# CHAPTER 10

# Sea Level and its Effects on Reefs in Hawai‘i

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The position of sea level, and changes in that position over time, is a primary force that influences reef initiation and development. Sea level can vary from millimeters to meters as a result of winds, tides, and waves, and over thousands of years sea level may rise and fall more than 100 m (330 ft) as continental ice sheets and glaciers expand and recede. In many locations, sea level rises or falls relative to the coastline and nearby reefs because of tectonic movements that make the land uplift or subside. As Earth's climate warmed following the last glacial period, sea level rose along island flanks and over coastal shelves around the world, enabling coral-reef animals and plants to settle, grow, and ultimately create the structural features we observe as reefs today. Most modern tropical reefs originated between 14,000 and 8,000 years ago, when sea level was 30 to 90 m (100–300 ft) below its present level.

In recent decades scientists have discovered that climate change and the rate of sea-level rise and fall have fluctuated widely (Alley and others, 1996; Bard and others, 1990, 1996; Blanchon and Shaw, 1995). Consequences for reefs have been equally variable. Studies of modern and Holocene reefs in Hawai‘i have shown that under rising and stable sea level, corals generally grow at rates of 1–2 cm/yr (0.4–0.8 in/yr) (Grigg, 1983; Grossman and Fletcher, 2004). Similar studies around the world reveal that where corals could not grow fast enough to keep up with sea-level rise, they "drowned." In other cases, corals grew vertically at the same rate that sea level was rising, thus keeping pace. Occasionally, reef communities have outpaced the rate of sea-level rise and spread laterally, building wide shelves. Because some species of reef-building animals and plants are better suited to specific depth and wave-energy settings, they may form assemblages unique to discrete subenvironments within a reef. These assemblages naturally become stratified into zones as reefs build and respond to the changes in sea-level position (and wave energy), often recording these in the structure of the reef. Coral skeleton also provides a unique record of ocean surface-water properties, including temperature, salinity, and ocean-water volume, because its formation is partly controlled by the temperature and chemistry of the surrounding seawater.

## Late Quaternary and Postglacial Eustatic Sea-Level History

Sea-level changes result primarily from four mechanisms: (1) eustatic or global sea-level change, (2) tectonic movements of the land or sea floor (for example, subsidence or uplift), (3) tides, and (4) storms and waves. Of these mechanisms, eustatic sea-level rise has had the most profound effect on the origin and development of Hawaiian coral reefs.

Eustatic sea-level change results from change in the volume or mass of water within the ocean basins. The two principal mechanisms that control eustatic sea-level change are (1) glacio-eustatic changes resulting from the growth and decay of high-latitude and alpine glaciers that add or remove water to and from the oceans and (2) thermal expansion or contraction of the ocean water as it warms or cools. On very long timescales, change in the volume of the ocean basins that hold ocean water also influences eustatic sea level. Our knowledge of eustatic sea level is derived from geologic and paleoenvironmental reconstructions of glaciers and their moraines, lake sediment, deep-sea sediment, and coral reefs and through the use of tide gages and radar altimetry from satellites.

It is now widely accepted from paleoenvironmental reconstructions that glacio-eustatic sea-level changes have ranged over approximately 120 m (400 ft) about every 100,000 years (fig. 1) during the late Quaternary (Lea and others, 2002). This resulted from high-latitude ice sheets expanding up to 1 to 3 km (0.6 to 1.9 mi) in thickness and later melting in response to variations in Earth's climate associated with changes in its orbit around the Sun. As sea level rose and fell as much as 120 m (394 ft) around the world, it alternately flooded and exposed large areas of coasts, continental shelves, and slopes, causing great environmental change.

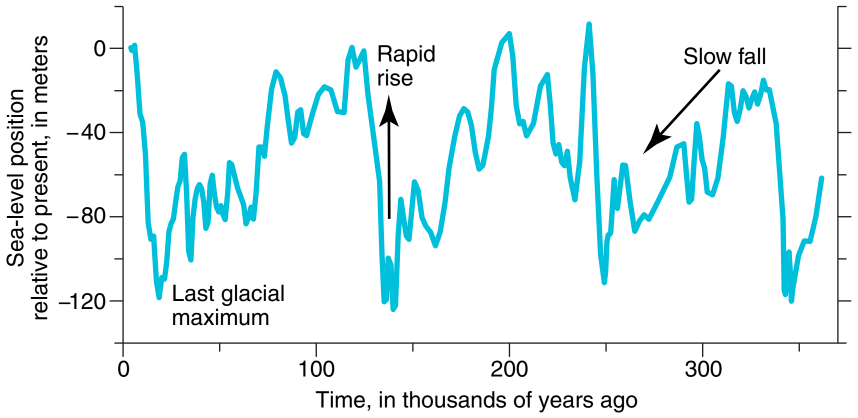

**Figure 1.** Late Quaternary sea level (after Lea and others, 2002) is marked by 100,000-year oscillations that on average range through 120 m (394 ft). Periods of warm climate like that of today are characterized by high sea level, while during glacial conditions like those of the last glacial maximum, sea level was 120 m lower than today. Sea level generally falls slowly over approximately 80,000 years toward lowstands, yet sea-level rise following full glacial conditions usually occurs rapidly in about 20,000 years (as indicated by the arrows).

