El Niño Control of Holocene Reef Accretion in Hawaii

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ABSTRACT

New observations of reef accretion from several locations show that accretion in the mid-Holocene 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 exposed to occasional 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 areas sheltered from intense wave energy are actively accreting. Analysis of cores reveals patterns of rapid early Holocene accretion that terminate by middle Holocene time, ca. 5,000 years ago. Previous analyses have suggested that changes in Holocene accretion were a result of reef growth "catching up" to sea level. New data indicate that a modification of that interpretation may be appropriate in some areas. Reef accretion histories from the islands of Kauai, Oahu, and Molokai may be interpreted to suggest that a change in wave energy severely reduced or terminated Holocene accretion by 5,000 years ago. In every case, the decrease in reef accretion occurred prior to the best estimates of the decrease in relative sea level rise (RSLR) during the mid-Holocene high stand of sea level in the main Hawaiian Islands. However, reef accretion should decrease following RSLR if reef growth were "catching up" to sea level. More compelling is evidence indicating that rapid accretion occurred at these sites in the early Holocene time, but 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 surface. We infer that forcing other than RSLR has altered the natural ability to support reef accretion on the Oahu shelf. The limiting factor in these areas today is wave energy. Numbers of both large North Pacific swell events and hurricanes in Hawaii are greater during El Niño years. We infer that if these major

reef-limiting forces were suppressed, net accretion would occur in some wave-limited areas in Hawaii. Studies have shown that El Niño /Southern Oscillation (ENSO) was significantly weakened during early-mid Holocene time, only attaining an intensity similar to today's ca. 5,000 years ago. We speculate that this shift in ENSO may explain patterns of Holocene Hawaiian reef accretion that are different from those of the present and apparently not related to RSLR. During the "Altithermal regime," from ca. 8,000 to 5,000 years ago, global temperatures were warmer than they are today. If that warming was a major factor in suppressing ENSO, then the Altithermal may be a model of future climatic conditions and their impact on coral reefs resulting from global warming. However, more recent studies suggest that increased concentrations of greenhouse gases are more likely to enhance the amplitude and frequency of ENSO.

New observations of reef accretion from several locations show that accretion in the mid-Holocene occurred in areas where today it is precluded by the wave regime, suggesting an increase in wave energy. 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. Holocene coral and coralline algae communities are often restricted to a patchy, scattered veneer of growth, resting unconformably on a Pleistocene fossil reef substrate (e.g. Sherman et al., 1999). A number of researchers have reported that Holocene reef accretion in Hawaii has predominantly been a function of sea level and exposure to wave energy (Grigg, 1998; Grossman, 2001). Other factors such as sedimentation, overgrowth by introduced algal species, and pollution restricted to relatively small and isolated areas (e.g., Jokiel, et al., 1993a and b; Grigg, 1995; Stimson et al., 2001).

Environmental Controls

Sea Level and Tides

The influence of tides on coral reefs in the Hawaiian Islands is relatively minor, as the coastal environment is microtidal, with a range of 0.7 m between mean high water (MHW) and mean lower low water (MLLW). On the other hand, relative sea level (RSL) has played a dominant role in controlling reef growth on scales of thousands of years. Eustatic sea level at the Last Glacial Maximum (LGM), ca. 21,000 years ago, is estimated to have been between 113 m and 135 m below the present level (Clark et al., 2001). In Hawaii, as seen in Figure 1, RSL is believed to have risen rapidly from the LGM to its present level ca. 5,000 years ago, and continued rising to about 2 m above that. The Holocene highstand was achieved ca. 3,000 years ago before dropping back down below the present level (Grossman and Fletcher, 1998) prior to the advent of tide gage recording.

Coral reefs can only grow in Hawaii between the critical depth of 30 m (Grigg and Epp, 1989) and the surface, with optimal growth occurring at about 12 m (Grigg, 1998). Thus, dramatic changes in sea level during Holocene time have exerted obvious constraints on reef growth. Smaller fluctuations in RSL since then are believed to have enabled and then terminated reef growth in other areas (Grigg, 1998). Today, modern sea level rise is recorded by tide gages on Oahu and Kauai at approximately 1.8 mm yr^{-1}.

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 general Hawaiian wave climate is characterized by four types of waves as well as those from occasional hurricanes and tsunamis.

Active about 75% of the time, especially in the summer, trade winds generate swells with typical deepwater wave heights of 1.2 m to 3.0 m and periods of 6 to 8 seconds (Bodge and Sullivan, 1999). These moderate energy swells usually benefit reefs by enhancing circulation and nutrient uptake. Likewise, increased circulation resulting from south swell generally has a positive effect on coral reefs in Hawaii (Grigg, 1998). Produced by storms in the southern hemisphere, usually between April and October, they are typically long period (12 to 20 seconds) waves with deepwater wave heights of <1 m to 2 m (Bodge and Sullivan, 1999).

