El Niño Influence on Holocene Reef Accretion in Hawai'i[1]

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Abstract: New observations of reef accretion from several locations show that in Hawai'i accretion during early to middle Holocene time occurred in areas where today it is precluded by the wave regime, suggesting an increase in wave energy. Accretion of coral and coralline algae reefs in the Hawaiian Islands today is largely controlled by wave energy. Many coastal areas in the main Hawaiian Islands are periodically exposed to large waves, in particular from North Pacific swell and hurricanes. These are of sufficient intensity to prevent modern net accretion as evidenced by the antecedent nature of the seafloor. Only in areas sheltered from intense wave energy is active accretion observed. Analysis of reef cores reveals patterns of rapid early Holocene accretion in several locations that terminated by middle Holocene time, ca. 5000 yr ago. Previous analyses have suggested that changes in Holocene accretion were a result of reef growth "catching up" to sea level. New data and interpretations indicate that the end of reef accretion in the middle Holocene may be influenced by factors in addition to sea level. Reef accretion histories from the islands of Kaua'i, O'ahu, and Moloka'i may be interpreted to suggest that a change in wave energy contributed to the reduction or termination of Holocene accretion by 5000 yr ago in some areas. In these cases, the decrease in reef accretion occurred before the best estimates of the decrease in relative sea-level rise during the mid-Holocene high stand of sea level in the main Hawaiian Islands. However, reef accretion should decrease following the termination of relative sea-level rise (ca. 3000 yr ago) if reef growth were "catching up" to sea level. Evidence indicates that rapid accretion occurred at these sites in early Holocene time and that no permanent accretion is occurring at these sites today. This pattern persists despite the availability of hard substrate suitable for colonization at a wide range of depths between −30 m and the intertidal zone. We infer that forcing other than relative sea-level rise has altered the natural ability to support reef accretion on Hawaiian insular shelves. The limiting factor in these areas today is wave energy. Numbers of both large North Pacific swell events and hurricanes in Hawai'i are greater during El Niño years. We infer that if these major reef-limiting forces were suppressed, net accretion would occur in some areas in Hawai'i that are now wave-limited. Studies have shown that El Niño/Southern Oscillation (ENSO) was significantly weakened during early-mid Holocene time, only attaining an intensity similar to the current one ca. 5000 yr ago. We speculate that this shift in ENSO may assist in explaining patterns of Holocene Hawaiian reef accretion that are different from those of the present and apparently not related to relative sea-level rise.

Although conditions of water temperature and clarity, irradiance, and substrate are sufficient in many coastal areas around the main Hawaiian Islands to support viable and accreting coral reef communities, their distribution is much more limited. Living coral and coralline algae communities are often restricted to a patchy, scattered veneer, resting unconformably on a Pleistocene fossil reef substrate (e.g., Sherman et al. 1999). A num-

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ber of researchers have reported that Holocene reef accretion in Hawai'i has been predominantly a function of sea level and exposure to wave energy (e.g., Grigg 1998, Grossman 2001). New observations of the timing of Holocene reef accretion from several locations show that accretion leading up to middle Holocene time occurred in areas where today it is precluded by the wave regime. The dramatic decrease in accretion at these locations, occurring ca. 5000 yr ago, is insufficiently explained solely as the product of relative sea-level rise and suggests an increase in wave energy in Hawaiian waters at that time.

Environmental Controls

SEA LEVEL. Relative sea level has played a dominant role in controlling reef growth in the Hawaiian Islands on scales of thousands of years. Eustatic sea level at the Last Glacial Maximum, ca. 21,000 yr ago, is estimated to have been between 113 m and 135 m below the current level (Clark et al. 2001). In Hawai'i, as seen in Figure 1, relative sea level is believed to have risen rapidly from the Last Glacial Maximum to its current level ca. 5000 yr ago and continued rising to about 2 m above that. The Holocene highstand culminated ca. 3000 yr ago (Fletcher and Jones 1996) before dropping back down below the current level (Grossman and Fletcher 1998) before the advent of tide gauge recording.

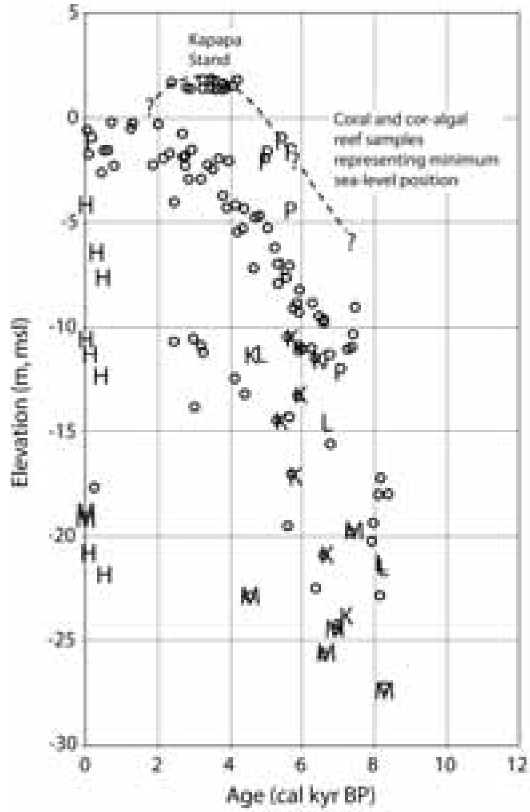

FIGURE 1. Dates and ages of potential sea-level indicators and modeled sea-level curve for O'ahu from Grossman and Fletcher (1998). Letters show age and depth of samples listed in Table 1: K, Kailua; L, Lono; H, Hikauhi; P, Punalu'u; M, Mānā. Note that Punalu'u samples near the sea-level curve are from non–in situ samples.

Coral reefs can grow in Hawai'i only between the critical depth of −30 m (Grigg and Epp 1989) and the intertidal zone, with optimal growth occurring at about −12 m (Grigg 1998). Thus, dramatic changes in sea level during Holocene and late Pleistocene time have exerted obvious constraints on reef growth. Smaller fluctuations in sea level associated with the middle Holocene Kapapa Stand of the sea (+2 m) are proposed to have enabled and terminated reef growth by changing both the area covered by seawater and amount of wave energy able to reach specific reef areas (Grigg 1998). At current rates, relative sea-level rise ranges from 13 cm per century on the island of Kaua'i to 32 cm per century on the island of Hawai'i, with other locations falling between these extremes (Permanent Service for Mean Sea Level, 2003). Over periods of up to a few centuries the relatively small changes in sea level are, given the −12 m depth for optimal growth, unlikely to have substantial effects on reef growth, except in limited areas near the modern tidal range.

WAVE ENERGY. The primary factor responsible for curtailing Holocene reef growth on scales of years to as much as a few centuries is exposure to wave energy. The moderate energy provided by northeasterly trade winds and south swell usually benefits reefs in Hawai'i by enhancing circulation and nutrient uptake (Grigg 1998). Although occasional large waves generated by Kona storms (low-pressure systems that develop during the Northern Hemisphere winter) have caused damage to reefs, they are infrequent enough to be of secondary importance in limiting reef accretion (Grigg 1998).

Long-period (12 to 20 sec) North Pacific swell on the other hand has been extensively reported to exert a substantial control on reef distribution (Grigg 1983, 1998, Storlazzi et al. 2002). Occurring during the winter season, these swells approach from a directional range of west-northwest through northeast with typical deepwater wave heights of 1.5 to 5 m, although waves as large as ca. 15 m have been reported (Bodge and Sullivan 1999).

Researchers have also noted the reef-limiting effects of major hurricanes in Hawai'i (Dollar 1982, Dollar and Tribble 1993, Grigg 1995, 1998). Hurricane 'Iwa, for example, struck the Islands in 1982 and reduced reef areas with 60–100% coral cover on O'ahu's south shore to rubble (Grigg 1995). Along the southwestern shore of Hawai'i, both hurricanes 'Iwa and 'Iniki (1992) destroyed stands of coral along more than 10 km of shoreline (Dollar and Tribble 1993). Most hurricanes tracking as far west as the main Hawaiian Islands pass to the south (e.g., Chu 2002). As a result, hurricane-induced wave energy generally has a more severe impact on southeastern to southwestern coasts, whereas North Pacific swell predominantly impacts west- to northeast-facing shores. However, longer-period swells can refract substantial energy around to coastlines facing away from the incident wave direction (e.g., Storlazzi et al. 2002).

