HOLOCENE REEF DEVELOPMENT WHERE WAVE ENERGY REDUCES ACCOMMODATON SPACE, KAILUA BAY, WINDWARD OAHU, HAWAII, U.S.A.

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ABSTRACT: **Analyses of 32 drill cores obtained from the windward reef of Kailua Bay, Oahu, Hawaii, indicate that high wave energy significantly reduced accommodation space for reef development in the Holocene and produced variable architecture because of the combined influence of sea-level history and wave exposure over a complex antecedent topography. A paleostream valley within the late Pleistocene insular limestone shelf provided accommodation space for more than 11 m of vertical accretion since sea level flooded the bay 8000 yr BP. Virtually no net accretion (< 1 m) took place on surrounding Pleistocene substrates shallower than 10 m. Holocene reef accretion occurred in three stages: (1) an early stage of catch-up framestone development in water depths of 11–17 m, (2) an intermediate stage characterized by either no accretion or by the *pile-up* of fore-reef-derived rubble (rudstone) and sparse bindstone, and (3) a final stage of *catch-up* bindstone accretion in depths > 6 m. Coral framestone accreted at rates of 2.5–6.0 mm/yr in water depths > 11 m during the early Holocene; it abruptly terminated at ~ 4500 yr BP because of wave scour as sea level stabilized. More than 4 m of rudstone derived from the upper fore reef accreted at depths of 6 to 13 m below sea level between 4000 and 1500 yr BP coincident with late Holocene relative sea-level fall. Variations in the thickness, composition, and age of these reef facies across spatial scales of 10–1000 m within Kailua Bay illustrate the importance of antecedent topography and wave-related stress in reducing accommodation space for reef development set by sea level. Although accommodation space of 6 to 17 m has existed through most of the Holocene, the Kailua reef has been unable to catch up to sea level because of persistent high wave stress.**

INTRODUCTION

The internal structure, composition, and geochronology of shallow carbonate reefs provides important information for understanding the natural variability and controls on reef development and their relationship to sea-level and climate variability (Fairbanks 1989; Bard et al. 1996; Cabioch et al. 1999). Investigations of Holocene reef development in particular have been instrumental in identifying detailed histories and patterns of reef development (Macintyre and Glynn 1976; Adey 1978; Macintyre et al. 1992) and changes in reef health (Aronson and Precht 1997) with which to assess modern and future change to reef systems. Fundamental to these analyses is an understanding of reef response to accommodation space, which may vary greatly in time and space because of site-specific variations in relative sea level, antecedent topography, tectonics, sedimentation, wave energy, and cor-algal growth potential (Darwin 1842; Daly 1915; Lowenstam 1957, Purdy 1974; Hubbard 1997). It is often assumed that reefs can fill the accommodation space set by sea level, but in settings of high wave energy, accommodation space may be significantly reduced by wave scour and wave-related stress.

Of particular interest to this paper are (1) the response and resulting architecture of Holocene reef accretion to moderately high wave exposure, (2) improving our understanding of the spatial and temporal variability of reef development, and (3) the role of rubble in reef framework construction. Although much has been learned of recent reef evolution with the advent of portable drill systems (Macintyre 1975), the only study of Holocene reef accretion in Hawaii prior to this work was obtained from the low-wave-energy environment of Hanauma Bay, Oahu (Easton and Olson 1976). Important models of Holocene reef development have been derived for the Atlantic–Caribbean (Adey and Burke 1976; Macintyre and Glynn 1976; Macintyre et al. 1992; Hubbard et al. 1986), South Pacific (Montaggioni et al. 1997), Great Barrier Reef (Davies and Hopley 1983), and Red Sea (Dullo and Montaggioni 1998), but the majority of these were derived from cores penetrating reef flats and/or algal ridges, leaving a void in our knowledge of the three-dimensional complexity of reef development through time. It has been proposed that extensive amounts of rubble can be incorporated into reef framework by catastrophic events (Blanchon et al. 1997), however, little is known of the constant influence of high ambient annual wave energy, because relatively few high-energy reefs have been studied in detail.

Windward-facing Kailua Bay, Oahu, is a unique setting to examine the relative roles of sea-level history, wave energy, and antecedent topography on Holocene reef development, because its size, orientation, and morphologic complexity are influenced by dynamic wave interactions with the substrate. Kailua also provides a location to compare reef architecture with that associated with wave-protected embayments like Hanauma Bay (Easton and Olson 1976). The insular shelves of the main Hawaiian Islands are characterized by complex and distinct tectonic histories, substrates, wave and/or circulation regimes, and earth-surface processes, suggesting that a wide range of reef development histories and architecture is likely and not necessarily represented by the Hanauma reef model. This paper explores the Holocene development of the windward Kailua reef to test the hypothesis that reef structure and accretion within Kailua Bay and around the island of Oahu record differences in accommodation space due to exposure to open-ocean swell and complex antecedent topography. The results show that accommodation space for reef growth in the Holocene has been significantly reduced across multiple spatial (10–1000 m) and temporal (seasons to millennia) scales by high wave-related stress, highlighting the need for more comprehensive models of reef development.

PREVIOUS WORK IN HAWAII

Prior to this investigation, the only detailed Holocene reef-accretion history from Hawaii was obtained from wave-protected Hanauma Bay, which is perched in a shallow (< 15 m water depth) volcanic crater on the southeast coast of the island of Oahu (Easton and Olson 1976). This earlier record is an important archive of the timing of reef development since 7000 yr BP in a wave-sheltered setting. However, most Hawaiian reefs are exposed to significantly greater wave energy, thus the Hanauma record may not be representative of Hawaiian reefs. In addition, low core recovery (16–38%; average = 26%) and limited documentation of faunal composition in the Hanauma reef study have led to questionable conclusions regarding the relationship of the Hanauma reef to sea-level position (Montaggioni 1988; Grossman and Fletcher 1998).

In an attempt to test the role of high wave energy on long-term reef accretion, Grigg (1998) surveyed reefs in four settings of different wave exposure and proposed that Holocene reefs on Oahu are largely thin ve-

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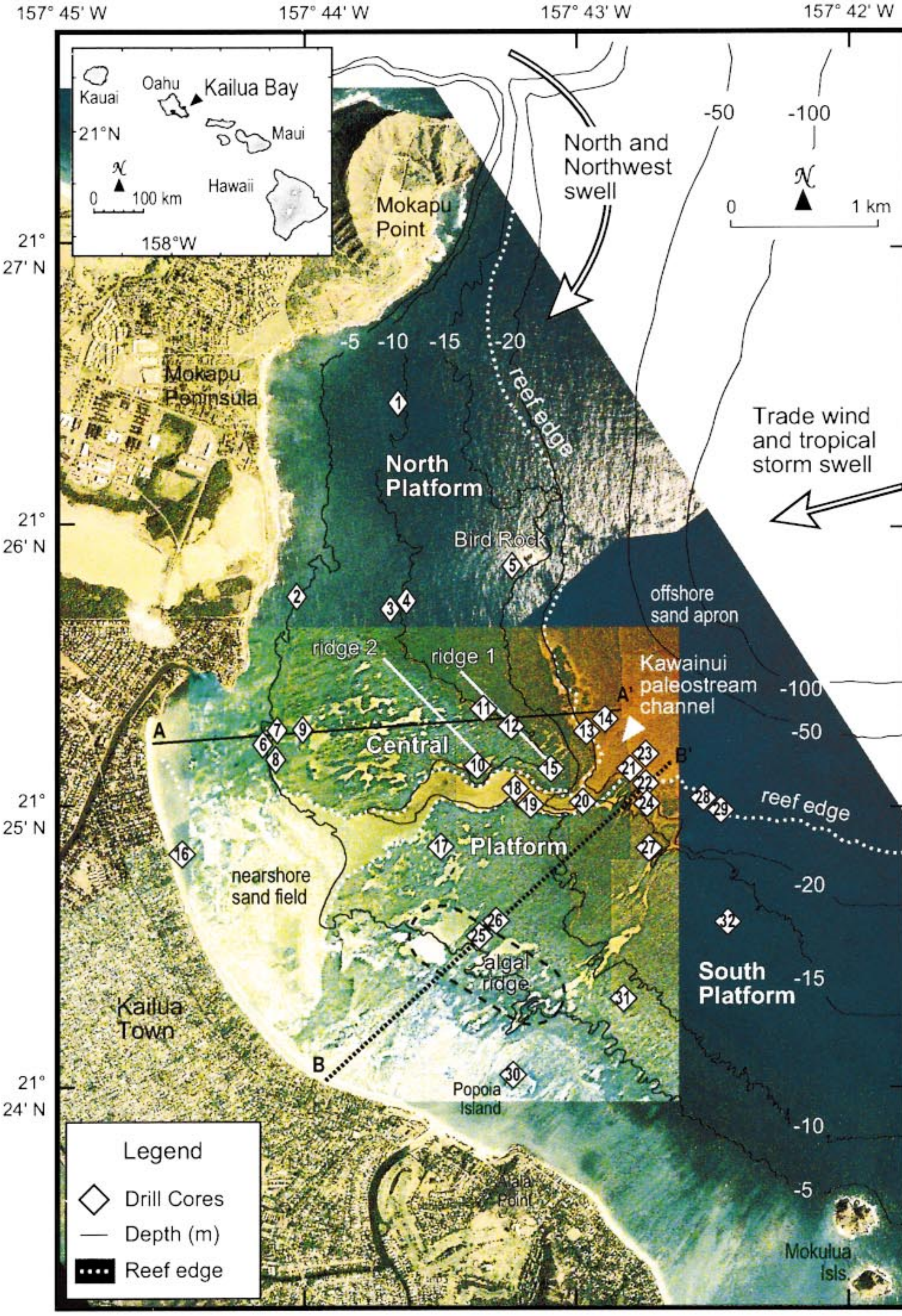
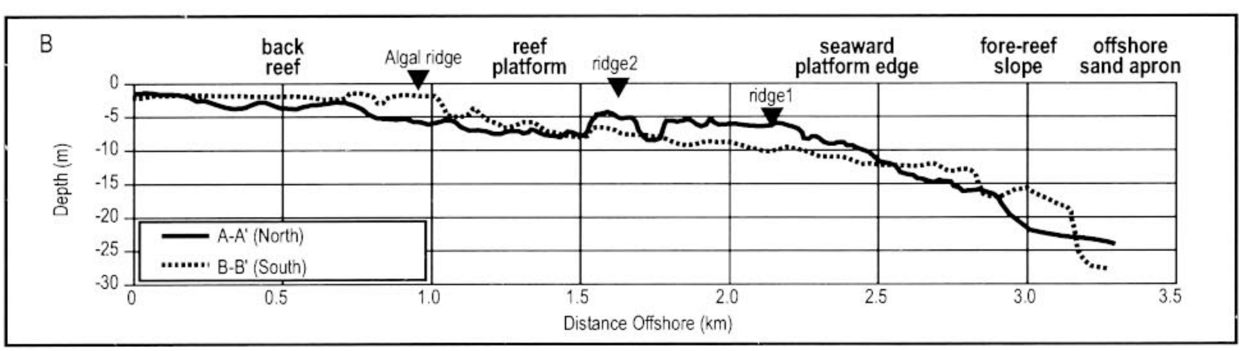


