kailua Bay (Harney et al. 1999). Minor sediment producers include echinoderms, bryozoans, and the tube-building worms; their combined contribution is small.

Skeletal carbonate sediments in Kailua Bay are thus produced by one of two primary processes: progressive destruction (mechanical, chemical, and biological) of reef framework limestone (primarily coralline algae and coral) into rubble and sand ("framework origin"); and "direct sedimentation" upon the death or senescence of calcareous organisms such as *Halimeda*, molluscs, and foraminifera (which seems to primarily occur in nearshore regions and along the landward portion of the reef platform). Skeletal grains are generally well-preserved and common to abundant in all submarine and subaerial environments in Kailua Bay, particularly when sediments are medium- to coarse-grained.

Nonskeletal carbonate sediments result from the diagenetic alteration of existing particles of various origin by such processes as micritization and recrystallization (cf. Macintyre and Reid 1992). Most intraclasts are of algal origin and are generally more common in offshore sediments (>10 m water depth) where grain size is medium to coarse. Crystalline particles reach their greatest abundance in nearshore and beach sediments where finer grain-size distributions are observed. These particles are probably the result of abrasion, but their exact origin remains uncertain.

Mineralogy of skeletal constituents

Departure from the normal aragonitic mineralogy of coral in sediments (C2, C9) compared with those still within the fossil reef framework (R3) could be due to the diagenesis and alteration that occurs with age and during transport within the littoral system or simply due to the inclusion of recrystallized material in the coral fragments analyzed. Coral grains in sediments from site C2 contain less total calcite (12%) than those from site C9 (20%). Peak-area analysis of the calcite present in these samples, however, indicates that a greater proportion of the C2 coral grains is low-Mg in character (18%) when compared with the low-Mg content of the C9 sample (2%). Site C2 is located in the nearshore region where wave energy is greater, sand grains are more abraded, and framework-derived components such as coral and coralline algae are older. The mineralogical differences between C2 and C9 coral grains may thus reflect differences in storage time.

Although living coralline (red) algae is composed of high-magnesian calcite, its skeletal remains in sediments contain up to 27% aragonite. This is probably due to extracellular or cavity-filling cements that form after deposition (cf. Bosence 1991). A low-Mg calcite component is found in grains of coralline algae from the fine size fraction (0.25–0.5 mm) of sediments from both the beach (B1) and far offshore (C10). These are also the oldest samples found in this study (4522 years B.P. at B1, 3236 years B.P. at C10), and their age may reflect the time scale over which resident particles are stored and altered in this carbonate system. After several millennia, coralline algae sediments are abraded, mineralogically-altered, and may occur relatively far from their original source atop the reef platform.

Living *Halimeda* segments are wholly aragonite, while modern and aged samples show some degree of mineralogical alteration to magnesian calcite (2–12%). In thin section, we observe the progressive micritization and textural alteration of *Halimeda* grains that apparently results in the observed magnesian calcite mineralogy (cf. Reid and Macintyre 1998). *Halimeda* grains of the fine fraction from offshore (C10) contained 12% calcite and were twice as old as the fine fraction from the beach (B1), which contained only 2% calcite. The degree of mineralogical alteration in *Halimeda* appears to be related to age, with those farther offshore being older and more altered than those proximal to their shallow-water source.

Radiocarbon ages and sources of error

Mineralogical alteration in sand grains of various skeletal origin can result in a radiocarbon age that appears to be younger than the true age. The extent to which our radiocarbon ages are affected by these post-depositional mineralogical changes is unknown, although the degree of diagenetic alteration is generally limited in the materials we selected for dating.

Substrate age has been reported as a source of radiocarbon variation in marine shells. Molluscs grazing on Pleistocene limestone substrates can have shells with apparent ages up to 1000 years older than those on adjacent volcanic coasts, owing to the incorporation of 'old carbon' in their skeletal materials (Dye 1994). Our dates on molluscan material both nearshore and offshore (259 and 737 calendar years B.P., respectively) are younger than most other sediment components at the same sites and thus may not reflect this condition.