Tsunamis originating from within the Pacific basin, including the Hawaiian Islands, strike Hawaiian shores. A few of these since the early 1800s have had amplitudes in excess of 10 m and caused substantial damage, suggesting that high bottom shear stresses capable of breaking and scouring reef structure occur during major tsunamis. One anecdotal account reported that a major tsunami several decades ago caused a substantial reduction of live coral cover on windward O'ahu reefs (B. Kapuni, pers. comm.). This potentially substantial control on reefs in some areas has been overlooked in most of the literature. Reports tend to focus on damage occurring on land, so there are little historical data available. Hence, impacts of tsunamis on reef morphology and accretion remain an important question to be addressed.

STUDY SITES. Sites of substantial Holocene accretion are limited to areas that receive some degree of sheltering from large waves and have substrate at depths suitable to support coral growth (Dollar and Tribble 1993, Grigg 1998, Storlazzi et al. 2002). New observations of reef accretion from several locations, however, show that accretion before the mid-Holocene occurred in some areas where today it is precluded by the wave regime. Sites showing this pattern include contrasting locations on the western end of Moloka'i's south shore, Kailua Bay and the reef at Punalu'u on the northeastern side of O'ahu, and Mānā Reef on the northwestern coast of Kaua'i (Figure 2). From dated core samples and interpretation of paleoecology at these sites we infer a substantial increase in wave energy in the central North Pacific starting ca. 5000 yr ago.

Moloka'i: The Hale o Lono and Hikauhi sites are located near the western end of Moloka'i's south shore and on part of the longest continuous fringing reef in the Hawaiian Archipelago (Maragos 1998). Although only 10 km apart, the sites are characterized by markedly different reef structure. Near the eastern site, Hikauhi, is a prominent gulch that drains the relatively arid watershed landward of the site and delivers substantial volumes of terrigenous mud during occasional rain events. Landward portions of the ~0.8-km-wide reef flat have been physically buried by the influx of mud and seaward progradation of the shoreline. Low wave energy, due to both shadowing effects of the island and a shallow reef crest, prevents terrigenous mud from being effectively dispersed and reduces suspended sediment in the water column outside the reef crest. Most of the substrate seaward of the reef crest is covered with live coral and gradually slopes down to an abrupt drop-off at about −17 m into a large sand field at −20 m. Several outcrops a few tens of meters in diameter and with high percentages

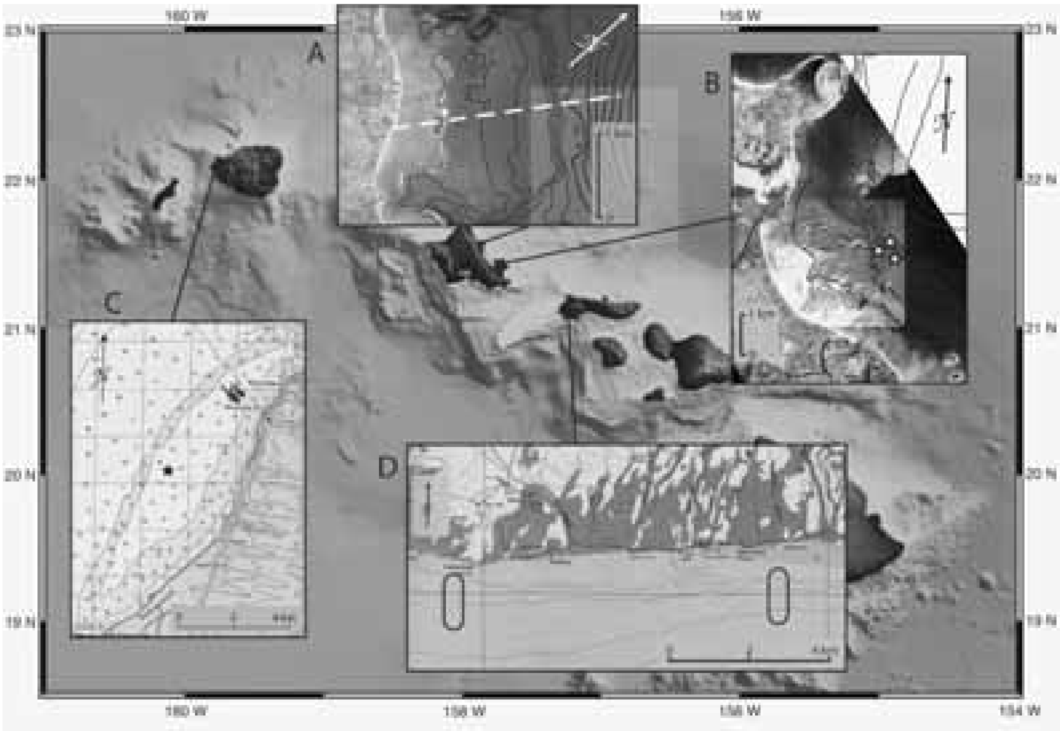

Figure 2. Location and magnified views of study sites and core locations. *A*, Aerial photograph of Punaluʻu, Oʻahu, shoreline and reef. Bathymetric contour interval is 5 m. Cores discussed in the text are located at appropriate depths along the dashed line. *B*, Aerial photograph of Kailua Bay, Oʻahu. Note paleostream channel in center of the bay, stars indicating core locations, and 5-, 10-, 15-, 20-, 50-, and 100-m bathymetric contours. *C*, Chart of Mānā, Kauaʻi. Shaded bathymetry indicates depths shallower than 18.3 m (60 ft). Star indicates sample collection location on inside edge of barrier reef. *D*, Hale o Lono and Hikauhi, Molokaʻi. Cores were collected inside ovals marking each site. Bathymetric contours are shown for 5.5, 18.3, 30.5, and 91.4 m.

of live *Porites compressa* are found farther offshore in depths ranging from about −20 to −25 m.

The Hale o Lono site is named for the local harbor. It receives less terrestrial sediment in runoff than does the Hikauhi site and experiences strong tidal and longshore currents and higher wave energy, particularly in the winter season, related to refracted North Pacific swell. The site features a narrow reef flat (∼0.3 km), generally sparse coral cover, and a gently sloping terrace of fossil reef from 0 to −5.5 m. This is followed seaward by a series of four shore-parallel and low-relief ridges of fossil reef separated by sand-filled channels, at depths ranging from −8.5 to −21.0 m.

Oʻahu: Kailua Bay is an embayment 4 km long on the windward or northeastern side of Oʻahu. A fossil reef terrace extends from the sandy beach ∼3 km offshore, gently sloping seaward to a depth of −20 m and dropping abruptly from there to a deeper, sand-covered terrace starting at −30 m. It is exposed to trade wind swell and the more easterly of, or refracted, North Pacific swell. The reef platform is bisected by the Kawainui paleostream channel that was cut through the largely Pleistocene-age shelf during periods of lower sea level (Grossman 2001).

The Punaluʻu site, farther north on the windward side of Oʻahu, features a shallow reef flat ∼0.5 km wide and a narrow reef crest area with a ribbon of fossil reef a few meters wide that extends as much as ∼0.2 m above mean lower low water. Seaward of the reef crest is a gently sloping fossil reef terrace extending ~1 km farther offshore to a wall that drops from −20 to −30 m, followed by a sand field with occasional low-relief limestone rises. Punaluʻu Reef stretches along 1.5 km of coastline and is terminated on either side by steep-walled channels located seaward of perennial streams. The reef structure is shore parallel, tending northwest to southeast, and directly exposed to northeasterly trade wind swell. Wave pumping over the reef crest drives a persistent and vigorous flow of water landward across the reef flat and then out to sea in the shore-normal channels on either side of the reef platform. The most northeasterly North Pacific swell events strike Punaluʻu Reef directly, with more westerly events refracting substantial wave energy there as well.

