A BUDGET OF CARBONATE FRAMEWORK AND SEDIMENT PRODUCTION, KAILUA BAY, OAHU, HAWAII

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ABSTRACT: **Sediments of the bay and coastal plain of Kailua (Oahu, Hawaii) are > 90% biogenic carbonate produced by destruction of primary reef framework (coral and encrusting coralline algae) and by direct sedimentation through the biological activity of calcifying organisms (the green alga *Halimeda*, the branching coralline alga *Porolithion gardineri*, molluscs, and benthic foraminifera). Field measurements of benthic community structure, gross carbonate production, bioerosion, and direct sedimentation in 17 physiographic zones in Kailua Bay are used to calculate modern calcareous sediment production rates in the 12 km² fringing reef system.**

Total gross carbonate productivity by corals and encrusting coralline algae (based on mapped percent cover and known growth rates) occurs at an average rate of 1.22 (± 0.36) kg m^{-2} y^{-1} over hard substrates of the reef platform, corresponding to 0.8 (± 0.2) mm y^{-1} (using a bulk density of 1.48 g cm^{-3}, the average of coral and coralline algae). Coralline algae contributes ~ 42% of the total gross productivity. Bioerosion of coral and coralline algae facies at and near the reef surface (estimated from slabbed reef samples) occurs at average rates of 0.10–1.15 kg m^{-2} y^{-1} and releases 1,911 (± 436) m^3 of unconsolidated carbonate sediment annually. Mechanical erosion (coral breakage) likely contributes an additional ~ 315 m^3 y^{-1}.

Carbonate sediment is also produced directly by the green alga *Halimeda*, branching coralline algae, molluscs, and benthic foraminifera at a combined rate of 1,822 (± 200) m^3 y^{-1} (using densities specific to sediment origin). The total rate of production of unconsolidated carbonate sediment in Kailua Bay is the sum of these sources, amounting to 4,048 (± 635) m^3 y^{-1}. Normalizing gross sediment production (in kg y^{-1}) by reef habitat area (in m^2) generates average rates of productivity (in kg m^{-2} y^{-1}) that are directly comparable to each other and to the literature; such rates can also be employed and tested in other reef settings. In Kailua Bay, the total production of calcareous sediment corresponds to an average (normalized) rate of 0.53 (± 0.19) kg m^{-2} y^{-1}, with 0.33 (± 0.13) kg m^{-2} y^{-1} contributed through erosion of the coralgal framework and 0.20 (± 0.06) kg m^{-2} y^{-1} contributed by direct sediment production on the reef surface.

Applying these modern sediment-production rates over the 5,000 years that Kailua Bay has been completely inundated by postglacial sea-level rise, an estimated 20.2 (± 3.2) × 10^6 m^3 of unconsolidated carbonate sediment has been produced in the system. The volume of sediment stored in the various reef channels and holes in Kailua Bay is 3.7 (± 0.3) × 10^6 m^3, or ~ 19% of that produced since 5,000 y BP. The volume of sand in the modern beach is 1.0 (± 0.1) × 10^6 m^3, or ~ 5% of Holocene sediment production. The volume of carbonate sediment stored in the coastal plain is estimated, using core-log data and associated radiocarbon ages, to be 10.0 (± 1.8) × 10^6 m^3, or ~ 51% of Holocene sediment production. The remaining 25% likely represents sediment loss due to the natural processes of dissolution, attrition, and transport offshore. These export terms are not well understood and emphasize the need for sediment dynamics to be incorporated into reef and sediment budgets. Although sediment production in this reef system is prodigious, the rate of ''new'' sediment supplied to the beachface is less than 2% of what moves on and off the beach seasonally.

INTRODUCTION

Sediment type and availability can govern the morphology and evolution of coastal margins, particularly under the influence of steady or slowly rising sea level (Carter and Woodroffe 1994). Sediment budgets quantify the sources, sinks, and fluxes of sediment within geographically defined natural systems and can be instrumental in understanding coastal behavior over both space and time. In settings like Kailua Bay (Oahu, Hawaii), where coastal sediments are chiefly calcareous and reef-derived, such a budget also improves our understanding of reef structure and shoreface evolution.

Carbonate productivity in modern reef systems has been studied from the geochemical level (e.g., Smith and Kinsey 1976; Smith 1983; Le Campion-Alsumard et al. 1993) to that of reef communities (e.g., Chave et al. 1972; Kinsey 1985) and whole-reef budgets. Land (1979) employed a simple reef carbonate mass-balance equation (*Gross production = Net accumulation + Sediment removed*) and observed that only 21% of gross carbonate productivity was retained in the reef edifice; most was lost in solution (56%) or exported (23%). The importance of bioerosion in reef systems has been well documented (e.g., Hutchings 1986; Glynn 1997; Perry 1998, 1999) and in some cases has exceeded the rate of gross carbonate production, resulting in a net carbonate budget deficit (e.g., Scoffin et al. 1980; Davies and Hutchings 1983; Eakin 1996). The importance of secondary depositional processes (Hubbard et al. 1990) and sediment export (Sadd 1984; Hubbard 1992) has also been emphasized in recent reef budgets.

Previous work demonstrates that comprehensive sediment budgets for shallow-marine carbonate reefs must assess initial (gross) carbonate production by framework-building corals and encrusting coralline algae, the erosion of the resulting reef edifice, and the direct addition of calcareous sediment through the biological activities of calcifying algae, molluscs, and other organisms. A budget should also recognize the source and role of allochthonous carbonate sediments (if they exist in the system) and analyze storage, flux, and export of sediment.

In this paper, we construct a field-based, biogeological sediment budget for windward Kailua Bay on the island of Oahu, Hawaii. Our model of calcareous sediment production considers details of benthic community structure, physiographic setting, biogenic carbonate production by framebuilding and reef-dwelling organisms, and erosion of carbonate facies by biological and mechanical means. Applying modern carbonate dynamics to the past 5,000 years, we estimate the volume of sediment produced since Kailua Bay was inundated by postglacial sea-level rise and compare it to stored volumes of carbonate sediment in the coastal plain, beach, and submarine sand bodies. Probable rates and modes of sediment export are implicated and discussed in considering the 5,000-year sediment budget.

STUDY AREA

Kailua Bay is located on the windward coast of the island of Oahu (Hawaii), bounded to the north by the volcanic headland of Mokapu Peninsula and to the south by Alala Point (Figs. 1, 2). A 12 km² fringing reef extends from near shore out to 25 m water depth and supports a variety of

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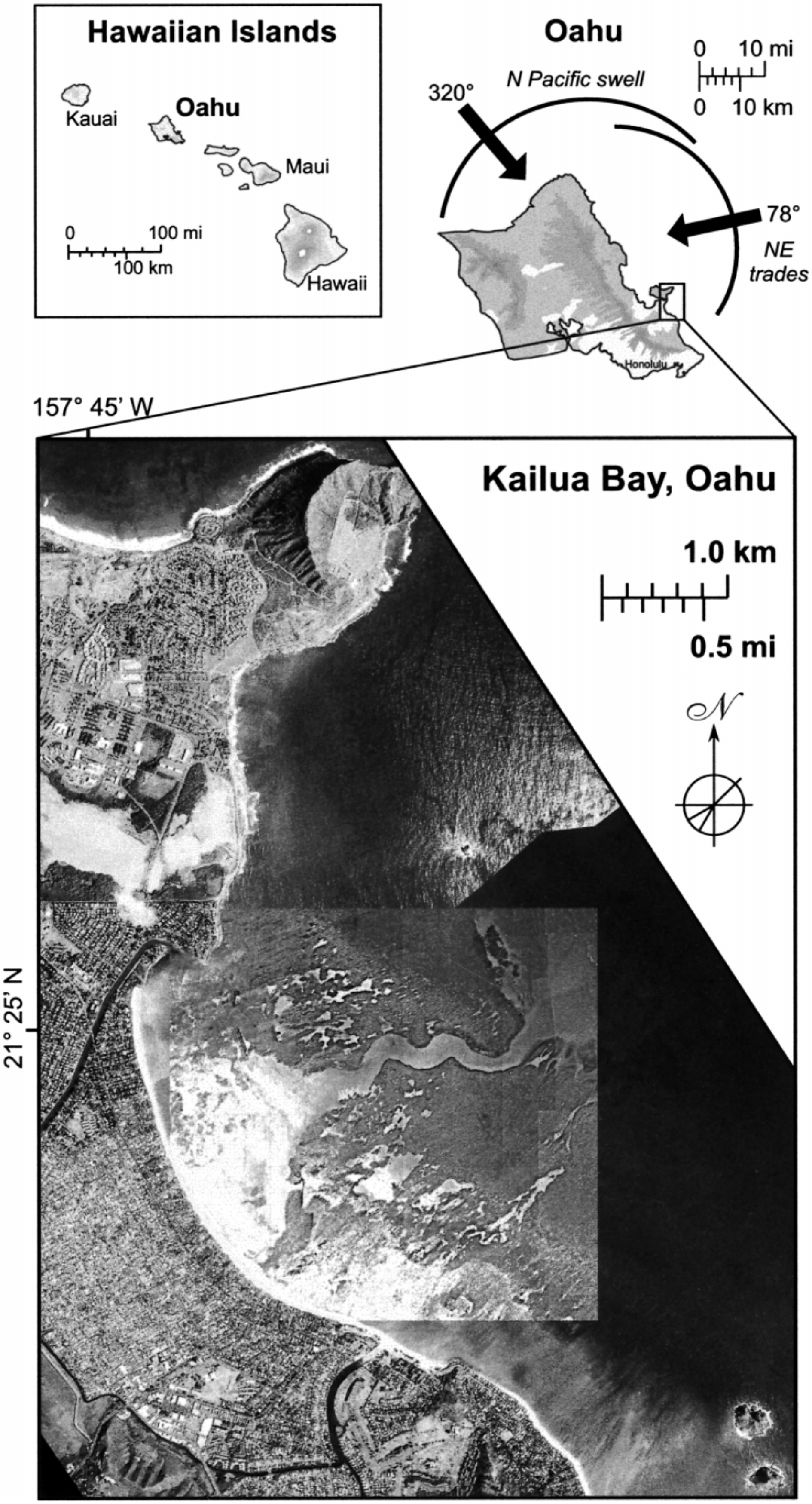

FIG. 1.—Study area of Kailua Bay on windward Oahu, Hawaii. High-resolution multispectral data of the reef surface (Isoun et al. 2003) are overlaid on the central portion of the NOAA aerial photo.