Wave energy is also generated by Kona storms; low-pressure systems that develop during the northern hemisphere winter and generally approach the islands from the west or southwest. Occasional large Kona storm waves typically have deepwater wave heights of 3 m to 5 m and periods of 6 to 10 seconds (Bodge and Sullivan, 1999). The severest Kona storm on record however, occurring in January, 1980, had a "catastrophic" effect on coral reef communities on southwestern coasts, resetting the coral community succession process to a "near-zero" state (Dollar and Tribble, 1993). Although large Konas have caused damage to reefs, they are infrequent enough to be of secondary important in terms of limiting reef accretion (Grigg, 1998).

Long period (12 to 20 second) North Pacific swell (NPS) on the other hand has been extensively reported to exert a significant 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 m 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 Hawaii (Dollar, 1982; Dollar and Tribble, 1993; Grigg, 1995; Grigg, 1998).

Hurricane Iwa for example struck the islands in 1982 and reduced reef areas with 60-100% coral cover on Oahu's south shore to rubble (Grigg, 1995). Along the southwestern shore of Hawaii, both hurricanes Iwa and Iniki (in 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 NPS predominantly impacts west to northeast-facing shores. Among these events, longer period swells can refract significant energy around to coastlines facing away from the incident wave direction (e.g., Storlazzi et al., 2002). It has been concluded by numerous studies that wave energy from hurricanes and long period NPS appear to be the primary agents limiting reef accretion in Hawaii today (Dollar, 1982; Grigg, 1983; Dollar and Tribble, 1993; Grigg, 1995, 1998; Storlazzi et al., 2002)

Tsunamis originating from around the Pacific, including the islands themselves, strike the Hawaiian Islands. Twenty six significant (runup > 1.0 m) tsunamis have been reported in the islands since 1819 (Fletcher et al., 2002). A number of these caused minor damage in a single area on one island. Others however have had amplitudes in excess of 10 m and caused significant damage, suggesting that high bottom shear stresses capable of breaking and scouring reef structure occur during major tsunamis. One anecdotal account reports that a major tsunami, probably the March 1975 event originating in the central Aleutians, caused a significant reduction of live coral cover on windward Oahu reefs (B. Kapuni, pers. comm.). This potentially significant 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 is little historical data available. Hence, impacts of tsunamis on reef morphology and accretion remain an important question to be addressed.

Study Sites

Sites where significant Holocene accretion has occurred 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; Fletcher et al. submitted; Storlazzi et al., 2002).

New observations of reef accretion from several locations however show that accretion in the mid-Holocene occurred in areas where today it is precluded by the wave regime, suggesting an increase in wave energy. Sites providing such evidence include contrasting locations on the western end of Molokai's south shore, Kailua Bay and the reef at Punaluu on the northeastern side of Oahu, and Mana Reef on the northwestern coast of Kauai (Figure 2). From dated core samples and interpretation of paleoecology at these sites we infer a significant increase in wave energy in the central North Pacific starting ca. 5,000 years ago.

Molokai

The Molokai sites, at Hale O Lono and Hikauhi, are located near the western end of the island's south shore and part of the longest continuous fringing reef in the Hawaiian archipelago (Maragos, 1998). Despite its prominence, this feature has received little past attention from researchers and until the present study, there had been no effort made to determine its internal structure or growth history. Although the sites are only 10 km apart, they are characterized by markedly different reef structure.

The more eastern site, Hikauhi, is named after a native Hawaiian fishpond that is now overgrown with mangroves. Just east of the fishpond is a prominent gulch that drains the relatively arid watershed landward of the site and delivers significant volumes of terrigenous mud during occasional rain events. Landward portions of the relatively wide (~0.8 km) reef flat have been physically buried by the influx of mud. Wave exposure outside of the reef crest is low to moderate however, so there is generally less suspended sediment in the water column here than at Lono (Engels et al., in prep.). Most of the substrate is covered with live coral and, seaward of the reef crest, gradually slopes down to an abrupt drop-off at about -17 m into a large sand field at -20 m, with a gentle depth gradient. Several outcrops several tens of meters in diameter and with high percentages of live coral cover are found further offshore in depths ranging from about -20 m to -25 m.

The Hale O Lono site is named for the harbor on its landward side. 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. The site features a narrow reef flat (~0.3 km) and generally sparse coral cover. The substrate is composed of a gently sloping terrace of fossil reef from 0 m to ~5.5 m, followed by a series of low relief, shore-parallel ridges of fossil reef with sand filled channels between them. Depths at the top of each ridge are at 8.5 m, 14.0 m, 17.7 m, and 21.0 m.

Oahu

Kailua Bay is a 4 km long embayment on the windward or northeastern side of Oahu. A fossil reef terrace extends from the sandy beach ~3 km offshore, gently sloping down 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 to the more easterly of, or refracted, NPS. The reef platform is bisected in center by the Kawainui paleostream channel that was cut through the largely Pleistocene age shelf during periods of lower sea level (Grossman, 2001).