Kauaʻi: The Mānā site, on the island of Kauaʻi, is described as one of two barrier reefs in Hawaiʻi (Maragos 1998). From offshore, the seafloor slopes steadily upward along a smooth fossil limestone pavement to a depth of −15 to −18 m, which constitutes the shallowest portion of the structure. Landward of this depth, the seafloor drops abruptly to a lagoon floor at a depth of −24 to −29 m. The reef is no longer accreting and only scattered live corals and coralline algae are found, along with a short algal turf, on the reef surface today. The landward-facing wall of the reef is composed of fossilized vertical columns of *Porites compressa.* The 13-km-long reef structure faces northwest, with a lens-shaped lagoon averaging 2.2 km wide that gradually shallows to a depth of −10 m before sloping rapidly upward to meet the shoreline. Although the tracks of three hurricanes have passed directly over the island or just a few kilometers away over the last half century, their impact on this unpopulated area of the coast is unknown. Facing northwest, the Mānā area receives the full force of North Pacific swell every winter.

MATERIALS AND METHODS

Drill cores were collected at all locations except Mānā Reef, Kauaʻi, using a diver-operated, submersible, hydraulic rotary coring drill (Tech 2000) with a 7.6-cm diameter diamond-studded drill bit. Wireline (NQ2) drill system components were added and the entire system attached to the seafloor using a tripod and center mast for stability. This configuration was utilized at the Kailua site to recover 6-cm-diameter cores up to 18 m long. Cores were collected at water depths from +2 to −34 m and sampled for petrographic, mineralogic, and radiometric analysis. Accuracy of sample depths within cores varied depending on the drilling method used and porosity of reef material. Kailua sample depth uncertainties averaged 0.03–0.1 m but were as high as ~1 m for two highly porous sections. Those from Punaluʻu averaged ±0.3 m, with higher uncertainties from unconsolidated reef flat cores. The reef in Molokaʻi, particularly at the Hikauhi site, is more porous than those at the Oʻahu sites, yielding a mean depth of certainty of ±0.6 m. Limestones from core samples were classified according to Dunham's (1962) scheme, as modified by Embry and Klovan (1971).

Logistical considerations precluded drilling at Mānā. However, vertical faces ~10 m high expose fossil reef growth. Hand samples were collected at a range of depths in a vertical line along an exposed face by divers using hammers and chisels. Sample depths, recorded from digital depth gauges, have an uncertainty of ±0.3 m.

Radiocarbon and X-ray diffraction sample material was prepared and analyzed for carbonate mineralogy and radiocarbon ages as per Grossman (2001). However, a more recent version of the radiocarbon age calibration software and calibration data set, Calib version 4.3 (Stuiver and Reimer 1993, Stuiver et al. 1998), was used for the samples from Molokaʻi and Punaluʻu. A regional marine reservoir correction (ΔR) of 220 ± 100 calendar yr (Dye 1994) was used for Punaluʻu samples.

Benthic community structure was quantitatively described from survey data collected at the Molokaʻi and Oʻahu sites using a modification of the line intercept technique. Dominant substrate types and descriptions along replicate transect lines surveyed across a range of depths were recorded on preprinted survey forms by scuba divers, at increments of 0.1 m. Corals and coralline algae encountered were identified to the species level and described in terms of colony size and morphology.

RESULTS

Moloka'i

The sparse living coral community at Hale o Lono is composed of a mix of species typical of Hawaiian coral reefs, especially *Pocillopora meandrina*, encrusting forms of *Montipora capitata*, *Montipora patula*, and *Porites lobata*, and, below depths of −10 m, *Porites compressa*. Percentages of live coral cover average ∼20% and coral colonies appear to be no more than a few years old, with most of the hard substrate composed of fossil reef covered by a short algal turf.

Ten cores were drilled and recovered at Hale o Lono, along a roughly shore-normal transect, at depths ranging from −5.5 to −21.0 m. The substrate gets progressively younger and shallower moving landward, ranging from an age of ca. 8100 calendar yr before present (cal. yr B.P.) at −21.0 m to ca. 4800 cal. yr B.P. at −5.5 m. The most common depositional texture of material recovered from the cores is bindstone, with a predominantly coralline algal matrix. Rudstone, composed of fragments of coral, coralline algae, and other reef rubble material, is the second most common constituent of the cores. Both textures indicate high-energy depositional environments (Sherman et al. 1999). Cores from −17.7 m, however, have sequences of branching framestone, in some cases topped by bindstone accreted ca. 7900 cal. yr B.P. Results of coring and analysis at Hale o Lono are summarized in Figure 3.

Although the species mix is similar at Hale o Lono and Hikauhi, growth morphologies tend to be more branched or massive and less encrusting at Hikauhi, and percentages of live coral cover are much higher, averaging ∼70%. Twenty-four cores recovered from the Hikauhi site, at depths between −4.0 and −19.8 m, contain mostly massive coral framestone or floatstone reef material. These facies are indicative of moderate to low wave energy depositional conditions (Sherman et al. 1999, Grossman 2001). Ages of core samples from Hikauhi are much younger than those from Hale o Lono, ranging in age from modern to 910 cal. yr B.P. and yielding an overall mean accretion rate of ∼5 mm yr^{-1}. Results of coring and analysis at Hikauhi are summarized in Figure 4.

Kailua

Grossman (2001) divided the reef terrace in Kailua Bay into three regions based on the dominant facies in the upper 1 m of the reef surface. The north and south platforms are characterized by a fossil reef surface with an encrusting coralline algae veneer. Landward portions are karstified and often covered by sand fields, and the southern platform features scattered massive and encrusting colonies of live corals. The central platform on the other hand, is dominated by living reef, with encrusting corals and coralline algae along the north and south margins. In the middle of the central platform, on each side of the Kawainui paleostream channel, are communities of mixed massive and encrusting corals, with branching coral communities dominating the substrate at its seaward margin.

A selection of the 32 cores drilled through the nearshore reef platform in Kailua Bay was subsampled for radiometric dating and other analyses (Grossman 2001). Three of these, cores K20, K21, and K27, recovered from the south central platform (see Figure 2), are of particular interest to this study and shown in Figure 5. Each of these cores is capped by thin (0.2–0.6 m) layers of bindstone, indicative of high-energy conditions. Underneath the bindstone are sequences of massive coral (core K20) or branching coral (cores K21 and K27) framestone, indicative of low to moderate and low-energy depositional environments, respectively. Underlying the branching coral framestone in core K21 are sequences of massive coral framestone interspersed with sand layers. Core K27 is too short to tell if a similar pattern exists under its location. Changes in accretion rates from