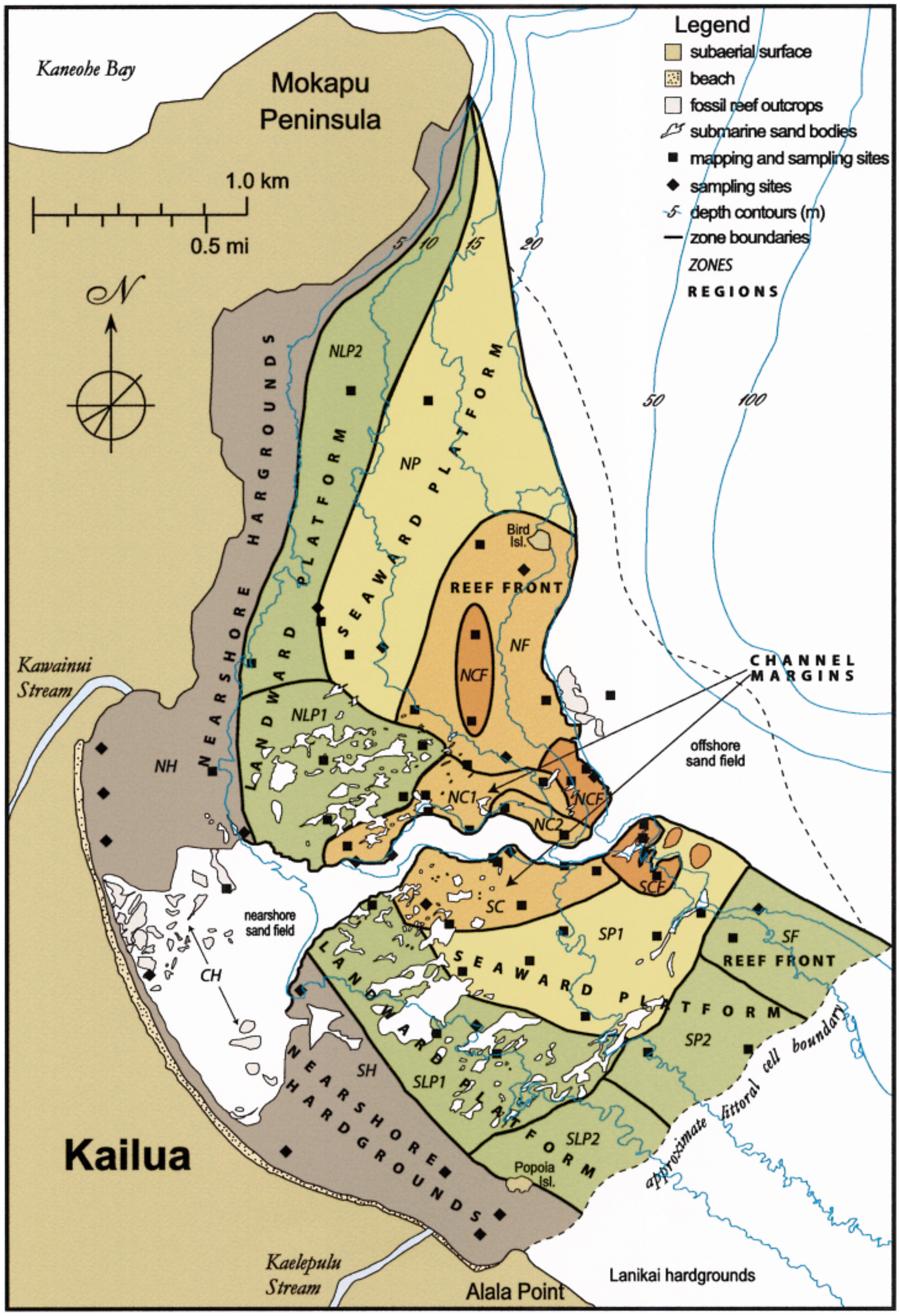

FIG. 2.—Map of the windward reef complex, Kailua Bay, Oahu, divided into 17 physiographic zones based on benthic community structure and hydrodynamic setting (see Table 2 for zone descriptions and abbreviations). Mapping and sampling locations are marked with symbols. Contours are in meters below mean sea level. Dotted line offshore is the approximate boundary of the reef-front sand field. Warmer colors indicate higher coral cover and diversity.

substrate types and benthic communities ($\sim$ 10 km^2 of consolidated ''habitat area''). Bisecting the broad reef platform is a 200-m-wide sand-floored channel that probably reflects the antecedent topography of a meandering stream that drained the windward Koolau mountains during Pleistocene low stands. The seaward end of the paleostream channel opens into a broad sand field lying 3 km offshore atop a gently sloping limestone terrace in 30–70 m water depth (Hampton et al. 1999). The landward end of the channel widens and shallows into a triangular sand deposit ($<$ 5 m water depth) with low-relief outcrops of fossil reef substrate.

Northeasterly trade winds averaging 10–20 knot speeds dominate in Kailua $\sim$ 70% of the year. Wind-generated waves 1–3 m in height with periods of 5–8 s occur during these conditions, particularly in summer months (April–September). Winter months bring lighter, more variable winds and long-period (14–20 s) northerly ocean swells that can refract into Kailua Bay as waves up to 5 m in height. Onshore flow, caused mainly by waves breaking across shallow hardgrounds close to shore, is balanced by offshore flow through the deeper central region of the bay (e.g., as bottom currents along the sand channel; Howd et al. 1999; Richmond et al. 2002). Although offshore circulation in the Kailua littoral cell is not well understood, Krock and Sundararaghavan (1993) suggest that flow outside the 5 m bathymetric contour is generally counterclockwise, parallel to bathymetric contours, and maintained by the dominantly onshore wind pattern. Seasonal ocean temperatures range from 24 to 27°C; tidal range is 0.8 m.

The structure of reef communities in Hawaii has been described in terms

TABLE 1.—*Equations employed in sediment budget calculations for each zone.*

#	Variable name	Symbol	Units	Equation
1	Diversity	$H'c^{a}$	none	$-\Sigma\ (p_i \times ln\ p_i)$ (where p_i = percent cover of the i^{th} species)
2	Habitat area	A_h	m^2	$A_Z\ (m^2) \times R$ (where A_Z = planimetric area; R = rugosity)
3	Carbonate Production Rate (gross)	CPR	$kg\ m^{-2}\ y^{-1}$	growth rate $(cm\ y^{-1}) \times (1\ kg/10^3\ g) \times (10^4\ cm^2/m^2)$
4	Gross carbonate production	G_i	$kg\ y^{-1}$	$A_h\ (m^2) \times CPR_i\ (kg\ m^{-2}\ y^{-1}) \times C_i\ (\%)$ where C_i = % cover of each coral or cor-alga
5	Gross framework production	G_F	$kg\ y^{-1}$	$\Sigma\ G_{i(corals)}\ (kg\ y^{-1}) + \Sigma\ G_{i(coralgae)}\ (kg\ y^{-1})$
6	Normalized gross framework production	G_{FN}	$kg\ m^{-2}\ y^{-1}$	$G_F\ (kg\ y^{-1}) \div A_h\ (m^2)$
7	Bioerosion rate	B_Z	$kg\ m^{-2}\ y^{-1}$	% bioeroded × sample volume (cm^3) × density $(g\ cm^{-3})$ ÷ sample area $(cm^2) \times (1\ kg/10^3\ g)$ ÷ time (y)
8	Bioeroded sediment	BS	$kg\ y^{-1}$	$B_Z\ (kg\ m^{-2}\ y^{-1}) \times A_h\ (m^2)$
9	Biomass	—	$kg\ m^{-2}$	dry weight of field sample (kg) ÷ surface area harvested (m^2)
10	$CaCO_3$ content	% $CaCO_3$	%	dry weight of inorganic remains (kg) ÷ dry weight of field sample (kg)
11	Sediment production rate (direct)	SPR	$kg\ m^{-2}\ y^{-1}$	Biomass $(kg\ m^{-2})$ × % $CaCO_3$ × turnover (y^{-1})
12	Annual sediment production (direct)	ASP	$kg\ y^{-1}$	SPR $(kg\ m^{-2}\ y^{-1}) \times A_h\ (m^2)$ × % cover
13	Normalized sediment production rate	SPR_N	$kg\ m^{-2}\ y^{-1}$	ASP $(kg\ y^{-1}) \div A_h\ (m^2)$
14	Predicted net framework accretion	N_F	$mm\ y^{-1}$	$[G_F\ (kg\ y^{-1}) - BS\ (kg\ y^{-1}) - MS^{b}\ (kg\ y^{-1})] \div 1480\ kg\ m^{-3}$ (density^{c}) $\div A_h\ (m^2) \times (1000\ mm/m)$

[a] Shannon and Weaver (1948) diversity index.
[b] Mechanical sediment production (see text).
[c] Average density of framework composed of both coral (1400 kg m^{-3}; e.g., Grigg 1982) and coralline algae (1560 kg m^{-3}; Stearn et al. 1977).

of wave exposure, intermediate disturbance, and sea-level history (e.g., Dollar 1982; Grigg 1983, 1995, 1998; Dollar and Tribble 1993; Harney 2000; Grossman 2001), but quantitative studies have largely been limited to leeward settings. The fringing reef in windward Kailua Bay lacks a protected back-reef setting and is dominated by broad, shallow carbonate platforms (< 5 m) with limited accommodation space.