The Punaluu site, further north on the windward side of Oahu, 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 ~0.2 m above MLLW. Seaward of the reef crest is a gently sloping fossil reef terrace that extends ~1 km further offshore and terminates in a near vertical wall that drops from -20 m to ~-30 m. Seaward of that is a broad sand field with occasional low relief limestone rises. Punaluu 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, so it is directly exposed to northeasterly trade wind swell. Field observations at Punaluu indicate that even after several day periods of negligible trade winds, background trade wind swell almost always pumped enough water over the reef crest to overwhelm tidal effects and maintain flow off the reef flat into shore-normal channels on either side. By maintaining a vigorous flow of offshore water across the reef crest and flat, this circulation pattern tends to isolate the reef area from damaging effects of fresh water and sediment from terrestrial runoff. NPS events do impact Punaluu however, with the most northeasterly swell striking the reef directly.

Kauai

The Mana site, on the island of Kauai, is described as one of two barrier reefs in Hawaii (Maragos, 1998). From offshore, the seafloor slopes steadily upward along a hard and relatively smooth pavement fossil limestone pavement to a depth of 15-18 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 24-29 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 exposed, landward facing wall of the reef is built of long, vertical, columns of *Porites compressa* extending continuously from ~28 m depth to the structure crest at ~18 m depth where they abruptly terminate at the wave-scoured seafloor. 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. Kauai has experienced significantly more hurricane activity than the other main Hawaiian Islands, at least over the last half century, with tracks of three hurricanes passing directly over the island or just a few kilometers away. In addition to the occasional hurricane, the Mana area also receives the full force of NPS every winter.

MATERIALS AND METHODS

Drill cores were collected at all locations except Mana Reef, Kauai, using a diver operated Tech 2000 submersible, hydraulic rotary coring drill 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 in length. 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 Punaluu averaged $\pm$ 0.3 m, with higher uncertainties from unconsolidated reef flat cores. The reef in Molokai, particularly at the Hikauhi site, is more porous than those at the Oahu sites, yielding a mean depth of certainty of $\pm$ 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 Mana, Kauai. However, vertical faces ~10 m high expose fossil reef growth (Figure 3). Hand samples were collected at a range of depths and locations along exposed faces by divers using hammers and chisels. Sample depths, recorded from digital depth gauges, have an uncertainty of $\pm$ 0.3 m.

Radiocarbon and X-ray diffraction (XRD) sample material was cleaned with ddH_2O in an ultrasonic cleaner until the supernatant was clear. Organic material was removed in a 15% H_2O_2 bath, followed by a second series of ddH_2O baths. A 15% HCl acid etch was performed in house or at the radiocarbon analysis facility to eliminate any final contamination, typically removing 10%-40% of the material. Oven drying at 38° C and weighing of samples completed the preparations.

Carbonate mineralogy was determined using a Scintag Pad V powder X-ray diffractometer using Cu Kα radiation. Calcite-to-aragonite composition ratios were determined using a standard curve generated from the peak area ratios (111 aragonite peak, 104 calcite peak) of known mixtures of aragonite and calcite (Sabine, 1992). Mole percentages of $MgCO_3$ of calcite phases were determined using the offset of the *d* spacing of the 104 calcite peak from that of pure calcite (Bischoff et al., 1983).

Radiocarbon ages were determined at the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) at Woods Hole, on samples with >97.5% aragonite (corals) or >12 mole % $MgCO_3$ (coralline algae). Ages were corrected for isotopic fractionation by NOSAMS using $\delta^{13}C$ values. Calibration to calendar years for Kailua and Mana samples was done with the INTCAL Calibration data set (Stuiver et al., 1998) and Calib 4.12 program (Stuiver and Reimer, 1993). A regional marine reservoir correction (ΔR) of 115 calendar years for regional Hawaiian marine waters was used (Stuiver and Braziuman, 1993). Samples from Molokai and Punaluu were calibrated with Calib version 4.3 and a regional marine reservoir correction of 220 ± 100 (Dye, 1994) was applied for Punaluu samples.

Benthic community structure was surveyed at the Molokai and Oahu sites using a modification of the line intercept technique. Dominant substrate types and descriptions along replicate transect lines 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. Surveys were conducted across a range of depths and habitats to gain an understanding of present day patterns of reef building organism recruitment and growth.

RESULTS

Molokai

As noted above, live coral cover at Lono is sparse. The coral community that does exist 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 go from 15% in the 0 - 5 m depth zone, to their maximum of 41% at a depth range of 5 m - 10 m, and down to a mean value of 8% at depths surveyed below 10 m. oral colonies appear to be no more than a few years old, with most of the hard substrate composed of fossil reef covered with a short algal turf.

Ten cores were drilled and recovered from outside Hale O Lono (Lono) Harbor along the southwest coast of Molokiai. Core locations were spaced along a roughly shore-normal transect, at depths ranging from 5.5 m out to 21.0 m below present mean sea level (MSL). The substrate gets progressively younger moving landward and shallower, ranging from an age of 8,100 calendar years before present (cal. yr. BP) at the top of the ridge at 21.0 m, to 4,800 cal yr BP at the top of the terrace at a depth of 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; Grossman and Fletcher, submitted). Cores from 17.7 m depths however have sequences of branching framestone, in some cases topped by bindstone with ages framestone of ca. 7,900 cal. yr. BP. Results of coring and analysis at Lono are summarized in Figure 4. This site was able to support reef accretion from when it was initially inundated ca. 8,000 years ago during the Holocene transgression until ca. 5,000 years ago. Since then reef material has been unable to accrete, despite the obvious ability of corals and coralline algae to recruit there, and suitable substrate available throughout a wide depth range.