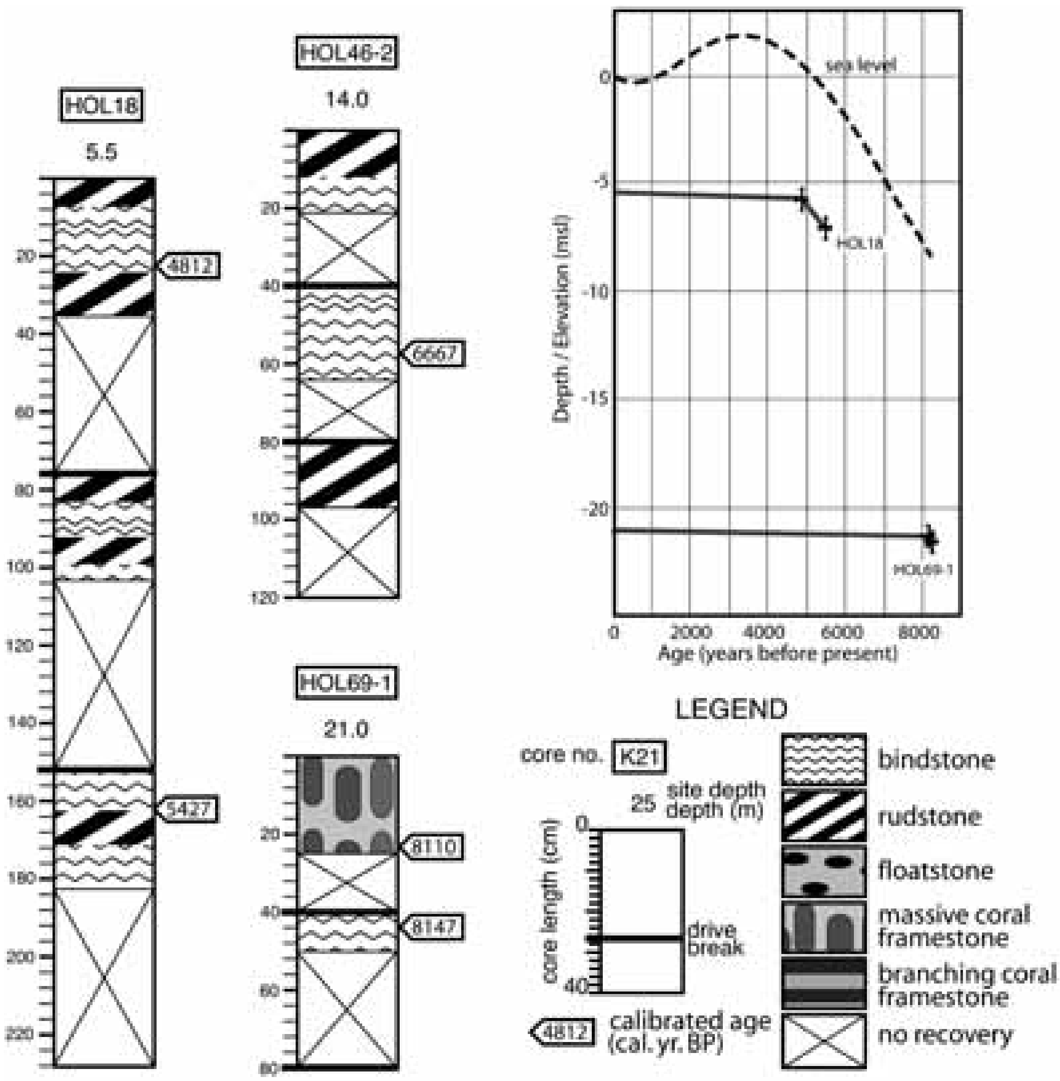

FIGURE 3. Logs of selected cores from the Hale o Lono site on Moloka'i. Their accretion rates, from radiocarbon dating of core subsamples, and the O'ahu sea-level curve are plotted against time in years. Note that relative sea level continued to rise well after accretion rates from core HOL18 decreased.

these three cores appear to coincide with changes in their lithologies, with average rates of ~4 mm yr^{-1} during framestone accretion, apparently abruptly decreasing to ~0.2 mm yr^{-1} during bindstone accretion.

The possible impact of North Pacific swell on coral communities was also investigated (Grossman 2001) using the Simulating Waves Nearshore (SWAN) model to simulate typical North Pacific swell conditions. Results indicate that the south central platform, where cores K20, K21, and K27 were drilled, is subject to the greatest breaking wave heights. Significant modeled breaking wave heights near these cores are ~4 m, while other areas in the bay with appreciable Ho-

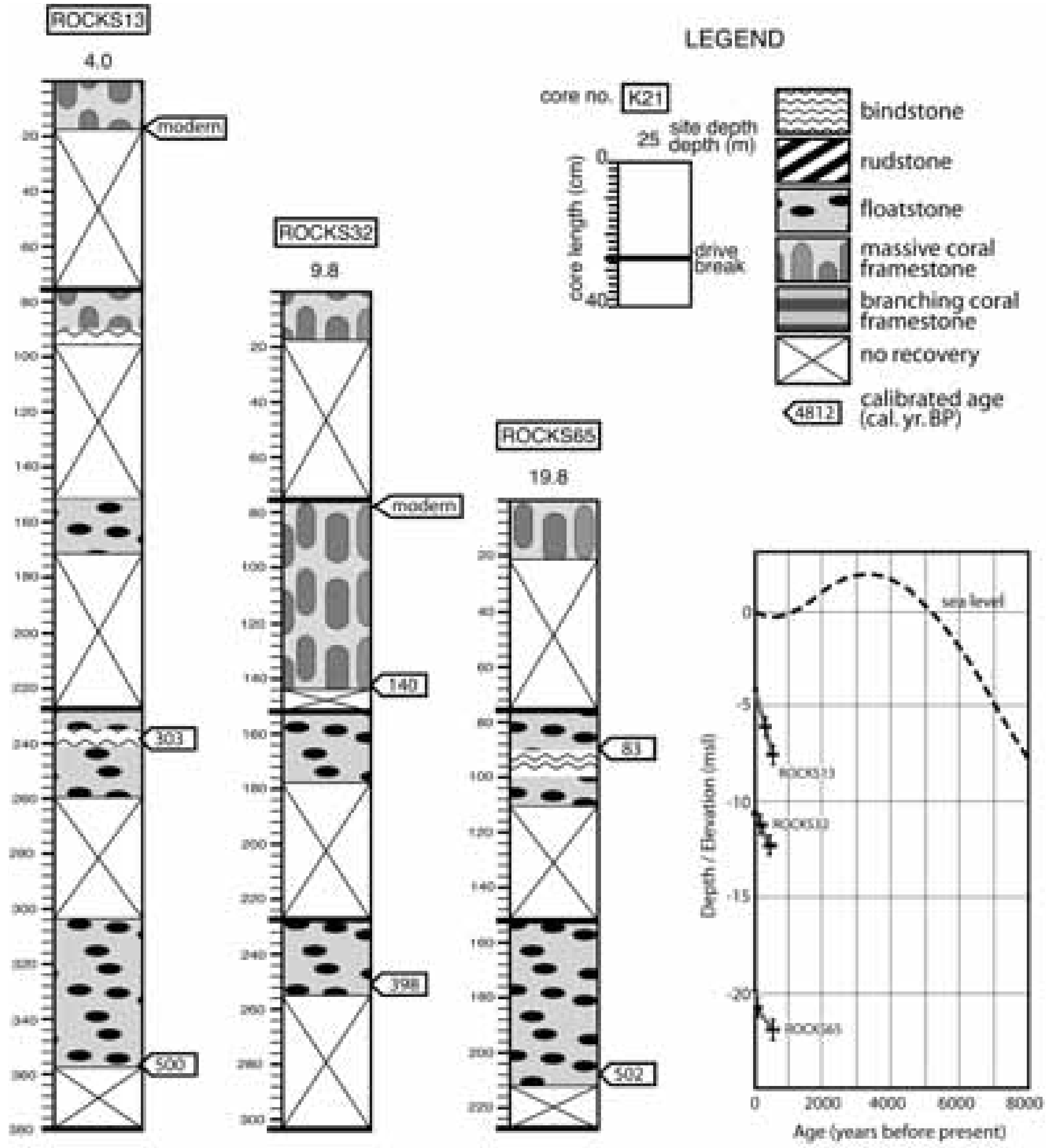

Figure 4. Logs of selected cores from the Hikauhi site on Moloka'i. Their accretion rates, from radiocarbon dating of core subsamples, and the O'ahu sea-level curve are plotted against time in years. All cores from this site show rapid recent accretion.

locene accretion are subject to wave heights of 2.5 m or less.

Punalu'u

Both corals and coralline algae are found on the reef flat, reef crest, and fore reef slope at Punalu'u between the −30-m isobath and the shoreline. On average, live corals cover 15% of the substrate and live coralline algae covers 20%, although distributions of both are patchy. Small corals, usually appearing to be between a few years and a few decades in age are found in all areas, as are patches of the