Drill-Hole Data

Site	Depth (m)	Length (m)	Recovery (%)
1	-9.1	0.70	(100)
2	-7.9	0.76	(72)
3	-9.8	1.60	(70)
4	-9.8	1.10	(79)
5	-9.8	0.40	(100)
6	-2.7	0.58	(100)
7	-2.7	0.74	(100)
8	-2.7	0.94	(100)
9	-4.0	0.76	(100)
10	-8.5	5.10	(71)
11	-9.8	1.22	(99)
12	-9.1	1.71	(77)
13	-18.9	1.00	(45)
14	-19.8	1.00	(20)
15	-9.8	3.24	(83)
16	-3.0	0.30	(100)
17	-6.1	1.47	(46)
18	-8.2	1.27	(80)
19	-9.1	0.66	(98)
20	-9.8	3.40	(90)
21	-13.1	10.82	(86)
22	-18.3	1.30	(35)
23	-12.5	0.95	(59)
24	-16.2	1.91	(60)
25	-3.8	1.30	(53)
26	-4.6	1.30	(55)
27	-10.4	1.70	(62)
28	-18.6	1.80	(97)
29	-16.8	0.25	(80)
30	1.8	18.04	(42)
31	-7.3	1.05	(83)
32	-12.8	1.25	(84)
Average recovery			(76)
Holocene recovery			(68)



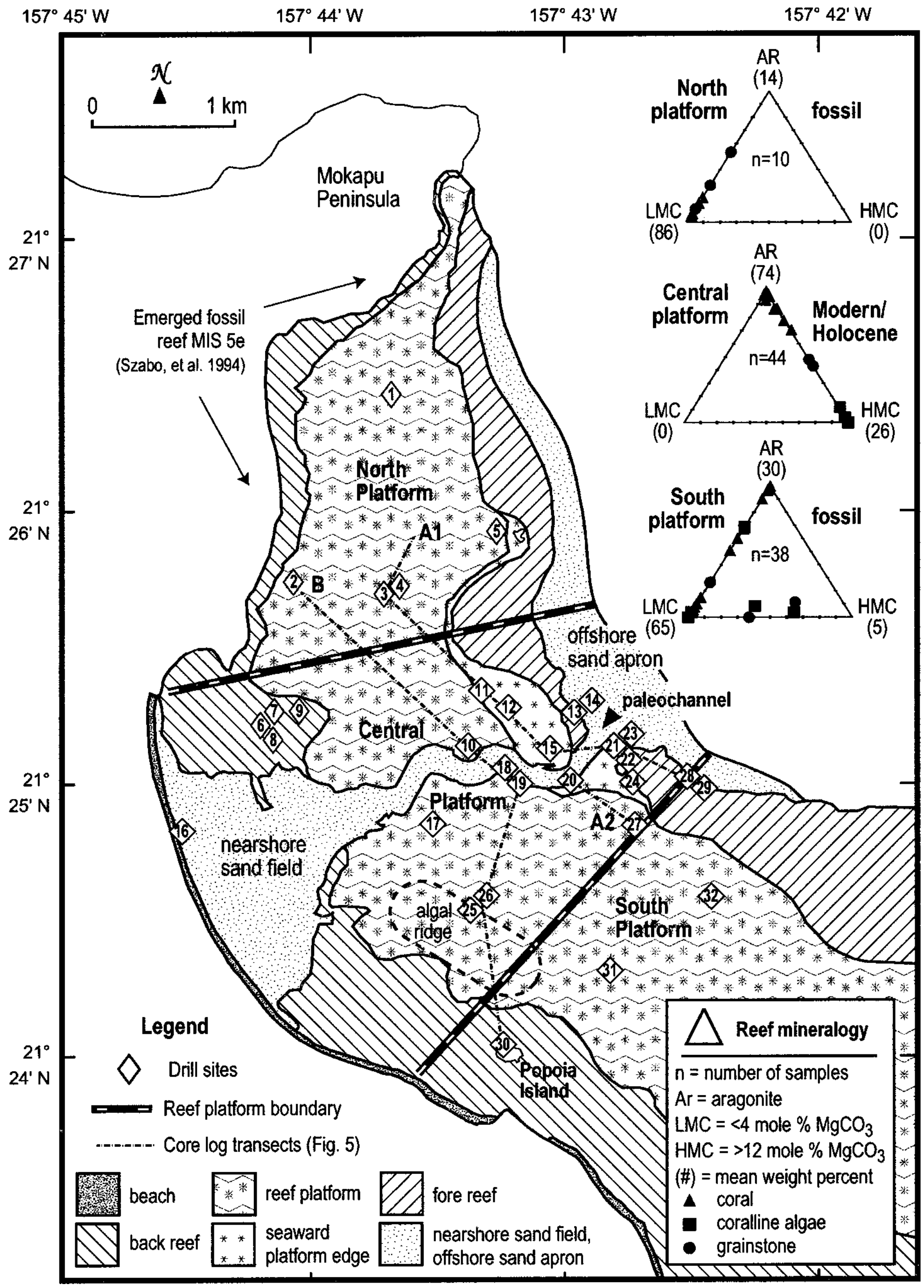


FIG. 2.—Depositional environments of Kailua reef based on substrate mapping (Grossman 2000) and drill cores (this study), and location of core log transects in Figure 5. Mineralogical analyses (XRD) of surface samples ($<$ 1 m depth) of coral (triangles), coralline algae (squares), and grainstones (circles) show pristine aragonite and Mg-calcite composition (14–17 mole % $MgCO_3$) of central reef in contrast to stabilized calcite mineralogy of fossil north and south platforms ($<$ 4 mole % $MgCO_3$).

neers and that the only appreciable reef development occurred in settings sheltered from long-period open-ocean swell. Sherman et al. (1999) found little Holocene reef accretion on Oahu's northwest and northeast coasts and determined that the bulk of the submerged carbonate terrace of Oahu between 0 and -20 m was formed during Marine Oxygen Isotope Stage (MIS) 7 ($\sim$ 210,000 yr BP). By examining reef accretion in Kailua Bay, we hoped to provide insight into reef development along a gradient in wave exposure between north coasts that directly face large annual swell and are void of Holocene reefs, and protected settings like Hanauma and Kaneohe bays where they occur (Easton and Olson 1976; Grigg 1998).

SETTING

The Kailua reef is located within an embayment bounded by the basalt headland of Mokapu Point in the north and the twin Mokulua Islands in the south (Fig. 1), remnants of the Koolau volcanic complex (2.8–3.2 Ma).

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FIG. 1.—**A)** Location map showing drill sites (site depth, core length, and recovery at right) and dominant features of the Kailua reef including: drowned Kawainui paleostream channel in the central reef; north, south, and central platforms; karst topography in back reef; nearshore sand field and offshore sand apron linked by paleostream channel; and annual swell types. **B)** Depth profiles A–A′ and B–B′ show fossil algal ridge on south platform, and two ridges on north reef platform and seaward edge.

TABLE 1.—*^{14}C AMS and ^{230}Th Ages*

Site	Sample #	Description	Depth (m, msl)	Percent Aragonite	Mole% $MgCO_3$	$\delta^{13}C$* (‰)	Conventional ^{14}C Age†	^{14}C Error	Calibrated Age‡	Cal Age 2(σ)	Accretion Rate (mm/yr)
Kailua, Oahu											
K10	NMC1-2-62	coral (PC)	−9.15	>97%	NA	0.390	2030	40	1471	1598–1318	1.10
K10	NMC1-7-265	coral (PC)	−11.18	>97%	NA	0.210	3540	50	3314	3450–3117	2.17
K10	NMC1-10-500	coral (PLM)	−13.53	>97%	NA	−1.880	4390	45	4396	4548–4186	—
K11	LH1-3-94	coral (PLM)	−10.69	93%	13.00	−0.326	2860	30	2467	2657–2328	0.64
K11	LH1-5-144	coral (PLM)	−11.19	100%	NA	−1.729	3500	35	3253	3376–3078	—
K12	E7-1-25	coral (PLE)	−9.39	>97%	NA	−1.550	2290	40	1773	1904–1606	1.04
K12	E7-6-180	coral (PC)	−10.94	>97%	NA	−1.830	3510	40	3262	3393–3084	—
K15	KC1-01-09	coral (MP)	−9.84	100%	NA	0.900	>mod	N/A	0	N/A	0.24
K15	KC1-02-80	coral (PC)	−10.55	>97%	14.86	0.272	3320	35	2992	3193–2840	2.05
K15	KC1-03-120	coral (PC)	−10.95	>97%	11.82	−2.488	3440	55	3187	3341–2967	1.59
K15	KC1-06-272	coral (PC)	−12.47	>97%	16.37	−0.330	4230	45	4142	4351–3961	2.72
K15	KC1-08-347	coral (PC)	−13.22	100%	NA	−1.974	4430	45	4418	4614–4240	—
K18	SMC2-2-55	coral (PC)	−9.69	>97%	NA	−0.980	6270	55	6600	6740–6411	—
K20	SOC1-2-70	coral (PLM)	−10.45	>97%	NA	−1.090	4920	45	5046	5267–4888	4.08
K20	SOC1-7-332	coral (PLM)	−13.15	>97%	NA	−1.520	5470	45	5709	5865–5593	—
K21	NEU3-05-105	coral (PC)	−14.46	100%	NA	−1.543	5030	55	5342**	5360–5324	6.91**
K21	NEU3-12-365	coral (PC)	−17.06	100%	NA	−0.219	5480	65	5718	5892–5583	4.52
K21	NEU3-22-610[a]	coral (PC)	−19.51	>97%	15.31	1.488	5360	95	5593	5860–5386	—
K21	NEU3-26-753	coral (PLM)	−20.94	100%	NA	1.888	6260	85	6577	6786–6347	2.53**
K21	NEU3-30-1080	coral (PLM)	−24.21	96%	16.29	2.261	6640	90	7870**	7932–7808	—
K25	AB2-1-25	cor-alg (PO)	−4.82	100% (mg)	16.00	1.330	4620	45	4693	4829–4508	—
K27	KAE1-1-10	coral (MP)	−10.46	>97%	17.00	1.040	5370	50	5598	5762–5456	1.38
K27	KAE1-3-115	coral (PE)	−11.51	100%	NA	−2.320	6070	45	6357	6505–6226	—

^{14}C AMS: a = out of place; PC = *P. compressa,* PLM = *P. lobata* (massive), PLE = *P. lobata* (encrusting), MP = *M. patula,* PE = *P. eydouxi,* PG = *P. gardineri,* PO = *P. onkodes*; (mg) = Mg-calcite; *, $\delta^{13}C$ error = 0.01‰; †, NOSAMS AMS analyses; ‡, $\Delta R = 115 \pm 50$ yr for marine samples from Hawaiian waters; **, Based on ^{230}Th age.