Results from the Hikauhi site are quite different from those at Lono. Although the species mix is similar at both sites, growth morphologies tend to be more branched or massive and less encrusting at Hikauhi, and percentages of live coral cover are much higher. Mean percentages of live coral cover are 52% for the 0 - 5 m depth range, 68% for the 5 m - 10 m range, and 86% for surveys at depths greater than 10 m.

Twenty four cores were recovered from the Hikauhi site, at depths of 4.0 m to 19.8 m. Most of the material recovered in this set of cores is massive coral framestone or floatstone. 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 Lono with seven having modern ages. The other thirteen range from 60 up to 910 cal. yr. BP at the oldest and yield an overall mean accretion rate of ~5 mm yr^{-1}. Results of coring and analysis at Hikauhi are summarized in Figure 5.

Kailua

As reported in Grossman (2001), the reef terrace in Kailua Bay can be divided into 3 regions based on the dominant facies on the upper 1 m of the reef surface. The north and south platforms are mostly 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 also features scattered massive and encrusting colonies of live corals. The central platform on the other hand, is dominated by living reef. The north and south margins of the platform are largely covered with encrusting corals and coralline algae. Towards the middle however, on each side of the Kawainui paleostream channel, are communities of mixed massive and encrusting corals. At the seaward margin of the central platform, branching coral communities dominate the substrate on both sides of the channel

Thirty two cores were drilled through the nearshore reef platform in Kailua Bay. Twelve of these, referred to as "primary cores," that best describe the biolithogic variability and accretion trends of the reef, were sub-sampled for radiometric dating and other analyses (Grossman, 2001). Three of the primary cores, numbers K20, K21, and K27, recovered from locations on the central platform (see Figure 2) and south of Kawainui paleostream channel, are of particular interest to the present study. Logs of these three cores and their accretion histories, based on ^{14}C dates of sub-samples taken from specified depths, are shown in Figure 6. The latter are compared to an estimated mid-Holocene to present sea-level curve included at the top of the figure.

In general, cores from the north and south platforms are dominated by bindstone facies and have thin layers of Holocene age material, with those from the south being somewhat thicker. Those from the central platform tend to have much thicker Holocene age sequences, although the contact between Holocene age and pre-Holocene material was below the maximum depth of drilling for all central platform cores. Cores K20, K21, and K27 are all capped by thin (0.2 - 0.6 m) layers of bindstone, indicative of high energy conditions. Underneath the bindstone are found 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, but core K27 is too short to tell a similar pattern exists under its location. Changes in accretion rates from these three cores appear to co-occur 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 NPS on coral communities was also investigated by Grossman (2001) using the Simulating Waves Nearshore (SWAN) model. Typical swell conditions (3.5 m significant deepwater wave height, 15 second period) were modeled as solitary waves over high-resolution gridded bathymetry. Of the twelve primary cores from this study, cores K20, K21, and K27 are subject to the greatest breaking wave height areas according to SWAN model output. Significant modeled breaking wave heights near core 20 are ~3.7 m, and >4.0 m for cores K21 and K27. Locations of other cores from the bay are subject to wave heights of 2.5 m or less (except core K28 from 20 m depth, which shows very low accretion rates).

Punaluu

Both corals and coralline algae are found within every major sub-sector of the reef complex (reef flat, reef crest, etc.) at Punaluu between the 30 m isobath and the shoreline. Benthic surveys across the reef found that, on average, live corals cover 15% of the substrate and live coralline algae covers 20%, although there is scatter in the data and distributions of both are patchy. Scattered large (2-3 m high) heads of *Porites sp.* are found on the wave-protected reef flat. Much smaller corals, usually appearing to be a few years old and a couple decades old at the most are found in all areas, as are patches of the encrusting coralline algae *Porolithon onkodes.* Of particular interest is a segment of the reef between the reef crest and the area seaward of it to a depth of ~2m. This zone contains ~95% cover of live encrusting coral and especially, encrusting and branching coralline algae which covers almost 80% of the substrate. It is a high-energy environment, subject to concussive impacts of smaller breaking waves and strong currents and surge. Still higher energy conditions exist however on the reef terrace fronting the reef crest, the landward half of which is subject to the direct impact of larger NPS. Despite the wide distribution of reef building organisms, analysis of drill cores indicates that active reef accretion does not appear to be occurring anywhere on Punaluu reef today.