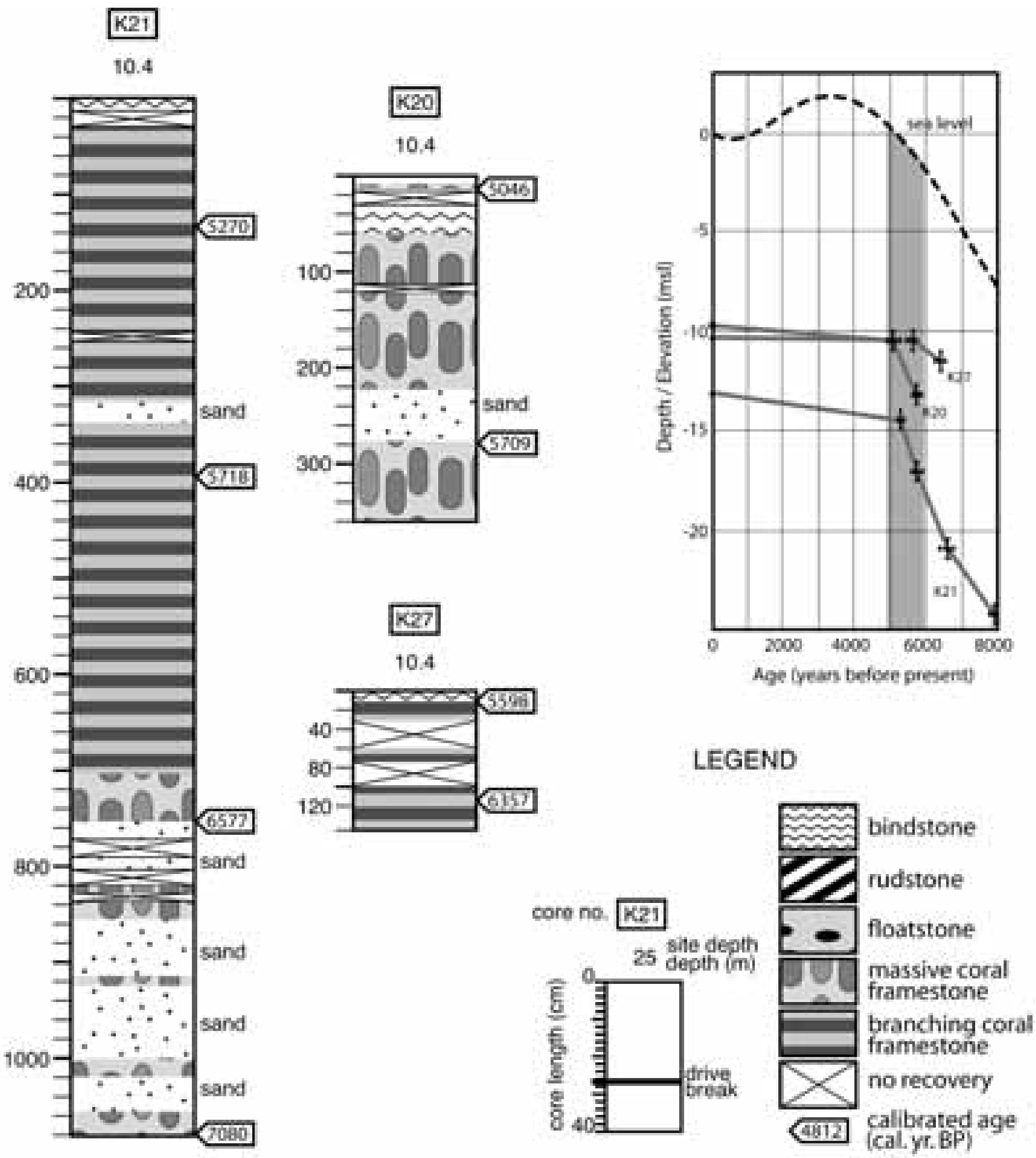

FIGURE 5. Logs of selected cores from the south central reef platform at Kailua, O'ahu. Their accretion rates, from radiocarbon dating of core subsamples, and the O'ahu sea-level curve are plotted against time in years. The gray vertical band indicates the temporal limits of dramatic changes in accretion rates from cores K20, K21, and K27. Note that relative sea level continued to rise for >1500 yr after accretion rates in the cores decreased.

encrusting coralline alga *Porolithon onkodes*. Of particular interest is a segment between the reef crest and the area seaward to a depth of −2 m. This zone contains 95% cover of live encrusting coral (15%) and encrusting and branching coralline algae (80%). It is a high-energy environment, subject to concussive impacts of moderate breaking waves and strong surge. Still higher-energy conditions exist, however, on the reef terrace seaward of

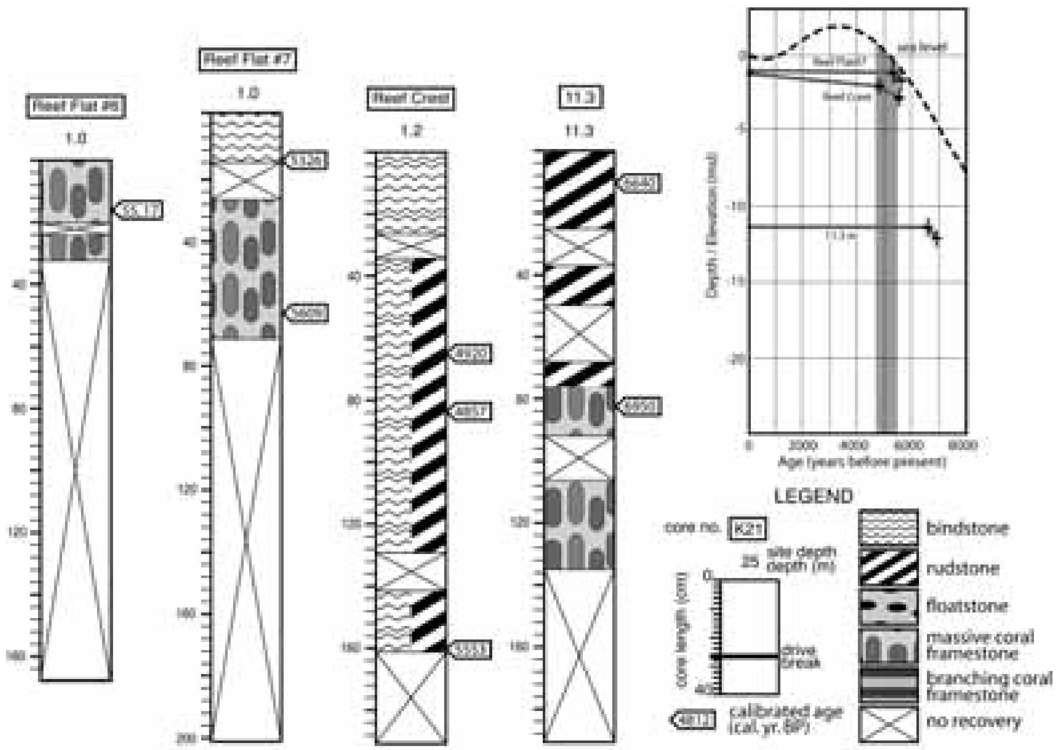

FIGURE 6. Logs of selected cores from the Punalu'u, O'ahu, site. Their accretion rates, from radiocarbon dating of core subsamples, and the O'ahu sea-level curve are plotted against time in years. The gray vertical band indicates the temporal limits of dramatic changes in accretion rates from the Reef Crest and Reef Flat #7 cores. All dated samples from the reef flat were taken from non–in situ coral rubble fragments. The second-oldest samples from the 11.3-m and Reef Crest cores are also from non–in situ material. However, in each case, the youngest accreted material predates the mid-Holocene decrease of relative sea-level rise.

the reef crest, the landward half of which is subject to the concussive impact of larger North Pacific swells.

Cores from Punalu'u were collected along a shore-normal transect from near the shoreline in <-1 m water depth, across the reef platform and seaward to a depth of -34 m. X-ray diffraction analysis of core samples indicates that mineralogy of fossil reef material composing the reef terrace has been diagenetically altered. These results are consistent with analyses from other areas of the carbonate terrace found around most of O'ahu and imply a pre-Holocene age (Sherman et al. 1999, Grossman 2001). However, radiometric dating of core samples indicates that reef accretion occurred in restricted areas on the Punalu'u reef during the Holocene epoch. The lithology of selected cores containing Holocene-age material is described here and shown in Figure 6, and calibrated ages and other information from samples are shown in Table 1.

Ten drill holes were scattered around the transect line on the reef flat. The seafloor there is characterized by frequent large coral heads, patches of sand, fossil limestone reef colonized by algae, and rubble accumulations. Although generally started in coral colonies or other hard substrate, after penetrating the first 0.1–0.3 m all holes drilled in the reef flat encountered layers of unconsolidated rubble with occasional sand layers. This unconsolidated material extended to a depth of at least -2 m.