Detailed analysis of sediment age and composition by Harney et al. (2000) revealed that sediments in Kailua Bay are Holocene in age and composed chiefly of carbonate skeletal fragments derived from two sources: (1) reef framework erosion by biological and mechanical means and (2) direct production by calcifying reef-dwelling organisms. Although living coral is abundant atop portions of the reef platform, coral fragments are a minor constituent of shoreface sediments, which are instead dominated by coralline algae. Other common calcareous constituents include *Halimeda*, molluscs, and benthic foraminifera. Echinoderms, bryozoans, volcanic fragments and unidentifiable components are less common, representing 0–4% combined. Of 18 radiocarbon ages reported in Harney et al. (2000), only one dated post-1950; twelve ages were 500–1,000 calendar years before present (cal y BP); five were 2,000–5,000 cal y BP.

METHODS

Physiographic zones within the Kailua reef complex were defined based on substrate type, organism abundance, and hydrodynamic setting. Gross production of carbonate framework was calculated for each zone on the basis of the abundance and growth rates of living corals and encrusting coralline algae within each zone. Estimates of bioerosion and mechanical erosion were used to calculate the amount of sediment produced annually by reef framework destruction. Direct sediment production by *Halimeda*, branching coralline algae, benthic foraminifera, and molluscs was quantified using field data on biomass, carbonate content, and turnover rate. Uncertainties, expressed as $\pm 1\sigma$ standard deviations around statistical means, were propagated through all calculations. These methods are described in greater detail below, and equations used are listed in Table 1.

Substrate Mapping and Zonation

Substrate type and benthic organism abundance was mapped by SCUBA divers employing a continuous line transect (see English et al. 1997), 30 m in length, at 60 sites (Fig. 2). Most sites were randomly distributed over the reef platform; some were selected to quantify observed differences in adjacent zones (e.g., along channel walls). Living corals were identified to the species level and their growth form recorded (e.g., *Porites lobata* encrusting). Species diversity (H'_c; Shannon and Weaver 1948) was calculated from transect data for each site (Eq. 1). Substrate rugosity (R) was computed as the ratio between a 2 m length of chain draped over the reef surface to the resulting horizontal distance it covered (1 for flat surfaces; up to 4 for rugose surfaces).

Transect data, bathymetry, image analysis, and field observations from reconnaissance tows and dives were used to delineate 17 physiographic zones on a georeferenced multispectral image of the Kailua reef. Transect data were pooled for each zone, and mean cover, diversity, and rugosity were calculated (with $\pm 1\sigma$ uncertainties) (Table 2). The planimetric area of each zone (A_Z) was measured by tracing zone boundaries in NIH Image software (available online at nih.gov). Areas of sand bodies were subtracted so that only consolidated substrates were included. The three-dimensional habitat area of each zone (A_h) was calculated by multiplying the planimetric area of the zone (A_Z) by its average rugosity (R) (Eq. 2). Calculations included uncertainties in areal measurements ($\pm$ 6%) and around rugosity means ($\pm 1\sigma$).

Gross Carbonate-Framework Production

The total mass of calcification accomplished by the skeletal growth of corals and encrusting coralline algae prior to erosion or alteration was calculated on the basis of published and measured growth rates of these organisms and their abundance in each zone. Growth rates of Hawaiian corals (in mm y^{-1}) were converted to carbonate production rates (CPR, in kg m^{-2} y^{-1}) using a density of 1.4 g cm^{-3} (after Smith and Kinsey 1976; Grigg 1982; Eq. 3). Growth rates for encrusting and massive corals and for stoutly branching *Pocillopora meandrina* and finger-branching *Porites compressa* corals are listed in Table 3; those in bold are employed in this study. *Pocillopora eydouxi* colonies were assigned the rate of *P. meandrina.* All other occasional coral species (e.g., *Pavona duerdeni*) and growth forms (e.g., platy) were conservatively assigned the CPR of encrusting corals (the lowest rate found). *Porolithon onkodes*, the most common crustose coralline alga in Hawaii (Adey et al. 1982), produces carbonate at a rate of 2.6 kg m^{-2} y^{-1} in most settings, but in shallow, wave-scoured settings the alga is limited to ~ 20% of its normal growth rate, or ~ 0.5 kg m^{-2} y^{-1} (Stearn et al. 1977; Agegian 1985; Agegian et al. 1988). These rates were used for all encrusting corallines in this study. Mean percent cover of each coral and coralline alga was calculated from transect data pooled by zone (Table 2).

Gross carbonate-framework production (G_i) by each coral in each zone was calculated by multiplying the habitat area of the zone (A_h) by the carbonate production rate (CPR_i) of each coral and its respective mean percent coverage (C_i) in that zone (Eq. 4). For example (using data in Table 2), in zone SF along the southern reef front, gross production by encrusting corals (G_e) is the product of A_h (377 [$\pm$ 21] $\times 10^3$ m^2), CPR_e (1.4 kg m^{-2} y^{-1}; Table 3), and C_e (0.23), totaling 121 ($\pm$ 13) $\times 10^3$ kg $CaCO_3$ per year. This calculation was similarly performed for all coral forms and

TABLE 2.—*Physiographic zones and their characteristics in Kailua Bay.*

Region ZONE	Substrate description	Depth (m)	Coral Diversity H'_c	Zone Area A_Z (10^3 m^2)	Rugosity R	Habitat Area A_h (10^3 m^2)	Encrusting Coral Cover C_e (%)	Massive Coral Cover C_m (%)	Platy Coral Cover C_p (%)	*Pocillopora meandrina* C_{Pm} (%)	*Porites compressa* C_{Pc} (%)	Total Coral Cover C_{Tc} (%)	Encrusting Cor-algae C_{ae} (%)
Nearshore hardgrounds													
NH	Fossil reef with encrusting coralline algae; no coral	3.0	0	1,366 ± 76	1.0 ± 0	1,366 ± 76	0	0	0	0	0	0	84 ± 0
SH	Fossil reef with encrusting cor-algae	3.0	0	840 ± 48	1.0 ± 0	840 ± 48	0	0	0	0	0	0	84 ± 0
CH	Fossil reef with encrusting coralline algae; no coral	2.7	0	81 ± 4	1.0 ± 0	81 ± 4	0	0	0	0	0	0	73 ± 0
Landward reef platform													
NLP1	Encrusting coralline algae and coral; karstified fossil reef	5.0	0.3	461 ± 36	1.4 ± 0.1	645 ± 115	6 ± 2	0	0	4 ± 1	0	9 ± 2	75 ± 4
NLP2	Fossil reef with encrusting coralline algae; some coral	6.2	0.3	785 ± 43	1.0 ± 0	785 ± 43	8 ± 2	0	0	1 ± 1	0	9 ± 3	10 ± 4
SLP1	Encrusting coralline algae and coral; karstified fossil reef	4.1	0.3	558 ± 55	1.6 ± 0.4	893 ± 311	6 ± 3	0	0	1 ± 1	0	7 ± 2	69 ± 13
SLP2	Fossil reef with encrusting coralline algae; some coral	6.2	0.3	295 ± 16	1.0 ± 0	295 ± 16	8 ± 2	0	0	1 ± 1	0	9 ± 3	10 ± 4
Channel margins													
NC1	Encrusting coral and coralline algae; fossil reef	8.4	0.8	185 ± 13	1.3 ± 0.2	241 ± 44	39 ± 8	1 ± 1	1 ± 1	2 ± 1	0	42 ± 8	35 ± 9
NC2	Encrusting coral and coralline algae; platy and some branching coral	10.2	0.5	60 ± 3	1.2 ± 0	71 ± 4	13 ± 2	0	6 ± 4	1 ± 1	1 ± 1	21 ± 4	70 ± 5
SC	Encrusting, massive, platy coral; encrusting cor-algae	9.9	0.8	264 ± 17	1.4 ± 0.2	370 ± 69	43 ± 9	3 ± 3	10 ± 5	1 ± 1	0	57 ± 7	28 ± 9
Seaward reef platform													
NP	Encrusting coral and coralline algae; fossil reef	9.4	0.8	1,349 ± 74	1.2 ± 0.3	1,619 ± 480	37 ± 7	2 ± 2	0	1 ± 1	0	43 ± 7	7 ± 3
SP1	Encrusting and massive coral; encrusting cor-algae	9.5	0.9	634 ± 39	1.3 ± 0.2	825 ± 203	52 ± 8	7 ± 4	0	2 ± 2	1 ± 1	62 ± 7	30 ± 9
SP2	Encrusting coral and coralline algae; fossil reef	11.1	1.0	360 ± 20	1.2 ± 0.1	432 ± 49	55 ± 2	4 ± 1	0	3 ± 1	0	61 ± 2	26 ± 8
Reef front													
NF	Encrusting coral and coralline algae; fossil reef	11.3	0.9	614 ± 34	1.3 ± 0.2	798 ± 173	34 ± 7	13 ± 4	1 ± 1	1 ± 1	1 ± 1	49 ± 4	39 ± 8
NCF	Encrusting, massive, branching, and platy coral	14.1	1.1	156 ± 9	1.2 ± 0	187 ± 17	54 ± 7	13 ± 3	2 ± 1	0	3 ± 2	72 ± 6	10 ± 4
SF	Encrusting coralline algae, fossil reef; some coral	13.2	0.6	342 ± 19	1.1 ± 0	377 ± 21	23 ± 0	2 ± 0	0	0	0	25 ± 0	75 ± 0
SCF	Encrusting, massive, branching, and platy coral	13.9	1.2	95 ± 8	1.5 ± 0.4	142 ± 47	35 ± 8	21 ± 4	12 ± 6	1 ± 1	5 ± 3	75 ± 8	22 ± 8

Mean values and ± 1 σ standard deviations were calculated from transect-mapping data at 60 sites pooled by zone. Equations for H'_c and A_h are listed in Table 1. Total planimetric zone area (A_Z) = 8,447 (± 514) × 10^3 m^2; total habitat area (A_h) = 9,968 (± 1,721) × 10^3 m^2.