SAMPLE	^{238}U	^{232}Th (ppt)	$\delta^{234}U$ (measured)	$^{230}Th/^{238}U$ (activity)	^{230}Th Age (corrected)	$\delta\ ^{234}U_i$ (corrected)
NEU3-05-105	3158 ± 4	802 ± 9	144.4 ± 1.2	0.05476 ± 0.00016	5342 ± 18	146.5 ± 1.2
NEU3-30-1080	3555 ± 4	15538 ± 83	145.8 ± 0.8	0.08087 ± 0.00026	7870 ± 62	149.1 ± 1.0

^{230}Th ages determined following Edwards et al. 1987 ($\lambda_{230} = 9.1577 \times 10^{-6}$ y^{-1}, $\lambda_{234} = 2.8263 \times 10^{-6}$ y^{-1}, $\lambda_{238} = 1.55125 \times 10^{-10}$ y^{-1}. $\delta^{234}U = ([^{234}U/^{238}U]_{activity} - 1) \times 1000$. ** $\delta^{234}U_{initial}$ was calculated based on ^{230}Th age (T), i.e., $\delta^{234}U_{initial} = \delta^{234}U_{measured} \times e^{\lambda_{234} \times T}$. Corrected ^{230}Th ages assume the initial $^{230}Th/^{232}Th$ atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$. Those are the values for a material at secular equilibrium, with a crustal $^{232}Th/^{238}U$ value of 3.8. The errors are arbitrarily assumed to be 50%).

These promontories are overlain by emergent reef facies of MIS 5e age that give an average uplift rate of ~ 0.05 mm/yr for Oahu during the late Quaternary (Szabo et al. 1994). The Kailua reef is exposed annually to moderately high (2–5 m) waves originating from long-period (14–20 s) north and northwest Pacific swell, trade-wind swell 70% of the year (1–3 m height, 5–8 s period), and occasional short-lived (< 2 weeks) high trade wind wave events (3–4 m height, 5–10 s). Episodically, east and southeast swell from tropical storms generate breaking wave heights of 2–5 m (12–15 s period). Relative to other Hawaiian coasts, Kailua is considered one of moderate wave exposure, but compared to many Caribbean and Indo-west Pacific regions it would rank as a high-energy coast. This is a microtidal region with an annual tidal range of 0.8 m. Sea surface temperatures range from 24° C in winter to 27° C in summer. Salinity is typical of open-ocean values (34.5–35‰; Juvik and Juvik 1998).

Depositional Environments and Reef Morphology

Detailed mapping of the substrate shows that the Kailua fringing reef covers 12 km^2 and consists of five primary depositional environments: back reef and nearshore sand field, reef platform, seaward platform edge (the slope break), fore reef, and offshore sand apron (Fig. 2). The north platform is 1.5 km wide and characterized by low relief (1–2 m high; 2–3 m wide) spurs with wide (20–50 m) grooves. This contrasts with the south platform, which is much wider (~ 2.5 km) and dominated by narrower spurs (0.5–1 m high; 1–2 m wide) and grooves (10 m wide) that grade northward into a broad smooth terrace. The hummocky central platform is composed of large spurs (3–5 m tall and wide) and moderately wide (3–7 m) grooves and numerous karst depressions in the back reef. Terraces occur at −8, −11, and −15 m in the central seaward platform, whereas the north and south platforms slope steadily to the seaward reef edge, where a distinct slope break above the fore reef is deeper in the south than in the north (Fig. 1B). Apart from a small algal ridge northwest of Popoia Island, the Kailua reef lacks a typical reef crest separating a shallow reef flat from the fore reef, common to most Pacific and Caribbean reefs. A channel that meanders across the central reef is the drowned incision of the Kawainui paleostream. Its walls range 3–15 m in height, and more than 12.5 m of unconsolidated sands cover the antecedent basement near its seaward terminus (Ericksen et al. 1997). The channel connects the nearshore sand field to a broad offshore sand apron at −30 to −45 m depth.

Modern Cor-Algal Reef Zonation

Nearshore hardgrounds of the back reef (0–3 m) are dominated by relict surfaces with sparse (<5–10%) cover consisting of encrusting, massive *Porites lobata,* and/or stout branching *Pocillopora meandrina* and moderate (~ 35–50%) coralline algae cover (*Porolithon onkodes, P. gardineri).* The reef platforms (3–10 m) are dominated (50–70%) by wave and sediment-tolerant encrusting *Montipora patula, M. capitata, P. lobata,* and *P. onkodes.* The highest diversity (six species) occurs in the central seaward reef edge (10–14 m), where extensive coral cover (> 90%) composed of massive and encrusting *P. lobata, M. patula,* and *M. capitata,* bladed *P. duerdeni,* and small colonies of *P. compressa* is maintained by intermediate levels of disturbance. Along the upper fore reef and channel walls (14–17 m), platy forms of *P. lobata, M. patula,* and *M. capitata* dominate. Across the central fore reef (> 15 m), *P. compressa* dominates in monospecific communities, whereas to the north and south the fore reef is devoid of live coral. Grossman (2000) proposes that wave energy is the primary control on modern coral cover diversity and community structure in Kailua Bay.

The upper depth limit (~ 14 m) of branching *Porites compressa* is similar to that for other open-ocean coasts (Maragos 1977, 1995; Dollar 1982) and is consistent with a threshold in shear stress (~ 275 Nm^2) that occurs in Kailua under mean high annual wave scour (Grossman 2000). Similar values of shear resulting in coral colony breakage have been observed among other branching coral species (Kjerfer et al. 1986). The upper

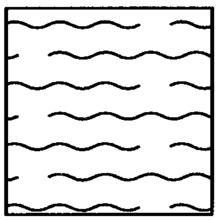
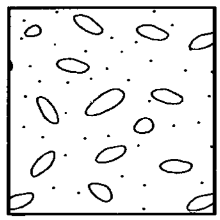
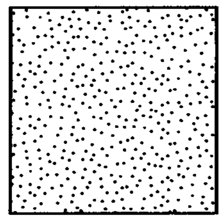
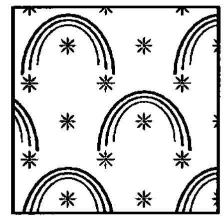
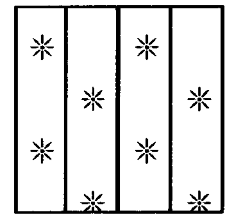
Bindstone	Rudstone	Grainstone	Massive coral Framestone	Branching coral Framestone
				
Composition: *In situ* encrusting forms of *Porolithon onkodes, Montipora patula, Porites lobata, M. capitata,* with algal rhodoliths, grainstone, and rudstone. Encrusting foraminifer *Homotrema,* vermetid gastropods, boring molluscs *Lithophaga* common; serpulids present. **Environment:** Indicative of high wave energy, scour, abrasion in agitated reef platforms, and back reef. **Occurrence:** Upper 10-25 cm of all cores, except isolated massive head corals.	**Composition:** Unsorted, subrounded clasts (0.5-3 cm) of delicate branching *Porites compressa* encrusted by coralline algae; *Pocillopora meandrina* and *P. eydouxi* present. Coarse skeletal remains of coral, *Halimeda,* coralline algae, echinoderms, and foraminifera common. Burrows and encrustations by foraminifera and bryozoans present in upper sections. **Environment:** Moderately high energy, active circulation and lithification by coralline algae. Present in agitated reef-flat platforms. **Occurrence:** Upper sections of central reef platform.	**Composition:** Moderately to well-sorted medium to coarse, rounded skeletal fragments of coralline algae, coral, and molluscs lithified by isopachous Mg-calcite cements. Skeletal grains of *Halimeda* are present but uncommon and are typically fine to medium in size. **Environment:** Moderate energy beach or nearshore environment, found in the form of beachrock indicating fossil shoreline or infilling reef cavities. **Occurrence:** Cores from central north platform, outcrops of fossil shorelines, beachrock.	**Composition:** Dominated by *in situ* massive *Porites lobata; encrusting P. lobata, M. capitata, P. onkodes* rare. Sponge microborings in cavities, borings by *Lithophaga,* serpulids common. Encrustations of foraminifer *Homotrema* and vermetid gastropods are present. **Environment:** Moderate to low wave energy, at depths of 10-14 m of seaward reef edge or in isolated patches of back reef. **Occurrence:** Base of cores from central reef platform and as isolated head corals near seaward reef edge.	**Composition:** *In situ* colonies of delicate branching *P. compressa* with isolated thick and massive or laminar, occasionally knobby crusts of Mg-calcite cement and internal sediment (coral, branching coralline algae, *Halimeda,* echinoderms, and micromolluscs) **Environment:** Calm or deep fore-reef settings. **Occurrence:** Lower to middle sections of cores from the central and seaward platform edge.

FIG. 3.—Biolithofacies common of the Holocene reef of Kailua, Oahu, Hawaii.

limit of massive *Porites lobata* along the seaward reef platforms in Kailua ranges from 7 to 8 m, and it dominates at 11–14 m where shear can be higher. Coral colony ages in the different reef sub-communities of Kailua range from 20 to 100 years. This contrasts with most wave-exposed coasts on Oahu, where entire reef communities were decimated by Hurricanes Iwa (1982) and Iniki (1992; Grigg 1995). The higher coral cover and older colony ages in Kailua indicate that the modern cor-algal community in Kailua has adapted to withstand episodic storms or has been largely shaped by annual processes. The modern community zonation is consistent with stresses related to mean annual high wave exposure.