The reef crest core is a bindstone/rudstone

TABLE 1

Core and Hand Sample Data

Sample No.	Core No.	Seafloor Depth (m, MSL)	Depth Below Seafloor (m)[a]	Description[b]	Calibrated Age[c] (B.P.)	Cal. Age Range (2σ)
Kailua, O'ahu						
SOC1-2-70	K20	10.4	0.09	IS coral	5046	5267–4888
SOC1-7-332	K20	10.4	2.79	IS coral	5709	5865–5593
NEU3-05-105	K21	13.1	1.35	IS coral	5270	5438–5013
NEU3-12-365	K21	13.1	3.95	IS coral	5718	5892–5583
NEU3-26-753	K21	13.1	7.83	IS coral	6577	6786–6347
NEU3-30-1080	K21	13.1	10.80	IS coral	7080	7018–7142
KAE1-1-10	K27	10.4	0.10	IS coral	5598	5762–5456
KAE1-3-115	K27	10.4	1.15	IS coral	6357	6505–6226
Hale o Lono, Moloka'i						
H18-D1-T	HOL18	5.5	0.23	IS coral	4812	4614–4935
H18-D3-B	HOL18	5.5	1.62	IS coral	5427	5279–5553
Hale46-2A	HOL46-2	14.0	0.58	IS coral	6667	6646–6977
Hale69-1A1	HOL69-1	21.0	0.24	IS coral	8110	8041–8323
H69-1-D2-B	HOL69-1	21.0	0.44	IS coral	8147	7992–8287
Hikauhi, Moloka'i						
R13-D1-B	ROCKS13	4.0	0.18	IS coral	Modern	Modern
R13-D4-B	ROCKS13	4.0	2.38	IS coral	303	229–463
R13-D5-B	ROCKS13	4.0	3.57	IS coral	500	394–618
R32-D2-T	ROCKS32	9.8	0.77	IS coral	Modern	Modern
R32-D2-B	ROCKS32	9.8	1.43	IS coral	140	43–263
R32-D4-T	ROCKS32	9.8	2.51	IS coral	398	280–473
R65-D2-B	ROCKS65	19.8	0.91	IS coral	83	0–238
R65-D3-B	ROCKS65	19.8	2.08	IS coral	502	419–609
Punalu'u, O'ahu						
Punalu'u12	Reef Flat #6	1.0	0.16	IS coral	55, 17	305–0
Punalu'u13	Reef Flat #7	1.0	0.15	Coral rubble	5326	5595–5035
Punalu'u14	Reef Flat #7	1.0	0.63	Coral rubble	5609	5886–5427
Punalu'u28	Reef Crest	1.2	0.65	NIS coral	4920	5283–4672
Punalu'u29	Reef Crest	1.2	0.84	Gastropod	4857	5255–4600
Punalu'u03	Reef Crest	1.2	1.60	ECA	5553	5741–5277
Punalu'u17	11.3 m core	11.3	0.10	Coral rubble	6640	6901–6382
Punalu'u19	11.3 m core	11.3	0.83	IS coral	6950	7235–6671
Mānā, Kaua'i						
Mānā62	NA	18.9	0	IS coral	Modern	Modern
Mānā63	NA	18.9	0.3	IS coral	Modern	Modern
Mānā65	NA	18.9	0.9	IS coral	7358	7462–7213
Mānā75	NA	18.9	4.0	IS coral	4543	4738–4412
Mānā80	NA	18.9	5.5	IS coral	6882	7047–6730
Mānā84	NA	18.9	6.7	IS coral	6616	6764–6416
Mānā89	NA	18.9	8.4	IS coral	8279	8383–8107

[a] Depths below seafloor at Mānā site are reported as depths below top of reef surface adjacent to the wall from which samples were collected.

[b] IS, in situ; NIS, non–in situ; ECA, encrusting coralline algae.

[c] All dates are National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) ^{14}C Accelerator Mass Spectrometry (AMS) analysis except sample NEU3-30-1080, which is from Thermal Ionization Mass Spectrometry (TIMS) ^{230}Th analysis.

mix, suggesting a high-energy depositional environment (Sherman et al. 1999, Grossman 2001). It contains gravel and smaller sediment and fragments of the coralline alga *Porolithon gardeneri*, bound together in a matrix of encrusting coralline algae. A distinctive reef terrace core, recovered from a depth of −11.3 m, contains a layer of rudstone with weakly cemented, rounded clasts of coral or other reef material overlain by a massive coral framestone.

Mānā

Hand samples of corals were retrieved from a variety of depths along a vertical wall on the landward side of the Mānā fossil barrier reef. Sample collection was limited to material that could be extracted quickly with hand tools. Although collected in a straight line moving up the reef face, samples lack the vertical continuity of cores. Despite these limitations, a few observations can be made. It became apparent during sample collection that at least the visible portion of the reef face is predominantly composed of in situ growth of *Porites compressa* coral that falls within the branching coral framestone facies described by Sherman et al. (1999) and Grossman (2001). The exposed seafloor above the barrier supports little live cover, but areas in the lee of the barrier display moderate to sparse live cover characterized by platy, encrusting, and massive morphologies. Without further data it is impossible to tell if the modern community is accreting or is just the most recent accumulation of ephemeral growth on a fossil substrate. However, the living coral community is best described as a mix of Grossman's (2001) encrusting cor-algal bindstone and massive coral framestone facies, suggesting a moderate to high-energy setting. Collection depths and calibrated ages of dated samples are shown in Table 1.

DISCUSSION

Moloka'i

Although the Hale o Lono site supported reef accretion until ca. 5000 yr ago, since then it has been unable to, despite the availability of suitable substrate and the obvious ability of corals and coralline algae to recruit there. Cores from Hikauhi, a few kilometers away, all show rapid and continual accretion over the late Holocene. This striking difference in modern reef accretion has been convincingly explained by Storlazzi et al. (2002). Using a combination of wave modeling and field observations, they found high correlations between changes in reef morphology and total coral cover versus benthic shear stress from North Pacific swell. They concluded that refraction of energy from large North Pacific swell around the east and west ends of Moloka'i is sufficient to inhibit coral development at these locations. The gradient of bed shear stress decreases sharply going east from the southwestern corner of Moloka'i past Hale o Lono and declines to a fraction of its former magnitude before reaching the Hikauhi site. Reduced North Pacific swell energy has allowed extensive growth of the delicate *Porites compressa* coral and substantial reef accretion at central south-shore locations.

Accretion was possible at Hale o Lono only during the early to mid-Holocene and in limited areas. The trend of progressively younger material moving landward suggests that some factor was curtailing the maximum depth of accretion. We do not yet fully understand the set of conditions that led to the formation of the observed reef sequence. One possible explanation is that accretion here was marginal and could only occur in a narrow zone, limited at shallow depths by wave energy. We speculate that within this zone, light was adequate to permit sufficiently rapid accretion that some new material was left on the reef between major wave events. Today, however, wave energy from North Pacific swell is preventing reef accretion at all depths at Hale o Lono. This suggests that there was an increase in North Pacific swell activity coincident with and responsible for the cessation of accretion there ca. 5000 yr ago.

Kailua

Holocene accretion rates in most of Kailua Bay are reasonably well correlated with and appear to be controlled by the relative sea-level rise (Grossman 2001). Cores show rapid accretion until ca. 3000 yr ago, coinciding with the peak of Holocene sea level for O'ahu (Grossman and Fletcher 1998). That correlation breaks down in the south central part of the bay, where rapid accretion terminated at ca. 5500 yr ago (Figure 5). This is also the area subject to substantially higher breaking wave heights from North Pacific swell, which led Grossman (2001) to conclude that accretion in these areas has been limited by wave energy from North Pacific swell since 5000 or 6000 yr ago.

Punalu'u

Corals and coralline algae are the most important reef-building organisms in Hawai'i today, with living coral reef found at depths from about mean lower low water to −30 m (Grigg and Epp 1989). Hard substrate and relatively clear water provide habitat suitable for coral and coralline algae recruitment from the inner reef flat to the base of the fore reef, as evidenced by the presence of these organisms on all benthic surveys within the 0 to −30-m depth range at Punalu'u. Although reef-building organisms are recruited successfully, cores indicate that reef material has been unable to accumulate permanently anywhere across the reef in the last ca. 5000 yr.