TABLE 3.—*Rates of growth and gross carbonate production (CPR) for reef organisms in Hawaii and reef budgets constructed elsewhere.*

Carbonate Source	Organism, Species, and Growth Form	Location	Growth Rate (mm y^{-1})	Gross $CaCO_3$ Production Rate (CPR) (kg m^{-2} y^{-1})	Reference
Corals	*Porites lobata* (massive)	Mamala Bay	13	18	Grigg (1982)
			7–10	10–14	Grigg (1995)
			10.1	14.1	Grigg (1998)
		Kailua Bay	6	**8.4**	Grossman (2001); this study[b]
	Porites compressa (finger branching)	Kanehoe Bay	7.66	**10.7**	Grigg (1998)
		Kailua Bay (cores)	4.5–15.4	6.3–21.6	Grossman (2001)
	Pocillopora meandrina (stout branching)	Sunset Beach	8.08	**11.3**	Grigg (1998)
			8.13	11.4	
	Montipora spp., *P. lobata* (encrusting, platy)	Kailua Bay	1	**1.4**	Grossman (2001); this study[c]
Coralline algae	*Porolithon onkodes* (encrusting)	Oahu		**2.6**	Agegian et al. (1988)
		scoured settings		**0.5**	Agegian (1985)
	Porolithon gardineri (branching)	Oahu		**20**	Agegian (1985)
		Kailua Bay		13–23	This study
Reef budgets	corals	Cane Bay, St. Croix		1.3	Hubbard et al. (1990)
	coralline algae			0.02	
	corals	Bellairs Reef, Barbados		6.35	Stearn and Scoffin (1977)
	encrusting coralline algae			2.55	
	corals	Discovery Bay, Jamaica		3.1	Land (1979)
	red and green algae			2.1	
	reef flat	model		2	Chave et al. (1972)
	reef slope	model		2–6	

Coral growth rates given in mm y^{-1} were converted to kg m^{-2} y^{-1} using a density of 1.4 g cm^{-3} (e.g., Grigg 1982). Numbers in boldface type are employed in the calculations of this study.

[a] Sclerochronology of 8 samples from five sites (massive range 3.3–10.5 kg m^{-2} y^{-1}).

[b] Image analysis of 14 samples from five sites.

[c] Image analysis of six samples from five sites.

for encrusting coralline algae. Gross framework production in each zone (G_F) is the sum of all G_i for each coral and coralline alga mapped in that zone (Eq. 5). Normalizing the gross production in a zone (G_F, in kg y^{-1}) by its habitat area (in m^2) provides an average rate of carbonate productivity (G_{FN}, in kg m^{-2} y^{-1}) that can be directly compared to rates from different settings (Eq. 6).

Sediment Production

Bioerosion.—Twenty-two samples collected from the upper 30 cm of the reef edifice in 10 zones were cut, photographed, and analyzed using NIH software to measure the surface area of empty bioeroded cavities (after Chazottes et al. 1995; Perry 1998). Using Equation 7, the percent bioeroded per sample volume provided an estimate of the volume of sediment released during internal bioerosion (mainly boring), which was converted to mass using a density of 1.4 g cm^{-3} for coral facies and 1.56 g cm^{-3} for coralline algae facies (Stearn et al. 1977). Dividing by the surface area of the sample and by the number of years the sample was available for bioerosion (vertical height divided by growth rate), a mean annual internal bioerosion rate was estimated for each sample. Rates were averaged for samples collected in the same zone and then extrapolated to the other seven unsampled zones on the basis of similarities in hydrodynamic setting and community structure. Assuming that sediment derived from such bioerosion near the reef surface is released from the edifice (aided by the turbulent setting), the mass of unconsolidated carbonate sediment derived from bioerosion in each zone (BS, in kg y^{-1}) is the product of the bioerosion rate (B_Z) and habitat area (A_h) of the zone (Eq. 8). Bioerosion deeper than 30 cm within the reef edifice was not assessed, nor was internal sedimentation. The only surface-bioeroding organisms observed in Kailua Bay were *Echinometra* urchins in nearshore settings, where their average abundance recorded on line transects was 0.133 individuals/m^2. Applying a reasonable erosion estimate of 7.3 g $CaCO_3$ per urchin per day (Stearn and Scoffin 1977) results in an average erosion rate of 0.36 kg m^{-2} y^{-1} to be applied only in nearshore hardground settings of the reef platform ($A_h = 2{,}287\ (\pm\ 128) \times 10^3\ m^2$).

Mechanical Erosion.—Grigg (1995) suggests that destruction of branching corals is the most common result of storm events, whereas massive and encrusting corals are more resistant. Using growth rate and colony size, we estimate *Pocillopora meandrina* coral turnover occurs once every 10 years, whereas *Porites compressa* colonies produce carbonate framework for ~ 100 years before being converted to sediment by storms. The modern gross annual production of each species is used to determine an average annual rate of sediment produced by the episodic turnover of branching corals during mechanical erosion.

Direct Sediment Production.—Samples of *Halimeda* ($n = 14$) and the branching coralline alga *Porolithon gardineri* ($n = 6$) were collected from the zones in which they were observed, rinsed in DI water, oven-dried, and weighed to estimate their biomass (kg m^{-2}; Eq. 9). After treatment with 30% hydrogen peroxide to remove organic material, samples were again dried and weighed to determine carbonate content (Eq. 10). A turnover rate of 2 y^{-1} was employed for *Halimeda* on the basis of seasonal field observations, consistent with published rates (e.g., 2.2 y^{-1}, Drew 1983; 3 y^{-1}, Freile et al. 1995). Mass-to-volume conversions employ a density of 700 kg m^{-3} (Drew and Abel 1985). For the branching coralline alga *Porolithon gardineri*, a turnover rate of 0.2 y^{-1} (inferred from field observations) was employed, and density was assumed to be the same as for encrusting algae (above). Biomass data on living populations of benthic foraminifera and micromolluscs were obtained from samples of rubble ($n = 6$) that were scrubbed of attached fauna (see Hallock 1981 for details). The biomass of molluscs living in *Halimeda* samples was also assessed. A turnover rate of 1 y^{-1} was applied for forams (Hallock et al. 1995) and 2 y^{-1} for micromolluscs (Kay 1973 and personal communication). Densities employed were based on samples of skeletal material of known mass and volume from previous radiocarbon studies: 1,400 kg m^{-3} and 1,200 kg m^{-3}, respectively (Harney et al. 2000). Direct sediment production rates (SPR, in kg m^{-2} y^{-1}) were determined for each organism on the basis of these data, habitat area, and percent cover in each zone (Eqs. 11–13). Detailed data on biomass, carbonate content, and sediment production rates in various settings of Kailua Bay can be found in the JSR digital repository (see Acknowledgments).

Uncertainty Analysis

Uncertainties reported for planimetric zone area (A_Z) are related to the 3 m resolution of the multispectral image (Isoun et al. 2003) and to precision limitations of the NIH software (including average deviations of ± 6% for each object traced during image analysis). The uncertainties reported also include those around calculations to subtract the areas of sand bodies within zones. Uncertainties reported for rugosity and percent cover are $\pm\ 1\sigma$ standard deviations around means generated during statistical analysis of transect data. All uncertainties were propagated through calculations of carbonate and sediment productivity to determine the total variation: the lowest outcome was subtracted from the highest outcome, divided in half, and reported as a ± value.

Certain assumptions must be made in order to model complex whole-reef systematics over time and space in the way we have attempted. When possible, uncertainties introduced by assumptions were included in the ± value (e.g., variability in percent cover between two zones for which data was pooled or extrapolated). Sensitivity analysis suggests employing multiplicative variables (e.g., the 5,000 year time scale) introduces uncertainty that may exceed the individual spatial and analytical errors provided here. It is thus important to recognize that the application of modern process rates back in time provides order-of-magnitude estimates of potential production, and results should be interpreted with this in mind.

RESULTS

Community Structure and Physiographic Zonation

Of the 47 species of scleractinian corals in Hawaii (Maragos 1977, 1995), 11 were mapped in this study, with three species comprising an average of 89% of the coral community in Kailua Bay: *Montipora patula* (48%), *Porites lobata* (22%), and *Montipora capitata* (19%). Encrusting forms of these species are the most common, accounting for 72% of the living coral community. Massive colonies of *P. lobata* are common at depths of 8–15 m (averaging 12% of the coral community); platy forms of this species and both *Montipora* spp. are generally found in deeper waters (> 10 m) or on relatively steep slopes. Finger-branching *Porites compressa* (5%) is common on reef slopes where, as a competitively superior species (Grigg 1982), it forms monospecific stands. *Pocillopora meandrina* (4%) is a robust, stoutly branching ''pioneer'' species (Grigg 1982) common in energetic settings of the landward reef platform. Encrusting coralline algae are abundant at all depths mapped in Kailua Bay, occupying an average of 84% of the substrate in nearshore areas. Extensive meadows of the calcareous green alga *Halimeda* are abundant in shallow, well-lit areas near shore, growing on both sandy and rocky substrates. Characteristics of each of the 17 zones are listed in Table 2 and approximate boundaries are shown in Figure 2. Benthic community structure in Kailua Bay has been described in detail (Harney 2000; Grossman 2001) and is the subject of a forthcoming paper. A summary description of five general settings is provided here.

Nearshore Hardgrounds.—Seaward of the sandy shoreline in depths < 5 m, abraded, low-relief fossil limestone surfaces are the abundant substrate (NH, CH, SH). Living coral is absent, whereas coralline algae encrusts most of the consolidated substrate. In some areas, dense-growth *Halimeda* meadows cover 100% of the substrate for up to 700 m^2.