Cores from Punaluu were collected along a shore-normal transect from near the shoreline in < 1 m water depth, across the reef platform and down to a depth of 34 m. XRD analysis of core sub-samples indicates that mineralogy of core material from most of the reef terrace has been diagenetically altered. These results are consistent with analyses of other cores from other areas of the carbonate terrace found around most of Oahu and imply a pre-Holocene age (Sherman et al., 1999, submitted; Grossman, 2001). TIMS Th-U ages of *in situ* corals from the windward Oahu reef terrace south of Punaluu correlate to marine isotope stage 7, with an age range of 186,000 to 242,000 cal. yr. BP, suggesting that most of the Punaluu reef is of a similar age. However, radiometric dating of core sub-samples indicates that reef accretion occurred in some areas on the Punaluu terrace during the Holocene epoch. The lithology of selected cores containing Holocene age material is described below and shown in Figure 7, while calibrated ages, depth down core, and other information from sub-samples shown in Table 1.

Ten holes were scattered around the transect line on the reef flat. The shallow reef crest on its seaward side protects the reef flat from severe wave energy yet allows wave driven water to pass though, ensuring a high flushing rate. 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 m - 0.3 m, all holes drilled in the reef flat encountered layers of unconsolidated rubble with occasional sand layers. This unconsolidated material extended to at least a depth of 2 m. Dates of three rubble samples from two cores indicate a modern age, ages of 5,300 and 5,600 cal. yr. BP for the others.

Three replicate holes were drilled in a single large head of *Porites evermanni* coral at the northern margin of the platform at a depth of -3.4 m. About 1.5 m of solid coral was recovered from each core. This head appears to have started accreting on a small fragment of rubble, as every core recovered a few pieces of reef rubble before encountering only sand for another ~0.5 m.

Four holes were drilled, at the reef crest (1.2 m depth) and across the reef platform at gradually increasing depths out to -19.8 m at its seaward corner. The final core was recovered from the base of the platform and ~200 m southeast of the transect line, from a depth of 34.1 m. The most common texture found in these cores is bindstone, suggesting a high energy depositional environment (Sherman et al., 1999; Grossman, 2001). The reef crest core is a bindstone/rudstone mix with predominantly gravel size and smaller sediment and fragments of the branching coralline alga *Porolithon gardeneri,* bound together in a matrix of encrusting coralline algae. Three samples from this core have ages of 4,900 to 5,400 cal. yr. BP.

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. A sample from one of the clasts shows an age of 6,400 cal. yr. BP while one from the massive coral framestone is overlying has an age of 6,700 cal. yr. BP.

The core from 15.2 m depth has a thin (3 - 10 cm) layer of encrusting coralline algal bindstone overlying a massive coral framestone, which may reflect an increase in wave energy from moderate to high during deposition. The originally aragonitic coral has been almost entirely altered to calcite, suggesting a pre-Holocene age. A core from the seaward corner of the reef terrace, at a depth of 19.8 m is a bindstone, also of apparently pre-Holocene age.

The deepest core was recovered from near the base of the terrace at a depth of 34.1 m. This core has a grainstone texture and appears to be from a cemented beach deposit. Unfortunately, efforts to obtain a reliable age from larger fragments from this core have been unsuccessful thus far.

Mana

Hand samples of corals were retrieved from a variety of depths and locations along vertical walls along the landward side of the Mana barrier reef. Samples collection was limited to material that could be quickly extracted with hand tools from exposed reef faces there. Although collected in a vertical line on an exposed wall, the 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 exposed faces were composed of *in situ* growth of predominantly branching *Porites compressa* coral that falls within the branching coral framestone facies described by Sherman et al. (1999) and Grossman (2001). This facies is typically found in relatively calm and low energy fore reef or lagoonal settings. Live coral colonies with platy, encrusting, and massive morphologies are found in the lee of the fossil barrier reef today. Without further data it is impossible to tell if the modern community is accreting, or just the most recent accumulation of ephemeral growth on a fossil substrate. However, the modern 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. The exposed seafloor above the barrier supports little live cover, while areas in the lee of the barrier display moderate to sparse live cover. Live colonies with branching morphologies are not found and live coral cover is much less than we expect it would have been when the areas we sampled were actively accreting. Collection depths and calibrated ages of dated samples are shown in Table 1. Calibrated ages of samples include two modern dates, and a range of mid-Holocene dates between 4,500 and 8,300 cal. yr. BP.

DISCUSSION

Molokai

Although the Lono site does not appear to have supported any reef accretion over the last several thousand years, cores from Hikauhi all show rapid and continual accretion over the last two to three thousand years (Engels et al., in prep.). The striking differences in modern reef accretion between the two sites 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 shear stress from NPS. Refraction of energy from these events around the east and west ends of Molokai apparently generates sufficient shear stress and near-bed orbital velocities to inhibit coral development at these locations. However, the gradient of bed shear stress decreases sharply going east from the southwestern corner of Molokai past Lono. It levels off at a level significantly reduced from its former magnitude before reaching the Hikauhi site, allowing extensive growth of the delicate coral species *Porites compressa* as well as substantial reef accretion, at central south shore locations. Engels et al. (in prep.) discuss these observations and conclusions in detail.