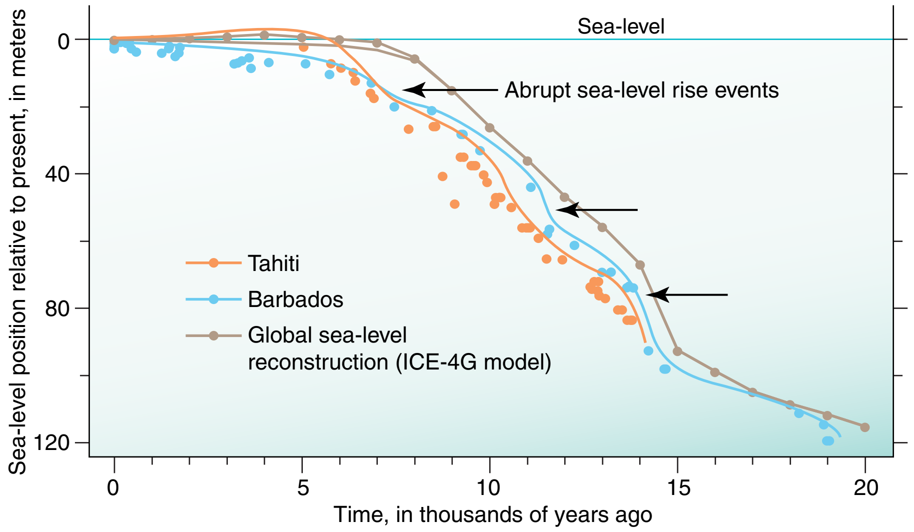

**Figure 2.** Curves of postglacial eustatic sea level derived from coral reef studies from Tahiti (orange symbols; Bard and others, 1996) and Barbados (blue symbols; Bard and others, 1990). The curves are marked by three periods of abrupt rise at approximately 14,500, 11,500, and 8,000 years ago. These reconstructions are supported by studies of glacier retreat and marine sediment that suggest rapid climate warming and ice melt at those times. Global sea-level reconstructions including the ICE-4G model (brown line; Peltier, 1994, 1999) also match the general character of these sea-level oscillations.

Detailed reconstructions and modeling show that periodic falls in glacio-eustatic sea level span approximately 80,000 years and are marked by rapid oscillations that sequentially fall deeper as climate approaches full glacial conditions. In contrast, eustatic sea level rises approximately 120 m very abruptly after the culmination of glacial conditions; these rapid fluctuations occur on average in only 10 to 20 thousand years. More importantly, recent studies show that the rise in eustatic sea level following the last glacial maximum (about 21,000 years ago) was characterized by episodic and abrupt jumps in position (fig. 2). During periods of steady ice decay, sea level rose between 1 and 10 mm/yr (0.04–0.4 in/yr); however, two (perhaps three) marked periods

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of rapid sea-level rise >20 to 40 mm/yr (>0.8 to 1.6 in/yr) occurred (Bard and others, 1990; Blanchon and Shaw, 1995; Edwards and others, 1993; Fairbanks, 1989). These abrupt jumps in sea level are thought to have been associated with rapid melting of ice sheets or catastrophic release of glacial lake water (water impounded in temporary lakes behind retreating ice sheets). The history of postglacial sea level is supported by numerical models of Earth's response to deglaciation that calculate the volume transfer of ice to ocean water through time (for example, ICE-4G, Peltier 1994, 1999). Such models take into account how climate evolved and how the land surface responded to the loading and unloading of massive ice sheets and the equivalent weight of ~120 m of ocean water added to the ocean floors (Peltier, 1999).

An important aspect of eustatic sea-level rise today is thermal expansion of seawater, also known as the "steric effect." Volumetric expansion of surface ocean waters occurs in response to increased temperature associated with global warming and/or changes in surface ocean currents. Thermal expansion is thought to be a major cause of present sea-level rise and may continue for centuries. It can affect sea level on timescales of days to years as it influences large-scale currents, such as the Gulf Stream in the Atlantic, as well as climate regimes, such as ENSO (El Niño-Southern Oscillation), that can temporarily warm the water and raise sea level by 10–30 cm (4–12 in). Sea-level rise and its interaction with other oceanographic and climate processes will affect areas regionally and across the entire globe.