Landward Reef Platform.—Karstified fossil reef substrate and sand-filled holes dominate the reef setting in 5–8 m water depth (NLP1, SLP1).

TABLE 4.—*Summary, by zone, of gross framework production, bioerosion, and sediment production.*

		Gross Framework Production (× 10^3 kg y^{-1})			Normalized				
Region	Zone	Corals (G_c)	Cor-algae (G_{ae})	Framework (G_F)	FW (G_{FN}) (kg m^{-2} y^{-1})	Bioerosion Rate (B_Z) (kg m^{-2} y^{-1})	Bioeroded Sed (BS) (× 10^3 kg y^{-1})	Direct Sed (DS) (× 10^3 kg y^{-1})	Total Sed (TS) (× 10^3 kg y^{-1})
Nearshore hardgrounds	NH	0	574 ± 133	574 ± 133	0.42	0.14	191 ± 11	542 ± 30	733 ± 41
	SH	0	353 ± 85	353 ± 85	0.42	0.14	118 ± 6.8	362 ± 21	480 ± 28
	CH	0	30 ± 7	30 ± 7	0.36	0.12	10 ± 0.5	32 ± 1.6	42 ± 2.2
Landward reef platform	NLP1	346 ± 179	242 ± 236	588 ± 415	0.91	0.12	77 ± 19	136 ± 24	213 ± 43
	NLP2	177 ± 146	39 ± 75	216 ± 22	0.28	0.14	110 ± 13	181 ± 10	291 ± 23
	SLP1	176 ± 262	308 ± 694	484 ± 956	0.54	0.12	107 ± 54	118 ± 41	226 ± 95
	SLP2	66 ± 55	15 ± 28	81 ± 83	0.28	0.14	41 ± 4.9	24 ± 1.3	66 ± 6.2
Channel margins	NC1	209 ± 171	219 ± 78	428 ± 249	1.78	1.15	277 ± 103	43 ± 12	320 ± 115
	NC2	35 ± 31	130 ± 13	165 ± 44	2.31	1.15	82 ± 12	9.3 ± 0.5	92 ± 12
	SC	405 ± 460	269 ± 111	675 ± 570	1.82	0.25	93 ± 34	27 ± 5.1	120 ± 39
Seaward reef platform	NP	1.280 ± 1,334	295 ± 173	1,575 ± 1,506	0.97	0.14	227 ± 99	239 ± 71	466 ± 170
	SP1	1,337 ± 1,168	643 ± 284	1.980 ± 1,452	2.40	0.31	256 ± 111	54 ± 13	310 ± 125
	SP2	618 ± 225	292 ± 99	910 ± 324	2.11	0.14	61 ± 13	29 ± 3.3	90 ± 16
Reef front	NF	1,397 ± 935	809 ± 276	2,206 ± 1,211	2.76	0.13	104 ± 36	11 ± 2.4	115 ± 38
	NCF	402 ± 187	49 ± 19	451 ± 207	2.41	0.55	103 ± 20	1.4 ± 0.1	104 ± 20
	SF	182 ± 25	734 ± 33	916 ± 58	2.43	0.10	38 ± 2.1	7.6 ± 0.4	45 ± 2.5
	SCF	423 ± 367	81 ± 46	505 ± 412	3.56	0.78	111 ± 60	1.0 ± 0.3	112 ± 60
Halimeda meadows							0	153 ± 8.6	153 ± 8.6
Urchin bioerosion in nearshore hardgrounds						0.36	824 ± 47		824 ± 47
Total bioeroded sediment production (BS)							2,828 ± 646		
Mechanical erosion of branching corals (MS)							441		441
Totals (× 10^3 kg y^{-1})		7,052 ± 5,546	5,083 ± 2,390	12,135 ± 7,935			**3,269 ± 646**	**1,972 ± 247**	**5,242 ± 892**
Totals (m^3 y^{-1})							**2,226 ± 436**	**1,822 ± 200**	**4,048 ± 635**
Normalized rates (kg m^{-2} y^{-1})		0.71 ± 0.24	0.51 ± 0.12	**1.22 ± 0.36**			**0.33 ± 0.13**	**0.20 ± 0.06**	**0.53 ± 0.19**
(mm y^{-1})		0.5 ± 0.2	0.3 ± 0.1	**0.8 ± 0.3**					

Conversions to m^3 y^{-1} and mm y^{-1} use densities specific to sediment origin (see text). Gross production rates (kg y^{-1}) are normalized (kg m^{-2} y^{-1}) using respective habitat area (A_h, m^2; Table 2). Additional data is available through JSR (see Acknowledgments).

Fossil spurs are 1–3 m above the sea floor, encrusted with living coralline algae. Coral cover and diversity are low, limited to encrusters and sturdy *Pocillopora meandrina.* In slightly deeper water (NLP2, SLP2), living coral is more abundant and diverse.

Channel Margins.—Spur-and-groove topography and nearly vertical walls with 3–5 m of relief characterize the central channel margins at depths of 8–10 m (NC1, NC2, SC). Encrusting coralline algae are abundant; coral cover and diversity are moderate and vary with depth and position on marginal walls (e.g., cover decreases toward the base of the margins where talus and sand are present).

Seaward Reef Platform.—On gentle slopes at depths of 9–11 m (NP, SP1, SP2), the benthic community is dominated by encrusting forms of coral and coralline algae.

Reef Front.—The reef platform gives way in water depths > 11 m and slopes seaward to a fossil limestone terrace at ~ 30 m depth. A mix of massive, encrusting, and branching corals and encrusting coralline algae forms are abundant along the northern reef front (NF). The southern reef front (SF) is characterized by a sloping fossil limestone ramp largely encrusted by coralline algae. Near the channel (NCF, SCF), substrates with 3–8 m of relief support dense coral growth, where thickets of branching *Porites compressa* and stacks of foliose corals dominate the reef substrate. In these zones, living coral cover and mean species diversity are the highest encountered in Kailua Bay.

Framework and Sediment Production

Gross Framework Production.—Results of calculations of gross production (G_F) reported in Table 4 are in units of 10^3 kg y^{-1}, thus some rounding occurs. Framework production is highest in zones on the seaward platform and reef front owing to higher species diversity, extensive coral cover, and dominance of massive and branching (i.e., faster-growing) morphologies. A total of ~ 12×10^6 kg of carbonate framework is produced annually in Kailua Bay. When normalized by reef habitat area (A_h), gross framework productivity (G_{FN}) ranges from 0.28 to 3.56 kg m^{-2} y^{-1}, consistent with the partitioning of reef environments into areas of low, moderate, and high rates of carbonate production, where 90% of reef environments calcify at low rates, generally < 4 kg m^{-2} y^{-1} (Chave et al. 1972; Smith and Kinsey 1976; Kinsey 1985). The contributions made by corals (~ 58%) and coralline algae (~ 42%) to the framework attest to the significance of calcifying rhodophytes in the reef community and in construction of the edifice itself.

Framework Erosion.—Bioerosion of the reef edifice is a principal source of unconsolidated sediment in Kailua Bay. Internal bioerosion rates in Kailua Bay range between 0.10 and 1.15 kg m^{-2} y^{-1}, consistent with observations reported in reefal settings (e.g., Scoffin et al. 1980; Kiene 1985; Tribollet et al. 2002). Rates are highest along channel margins (0.25–1.15 kg m^{-2} y^{-1}) and portions of the reef front (0.55–0.78 kg m^{-2} y^{-1}) (Table 4). The total volume of unconsolidated carbonate sediment produced by biological (BS) and mechanical (MS) erosion is 2,226 (± 436) m^3 y^{-1} (using a density of 1,400 kg m^{-3} for corals and 1,560 kg m^{-3} for coralline algae). When normalized by habitat area, sediment production by reef erosion averages 0.33 (± 0.13) kg m^{-2} y^{-1}, or ~ 27% of gross framework production.

Direct Sediment Production.—Rates of direct production are available digitally and in greater detail than summarized here (see Acknowledgments). *Halimeda opuntia* produces sediment at rates of 0.6–3.0 kg m^{-2} y^{-1} in most shallow reef zones and can reach 6.7 kg m^{-2} y^{-1} in dense-growth meadows. The alga contributes sediment at an average rate of 0.23 (± 0.03) kg m^{-2} y^{-1} over the area it inhabits, corresponding to a volume of 769 (± 46) m^3 y^{-1} (using a density of 700 kg m^{-3}; Drew and Abel 1985). Branching coralline algae produce carbonate at rates of 8.5–17.8 kg m^{-2}, consistent with growth-rate studies of *Porolithon gardineri* in Hawaii (Agegian 1985). If 20% of the living population turns over each year (i.e., each lasts ~ 5 y), the resultant sediment contribution totals 283 (± 46) m^3 y^{-1} (using a density of 1,560 kg m^{-3}; Stearn et al. 1977). Benthic foraminifera produce sediment at rates of 0.01–0.14 kg m^{-2} y^{-1}, consistent with those published for Oahu (0.038–0.50 kg m^{-2} y^{-1}, Hallock 1981) and for Kailua Bay specifically (0.11–0.41 kg m^{-2} y^{-1}, Harney et al. 1999). These rates apply to consolidated substrate without living coral and result in the contribution of 344 (± 69) m^3 of sediment annually. Similarly, molluscs contribute 426 (± 39) m^3 of sediment annually. The total mass

TABLE 5.—*Summary of annual sediment production by source.*

Sediment Source	Mass Sediment Production ($\times 10^3$ kg y^{-1})	Volume Sediment Production (m^3 y^{-1})	Normalized Sediment Production (kg m^{-2} y^{-1})	Contribution (By Volume) (%)
Framework bioerosion (BS)	2,828 ± 646	1,911 ± 436		47
(echinoid grazing)	(824 ± 47)	(557 ± 31)		
Mechanical erosion (MS)	~441	~315		~8
Framework erosion total (BS+MS)	3,269 ± 646	2,226 ± 436	0.33 ± 0.13	55 ± 19
Halimeda	538 ± 32	769 ± 46		19
branching cor-algae	441 ± 72	283 ± 46		7
foraminifera	482 ± 97	344 ± 69		8
molluscs	511 ± 46	426 ± 39		11
Direct production total (DS)	1,972 ± 247	1,822 ± 200	0.20 ± 0.06	45 ± 12
Total sediment production	5,242 ± 892	4,048 ± 635	0.53 ± 0.19	

Volume conversion use densities specific to sediment origin (see text). Sediment production by framework bioerosion includes the contribution of grazing echinoids (given in parentheses). Normalized sediment production calculated using Eq. 13.

of unconsolidated carbonate sediment produced by these direct means (DS) is 1,822 (± 200) m^3 y^{-1} (Tables 4, 5). When normalized by the entire reef habitat area, direct sediment production averages 0.20 (± 0.06) kg m^{-2} y^{-1}.