The lack of modern accretion found at Punalu'u is consistent with results from cores collected elsewhere on O'ahu (Sherman et al. 1999). These and numerous other studies mentioned here found that wave energy is the primary factor preventing reef accretion today. The Punalu'u site is highly exposed to North Pacific swell and relatively protected from major hurricanes, which usually pass south of the Islands. Accordingly, we hypothesize that the larger North Pacific swell wave events are preventing reef accretion at this site by subjecting recent growth of corals and coralline algae to concussive impact, high shear stresses, and abrasion.

Cores indicate that a different situation existed here during the early to mid-Holocene. The composition of the reef subsurface (Figure 6) shows that during that time there was active reef accretion in three areas. The core from −11.3-m depth contains a framestone of massive in situ coral overlain by a rudstone, which is consistent with an increase in wave energy. We infer from the relatively large size of the fossil in situ coral colony, and the lack of large corals or rubble accretion on the platform today, that wave energy during early to middle Holocene time was less intensive than currently.

Mid-Holocene accretion is also documented in a core from the reef crest, with ages ranging from 4900 to 5600 yr. Only the sample from −1.6-m core depth was from in situ material, perhaps explaining the apparent inversion in the top two dates, as seen in Table 1. Although the reef crest has the highest combined living cover of coral and coralline algae of any area at the site, evidence from the core suggests that the live community is only a thin and ephemeral coating on a fossil edifice that stopped accreting ca. 5000 yr ago. Sea level around the time the reef crest was accreting was continuing to rise (Figure 1), suggesting that other factors are responsible for the change in accretion. We hypothesize that major wave events now subject the reef crest to concussive impacts from breaking waves and severe scour, effectively inhibiting buildup of accreted material.

Holocene accretion also occurred on the reef flat, where most of at least the top 2 m of reef flat appears to be composed of unconsolidated coral and reef rubble interspersed with sand. Reef flats have often been reported to be depositional areas, where rubble from the fore reef is deposited during large wave events (e.g., Fairbridge 1968), and this appears to be the case for Punalu'u. Two of the three samples dated from the reef crest have ages of slightly over 5000 cal. yr B.P., with the third sample being of modern age. This may reflect a greater availability of live coral on the fore reef in mid-Holocene time, which then decreased dramatically following an increase in wave energy sufficient to prevent new accretion.

The cores from Punalu'u discussed here indicate that limited accretion of coral and coralline algae reefs was occurring before approximately 5000 yr ago, possibly reflecting a lower level of incident wave energy from North Pacific swell. Although sampling is insufficient to be considered conclusive, the results thus far are consistent from cores taken at different parts of the reef, adding credibility to this hypothesis.

Mānā

The branching coral framestone facies of the mid-Holocene reef community is typically found in calm and low-energy fore reef or lagoonal settings (Sherman et al. 1999). In comparison, the facies characterizing the relatively sparse modern coral community is commonly found in moderate to high-energy environments. These differences do not appear to be a result of variations in sea level. Relative sea-level rise on Kaua'i today is close to that on O'ahu, and we assume that their sea-level histories are similar over the Holocene. Today the top of the Mānā fossil reef complex is −15 to −18 m deep, and there is limited coral growth landward of and partially sheltered by the shallowest portion of the fossil reef. None of the live coral communities there today is similar to the vertical growths of *Porites compressa* that appear to be the dominant community there between ca. 5000 and 8000 yr ago. *Porites compressa* is the dominant coral at depths to −21 m at the Hikauhi site, where it is growing luxuriantly and is apparently limited by the lack of hard substrate from colonizing deeper areas. Dollar (1982) showed the *P. compressa* zone off Kailua-Kona extending to a depth of ∼−30 m. The depth range at Mānā of available substrate today extends from −15 to −30 m, so all of it is theoretically available for colonization by *P. compressa*. This species was able to colonize and dominate the reef community there at depths, corrected using the O'ahu sea-level curve, between −13 and −22 m until ca. 5000 yr ago. Sea level 7400 yr ago (the age of our second-oldest Mānā sample) was probably about 7 m shallower than it is today. Although less wave energy would be able to pass over the reef crest than can today, waves at least 6–9 m high would have been able to. Waves larger than that are common in the winter season at Mānā today but are not likely to be compatible with the *P. compressa*–dominated branching coral framestone facies found there in the mid-Holocene. This facies change suggests an increase in wave energy ca. 5000 yr ago that is greater than that explained by relative sea-level rise. The collection and analysis of cores from Mānā would help to resolve the history of reef accretion at this unique site and Holocene climate in the central Pacific.

These examples, from a variety of sites on three different islands, illustrate a similar pattern of reef accretion during the early-mid-Holocene in Hawai'i. Accretion was terminated or greatly reduced ca. 5000 yr ago and appears to be limited at these sites today by North Pacific swell (and possibly hurricane activity). This widespread and consistent pattern of dramatic decreases in accretion preceding the culmination of relative sea-level rise ca. 3000 yr ago suggests that a powerful and geographically prominent environmental factor experienced heightened influence during middle Holocene time. We hypothesize that the El Niño/Southern Oscillation (ENSO) phenomena modulate wave energy from North Pacific swell and hurricanes in Hawaiian waters and that this effect gained magnitude in middle Holocene time and caused the end of reef accretion at some locations in Hawai'i.

Influence of ENSO on Wave Climate

The wave climate along the western coast of North America was found to be well correlated with the Southern Oscillation, with greatly increased wave activity during El Niño events in the southern portion and during non–El Niño years in the northern part (e.g., Seymour et al. 1984, Inman and Jenkins 1997, Seymour 1998, Allan and Komar 2000, Storlazzi and Griggs 2000). In Hawaiian waters, larger and more consistent northwest swells are observed between September and April of El Niño years (Caldwell 1992). Corroborating this observation, Wang and Swail (2001) found that values of extreme seasonal substantial wave heights in the central North Pacific are strongly negatively correlated with winter season values of the Southern Oscillation Index and occur in association with a deeper and eastward-extended Aleutian Low. The Southern Oscillation Index, a commonly used measure of El

Niño/Southern Oscillation intensity, has negative values during El Niño conditions and positive values during La Niñas (IRI/LDEO Climate Data Library 2002). The jet stream and storm tracks in the North Pacific also shift southward and closer to Hawai‘i, enhancing wave energy during the El Niño phase of ENSO (e.g., Inman and Jenkins 1997).

We further investigated the relationship between ENSO and extremes of winter season substantial wave height in Hawaiian waters using the longest available (1981 to present) buoy record, from the National Data Buoy Center buoy no. 51001. Trade wind waves are filtered out and hourly buoy observations are reduced to monthly values by extracting the highest recorded significant wave heights. The latter step enables comparison with climatic indices, including the Southern Oscillation Index and the Pacific Decadal Oscillation, which are also recorded on a monthly basis. The Pacific Decadal Oscillation is a climatic phenomenon with patterns similar to those of ENSO but more focused in higher latitudes and with each phase lasting two to three decades (Mantua et al. 1997).

Values of the Southern Oscillation Index and Pacific Decadal Oscillation corresponding to the 60 highest monthly wave heights are compared with long-term mean values of the index for that specific month of the year. In other words, the Southern Oscillation Index value during a high wave event in January 1988 is compared with the mean of all January Southern Oscillation Index values (the monthly mean). If the next highest wave event occurred in December 1998, that month's Southern Oscillation Index value is compared with that of the mean of all December Southern Oscillation Index values. The large wave events are found to have a mean Southern Oscillation Index value that is more negative (more El Niño–like) and is significant at the 80% level. Months with large wave events also have a mean Pacific Decadal Oscillation value that is higher (more El Niño–like) than the overall mean of monthly means and is significant at the 95% level. That the Pacific Decadal Oscillation has a stronger relationship with winter season extremes of substantial wave height than does the Southern Oscillation Index is not surprising, given the greater deepening of the Aleutian Low typically associated with positive Pacific Decadal Oscillation phases. Wave buoy data appear to corroborate Wang and Swail's (2001) central North Pacific results for Hawaiian waters and to confirm Caldwell's (1992) observation that North Pacific swell activity is greater during El Niño winters.