Although eustatic sea level is considered a global phenomenon driven by additions of water to the ocean basins, regional to local variations in the rate of sea-level change occur as a result of tectonic movements, which change the position of the sea floor and/or land level. Tectonic movements of the land are observed in many areas around the world and are especially common where Earth's lithospheric plates interact and faults are active. Tectonic movements also occur in plate interiors, where enormous amounts of sediment discharging from large rivers like the Mississippi River depress the coast and shelf, and in settings like Tahiti and Hawai‘i, where growing volcanoes place a large load on the sea floor.

Tides and waves, especially those associated with storms (or tsunamis), also alter sea-level position, although these generally influence reefs temporarily on timescales ranging from days to years, and reefs can usually recover from the damage they cause. More important to reefs than water-level changes associated with tides and waves are the destructive effects of scour and shear resulting directly from wave and current impacts. In areas of high tidal range or settings protected from waves and storms, often it is the low tide levels that restrict upward accretion of reefs.

Because of these different influences on sea level, coastal and reef scientists working on particular coastlines are generally most concerned with local or regional relative sea-level change. Satellite monitoring and tide-gauge records from around the world now show that global eustatic sea level is rising at ~2–3 mm/yr, or about one inch per decade, as a result of thermal expansion and glacial meltwater additions to the oceans. Because of tectonics, regional relative sea-level change can vary as much as 5–10 mm/yr (0.2–0.4 in/yr) faster or slower than that rate.