METHODS

Thirty-two drill cores (6 cm diameter) were collected in water depths ranging from +2 to −18 m using a submersible wireline (NQ2) drill system (Fig. 1). Penetration ranged from 0.3 to 18 m, and sample recovery was 35–100% with an average of 68% in the Holocene reef. Sample depths were determined by measuring hole depth and sample recovery after each core interval with a 3 cm division survey rod. The presence of subsurface cavities and changes in lithology, reflected by noticeable changes in penetration rate and cutting sound, were recorded during drilling. The accuracy of sample depths ranges from 0.03 to 0.1 m within individual cores but is reduced to 0.5–1.0 m between different core sites because of uncertainties associated with tides and wind and wave set-up. These uncertainties are included in all analyses reported. Cores were cut lengthwise and photographed, and descriptions of lithology, coral and coralline algae species composition, bioerosion, and cementation were logged using macroscopic and microscopic petrologic techniques.

Geochemical and radiometric analyses were conducted on samples after removal of secondary contaminants (e.g., encrustation, sediment infill, cement precipitation) under a binocular microscope and cleansing in an ultrasonic bath of 20% laboratory-grade H_2O_2 until the supernate was clear and oxidation ceased. Sample mineralogy was determined in duplicate (selected samples in triplicate) using a Scintag Pad V powder X-ray diffractometer (XRD) and a 10% by weight CaF_2 standard. Determinations of percent aragonite and calcite by weight were made from peak area curves of aragonite (peak 111) and calcite (peak 104) after Sabine (1992). The mole percent of $MgCO_3$ in calcite phases was calculated from the *d*-spacing offset of the calcite peak owing to incorporation of Mg following Bischoff et al. (1983). Between-sample variation in $MgCO_3$ was < 0.8 mole % (avg = 0.15 mole %), and reported values are therefore averages of replicates.

Radiometric ages (Table 1) were obtained by ^{14}C AMS and TIMS Th/U analyses on replicate samples screened by XRD to have > 97.5% primary aragonite (corals) or high-Mg calcite (coralline algae), unless otherwise noted. All ^{14}C ages were corrected for isotopic fractionation using $\delta^{13}C$ (± 0.01‰) and calibrated to calendar years using the 1998 INTCAL Calibration data set (Stuiver et al. 1998) and Calib 4.12 (Stuiver and Reimer 1993). A regional marine reservoir correction (ΔR) of 115 ± 50 years for marine samples from Hawaiian waters was applied in the calibration (Stuiver and Braziunas 1993). TIMS ^{230}Th ages followed the protocol of Edwards et al. (1987). Accretion rates were calculated between dated samples and core tops and represent the average accretion history between samples. Growth rates of individual coral colonies were determined by counting annual bands produced by skeletal density variations imaged by X-rays of 1-cm thick core slabs following Buddemeier et al. (1974).

RESULTS

Internal Reef Structure

Biolithofacies.—Five biolithofacies were identified within the Holocene reef on the basis of their combined bioclast composition and lithology (after Embry and Klovan 1971; Longman 1981). In order of decreasing depositional energy they are bindstone, rudstone, grainstone, massive coral framestone, and branching coral framestone facies (Figs. 3, 4). The dominant facies found in the Holocene reef are the rudstone, massive coral framestone, and branching coral framestone facies. The rudstone facies constitutes more than 4 m of the upper sections of the reef platforms. It is composed of marine cemented, subrounded and algal-coated cobble-size fragments of the delicate branching coral *Porites compressa,* found growing today only in deeper settings of the fore reef below 14 m (Grigg 1983). The rudstone represents principally fore-reef-derived rubble (some perhaps derived locally) that was transported onto the reef platforms, where it became subsequently lithified and/or bound by coralline algae. The massive and branching coral framestone facies constitute the bulk of the foundation of the Holocene reef. The massive coral framestone facies is dominated by massive colonies of *P. lobata* that can sustain moderate to high frictional and sedimentation stress common in intermediate depths (−7 to −14 m, Grossman 2000). The branching coral framestone facies is composed exclusively of the delicate and fast-growing *P. compressa*, which is the competitively superior coral species in Hawaii, and generally restricted to deeper fore-reef settings below −14 m (Grigg 1983).

Mineralogy.—Corals from the Holocene reef are almost entirely aragonite, and coralline algae exhibit a normal range of 15–19 mole % $MgCO_3$ (Fig. 2). Occasionally, interskeletal coral cavities are encrusted by coralline algae or partly infilled with Mg-calcite microcrystalline cements. Bulk mineralogy of Holocene grainstones reflect the wide range of mineralogies (50–60% aragonite and 40–50% Mg-calcite) of extant coralline algae, *Halimeda,* coral, molluscs, and foraminifera that contribute the bulk of carbonate sands within the Kailua littoral system (Harney et al. 2000). The near pristine mineralogy of the Holocene reef differs significantly from the stabilized (calcite) mineralogy of the late Pleistocene reef found in cores from the central reef and outcropping at the surface on the north and south reef platforms (Fig. 2). The late Pleistocene fossil reef is characterized by wholesale dissolution of aragonite, extensive vuggy porosity, and the subsequent infilling of interskeletal and intraskeletal cavities by sparry and drusy calcite (Fig. 2), indicative of diagenesis in the vadose and meteoric phreatic zones.

Cementation.—Cementation of the Holocene reef is dominated by massive peloidal micrite, grain coatings, and void-lining cements composed of Mg-calcite. Aragonite cement is rare and restricted to overgrowths and interskeletal coral cavities, where it occurs as thin acicular fibrous needles (Fig. 4F). The most abundant cements in the Holocene reef are massive peloidal micrite, knobby club-shaped micrite, and laminar crusts (Fig. 4G)

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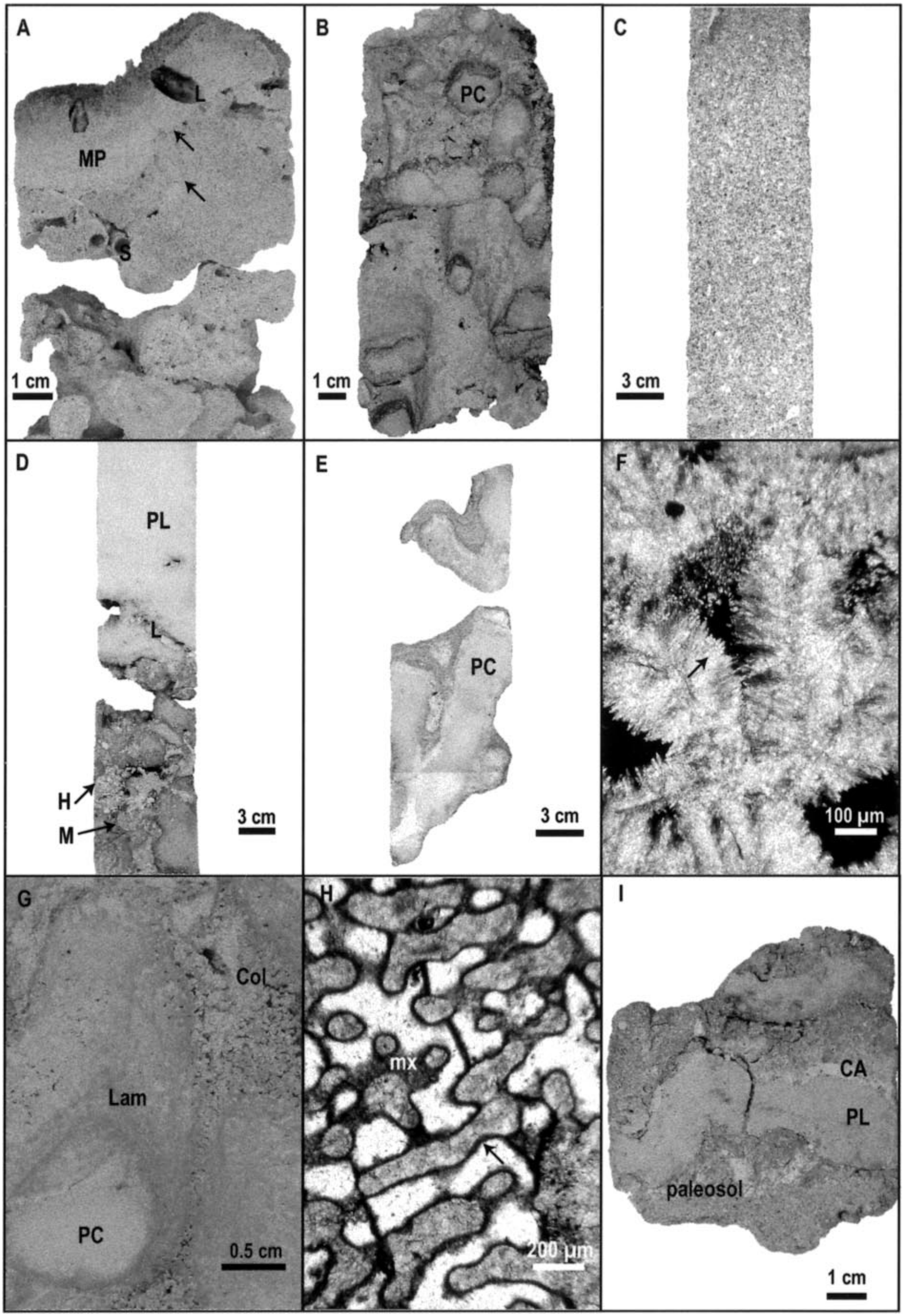
FIG. 4.—Holocene biolithofacies. **A)** Bindstone overlying rudstone. Bindstone characterized by borings of *Lithophaga* (L) and serpulids (S) near surface. *Montipora patula* (MP) shows growth hiatuses (arrows) and recolonization (K21, Modern); **B)** Rudstone dominated by clasts of *Porites compressa* (PC) and massive peloidal micrite crusts (K15, 2992 yr BP); **C)** Grainstone (K8); **D)** Massive coral framestone comprised of *Porites lobata* (PL) with borings of *Lithophaga* (L) overlying rudstone with coarse skeletal debris of *Halimeda* (H) and molluscs (M) (K18, 6600 yr BP); **E)** Branching coral framestone comprised of delicate-branching *Porites compressa* with fine laminar micrite (K15, 4142 yr BP); **F)** Fibrous aragonite needle cements (arrow) are rare in the Holocene reef and are observed only in interskeletal cavities of corals (K15, polarized light, 3187 yr BP); **G)** Massive crust of micrite showing laminae (Lam) above *Porites compressa* (PC) branch and knobby columns (Col) above (K21, ~ 6000 yr BP); **H)** Mg-calcite linings and rim cements (arrow) and microcrystalline Mg-calcite (mx) are common but not as abundant as peloidal micrite cements in the Holocene reef (K21, plain light, 6577 yr BP). **I)** Encrusting to lobate *Porites lobata* (PL) in growth position encrusted above but not below by coralline algae (CA) on mixed, unconsolidated fluvial–marine sands and caliche (paleosol) crust at base of site K21 (7870 yr BP).