In contrast to today, accretion was possible at Lono during the mid-Holocene. Instead of growing in "layer cake" fashion such as is seen at the Hikauhi site, with accretion occurring simultaneously across the entire profile, reef accumulation at Lono was more restricted. The trend of progressively younger material found at the top of increasingly shallow cores suggests that some factor was curtailing the maximum depth at which accretion was able to occur. We speculate that during the mid-Holocene, as sea-level was rising, the dry land off Molokai was being inundated for the first time since at least marine isotope stage 5a, ca. 80,000 years ago. During the intervening period, reservoirs of terrestrial sediments eroded from higher elevations on the island were probably deposited in many areas. The rapidly rising sea level during the Holocene transgression may have resulted in continuously elevated turbidity levels, limiting reef accretion to a narrow window below the wave base but above relatively shallow depths at which light became too limited. Today however, wave energy from NPS is preventing reef accretion at all depths at Lono and water quality is high. Although young coral colonies are found at all depths where there is hard substrate, their maximum size is limited, indicating that they are periodically removed before reaching a larger size. This suggests that there was an increase in NPS activity coincident with and responsible for the cessation of accretion at Hale O Lono, ca. 5,000 years ago.

Kailua

Grossman (2001) found that, as a whole, Holocene accretion rates in Kailua Bay are reasonably well correlated with and appear to be controlled by the rate of change of sea level. That correlation appears to breaks down however in the south central part of the bay. Cores from other parts of the bay show rapid accretion until ca. 3,000 years ago, coinciding with the peak of Holocene sea level for Oahu (Grossman and Fletcher, 1998). Rapid accretion in the three cores in Figure 6 however terminates at ca. 5,000 years ago.

As reported earlier, SWAN model results indicate that breaking wave heights ≥ 3.7 m from a typical large NPS, are incident to the southern portion of the reef at Kailua. Other primary cores from the bay (the only cores for which dates were obtained) are subject to wave heights of 2.5 m or less. It was concluded (Grossman, 2001) that accretion in these areas has been limited by wave energy from NPS since 5,000 or 6,000 years ago, although no explanation is offered for the apparently abrupt increase in wave energy

Punaluu

Corals and coralline algae are the most important reef-building organisms in Hawaii today with living coral reef found at depths from about MLLW to perhaps 30 m (Grigg and Epp, 1989). Hard substrate and relatively clear water, seaward of the reef crest in particular, provide habitat suitable for coral and coralline algae recruitment from the shoreline out across the entire reef platform, as evidenced by the presence of these organisms on all benthic surveys within the 0 - 30 m depth range at Punaluu. Although reef-building organisms are successfully recruited, cores indicate that reef material has been unable to permanently accumulate anywhere across the reef terrace in the last ca. 5,000 years.

The lack of modern accretion found at Punaluu is consistent with results from cores outside Kaneohe Bay, 18 km south of Punaluu, and from the western side of Oahu (Sherman et al., 1999; Sherman et al., submitted). These and numerous other studies mentioned above find that wave energy is the primary factor preventing reef accretion today. The Punaluu site is highly exposed to NPS and relatively protected from major hurricanes, which usually pass south of the islands. Accordingly, we hypothesize that the larger NPSs are preventing reef accretion at the site by periodically subjecting corals and coralline algae that have recruited there since the preceding major wave event to concussive impact, high shear stresses, and abrasion.

Cores from Punaluu indicate that a somewhat different situation existed there during the early to mid-Holocene. During this time, as evidenced in Figure 7, there was active reef accretion in three areas. The core from 11.3 m depth contains a framestone of massive *in situ* coral dated at 7,000 cal. yr. BP, overlain by a rudstone dated at 6,600 cal. yr. BP. 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 significantly less intensive than at present.

Further, the appearance of coral rudstone overlying the framestone is consistent with an increase in wave energy.

Mid-Holocene accretion is also documented in a core from the reef crest. The core was recovered from ~1 m depth, although portions of the reef crest we were unable to core are as much as 1 m higher. Ages of samples from this core are shown in Table 1. Note that only the sample from 1.6 m core depth was from *in situ* material, perhaps explaining the apparent inversion in the top two dates. Sea-level data from Hawaii suggest that sea level around the time the reef was accreting was very close to its present level (Figure 1). The core is a bindstone/rudstone mix, reflecting a high energy depositional environment (Sherman et al., 1999; Grossman, 2001). Although the reef crest has the highest combined 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. 5,000 years ago. We hypothesize that major wave events subject the reef crest to concussive impacts from breaking waves and severe scour, minimizing buildup of accreted material.

Holocene accretion also occurred on the reef flat. Recovery of core was difficult at all of the ten holes drilled there. The shallow reef crest on its seaward side protects the reef flat from severe wave energy yet allows wave driven water to pass though, ensuring a high flushing rate. hole. Even if started in hard substrate or coral heads, the drill rapidly ran into sequences of rubble and sediment, which tends to fall out of the core barrel as it is extracted from the hole. The fact that we ran into this problem on every hole drilled there suggests that most of at least the top two meters of reef flat is composed of unconsolidated coral and reef rubble interspersed with mostly sand size sediments. 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 Punaluu. It is of interest that two of the three samples dated from the reef crest have ages of slightly over 5,000 cal. yr. BP, with the third sample being of modern age. We infer that this reflects a greater availability of live coral on the fore reef in mid-Holocene time, consistent with other cored results. Availability of rubble source material may have decreased dramatically after that time if there was an increase in wave energy sufficient to prevent new accretion.