In calibrating radiocarbon ages to calendar ages, two corrections are made for marine carbonates: a global reservoir correction of 400 years (due to the slow diffusion of atmospheric CO_2 into the surface ocean) and a regional reservoir correction ($\Delta R = 117 \pm 51$). The regional correction for Oahu (Stuiver and Braziunas 1993) was determined based on the offset of a single radiocarbon date of a mollusc shell of known historical age (~1840) collected from Pearl Harbor (Broecker and Olson 1961). Further radiocarbon age determinations should be made on historically-aged marine materials such as coral or coralline algae collected from other Hawaiian localities to refine regional reservoir corrections, particularly because of the false-aging potential in marine mollusc shells.

Since radiocarbon-age data are statements of probability, statistical uncertainties also exist. Although statistical analysis of large quantities of material is required to reduce the range of uncertainty, in the case of unconsolidated sediments, this approach may complicate the analysis. The mixing of a large number of carbonate sediments of various origin, age, and alteration history provides a date that reflects an 'average' radiocarbon content of the entire assemblage of grains. In most cases, we date as few grains as possible to reduce the degree of age averaging.

Bulk sand ages are particularly subject to age averaging, owing to their highly varied, site-dependent sedimentology and mixed mineralogy. While the age of a bulk sample is not predictable based on the abundance and age of the individual skeletal components, our offshore sample is younger (1001 years B.P. at site C9) than our nearshore sample (1818 years B.P. at site C2), possibly reflecting the greater proportion of younger, coarser, framework-derived coralline algae that exists in sand collected offshore.

Sediment source and storage time

The age range of various skeletal materials in sediments supports observations of the partitioning of sediment production in 'primary source areas' of the Kailua shoreface (Fig. 5). The primary source of framework-derived sediments (coral and coralline algae) is the reef platform offshore; these components are older in nearshore sand. In contrast, the primary sources of directly produced sediments (*Halimeda*, molluscs, and forams) are nearshore fossil reef hardgrounds and along the landward portion of the reef platform; these components are older in offshore sand. These differences in sediment-component ages probably reflect the time spent in storage and transport from the primary source of production.

Benthic foraminifera provide one example. The age of foram tests is younger in nearshore sand (649 years B.P.) than in offshore channel sand (1270 years B.P.). In Kailua Bay, populations of living benthic forams are most dense in shallow, nearshore waters on relatively barren substrates such as rubble and coral skeletons; they are generally absent on substrates colonized by living coral and coralline algae (Harney et al. 1999). It is thus unlikely that the foraminiferal remains found at site C9 (−20 m) were produced on the adjacent reef platform, which is composed of nearly 100% living coral. In contrast, site C2 lies in a nearshore sand field where limestone outcrops and patches of rubble are the dominant consolidated substrate. Since sediment production by foraminifera is more likely to occur in such areas shoreward of the living reef platform, their test ages in nearshore sediments (C2) would probably be younger than in offshore sediments (C9), as we observe.

Further support of this hypothesis is derived from our studies of coralline algae and *Halimeda*. These calcareous algae are abundant in Kailua Bay, have been characterized in terms of production potential, and possess different mineralogies (high Mg-calcite vs. aragonite), thus providing a range of perspectives in sediment dynamics.

Coralline algae sediments are highly varied in age. Of the shoreface samples analyzed, the oldest grains are found on the beach (4522 years B.P. at B1); grains of intermediate ages are found nearshore (1556 years B.P. and 2354 years B.P. at C2); the youngest grains are found offshore (540 years B.P. at C9, 558 years B.P. at C10; except for the fine size fraction at C10, see below). Coralline algae is the only sediment producer that exploits every habitat and depth within the bay. Atop the extensive reef platform and on isolated outcrop surfaces, it is the most ubiquitous marine taxa and the most prolific producer of sediment. The age distribution of coralline algal fragments reflects the probability that most of the sediment production by these red algae is accomplished atop the reef platform. In sediments collected offshore from the seaward mouth of the channel (C10), fine grains of coralline algae are distinctly older (3236 years B.P.) than coarse grains (558 years B.P.), suggesting that coralline-algal grains have long sediment storage times between initial production and loss by abrasion or by transport to deep water.