A
L
MP
S
1 cm
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C
3 cm
D
PL
L
H
M
3 cm
E
PC
3 cm
F
100 µm
G
Col
Lam
PC
0.5 cm
H
mx
200 µm
I
CA
PL
paleosol
1 cm

similar to those found elsewhere (Macintyre 1977; Macintyre and Marshall 1988). These cements constitute a major portion of the branching coral framestone facies and help to lithify vast amounts of internal sediment trapped within interskeletal and intraskeletal cavities. Micritic Mg-calcite cement also occurs as thin grain coatings and void linings (Fig. 3H) and as thin isopachous rim cements in all Holocene facies.

Geochronology.—Radiometric ages of *in situ* and reworked fragments of Holocene reef skeletal components range between modern and 7900 yr BP (Table 1). Among the 23 samples dated, only one chronologic inversion was found, despite the analysis of several non-*in situ* rudstone samples investigated to determine the history of rubble deposition and sediment infilling. The inverted sample (NEU-22–610) is likely biased to a younger date by the incorporation of a secondary encruster (coralline algae, foraminifera) or Mg-calcite cement. We have adopted the ^{230}Th age of two samples analyzed by both ^{14}C-AMS and ^{230}Th. The age of sample NEU-05–105 by both methods agree within the 2σ uncertainty range of the ^{14}C age determination. Sample NEU-30-1080 suffers from slight excess Mg-calcite and ^{232}Th. A detrital correction of 120 years for excess ^{230}Th from basalt-derived contamination is consistent with incorporation of terrigenous sediment or paleosol in the coral skeleton (Fig. 4I). Samples identified as pre-Holocene reef limestones, on the basis of mineralogy and petrology (from sites K2 and K30), were analyzed by ^{14}C and TIMS ^{230}Th. They proved to be of late Pleistocene age and are correlated with facies across the reef to constrain the age of the underlying antecedent topography.

DISCUSSION

Spatial Pattern of Holocene Reef Accretion: The Role of Antecedent Low Topography

The Holocene reef is restricted almost exclusively to central Kailua Bay in the immediate vicinity of the drowned Kawainui paleostream channel, where reef facies are more than 11 m thick (Fig. 5). North and south of the channel, the Holocene reef thins to a veneer ($<$ 1 m thick) of modern encrusting coral and/or coralline algae or is entirely absent. Where Holocene deposits are absent, the relict reef surface exhibits up to two generations of meteoric diagenesis and wholesale conversion of primary aragonite and Mg-calcite mineralogy to calcite (Fig. 2). In shallow settings ($<$ 13 m, sites K1, K2, K5, K31, K32), these fossil reef facies are correlated lithologically to MIS 5e dated reef samples in core K30, whereas along the south fore reef ($>$ 15 m, K28, K29) and north platform interior ($>$ 10 m, K3, K4), they are correlated to similar altered reef facies of MIS 7 age in core K30 and neighboring Kaneohe Bay (Sherman et al. 1999). Isolation of the Holocene reef to the central drowned paleostream channel has been corroborated by recently acquired seismic-reflection data (unpublished data).

The Timing of Holocene Reef Accretion in Kailua Bay

Early Holocene (8000 to 6000 yr BP).—Reef accretion in Kailua initiated by ~ 7900 yr BP at −24 m near the present seaward reef edge and mouth of the Kawainui paleostream channel (site K21, Figs. 5, 6). Encrusting and massive forms of *Porites lobata* accreted on unconsolidated sands and a paleosol (Fig. 4I). Vertical accumulation of 3–4 m of encrusting and massive *Porites lobata* intercalated with sand lenses ~ 0.5 to 1 m thick continued at site K21 until ~ 6500 yr BP, then eventually graded into massive *in situ P. lobata* colonies. Branching colonies of *Porites compressa* succeeded massive *P. lobata* growth. If core K21 is representative, then 7.5 m or more of massive framestone facies was added to the reef. Accretion at site K21 abruptly ended at 5300 yr BP. In the south platform interior (site K27), stout-branching corals (*Pocillopora eydouxi*) that were accreting at 6500 yr BP added 1.5 m to the reef frame until ~ 5500 yr BP, when accretion of branching and massive corals largely terminated on the entire south and central platform. Only along the margins of the Kawainui channel (site K18, K20) did massive corals continue to accrete beyond 6000 yr BP; there, vertical accretion terminated about 5000 yr BP.

Middle Holocene (6000–3500 yr BP).—Contemporaneous with *Porites compressa* accretion along the seaward reef edge in central Kailua Bay, massive *P. lobata* contributed more than 3 m of accretion in the central reef interior between 6000 and 5000 yr BP (sites K18, K20, Figs. 5, 6). At 5300 yr BP framestone accretion on the south platform entirely ceased, except along the back reef margin, when ~ 2 m of coralline algal ridge formed at sites K25 and K26 ca. 4700 yr BP. Accretion after 4500 yr BP was confined to the north and central reef platforms.

Two topographic ridges observed today on the north-central platform were constructed since 4500 yr BP. Along the seaward ridge near site K15, 1–2 m of *in situ* colonies of branching *P. compressa* accreted from 4400 to 3200 yr BP and were abruptly replaced by rudstone at ~ 3000 yr BP. Along the landward ridge near site K10, massive *P. lobata* accreted at 4400 yr BP before being buried by 1 m of sand. At site K10, mixed branching *P. compressa* and rudstone continued to accrete until ~ 3300 yr BP.

Late Holocene (3500 yr BP to Present).—Reef accretion in the late Holocene was entirely restricted to the north central reef and was dominated by rudstone accumulation and mixed encrusting cor-algal growth with isolated massive corals. Along the seaward topographic ridge of the north central reef platform (site K12), 2–3 m of rudstone accreted between 3300 and 1800 yr BP (Figs. 5, 6). Rudstone accumulation also characterizes the upper 3–4 m of site K10, which continued to accrete until at least 1500 yr BP. Although coral and coralline algae growth has been prolific (Harney et al. 2000), there has been little preservation of reef framestone since 1500 yr BP, reflecting high sediment production (Harney and Fletcher 2003). A modern thin veneer ($<$ 0.5 m) of encrusting coral and coralline algae has developed on the reef platforms, and a mixed encrusting-massive coral community that sparsely occupies the central reef likely turns over with an ~ 100 yr periodicity (Grossman 2000).

Controls on Holocene Reef Development

Primary Controls: Influence of Antecedent Topography and Wave Energy on Accommodation Space.—The restriction of significant Holocene reef development to the vicinity of the central drowned Kawainui paleostream channel and to depths of −8 to −14 m reflects the importance of antecedent topography and wave energy as primary controls on Holocene reef accretion in Kailua. As postglacial sea level flooded the insular Kailua shelf about 8000 yr BP, framestone accreted exclusively within the low topography provided by the drowned Kawainui stream valley (Fig. 5). Accumulation of more than 11 m of cor-algal reef within the paleostream valley was associated with the greatest accommodation space and the lowest near-bottom, wave-induced currents. While Purdy (1974) elegantly showed that antecedent topography, especially elevated topography, was ideally suited for coral colonization, in Kailua Bay high wave exposure has restricted accretion, and deeper areas have provided refuge sites where wave-initiated destruction was minimized.