Each of the cores from Punaluu discussed above suggests that accretion of coral and coralline algae reefs was occurring prior to approximately 5,000 years ago, most likely reflecting a lower level of incident wave energy from NPS. Although sampling is insufficient to be considered conclusive, consistent results from cores taken at different parts of the reef add credibility to this hypothesis.

Mana

Present RSLR on Kauai is about the same as it is for Oahu, so we expect that, as with our sites on Oahu, other factors are having a more significant impact of reef accretion. Given the exposure of this area to hurricanes and NPS, we hypothesize that the differences in accretion between the early to middle Holocene time and today suggest that there was an increase in wave energy from one or both of these sources about 5,000 years ago. The collection and analysis of cores from Mana would help to resolve the history of reef accretion at this unique site, and Holocene climate in the central Pacific.

The above examples, from a variety of sites on three different islands, illustrate a similar pattern of reef accretion during the early-mid Holocene in Hawaii. Accretion was terminated or greatly reduced approximately 5,000 years ago, and appears to be limited at these sites today by NPS (and or hurricane activity at Mana). The discovery of such a widespread and consistent pattern and the fact that accretion ended prior to the culmination of sea level approximately 3,000 years 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 modulates wave energy from NPS and hurricanes in Hawaiian waters and that this effect gained magnitude in middle Holocene time and caused the end of widespread reef accretion in Hawaii.

Influence of ENSO on Wave Climate

The significant influence of ENSO on wave patterns has been well documented in some areas of the Pacific. The wave climate along the western coast of North America for example is 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, 1984, 1998; Inman and Jenkins, 1997; Allan and Komar, 2000; Storlazzi and Griggs, 2000). Surprisingly, there is little published information regarding effects of ENSO on Hawaiian wave climate, although Caldwell (1992) reports larger and more consistent northwest swells in Hawaiian waters between September and April of El Niño years. Wang and Swail (2001) find that values of extreme seasonal wave heights in the central North Pacific increase in association with a deeper and eastward extended Aleutian Low, that is characteristic of El Niño conditions. The jet stream and storm tracks in the North Pacific also shift southward and closer to Hawaii, enhancing wave energy during the El Niño phase of ENSO (e.g. Inman and Jenkins, 1997).

Given the relative lack of quantitative data correlating NPS and ENSO activity in Hawaii, we investigate this connection using the longest record of NPS available for the islands, obtained from the National Ocean Data Center Hawaii Liaison Office. The data are visual observations from the north shore of Oahu of the maximum daily wave height, at the moment of maximum cresting, from 1968 through the present. Uncertainty is estimated as ± 10% for wave heights in excess of 3 m and ± 20% for those greater than 6 m. Maximum monthly wave heights extracted from this record are filtered with a 5 year running mean to smooth out seasonal signals. The resulting data set, available from the IRI/LDEO Climate Data Library (2002), is compared to monthly values of the Southern Oscillation Index (SOI), a commonly used measure of ENSO intensity (Figure 8). Given the tendency of successive measurements in a time series to have similar values, the degrees of freedom of the data were reduced to accommodate this non-independence prior to testing for significance. We find the correlation between maximum monthly NPS wave heights and the SOI are significant at the 90% significance level, corroborating other reports of El Niño conditions enhancing NPS.

Along with NPS, wave energy from hurricanes has been reported to be a major factor limiting reef accretion in Hawaii on timescales of years to decades. In order for hurricanes to form, several conditions need to be met. For example, sea surface temperatures (SSTs) of about 27° C or higher, and a layer of warm surface water of sufficient thickness to prevent upwelling of cold water induced by a growing hurricane, must exist. These and other required conditions are frequently met in the eastern tropical Pacific and many hurricanes and tropical storms are formed there (Schroeder, 1998). During El Niño conditions however, changes in SST 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 (TCs, tropical storms and hurricanes) is greater during El Niño years than non-El Niño years in the vicinity of Hawaii. Clark and Chu (2002) took this a step further, showing that correlations between the number of TCs and the SOI were significant at the 95% confidence level or higher for the central North Pacific. They also found that three times more TCs 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 NPS 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 Hawaii, removing reef building corals and coralline algae that have managed to accumulate since the previous major event.

Holocene Changes in ENSO

Evidence of a significant reduction in reef accretion occurring in Hawaii ca. 5,000 years ago is hypothesized to reflect an increase in ENSO intensity. Results of a number of studies suggest that ENSO had significantly less of an affect on climate during the early-mid Holocene. Investigating changes in vegetation patterns in Australia, New Zealand and South America, McGlone et al. (1992) reported that interannual variability prior to ca. 5,000 years ago was significantly less, suggesting that modern ENSO-related climate patterns did not develop until about then.

Rodbell et al. (1999) and Moy et al. (2002) infer that the periodicity of ENSO events was reduced in early to mid Holocene time, based on a 15,000 year sediment record from a lake in the Ecuadorian Andes. From the temporal spacing of clastic sedimentation events they argue that ENSO periodicity began increasing ca. 7,000 years ago, with present day periodicities most apparent after ca. 5,000 years ago.