A total volume of 4,048 (± 635) m^3 of calcareous sediment is produced annually in Kailua Bay by bioerosion of the reef framework (~ 55%) and direct production (~ 45%) (Table 5). Table 6 summarizes the contribution by volume of the carbonate producers compared to the average composition of sediment in Kailua Bay determined by Harney et al. (2002).

DISCUSSION

Reef and Sediment Productivity

Carbonate framework (G_F) is constructed at an average rate of 1.22 (±0.36) kg m^{-2} y^{-1} over the nearly 10 km^2 of reef habitat area (sum of A_h values for all zones; Table 2), with 0.71 (±0.24) kg m^{-2} y^{-1} contributed by corals and 0.51 (± 0.12) kg m^{-2} y^{-1} by encrusting coralline algae. These results are consistent with those from Cane Bay (St. Croix), in which gross carbonate production averaged 1.15 kg m^{-2} y^{-1}, contributed almost entirely by corals (Hubbard et al. 1990; Table 3). As expected, gross productivity is lower on this windward Hawaiian reef than in protected, leeward settings such as Bellairs Reef (Barbados), where carbonate productivity averaged 8.9 kg m^{-2} y^{-1} (Stearn et al. 1977; Table 3), owing to higher coral growth rates and diversity. However, coralline algae make a significant contribution to the carbonate and sediment budget of Kailua Bay, accounting for ~ 42% of gross reef framework construction and ~ 27% of the volume of biogenic sediment production annually. Encrusting coralline algae have been recognized as binders and cementers of reef framework and rubble, but the importance of branching forms has gone generally unmentioned in settings other than reef crests. The abundance and persistence of these rhodophytes in Kailua Bay demonstrate their importance in terms of carbonate dynamics and reinforce their significance in Hawaiian reef systems (Littler and Doty 1975; Adey et al. 1982), flourishing in turbulent settings where there is little competition from corals.

Direct sediment production by reef-dwelling algae, molluscs, and other organisms accounts for 45% of the annual mass of sediment produced in Kailua Bay. The importance of *Halimeda* productivity has been established in many reef settings (e.g., Drew and Abel 1985; Freile et al. 1995); this study illustrates the significance of the alga in the sediment budget of this Hawaiian reef system. Although previous budgets have estimated some direct production on the basis of abundance of skeletal remains in sediments (e.g., Land 1979; Hubbard et al. 1990; Calhoun et al. 2002), understanding calcification rates and population structure of reef-dwelling organisms will more accurately quantify their role in whole-reef systems. In addition, the sediment production potential of infaunal organisms (not assessed in this study) is not well understood but may be important in carbonate budgets.

TABLE 6.—*Sediment contribution by volume.*

Carbonate Source	Contribution (By Volume) (%)	Sediment Composition (%)
Coral	35%	12%
Coralline algae	27%	36%
(encrusting)	(20%)	
(branching)	(7%)	
Halimeda	19%	15%
molluscs	11%	11%
foraminifera	8%	5%

Erosion of reef framework yields ~58% coral and ~42% encrusting coralline algae. Sediment composition is based on point counts of samples from Kailua Bay (Harney et al. 2002).

Bioerosion

Many carbonate budgets have demonstrated that constructive and destructive processes are nearly balanced on most reefs, with net accumulation barely keeping ahead of net loss (Glynn 1997). Bioerosion is one of the most important agents of reef alteration and plays a significant role in reefal sediment production (Neumann 1966; Warme 1976; Hutchings 1986; Perry 1999). Although bioerosion can be estimated by a number of techniques from surface-lowering (e.g., Kiene 1985) to core-logging (Hubbard et al. 1990), analysis of slabbed reef samples (e.g., Chazottes et al. 1995) enables the study of modern bioerosion rates in specific reef zones or subenvironments, which have been shown to differ significantly (Perry 1999). In addition, such rates are not a function of gross carbonate productivity, do not require long cores or a knowledge of Holocene reef accretion, and can be valuable in assessing bioerosion over time scales of months to decades.

Although this method is useful to observe the work of boring sponges, bivalves, and serpulids, considered the major agents of internal bioerosion (e.g., Risk et al. 1995), the affects of grazers at the reef surface may be missed. An estimated 824 (± 47) × 10^3 kg of sediment was added to the annual sediment production model to account for *Echinometra* urchins observed on nearshore transects in Kailua Bay, but basic knowledge of echinoid population structure is lacking, and this is likely a minimum estimate of their activity.

Internal bioerosion occurring at rates of 0.10–1.15 kg m^{-2} y^{-1} (B_Z, Table 4) results in the conversion of 4–65% of the gross annual framework production in a zone to unconsolidated sediment. The average rate at which sediments are bioeroded and released from the reef edifice is 0.33 ± 0.13 kg m^{-2} y^{-1} (Table 7), ~ 27% of annual framework construction. This is remarkably consistent with results from Cane Bay in which Hubbard et al. (1990) determined from drilled cores that ~ 24% of annual gross carbonate production was bioeroded and released from the reef edifice into channels.

Mechanical Erosion

Mechanical energy plays an implicit role in flushing bioeroded debris from the upper surface of the reef into sand bodies, as well as turning over

TABLE 7.—*Average rates of sediment production (kg m^{-2} y^{-1}) by framework bioerosion and direct contributions in general settings of the windward Kailua reef.*

Setting	Coral	Enc cor-algae	*Halimeda*	*P. gardineri*	Foraminifera	Molluscs	Frame erosion	Direct sediment	Total sediment
Nearshore hardgrounds	0.08	0.06	0.23	0.06	0.01	0.12	0.14	0.41	0.55
Landward reef platform	0.07	0.05	0.00	0.08	0.09	0.01	0.13	0.18	0.30
Channel margins	0.38	0.28	0.01	0.02	0.07	0.02	0.66	0.12	0.78
Seaward reef platform	0.11	0.08	0.00	0.03	0.06	0.02	0.19	0.11	0.30
Reef front	0.14	0.10	0.00	0.00	0.01	0.00	0.24	0.01	0.05
Average contribution							0.33 ± 0.13	0.20 ± 0.06	0.53 ± 0.19

Normalized rates are calculated from data pooled by region (Eq. 13). Average contribution is based on different habitat areas in the five settings and is not the mean of the table values.

populations of *Halimeda* and *P. gardineri.* Mechanical erosion also plays a direct role in the breakage of corals during storms, but quantitative measurements of the impact of long-period swells and sustained tradewinds on reefs are lacking. Rates derived from estimates of branching coral turnover suggest that infrequent (albeit severe) storms are less effective than bioerosion in producing sediment from reef framework (Table 5), particularly in a windward reef system dominated by encrusting and massive growth forms. Although likely providing only minimum estimates of mechanical erosion, the turnover approach is supported by evidence from cores that no significant accretion of branching-coral facies has occurred during the last 5,000 y (Grossman 2001; Grossman and Fletcher 2004). The paucity of coral in sediments of the bay and beach (Harney et al. 2000) also suggests that large-scale destruction of coral colonies by mechanical erosion is not a principal source of sediment.

Predicted Reef Accretion

Employing a mass-balance approach (Land 1979; Hubbard et al. 1990), the simple model *Gross* − *Sediment* = *Net* can be used to estimate net carbonate productivity (reef accretion) (Eq. 14). Gross production averages 1.22 (± 0.36) kg m^{-2} y^{-1} in Kailua Bay; sediment production by framework erosion averages 0.33 (± 0.13) kg m^{-2} y^{-1}. The difference between these is net production, 0.89 (± 0.49) kg m^{-2} y^{-1}. In Cane Bay, gross production (Pg) averaged 1.15 kg m^{-2} y^{-1} and net production (Pn) averaged 0.91 kg m^{-2} y^{-1} (Hubbard et al. 1990). The estimate of net production for Kailua Bay corresponds to an accretion rate of 0.60 (± 0.35) mm y^{-1} (using a density of 1.48 g cm^{-3}). This rate is lower than the 3 mm y^{-1} accretion rate characteristic of most Holocene ''margin reefs'' (Smith 1983) and the 1–4 mm y^{-1} range suggested for fringing reef systems (Davies and Hopley 1983), but it is consistent with recent findings by Grossman (2001) for Holocene accretion in this windward setting. Accretion at this rate for 5,000 years predicts an average thickness of 3 m for the mid- to late Holocene reef unit in Kailua Bay. Analysis of reef cores (Grossman and Fletcher 2004) suggest that significant Holocene reef accretion in Kailua Bay has been limited to scattered packages in wave-shadowed subenvironments of the bay owing to limited accommodation space. Accretion was rapid along the reef front during the early mid-Holocene (2.5–6.0 mm y^{-1}) and resulted in units 11 m thick in some places. However, reef accretion over much of the platform was limited to $<$ 0.2 mm y^{-1}, resulting in Holocene thicknesses of $<$ 1 m in most areas. These results suggest that Hawaiian reefs, owing to their relatively low diversity and high wave energy, are not well understood in the context of modern function or Holocene development.