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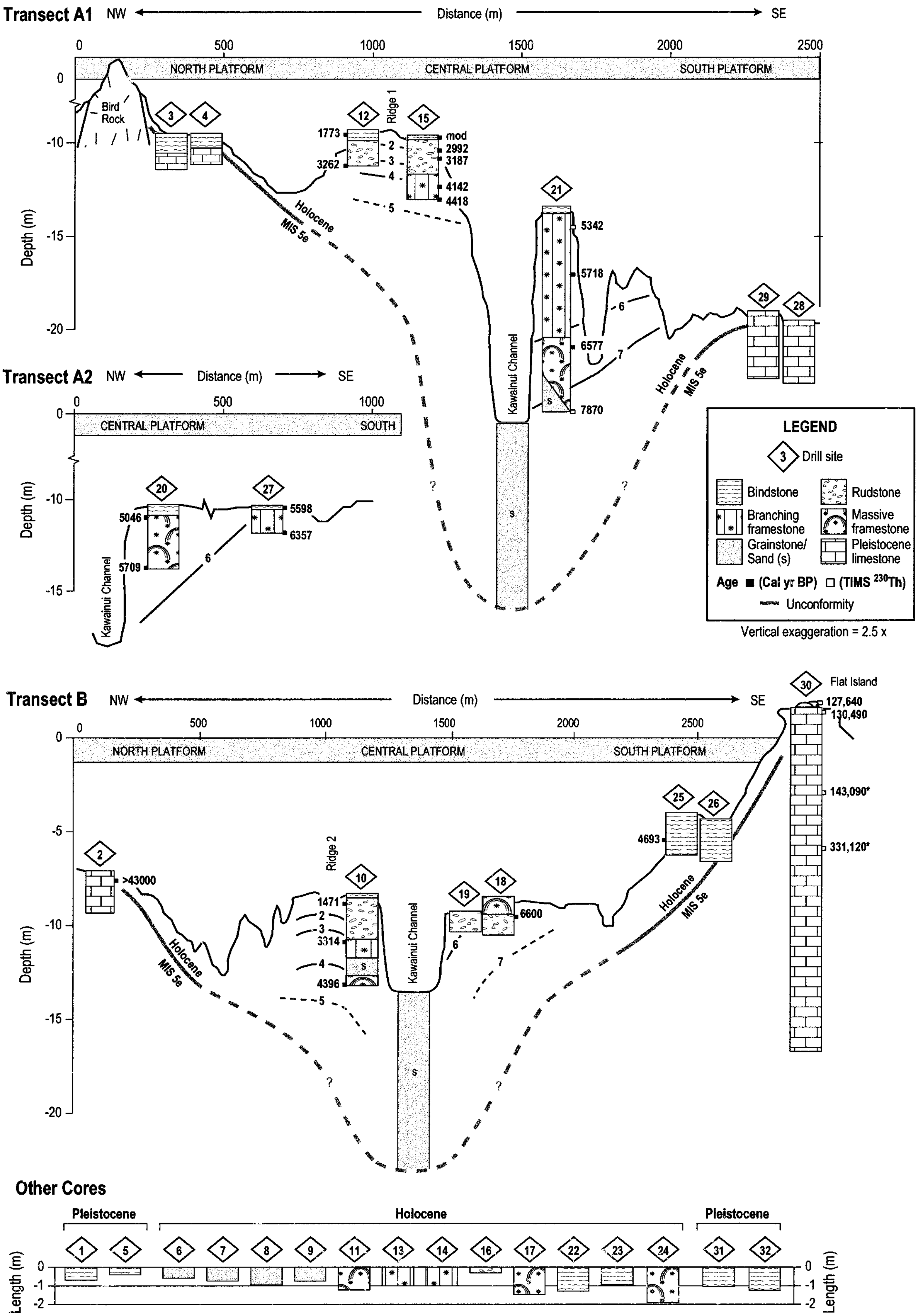
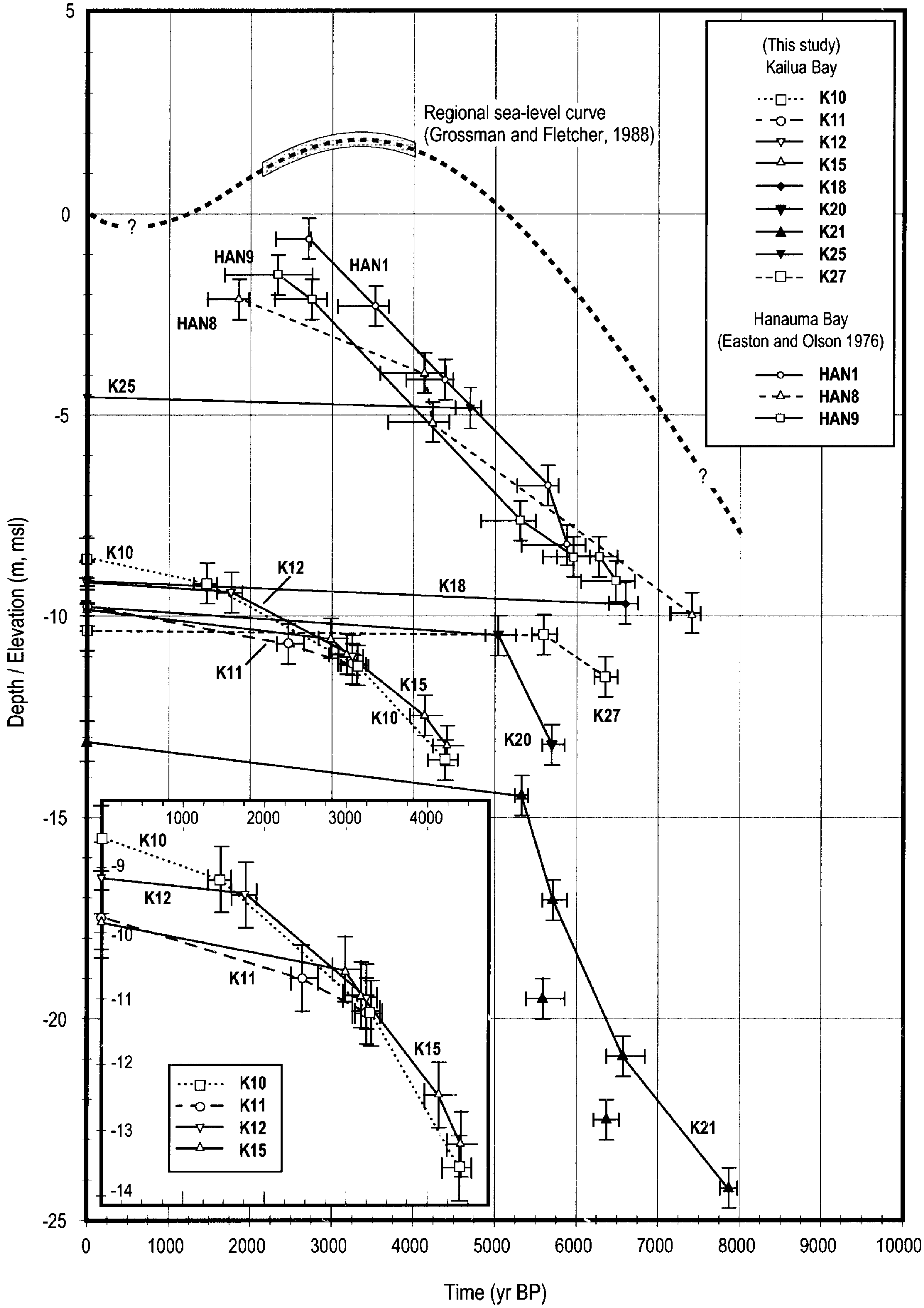
FIG. 5.—Drill-core lithologies and radiometric dates from seaward reef edge (transect A1), central reef (transect A2), and landward reef (transect B). Fossil reef of MIS 5e age outcrops at the reef surface in the north and south, while in the center, more than 11 m of Holocene accretion has occurred within the paleostream channel. Seismic reflection profiles corroborate jet-probe studies that more than 10 m of unconsolidated sands infill channel and that the Holocene unconformity rises toward the surface north and south away from central channel.


Transect A1
NW Distance (m) SE
NORTH PLATFORM
CENTRAL PLATFORM
SOUTH PLATFORM
Bird Rock
Ridge 1
Depth (m)
Holocene
MIS 5e
Kawainui Channel
1773
3262
mod
2992
3187
4142
4418
5342
5718
6577
7870
Transect A2
NW Distance (m) SE
CENTRAL PLATFORM
SOUTH
5046
5709
5598
6357
LEGEND
Drill site
Bindstone
Rudstone
Branching framestone
Massive framestone
Grainstone/ Sand (s)
Pleistocene limestone
Age ■ (Cal yr BP) □ (TIMS 230Th)
Unconformity
Vertical exaggeration = 2.5 x
Transect B
NW Distance (m) SE
Flat Island
127,640
130,490
143,090*
331,120*
NORTH PLATFORM
CENTRAL PLATFORM
SOUTH PLATFORM
Ridge 2
>43000
1471
3314
4396
6600
4693
Other Cores
Pleistocene
Holocene
Pleistocene
Length (m)



(This study)
Kailua Bay
K10
K11
K12
K15
K18
K20
K21
K25
K27
Hanauma Bay
(Easton and Olson 1976)
HAN1
HAN8
HAN9
Regional sea-level curve
(Grossman and Fletcher, 1988)
Depth / Elevation (m, msl)
Time (yr BP)

Accommodation space for significant framestone development in Kailua Bay in the Holocene existed only between 8000 and ~ 4000 yr BP, prior to the stabilization of sea level near its present position (Fig. 6). Framestone accretion in Kailua (K21, K27, K20, K18, K15, K10) terminated abruptly at 4000–4500 yr BP and never built into water depths less than 10 m (except for K27, where stout-branching *Pocillopora eydouxi,* occasionally found in higher wave energy than *P. compressa,* accreted in ~ 8.5 m; Fig. 7A). Accretion histories from Hanauma Bay (calibrated to calendar years: HAN1, HAN8, HAN9, Fig. 6; Easton and Olson 1976) show that framestone accreted until ~ 2500 yr BP at depths of 3 to 6 m below sea level (Montaggioni 1988), much shallower than in Kailua Bay. This striking vertical offset between accretion histories reflects the greater depth at which wave energy limits accommodation space in wave-exposed Kailua Bay relative to wave-protected Hanauma Bay. Higher wave energy in Kailua also helps to explain the exclusive formation of rudstones and bindstones in Kailua after 4500–5500 yr BP while the greater part of the Hanauma reef formed as framestone. Interestingly, the average rate of accretion of framestones in Kailua (3.3 mm/yr) is identical to the average rate found in Hanauma over the period 5800 and 3500 yr, before lateral accretion abruptly took over (Easton and Olson 1976). This suggests that a common primary control (the rate of change in accommodation space due to sea-level history) simultaneously influenced both reefs. The reduction of accommodation space by higher wave energy limited the Kailua reef to deeper depths and resulted in earlier termination of framestone accretion.

The abrupt transition from framestone to rudstone accretion at ~ 14 m depth in core K21 (Fig. 5) is consistent with breakage thresholds computed for branching corals at similar water depths today (~ 275 Nm^2). These shear-stress levels are associated with typical high annual north and northwest Pacific waves that reach Kailua Bay (Grossman 2000). Equivalent breakage values have been observed elsewhere among similar branching coral species (Kjerfer et al. 1986). The restriction of framestone accretion in Kailua throughout the Holocene to depths below −8 and −14 m suggests that wave scour since 8000 yr BP has been similar to levels found today.

The dominant form of accretion since 4500–5000 yr BP in Kailua has been rudstone and bindstone accumulation (Fig. 5, 7A), with occasional massive framestone filling isolated low topographic settings on the platform interiors. More than 4 m of vertical accumulation of rudstone occurred on the reef platforms as accommodation space decreased steadily from 14 m to 8 m (Fig. 7A). Accumulation, primarily of fore-reef derived rubble, continued later into the Holocene and to shallower depths at more landward sites (K10) than along the seaward reef edge (K12 and K15, Fig. 6). This is consistent with increased dissipation of energy of breaking waves that would result following aggradation of the seaward reef edge (K15) by ~ 3000 yr BP (e.g., waves would shoal farther seaward as the reef at K15 accreted into depths influencing wave friction). As a result, aggradation of framestone to depths that experienced wave friction by ~ 5000 yr BP led to both the demise of framestone accumulation in Kailua and the establishment of favorable conditions for rubble deposition and lithification on the reef platforms through wave dissipation.

The formation of rudstone in a shallow marine environment requires a unique circulation regime; the wave and current energy that is initially of sufficient magnitude to scour and transport rubble must eventually decrease to a level to enable deposition and promote cementation. Perhaps more importantly, the frequency of such transport events must be high enough to foster net sedimentation but low enough to facilitate preservation (i.e., adequate time for lithification through cementation and/or binding by encrusting coral and coralline algae). It is suggested here that the distribution of framestone-building corals below critical depths of ~ 14 m in the past and present and the resultant shallowing-upward facies sequence characterized by the grading of framestone to rudstone to bindstone supports the notion that the Holocene reef surface has steadily come into equilibrium with sea-level position and the dominant wave regime.