Studies of Holocene molluscan assemblages in archaeological and paleontological deposits along the Peruvian coast (Sandweiss et al., 1996, 2001) suggest the presence of stable, warm tropical water as far south as 10ºS during the early mid-Holocene (ca. 8,000 to 5,000 years ago), suggesting that ENSO did not occur during this period.

Coral records from the western Pacific are consistent with the above studies, showing higher SSTs and reduced variability around 5,400 and 6,500 years ago, consistent with significantly less vigorous ENSO (Gagan et al., 1998, Tudhope et al., 2001) and a strong ENSO signal by ca. 4,200 years ago (Corrège et al., 2000).

Investigating metals from sediment layers in the anoxic Cariaco Basin at ~10º N off the Venezuelan coast, Haug et al. (2001) found increased precipitation between ca. 10,500 and 5,400 years ago. They interpret this signal as indicating a more northerly and consistent position of the intertropical convergence zone (ITCZ) suggesting that this was a period of weak ENSO and low ENSO variability.

Variations in Holocene ENSO intensity have been reproduced and investigated with numerical models as well. Liu et al. (2000) used a coupled ocean-atmosphere global circulation model to investigate Holocene climate. Their model simulated reduced ENSO intensity at 6,000 and 11,000 years ago, which they find is due to effects of higher boreal summer insolation and stronger austral winter insolation. Using a simple numerical model of the tropical coupled ocean-atmosphere system, Clement et al. (2000) find that extreme warm El Niño events were smaller in amplitude and occurred less frequently in the mid-Holocene. They argue 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 5,000 years ago and perhaps starting ca. 8,000 years ago, has been found in areas all around the tropical Pacific using several different paleoclimatological records. 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 above at several locations in the main Hawaiian Islands, which are suggestive of a shift in the wave regime coincident with changes in ENSO. Although by no means conclusive, results of the present study suggest that ENSO-related variations may be an important consideration in evaluating Quaternary reef accretion and paleoclimatology in Hawaii and other Pacific islands and warrants further investigation.

Impacts of Future Climate Change

It has been suggested for some time that the weak ENSO conditions of early-middle Holocene time, the so called "altithermal" period or "thermal maximum," may provide a model of the effects of a greenhouse-warmed Earth on ENSO (Diaz et al., 1992). This idea was again proposed by Rodbell et al. (1999) to explain evidence they found in Ecuadorian alpine lake sediments of reduced ENSO conditions prior to ca. 5,000 years ago. They invoke model results of Sun (2000) to suggest that, if greenhouse-induced warming of SSTs at high latitudes occurs faster than in tropical areas, a subsequent weakening of the equatorial thermocline may weaken ENSO. Similarly, Liu et al. (2000) find that enhanced austral winter insolation resulted in stronger warming of South Pacific surface waters during the altithermal period. Equatorward subduction of these waters weakened the main thermocline, contributing to a reduced ENSO. This mechanism could reduce ENSO, if greenhouse warming raised SSTs in the South more than the equatorial Pacific.

Results of recent modeling efforts however suggest a different alternative. Influences of increasing concentrations of greenhouse gases were investigated by Timmermann et al. (1999) and Collins (2000) using different models, both of which 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 the models under enhanced greenhouse gas conditions, they both predict strengthening of the equatorial thermocline, resulting in an intensified ENSO signal, with higher amplitude and more frequent events. Although these and earlier studies (e.g. Meehl et al., 1993; Knutson et al., 1997) all show results that are somewhat different, the balance of evidence to date suggests that greenhouse forcing is most likely to enhance ENSO strength. If that happens, the generation of reef accretion limiting NPS and hurricane events, shown in decades past to be positively correlated to El Niño activity, may increase as well.

Although enhancement of ENSO may in turn increase hurricane activity in the central Pacific, efforts have been made to directly assess the influence of greenhouse warming on hurricane formation. Although, as discussed above, increased concentrations of greenhouse gases can be expected to raise SSTs, it has been shown that upper atmosphere warming compensates to some degree for warming of the ocean, requiring higher SSTs to support TC genesis (Holland, 1997). The number of and general areas of affected by hurricanes may not therefore increase significantly in the near future. However, since El Niños today enhance TC 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 SSTs will change hurricane intensities. Studying 51 western Pacific tropical storm cases under present conditions, Knutson et al. (1997) compared them to 51 storm cases under conditions of high concentrations of $C0_2$. They found increases of five to twelve percent in wind speed and seven to twenty 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.

Although virtually all studies profess the need for further study and more data, the balance of evidence at this time suggests that the frequency and intensity of El Niño events are most likely 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 NPS events capable of removing reef material that accreted since the preceding event. This additional stress on already limited reef systems has coral reef management implications. It suggests that the reduction of anthropogenic stresses, on top of the possibly increasing natural ones, is of increasing importance. Secondly, it reinforces the notion that management be concentrated on relatively sheltered areas where anthropogenic influence is of comparable or greater magnitude than natural forces.

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