TABLE 8.—*Sediment storage in Kailua Bay compared to 5,000 years of potential sediment production.*

	(× 10^3 m^3)	% of Modern Storage	% of Holocene Production
Potential sediment production (5 ky)			
Framework erosion	11,129 ± 2,178		
Direct production	9,109 ± 999		
Total sediment production	20,239 ± 3,177		
Modern sediment storage			
Submarine reservoirs			
Channel	2,220 ± 185	15% ± 4%	11% ± 3%
Reef sand bodies (north)	145 ± 15	1% ± 0.3%	1% ± 0.2%
Reef sand bodies (south)	604 ± 60	4% ± 1%	3% ± 1%
Nearshore triangle	285 ± 29	2% ± 1%	1% ± 0.2%
Offshore mouth	471 ± 47	3% ± 1%	2% ± 1%
Total submarine storage	3,726 ± 336	26% ± 6%	19% ± 5%
Subaerial reservoirs			
Beach	1,000 ± 1,000	7% ± 1%	5% ± 1%
Coastal plain	10,049 ± 1,809	68% ± 24%	51% ± 17%
Total subaerial storage	11,049 ± 1,909	75% ± 25%	56% ± 18%
Total storage	14,775 ± 2,244		75% ± 23%

Potential sediment production applies modern rates (Table 9) over 5,000 years. Storage volumes include a porosity of 40% (after Friedman et al. 1992). Channel volume estimated using data from Casciano (1979). Beach sand storage estimated from profile data (Norcross et al. 2002). Storage in coastal plain estimated using core logs (Figs. 3, 4).

Sediment Production and Storage in the Last 5,000 Years

If modern sediment production in Kailua Bay (4,048 [± 635] m^3 y^{-1}; Table 5) is applied over the 5,000 years the bay has been completely inundated by postglacial sea-level rise (Fletcher and Jones 1996; Grossman and Fletcher 1998), an estimated 20,239 (± 3,177) × 10^3 m^3 of calcareous sediment could have been produced in the system (Table 8). Although this approach does not consider changes in reef community structure, erosion, or direct sedimentation that have likely occurred in the last 5,000 years, it provides an order-of-magnitude estimate of the sediment-production potential in the system over long time scales, which can then be compared to stored sediments of known Holocene age to assess the long-term balance of the sediment budget.

The bay and coastal plain of Kailua store significant volumes of calcareous sediment of Holocene age (Table 8; Figs. 3, 4). The volumes of sand stored in submarine reservoirs were estimated on the basis of sediment thicknesses from jet-probings and from a single seismic line near the seaward end of the channel in 25 m water depth (Ericksen et al. 1997) that suggests a fossil basement 12 m below the sandy seafloor. Judging from surficial sediment ages (Harney et al. 2000) and sea-level history, the total volume stored in water depths $<$ 30 m in Kailua Bay (3,726 [± 336] × 10^3 m^3) is inferred to be $<$ 5,000 years old. Sediments farther offshore on deeper submarine terraces have not been age-dated but may also be of Holocene age.

Using beach-profile data, Norcross et al. (2002) calculated the volume of sand stored in the beach face (from the berm crest to the sand–rock interface offshore) to be 1,000 (± 100) × 10^3 m^3. Coastal-plain deposits contain 10,049 (± 1,809) × 10^3 m^3 of carbonate sand and silt of Holocene age in both Kawainui Marsh and the sandy berm on which the town of Kailua is built. Kraft (1982, 1984) and Athens and Ward (1991) suggest the marsh was a marine embayment during the mid- to late Holocene sea-level highstand and became a terrestrial wetland ∼ 2,200 years BP because of a fall in relative sea level. This resulted in the abandonment of lagoonal sediments in the marsh and stranded a thick berm of calcareous sand landward of the present shoreline position.

The locations of sediment cores from the marsh and berm (collected over the last six decades by researchers and geotechnical organizations) are illustrated in Figure 3. The numbered transects X1 and X2 correspond to

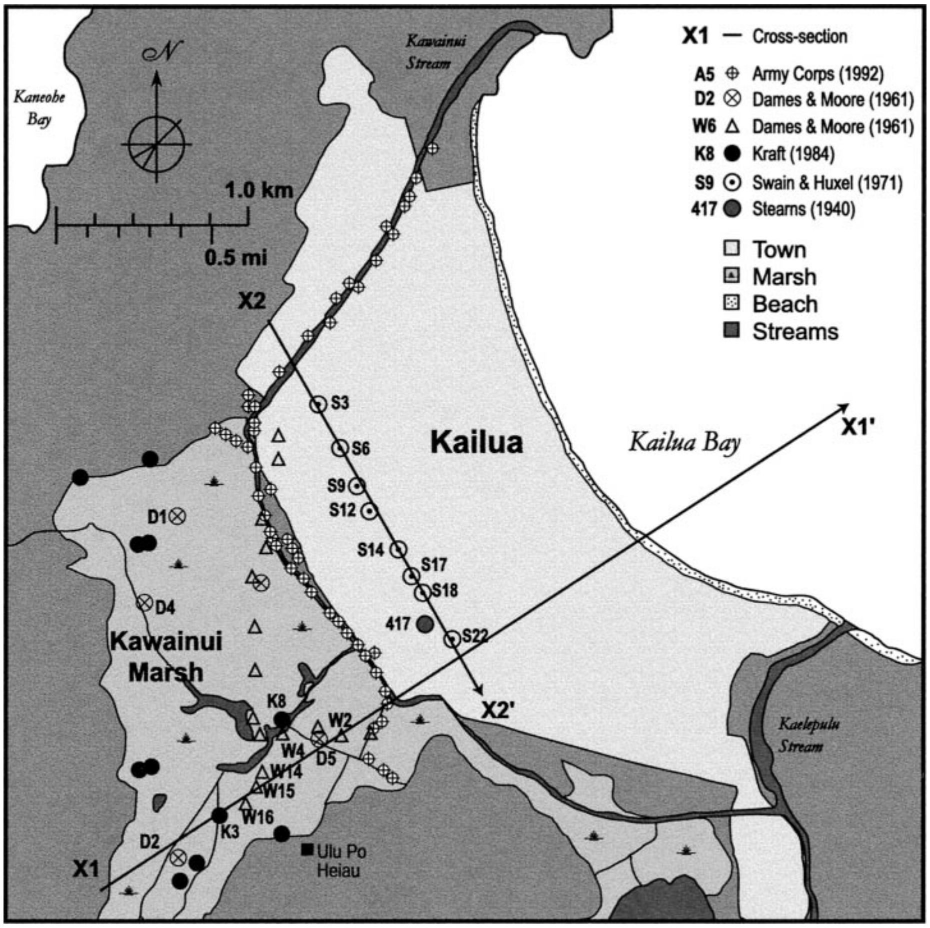

FIG. 3.—Location of sediment cores in Kawainui Marsh and Kailua town used to examine the volume of calcareous sediment of Holocene age stored in the coastal plain. Transects X1 and X2 refer to cross sections in Figure 4. Only the cores shown along these transects are labeled with site names.

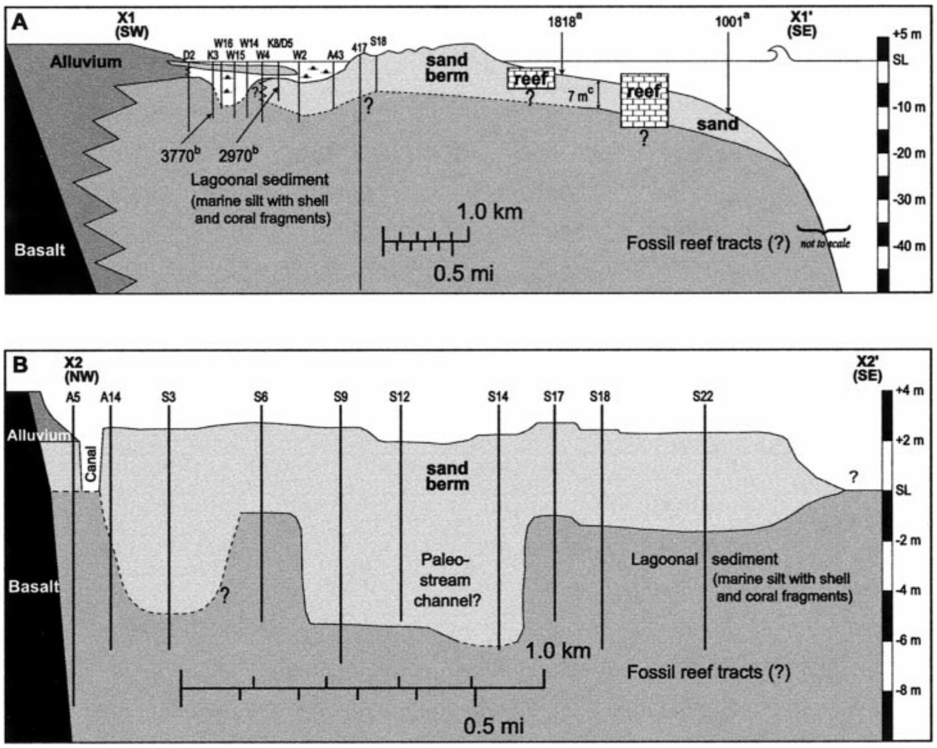

FIG. 4.—**A)** Cross-section of Kawainui marsh and the sandy Kailua berm along transect X1–X1′. Arrows point to radiocarbon ages of bulk sediments (a, from Harney et al. 2000) and skeletal fragments in lagoonal mud (b, from Kraft 1984). One core (417, from Stearns 1940) penetrated nearly 50 m of marine sediment. Jet-probing on the submarine flanks of the sand berm (c) where sediment thickness was 7 m. **B)** Cross section of the Kailua berm (composed of fine- and medium-grained calcareous sand) along transect X2–X2′ illustrating sediment thickness and lithology. Sections are modified from Kraft (1984). Core locations are shown in map view in Figure 3.

the cross sections in Figure 4. Graphical reconstructions of the carbonate sand and silt underlying the marsh and berm are modified from Kraft (1984) in conjunction with sediment core logs from additional sources (see figure legend for references). Transect X1–X1′ (Fig. 4A) is a SW–SE cross section from Kawainui Marsh across the sandy berm and offshore. Cores in the marsh penetrate 15 m of peat, terrestrial mud, and lagoonal sediment. Sediment cores in the berm suggest that a deposit of medium- to coarse-grained calcareous sand 3–10 m thick underlies Kailua town. One core (#417, from Stearns 1940) penetrated more than 10 m of marine sand underlain by another 40 m of lagoonal silt. None of the cores reached fossil reef or basalt basement. Calcareous skeletal materials found in lagoonal mud 7 m and 15 m below the marsh surface were radiocarbon age-dated at 3,770 and 2,970 y BP, respectively (Kraft 1984).