Along with North Pacific swell, wave energy from hurricanes has been reported to be a major factor limiting reef accretion in Hawai‘i on timescales of years to decades. The conditions required for hurricane formation are frequently met in the eastern tropical Pacific and many hurricanes and tropical storms are generated there (Schroeder 1998). During El Niño periods, however, changes in sea surface temperature and other climatic patterns favor hurricane formation in the central Pacific. This was demonstrated by Chu and Wang (1997), who found that the mean number of tropical cyclones (tropical storms and hurricanes) is greater during El Niño years than non–El Niño years in the vicinity of Hawai‘i. Clark and Chu (2002) took this a step further, showing that correlations between the number of tropical cyclones and the Southern Oscillation Index were significant at the 95% confidence level or higher for the central North Pacific. They also found that three times more tropical cyclones occur during El Niño hurricane seasons (June–November) than during La Niña hurricane seasons. We conclude that the El Niño phase of ENSO enhances both hurricane and North Pacific swell wave energy in Hawaiian waters. By enhancing wave energy from both of these reef-limiting sources, we hypothesize that El Niño conditions are the most likely periods for generation of the occasional large wave events that strike Hawai‘i, removing new accretion of reef-building corals and coralline algae.

It appears reasonable to expect more reef-limiting North Pacific swell activity during El Niño periods, but large wave events do occur during La Niñas. For example, the largest

North Pacific swell, 12.2 m (40 ft), from a record of visual observations of breaking wave height (P. Caldwell, unpubl. data) occurred on 4 December 1969, when the Southern Oscillation Index value indicates light to moderate La Niña conditions. However, not just the magnitude of major wave events, but also their frequency, is important in determining how much they will limit long-term reef accretion.

Although the largest wave events may remove live and recently dead reef growth, if such events are rare enough a reef may be able to recover from the event and go on to accrete enough new material that there will be net accretion on the reef after the next major wave event. If, however, major events are more frequent, there may be insufficient time for recovery and enough new reef growth to accumulate before the next episode of large waves occurs, removing all material that accreted to the reef since the preceding event. We expect that an ENSO-induced change from rare to more common major wave events would be most obvious in areas that were already stressed by the initial more moderate wave climate but still able to produce net accretion. Only a modest increase in the frequency of major wave events in such areas might be all that was required to greatly reduce accretion or stop it altogether. Evidence supporting the feasibility of such a scenario is provided by Connell's extensive (1997) study of disturbance and recovery of coral assemblages. Using quantitative records of coral abundance of at least 4 yr duration from 65 areas in the western Atlantic and Indo-Pacific, he found that the principal reason corals recovered in some areas but not others appears to be related to the type of disturbance. Coral cover was found to recover after 69% of the acute, short-term disturbances. However, recovery following chronic or long-term disturbances, including acute disturbances that occur so frequently that there is little time between them for recovery, only occurred 27% of the time. We speculate that an increase in the frequency and magnitude of major wave events related to the onset of modern ENSO conditions at the sites discussed here may have been sufficient to reduce or preclude further accretion at those locations.

Holocene Changes in ENSO

Evidence of a substantial reduction in reef accretion occurring at select locations in Hawai'i ca. 5000 yr ago can be explained by an increase in wave energy, which is in turn hypothesized to reflect an increase in ENSO intensity. Results of a number of studies suggest that ENSO had substantially less effect on climate during early to mid-Holocene time. Investigating changes in vegetation patterns in Australia, New Zealand, and South America, McGlone et al. (1992) reported that interannual variability before ca. 5000 yr ago was substantially less, suggesting that modern ENSO-related climate patterns did not develop until about then. Based on a 15,000-yr sediment record from a lake in the Ecuadorian Andes, Rodbell et al. (1998) and Moy et al. (2002) confirmed that Holocene ENSO events were less frequent than currently until ca. 5000 yr ago.

Investigating metals from sediment layers in the anoxic Cariaco Basin at ~10 °N off the Venezuelan coast, Haug et al. (2001) found increased precipitation between ca. 10,500 and 5400 yr ago. They interpreted this signal as indicating a more northerly and consistent position of the intertropical convergence zone, suggesting that this was a period of weak ENSO and low ENSO variability.

Coral records from the western Pacific are consistent with those studies, showing higher sea surface temperatures and reduced variability around 5400 and 6500 yr ago, suggestive of a substantially less vigorous ENSO (Gagan et al. 1998, Tudhope et al. 2001) and a strong ENSO signal by ca. 4200 yr ago (Corrège et al. 2000).

Variations in Holocene ENSO intensity have been reproduced and investigated with numerical models as well. Using a coupled ocean-atmosphere global circulation model, Liu et al. (2000) simulated reduced ENSO intensity at 6000 and 11,000 yr ago, which they attributed to the effects of higher boreal summer insolation and stronger austral winter insolation. Clement et al. (2000) found that extreme warm El Niño events were smaller in amplitude and occurred less frequently in the mid-Holocene, based on results from a simple model of the tropical coupled ocean-atmosphere system. They argued that changes in the tropical Pacific are a response to orbitally driven changes in the seasonal cycle of solar radiation in the Tropics.

Evidence for a reduced amplitude and frequency of ENSO events during early to mid-Holocene time, before 5000 yr ago, has been found in areas all around the tropical Pacific using a variety of approaches. Although the exact timing, nature, and causes of the change are still being actively debated, there appears to be wide agreement that it did occur. This is consistent with Holocene variations in reef accretion discussed here at several locations in the main Hawaiian Islands, which are suggestive of a shift in the wave regime. Although by no means conclusive, results of this study suggest that ENSO-related variations may be an important consideration in evaluating Quaternary reef accretion and paleoclimatology in Hawai'i and other Pacific islands and warrant further investigation.

Impacts of Future Climate Change

An important area of active scientific research and debate involves the future of ENSO in a greenhouse-warmed Earth. Influences of increasing concentrations of greenhouse gases were investigated by Timmermann et al. (1999) and Collins (2000) using different models. Both models generate reasonable simulations of ENSO dynamics consistent with observations during control runs, in contrast to earlier studies (e.g., Meehl et al. 1993, Knutson et al. 1997). Running them under enhanced greenhouse gas conditions, both models predict strengthening of the equatorial thermocline, resulting in an intensified ENSO signal, with higher amplitude and more frequent events. Those and earlier studies (e.g., Meehl et al. 1993, Knutson et al. 1997) show results that are somewhat different. However, the balance of evidence to date suggests that greenhouse forcing may enhance ENSO strength. If that happens, the generation of reef accretion–limiting North Pacific swell and hurricane events, shown in decades past to be positively correlated with El Niño activity, may increase as well.

Enhancement of ENSO may in turn increase hurricane activity in the central Pacific, and efforts have been made to directly assess the influence of greenhouse warming on hurricane formation. Although, as discussed here, increased concentrations of greenhouse gases can be expected to raise sea surface temperature, it has been shown that upper-atmosphere warming compensates to some degree for warming of the ocean, requiring higher sea surface temperatures to support tropical cyclone genesis (Holland 1997). The number of and general areas affected by hurricanes may not, therefore, increase substantially in the near future. However, because El Niños today enhance tropical cyclone activity in the central North Pacific, in a greenhouse-warmed world subject to enhanced ENSO the number of hurricanes found there may increase as well. It is also possible that higher sea surface temperatures will change hurricane intensities. Studying 51 western Pacific tropical storm cases under current conditions, Knutson et al. (1997) compared them with 51 storm cases under conditions of high concentrations of CO_2. They found increases of 5 to 12% in wind speed and 7 to 20 millibars for central surface pressure under greenhouse conditions, using both a high-resolution hurricane prediction model and theoretical estimates. Although their study did not address a number of variables that are likely to influence the outcome, the results suggest that hurricane activity may increase slightly under conditions of increased greenhouse gas concentration.

Virtually all studies profess the need for further study and more data. However, the balance of evidence at this time suggests that the frequency and intensity of El Niño events are possibly going to increase in the coming decades due to increasing concentrations of greenhouse gases. Taken as a whole, this suggests that the Hawaiian Archipelago will experience more hurricane and North Pacific swell events capable of removing reef material that accreted since the preceding event. This additional stress on already limited reef systems has implications for management of coral reef habitats. It suggests that the reduction of anthropogenic stresses, on top of the possibly increasing natural ones, is of increasing importance. Second, it reinforces the notion that management should be concentrated on relatively sheltered areas where anthropogenic influence is of comparable or greater magnitude than natural forces.

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