Secondary Controls: Balance Among Coral Growth Rate, Rate of Sea-Level Change, Bioerosion, and Sediment Abrasion.—Coral colony growth rates derived from measured growth-band thicknesses of dated core sections indicate that growth rates throughout the Holocene have been comparable to today (and perhaps have increased slightly most recently; Fig 7C). This trend suggests that variations in accretion are primarily due to factors across the reef other than those directly influencing coral growth. Obviously the rate of sea-level change has been intrinsically tied to the creation of accommodation space. Beyond that, however, bioerosion patterns may have closely mimicked accretion.

The highest rates of reef accretion (3–6 mm/yr) occurred 8000–5000 yr BP, when branching corals built the reef upward at a rate of 2–3 times that of sea-level rise (1–4 mm/yr; Figs. 6, 7B). In these facies evidence of bioerosion is sparse (Fig. 4), suggesting that accumulation rate exceeded the capacity for bioeroders to limit accretion. In contrast, after 5000 yr BP, when extensive rudstone accumulation abruptly replaced framestone development, rates of accretion dropped to an average of 0.7 mm/yr as the rate of sea-level rise decreased to < 1 mm/yr (and then fell at rates of 1–2 mm/yr). It is precisely in the rudstone facies that the influence of bioeroders is most widely expressed (Fig. 4). In addition, as rudstone development implies, a prominent source of sediment was being produced, through the scour of the aggrading fore-reef and ephemeral cor-algal communities on the platforms. An increase in sediment supply would further restrict reef accretion, by limiting habitat for recruitment and promoting sediment abrasion, especially on the wide, shallow platforms. The wholesale shift in cor-algal community from delicate, branching *Porites compressa* to sediment-tolerant encrusting forms of *Montipora patula, M. capitata, and Porolithon onkodes* observed in our cores is consistent with increased sediment-related stress. Finally, high sediment production since 5000 yr BP has led to high sediment accumulation within the inner sand field, the drowned Kawainui stream channel, and the offshore sand apron. Sediment in these reservoirs has likely limited vertical accretion and lateral progradation by abrasion and the formation of an unconsolidated shifting substrate.

Reef Depositional Model and Holocene Reef Architecture

The Holocene reef in Kailua developed in three stages (Fig. 8). The combined influence of regional sea-level history, late-Quaternary island uplift, high wave exposure, and extensive shallow antecedent platforms resulted in a narrow depth window of usable accommodation space for Holocene reef accretion. Wave scour at depths (8–14 m) comparable to depths penetrated annually today by high wave energy has effectively reduced accommodation space since sea level flooded Kailua Bay ~ 8000 years ago, and has restricted accretion to low topographic settings, such as the central drowned Kawainui stream channel (valley), erosional gullies, and presumably karst features.

The resulting pattern of reef development is characterized by infill of low topography (paleostream channel) initially by massive framestone and

←

FIG. 6.—Reef accretion histories from Kailua (K) and Hanauma Bay (HAN), and sea-level curve after Grossman and Fletcher (1998). Inset shows expanded histories (K10, K11, K12, K15) from north central reef. The Kailua reef tracks accretion of the wave-protected Hanauma reef but at significantly greater depth (3–14 m) because accommodation space is reduced by higher wave energy in Kailua relative to Hanauma Bay. An abrupt shift in reef accretion rate in Kailua at ~ 5000 yr BP also marks the transition of framestone accretion to rudstone or bindstone accumulation, and reflects reduced accommodation space.

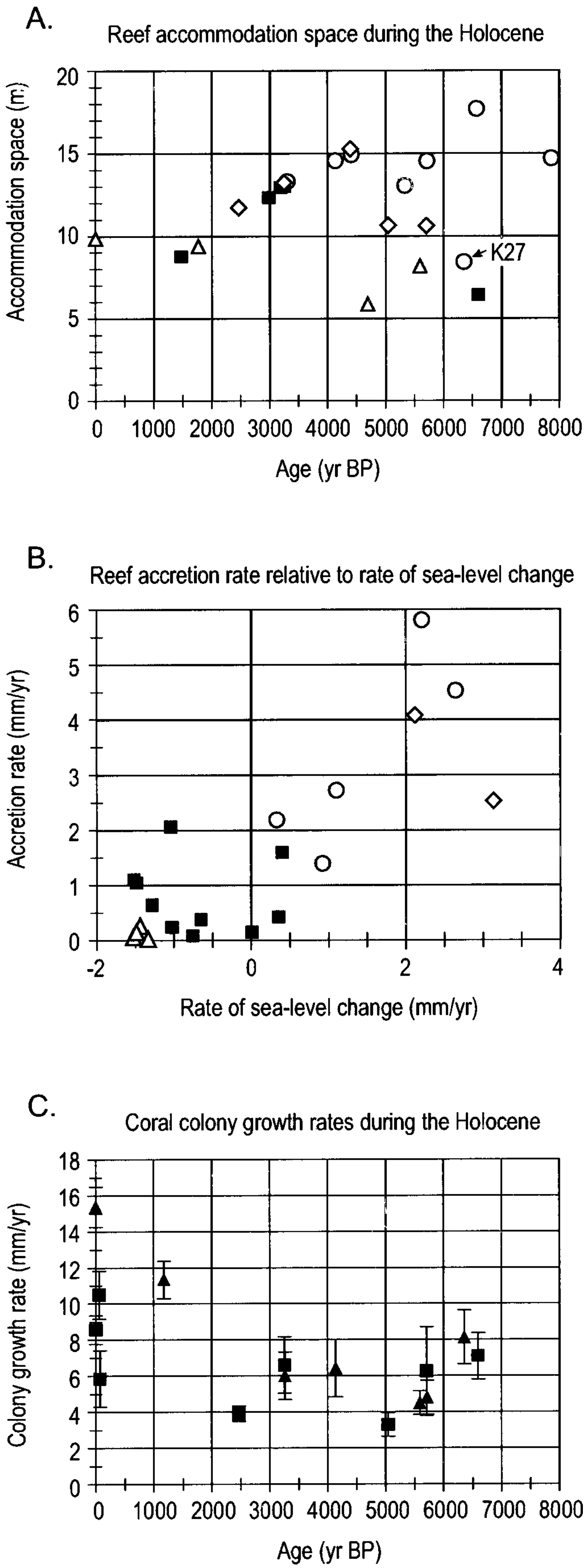


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FIG. 7.—**A)** Accommodation space during the Holocene at sites shown in Figure 5 associated with the accretion of branching framestone (circles), massive framestone (diamonds), rudstone (squares), and bindstone (triangles). Prior to ~ 4500 yr BP water depths of 6–17 m afforded suitable accommodation space for branching and massive framestone, and bindstone accretion. Branching framestone generally required > 13 m (except at K27, see discussion), massive framestone accreted in depths of 10 to 15 m, and bindstone accreted in 5 to 10 m. After ~ 4500 yr BP, a steady decrease in accommodation space characterizes most settings along with an increase in accumulation of rudstone and bindstone. **B)** Accretion rate plotted relative to the rate of sea-level change (symbols for facies are the same as in Part A). Rate of framestone accretion decreased as the rate of sea-level rise decreased, and no branching framestone accreted since ~ 3300 yr BP when the rate of sea-level rise decreased below ~ 1 mm/yr. Rudstones accreted during rates of sea-level rise < 1 mm/yr, and sea-level fall of 1–2 mm/yr since the mid-Holocene sea-level highstand. Accretion in the last 3000 years has been dominated by bindstone and rudstone during sea-level fall. **C)** Growth rates based on analyses of growth band thickness of individually dated branching (triangles) and massive (squares) coral colonies indicate that growth rates throughout the Holocene have been comparable to today (perhaps a slight increase) and that variations in accretion are due primarily to differential preservation across the reef.

sand (some encrusting colonies) followed by branching framestone (Stage 1) until the reef aggraded into depths influenced by wave scour when sea-level rise slowed ~ 5000 yr BP. Shoaling of the reef relative to sea-level position, terminated framestone accretion and promoted erosion and transport of framestone-derived rubble from the seaward edge and fore reef, leading to rudstone pile-up on platform interiors (Stage 2). A thin veneer of bindstone (Stage 3) caps the rudstone of the platform interiors and portions of the more wave-exposed south fore reef. Greater sheltering of North Pacific swell by Mokapu Peninsula on the north platform than on the south platform has allowed a thicker sequence of rudstone to be deposited, bound, and cemented on the north platform. Greater scour on the south platform led to an extended hiatus of nondeposition between ~ 5000 yr BP and modern bindstone development. The resulting architecture is therefore composed of a shallowing-upward sequence characterized by framestone to rudstone to bindstone accumulation.

A significant volume (more than 4 m thick) of the reef edifice on the central north platform is composed of rudstone that formed at depths of 8 to 14 m and accreted since sea level stabilized ~ 5000 yr BP. Similar cemented rudstone deposits have been cited as evidence of reef-flat planation and subsequent deposition owing to past sea-level oscillations (Schofield 1977; Pirazzoli and Montaggioni 1988; Sherman et al. 1993), although these generally formed within 1–2 m of sea-level position. The Holocene reef archive in Kailua shows that rudstone can form at considerable depths given a suitable wave and/or circulation regime that fosters coral growth, as well as scour, transport, deposition, and marine lithification within the system. In Kailua Bay, rudstone development appears to represent a transitional facies related to shallowing. Even at depths of 8 to 14 m it may be a sensitive recorder of sea-level fall (from the mid-Holocene sea-level highstand), because of high wave exposure, which modulated reef architecture within the accommodation space afforded by sea-level position.