Transect X2–X2′ (Fig. 4B) is a NW–SE cross-section of the Kailua berm composed of fine- and medium-grained calcareous sand. The thick, central portion of the berm suggests it is the onshore expression of the meandering paleostream channel bisecting the fringing reef offshore. Underlying the sand berm is 2–8 m of marine silt with shell and coral fragments (the lagoonal sediment that also underlies the marsh). No sediment cores have been found that penetrate alluvium or basalt basement beneath the Kailua coastal plain, suggesting a long and complex carbonate sedimentation history.

Using core logs and interpretations illustrated in Figure 4, an estimated 10,049 (± 1,809) × 10^3 m^3 of marine sediment of Holocene age is stored in the Kailua coastal plain. This volume constitutes 70% of the total stored in both submarine and subaerial reservoirs (14,775 [± 2,244] × 10^3 m^3; Table 8). Just over one-quarter of the total volume is contained in submarine reservoirs, whereas only 7% is in the beach face. Storage of Holocene sediment accounts for 75 (± 23) % of the total volume estimated to have been produced in the last 5,000 years using modern production rates. It is reasonable to suggest the remaining 25% needed to ‘‘balance’’ the long-term budget is sediment lost from the system due to dissolution, abrasion, and transport offshore.

Sediment Loss

Both bedform migration and suspended-sediment transport have been shown to be effective in removing sediment from reef systems, particularly during storm events (Hubbard 1992). In Kailua Bay, the central channel is floored by calcareous sand of medium size formed into large, long-crested ripples with wavelengths of 0.5–1.0 m and heights of 6–12 cm. Richmond et al. (2002) estimated that offshore migration of bedforms at a rate of 0.5 m d^{-1} could remove sediment at a rate of 6.7 × 10^3 kg d^{-1} during sustained trade-wind events. Applying this rate to an estimated 40 days per year of 30 knot winds predicts that ~ 223 m^3 of sediment can be transported offshore annually (using a sediment density of 1,200 kg m^{-3} based on the average of ten bulk sediment samples of known volume).

Suspended-sediment concentrations can provide a basic, order-of-magnitude estimate of annual sediment loss via transport out of the system in suspension (Harney 2000). During moderate trade wind conditions (15–20 kts), the upper 2 m of the water column in the area over the channel (3 × 10^5 m^2) contains ~ 6 × 10^5 L of water carrying an estimated 0.5 mg L^{-1} of sediment in suspension (observed), or a total of 300 × 10^3 kg (~ 250 m^3) of suspended sediment. A total of 1,500 m^3 y^{-1} could be removed from the system if only 10% of suspended material is lost per day during such conditions (~ 60 days per year).

By these estimates, combined bedload and suspended-load transport can remove ~ 1,723 m^3 of sediment from the Kailua system annually, amounting to ~ 8,615 ×10^3 m^3 of sediment over 5,000 years. This volume is ~ 43% of predicted Holocene sediment production, accounting for well over the ‘‘missing’’ 25% (Table 8). Sediment loss due to dissolution (e.g., Walter and Morse 1984) was not assessed but is likely a significant process in carbonate sediment budgets. Although more intensive study is needed to better quantify the modes and rates of sediment transport and dissolution in Kailua, it is reasonable to implicate basic rates of sediment loss to balance the long-term sediment budget.

Implications for Coastal Sedimentation

In Hawaii and on other oceanic islands lacking a continental sand source, where coastal sediments are largely calcareous, reef productivity is the principal control on sediment supply. Analysis of carbonate sediment supply is thus valuable in assessing the depositional history of an area, in predicting the response of a coastline to changes in sea level, in accounting for sand volume in coastal deposits, and in understanding shoreface evolution. Sediment budgets derived from quantitative observations in reef systems can provide a better understanding of carbonate dynamics, reef ecology and development, benthic diversity, and coastal processes and can offer practical opportunities to improve coastal- and resource-management practices. The methodology involved in estimating annual sediment production in various reef settings can be applied to other coastal and reef systems in Hawaii and other oceanic islands (e.g., employing and testing setting-specific rates in Table 7).

If the total volume of sediment produced annually in Kailua Bay (4,048 [± 635] m^3) (Table 4) were deposited in sand bodies and channels in the reef (an area of ~ 2,050 × 10^3 m^2), sediment accumulation would occur at a rate of ~ 1.9 mm y^{-1}, exceeding the 0.6 mm y^{-1} rate of predicted reef accretion and eventually burying the reef in its own sediment. Deep, unfilled reef channels and long sediment residence times (Harney et al. 2000) suggest that long-term sediment accumulation has been accommodated by the reef channels, not necessarily requiring mass removal by storms as implicated in other studies (e.g., Hubbard et al. 1990). This accommodation enables sediment to be stored within the littoral system and remain available to replenish seasonal or storm-related erosion. In fact, Kailua Beach is one of the few sites on Oahu experiencing net long-term beach accretion (Norcross et al. 2002). This study supports the link between the long-term accretion of Kailua Beach and the sand storage capacity of its offshore reef, suggesting that perturbation (e.g., in the form of mining sediments stored in reefs) may have long-term effects on even relatively stable systems. A significant difference exists between the rates of shoreline change and sediment supply. The net rate of seasonal shoreline change along Kailua Beach is 43 m^3 per meter of beach length, which is equal to an annual flux of 172,000 m^3 of sand along the 4,000 m beach (Norcross et al. 2002). Total annual sediment production over the entire reef complex is only 4,048 m^3 y^{-1}, corresponding to a rate of ~ 1 m^3 per m of beach length. This indicates the rate of ‘‘new’’ sediment supplied to the beach occurs 40 times more slowly than the rate of seasonal shoreline change (which does not include severe storms and erosion events) and suggests that the rate at which a reef supplies sediment is insufficient to restore a degraded system on time scales of human need. This has implications for coastal erosion measures and beach sand mining issues, particularly along Hawaiian coasts troubled by chronic shoreline retreat and beach loss.

CONCLUSIONS

This biogeological model of sediment production in various settings of a windward Hawaiian reef quantifies the modern processes of gross carbonate framework construction (by corals and encrusting coralline algae), its subsequent erosion into loose sediment by biological and mechanical means, and the direct sediment production by reef-dwelling organisms. Quantitative results of the sediment budget include:

Carbonate sediments are produced at a volumetric rate of 4,048 (± 635) m^3 y^{-1} in the Kailua Bay complex. Bioerosion of the reef framework at rates of 0.10–1.15 kg m^{-2} y^{-1} accounts for 1,911 (± 436) m^3 y^{-1} (including an ~ 557 m^3 contribution from grazing echinoids). The calcifying activities of direct sediment producers account for 1,822 (± 200) m^3 y^{-1}

of the total sediment produced annually. Of this direct sediment volume, the green alga *Halimeda* contributes 769 (± 46) m^3 y^{-1}, the branching coralline alga *Porolithon gardineri* contributes 283 (± 46) m^3 y^{-1}, benthic forams contribute 344 (± 69) m^3 y^{-1}, and molluscs contribute 426 (± 39) m^3 y^{-1}.

Gross framework production in Kailua Bay averages 1.22 (± 0.36) kg m^{-2} y^{-1}, of which coral contributes 58% and encrusting coralline algae 42%. Sediment is produced at an average rate of 0.53 (± 0.19) kg m^{-2} y^{-1} over the Kailua reef complex, with 0.33 (± 0.13) kg m^{-2} y^{-1} contributed through bioerosion of the coralgal framework and 0.20 (± 0.06) kg m^{-2} y^{-1} by direct sediment production.

Extrapolating modern rates of carbonate sediment production over the 5,000 years that Kailua Bay has been completely inundated by postglacial sea-level rise predicts that 20.2 (± 3.2) $\times 10^6$ m^3 of unconsolidated calcareous sediment may have been produced in the system since the mid-Holocene. Of this, 75% (± 23%) remain stored in the bay and coastal plain.

Modern sediment accumulation in channels and sand bodies in the reef occurs at a rate of ~ 1.9 mm y^{-1} and enables sediment to be stored within the littoral system over long time scales, remaining available to replenish the seasonally eroded beach. On annual time scales, ''new'' sediment is supplied to the beachface at a rate of ~ 1 m^3 of sediment per meter of beach length each year, which is only 2% of the rate of seasonal shoreline change.

Average sediment production of corals, coralline algae, and direct producers in five general settings of this windward Hawaiian reef can be employed and tested in other reef systems to improve understanding of carbonate dynamics in various settings.

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The data described in this paper have been archived, and are available in digital form, at the World Data Center for Marine Geology and Geophysics, NOAA/NGDC, 325 Broadway, Boulder, CO 80303; phone 303-497-6339; fax 303-497-6513; email wdcmgg@ngdc.noaa.gov; URL http://www.ngdc.noaa.gov/mgg/sepm/archive/index.html.

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