Halimeda sediments are distinctly younger in nearshore samples (< 250 and 353 years B.P.) than in all others, presumably due to their proximity to *Halimeda* production sites in shallow meadows. Fragments on the beach, all very small in size (0.1–0.4 mm), are of intermediate age (943 years B.P. at B1) but are younger than those offshore (3217 years B.P. at C9, 2114 years B.P. and 1870 years B.P. at C10), perhaps reflecting a time lag associated with transport of these shallow-water sediments to deeper waters. We do not find a significant age difference between coarse and fine *Halimeda* fragments collected from the channel's seaward mouth at 30 m water depth, suggesting that the transport of *Halimeda* segments from their shallow-water source occurs without size preference. *Halimeda*'s greatest contribution is made to seafloor sediments adjacent to its shallow meadows, but its sedimentary products are found on the beach, in the channel body, and far offshore, reflecting storage times as great as 3200 years.

The most surprising result of this work is that the skeletal sediments of this productive, well-circulated system are very old. Even coralline algae, the most ubiquitous modern producer, are not represented in the sediments by a dominant modern-aged signal. Of 20 radiocarbon dates on sediment constituents in this study, only one is of modern (post-1950) age (*Halimeda* grains from nearshore site C2; other modern ages are from living materials or in situ coral). Similar millennial-aged *Halimeda* fragments and other skeletal materials have been found in shelf sediments of the Great Barrier Reef, apparently deposited during post-glacial sea-level rise and subsequently buried 2–3 m below the seafloor (Harris et al. 1990). Could an aragonitic grain even up to 1 cm in size survive abrasion and transport in the windward turbulence of Kailua Bay for several thousand years? Sediment confinement by shallow burial in the channel and other sand bodies would retard the processes that surficial particles are subjected to, thereby reducing the loss of grains by erosion and abrasion or transport to deep water. The deeply-incised Kailua channel represents an in situ storage capacity for carbonate sediments produced atop the reef platform and in shallower back-reef areas. The fact that the channel is not filling up with sediment along its length suggests that sand is continually transported in or out of the channel. Recent work on sediment dynamics in the Kailua channel has revealed that migrating bed forms proceed shoreward at a rate of 0.5 m/day during trade wind conditions and seaward at approximately the same rate during winter ground swell conditions (Cacchione 1998). Loss of carbonate particles by abrasion and/or transfer across the 'littoral fence' to deep water may not necessarily be a rapid process, as there remains a strong fossil component in sediments of the shoreface. The relationship between circulation, wave forcing, and sediment movement in Kailua Bay is still poorly understood but is an important subject for future research.

Modern and paleoproductivity

The minor importance of volcanic minerals and the great areal extent and age of carbonate sand contained in the beach and channel reservoirs indicate that the storage time of biogenic carbonate sediment in Kailua Bay is of millennial scale. While the composition of surficial sands in Kailua broadly reflects the existing zonation of benthic habitats and production areas, the distribution of ages (Fig. 6) may also reflect changes in carbonate productivity during the Holocene. Under a +1–2 m mid- to late Holocene sea-level high stand (Grossman and Fletcher 1998), the flooding of Kailua's broad, low coastal plain would have resulted in significant expansion of shallow, nearshore areas (Kraft 1982; Athens and Ward 1991). The production of calcareous algae and their sediments may have proliferated in this back-reef lagoon zone, and (in part due to long storage times) their fossil signature may be significant in the present surficial sediment pool. The long-term storage and release of fossil sediments and the effects of fluctuating sea level on shallow-marine productivity may have moderated the contemporary signature of the present benthic community, but do not completely mask background patterns of partitioned sediment production. A numerical carbonate sediment budget is necessary to further investigate differences in modern and paleoproductivity.

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