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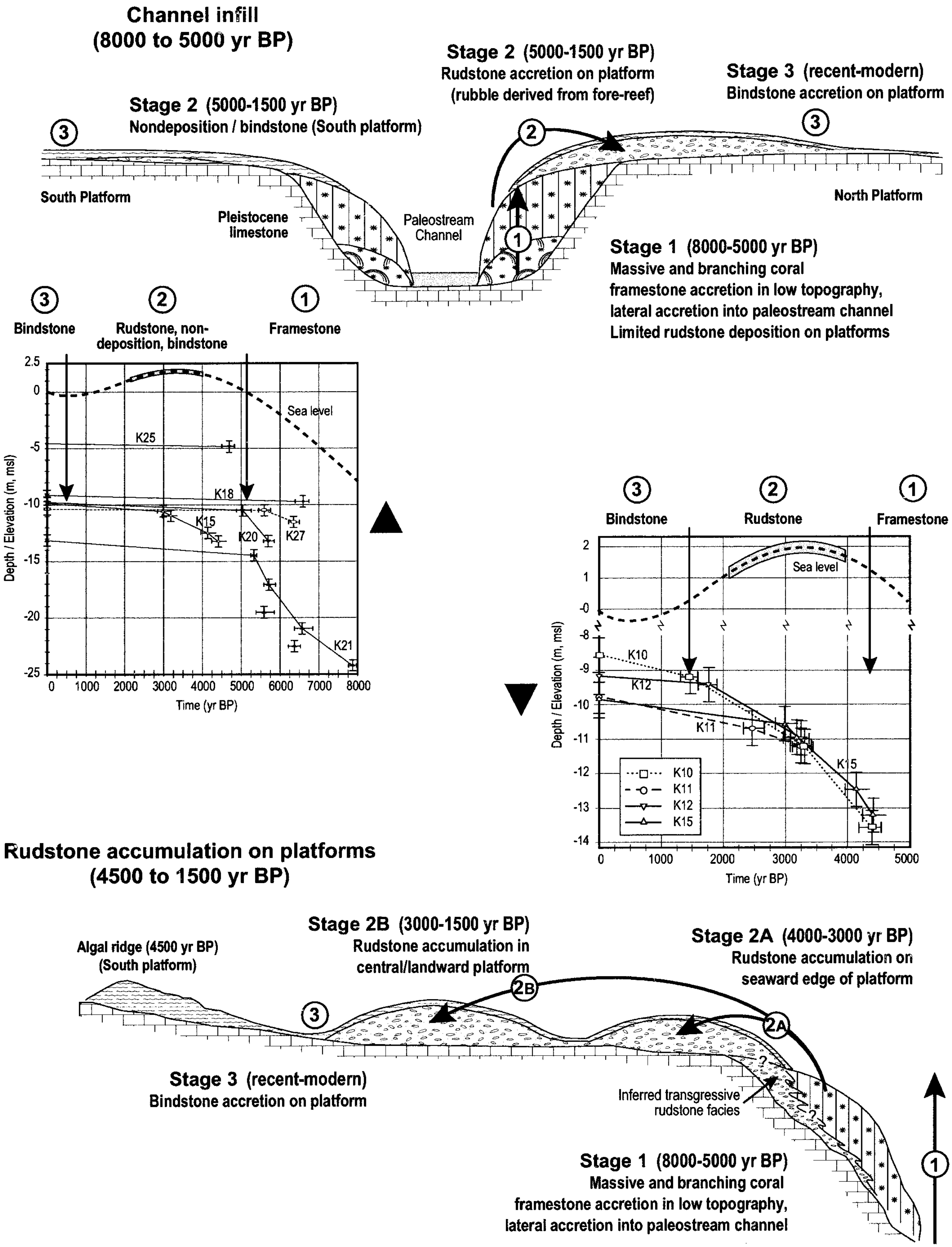
FIG. 8.—Depositional model showing three stages of reef accretion in Kailua. A reduction of accommodation space by wave energy has led to infill of low topography (paleostream channel) by framestone (Stage 1), followed by rudstone *pile-up* on platform interiors (Stage 2), and bindstone accumulation since ~ 3000 yr BP (Stage 3). On the north platform, a shallowing-upward sequence of framestone to rudstone to bindstone has resulted from reef aggradation into depths influenced by wave scour. Rudstone is thicker and more extensive on the north platform than on the south, where wave scour is reduced due to wave shadowing by Mokapu Peninsula. A significant volume of the reef edifice (> 4 m) is composed of rudstone that formed at significant depth (8–14 m) and accreted since sea level stabilized ~ 5000 yr BP.


Channel infill
(8000 to 5000 yr BP)
Stage 2 (5000-1500 yr BP)
Rudstone accretion on platform
(rubble derived from fore-reef)
Stage 3 (recent-modern)
Bindstone accretion on platform
Stage 2 (5000-1500 yr BP)
Nondeposition / bindstone (South platform)
South Platform
North Platform
Pleistocene
limestone
Paleostream
Channel
Stage 1 (8000-5000 yr BP)
Massive and branching coral
framestone accretion in low topography,
lateral accretion into paleostream channel
Limited rudstone deposition on platforms
Bindstone
Rudstone, non-deposition, bindstone
Framestone
Sea level
K25
K18
K15
K20
K27
K21
Depth / Elevation (m, msl)
Time (yr BP)
Bindstone
Rudstone
Framestone
Sea level
K10
K12
K11
K15
Depth / Elevation (m, msl)
Time (yr BP)
Rudstone accumulation on platforms
(4500 to 1500 yr BP)
Algal ridge (4500 yr BP)
(South platform)
Stage 2B (3000-1500 yr BP)
Rudstone accumulation in
central/landward platform
Stage 2A (4000-3000 yr BP)
Rudstone accumulation on
seaward edge of platform
Stage 3 (recent-modern)
Bindstone accretion on platform
Inferred transgressive
rudstone facies
Stage 1 (8000-5000 yr BP)
Massive and branching coral
framestone accretion in low topography,
lateral accretion into paleostream channel

Rubble reef cores have been proposed to result from hurricane deposition (Blanchon et al. 1997) and although hurricanes have likely impacted the Kailua reef, the absence of rudstone in Kailua reef facies older than ~4500 yr BP would imply less intense hurricane influence prior to the mid-Holocene or that rubble formation from hurricane waves was mitigated by higher rates of sea-level rise prior to ~ 4500 yr BP. Also, as described above, annual high wave energy can account for the scour of the upper fore reef and deposition of framework-derived rubble in Kailua; understanding the mechanisms and rates of marine cementation and rubble preservation would further our ability to model rudstone development.

Holocene Accretion Style

The general accretion strategy of the Holocene reef in Kailua Bay is a *catch-up* strategy (Neumann and Macintyre 1985) of branching framework development at rates twice as great as the rate of sea-level rise. Shallow facies at the base suggest a temporary initial deepening sequence of encrusting to massive framestone and sand before the bulk of branching framestone was deposited. Late stages were characterized by *catch-up* with the pile-up of rudstone and accumulation of bindstone. For portions of its history, the reef tracked the rate of sea-level rise similar to a *keep-up* reef, but at depths of 6–14 m below sea-level position because of high wave scour that reduced accommodation space. As the reef shoaled into depths of wave scour (6–14 m) during this *catch-up* style of development, framestone accumulation was discouraged as high near-bottom shear stresses promoted erosion and transport of framestone-derived rubble and the pile-up of rudstone on platform interiors. As a result, the Kailua reef was unable to catch up to sea level. Because accommodation space in Kailua Bay and presumably many wave-exposed Hawaiian reef settings is significantly reduced by high wave energy, Holocene reefs may be unable to catch up to sea level. This catch-up strategy is quite different from that originally proposed by Neumann and Macintyre (1985) and indicates that in settings of high wave energy a *catch-up* reef may not ever catch up unless sea level drops below to expose it.

Implications for Holocene Reefs on Oahu

Sherman et al. (1999) determined that the bulk of the submerged carbonate terrace from 0 to −20 m on Oahu's northwest and northeast coast is fossil, owing to reef accumulation during MIS 7 ~ 210,000 yr BP. Grigg (1998) tested the hypothesis that Holocene reef accretion has been controlled by exposure to long-period ocean swell, and proposed that the only settings containing significant Holocene reef accretion were wave-protected sites such as Hanauma and Kaneohe Bays. This study reveals that Holocene reef development is restricted not only regionally by coastal orientation relative to incident wave energy but also in time by the combined influence of sea-level history, wave energy, and antecedent topography, which control accommodation space. Knowledge of the antecedent substrate and the interaction of wave shoaling on complex seafloor topography have elucidated reef development strategies and controls in a transitional setting with respect to wave forcing. More than 11 m of vertical accumulation of reef framestone on the wave-exposed coast of Kailua exceeds the thickness of Holocene reef found in the protected Hanauma Bay, indicating that the dynamic interaction of sea-level behavior, wave energy, reef growth, and antecedent topography is highly spatially and temporally specific. The abrupt turn-off of framestone development at 4500–5500 yr BP in Kailua and between 2500–3500 yr BP in Hanauma Bay (Easton and Olson 1976) marks a dramatic change in reef accretion history as near-bottom turbulence influenced accommodation space.

CONCLUSIONS

Within the 12 km^2 windward Kailua Reef, marked differences in accretion history and development style occurred in the Holocene as a result of differential wave exposure and its interaction over a morphologically complex antecedent substrate. More than 11 m of framestone accreted since ~ 8000 yr BP, suggesting that Holocene reef accretion in Hawaii is not necessarily limited to wave-protected settings but to settings where available accommodation space existed below critical levels of wave-related stress. In Kailua, stream incision and karst erosion of the late Pleistocene reefal limestone during lower sea levels created ample accommodation space for early to mid-Holocene reef accretion. Reef accretion was limited, however, to water 5–8 m deeper than that associated with similar reef development in protected Hanauma Bay. This offset is consistent with similar wave-related stresses occurring at greater depth in Kailua Bay than Hanauma Bay, and at levels comparable to those that control modern cor-algal reef zonation.

Early Holocene reef development was characterized by rapid *catch-up* branching and massive framestone accretion where suitable substrate existed below wave base. This strategy abruptly gave way to an intermediate stage in the middle and late Holocene dominated by rudstone *pile-up* in reef sub-environments where circulation was sufficient to promote the cementation of fore-reef-derived rubble but not its redistribution. Where near-bed shear stress was too high, a hiatus of nondeposition is found in the record of reef accretion. A final stage of *catch-up* bindstone accretion characterizes recent development across most of the reef under modern sea-level rise. Despite its *catch-up* accretion strategy, the Kailua reef throughout the Holocene has been unable to catch up to sea level because of high wave exposure, unlike the Hanauma Bay reef, which caught up to sea level by at least 2500–3500 yr BP.

Moderately high and persistent wave energy decreased primary porosity and strengthened the windward Kailua reef structure by promoting high sediment production, prolific binding by encrusting cor-algal communities, and pervasive cementation. This enabled the development of more than 4 m of rudstone within the interior core of the reef. Despite prolific vertical accretion of more than 11 m of framestone, significant lateral progradation was likely limited by high sediment production, which formed extensive shifting sand deposits unsuited for cor-algal colonization. As a result, despite 8000 years of time, the Holocene reef has been unable to mask the antecedent topography of the drowned stream channel. Instead the paleo-stream meanders have been maintained because of strong circulation and/or rapid lithification of sediment along its meanders. Despite Hawaii's environment of relatively low diversity, high wave exposure, and oceanographic and latitudinal isolation, a few resilient coral species have adapted to relatively high wave stress to construct localized Holocene reefs at rates comparable to higher-diversity settings of the tropical Caribbean and Indo-West Pacific.

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