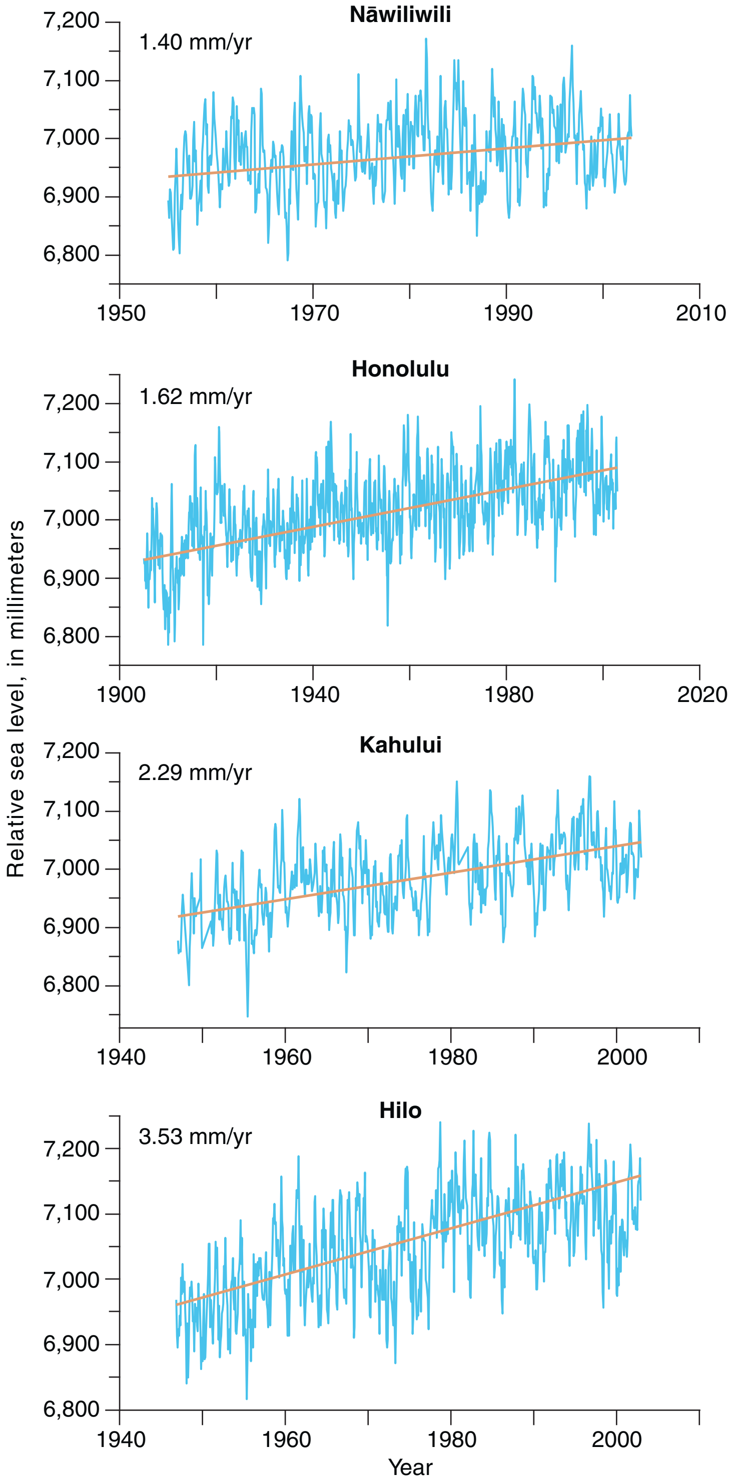

**Figure 3.** Least median of squares regression of tide-gauge data from Nāwiliwili (Kaua‘i), Honolulu (O‘ahu), Kahului (Maui), and Hilo (Hawai‘i), showing that the rate of relative sea-level rise increases toward the Big Island of Hawai‘i. The difference in the rates is thought to be related to differential island subsidence associated with volcano building, which is centered today near the southern coast of the Big Island. Tide-gauge data from the Permanent Service for Mean Sea Level (http://http.pol.ac.uk/psmsl/, last accessed April 29, 2008).

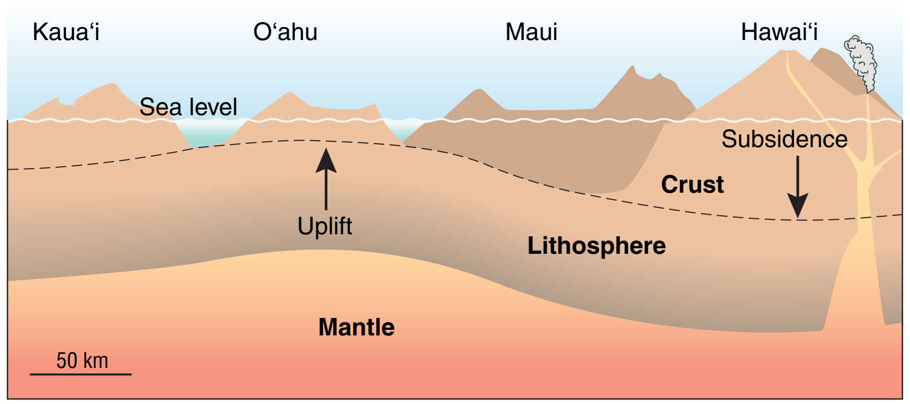

**Figure 4.** Lithospheric flexure is a hypothesis that is largely validated by tide-gauge measurements as shown in figure 3, studies of fossil shorelines that indicate uplift near O‘ahu and subsidence near the Big Island of Hawai‘i, and modeling of plate interactions at hot spots. Lithospheric flexure leads to rapid subsidence near the recent volcanic load emplaced on the sea floor near Mauna Loa and Kīlauea on Hawai‘i and uplift at some distance away from the load (for example, near O‘ahu). A similar phenomenon occurs in Tahiti, where a young volcano is building and inducing higher rates of relative sea-level rise than on neighboring islands. Lithospheric flexure, through its influence on relative sea-level rise, affects coral reefs in different ways on each island. For example, an early postglacial reef on the Big Island of Hawai‘i that formed when sea level was ~90 m (295 ft) below present terminated coral growth about 14,000 years ago and is now found 150 m (492 ft) below sea level, capped by deep-water coralline algae (see text).

In Hawai‘i the most important influence on relative sea-level rise is the variation in island stability due to tectonics. Tide gauge records measure the change in sea-level position owing to movements of the tides, winds, waves, and decadal-scale climate change. Tide gauges on Kaua‘i, O‘ahu, Maui, and the Island of Hawai‘i show considerably different rates of sea-level rise after averaging out the effects of tides, winds, and waves (fig. 3). The global eustatic component of sea-level rise should be the same across the relatively small area spanning the main Hawaiian Islands, and the difference in the relative rates observed in the tide gauges is best explained by vertical island movements. Studies of fossil reefs and shorelines on the main Hawaiian Islands and modeling studies support the notion that the lithosphere (Earth's crust and upper mantle) is flexing under the weight of the Island of Hawai‘i's young and massive Mauna Loa and Kīlauea volcanoes (fig. 4). Lithospheric flexure, also observed in Tahiti and other island chains, creates maximum subsidence where the greatest load is placed on the sea floor and uplift at some distance away from the load. The amount of flexure is governed by the size of the load and the rigidity of the sea floor and lithosphere. In the main Hawaiian Islands, flexure has resulted in rates of relative sea-level rise that vary from 1.4 and 1.6 mm/yr on Kaua‘i and O‘ahu, respectively, to 2.3 mm/yr at Kahului, Maui, and 3.5 mm/yr at Hilo, Hawai‘i.

Hawaiian records of postglacial sea-level history have been primarily derived from studies of drill cores and samples from Kaua‘i, O‘ahu, and

Moloka‘i (Easton and Olson, 1976; Engels and others, 2004; Grossman and Fletcher, 2004; Rooney and others, 2004). Samples have been collected from depths between 50 m (164 ft) and mean sea level, with cores ranging from 1 to 18 m (3.3 to 59 ft) in length. The texture, composition, age, and diagenetic (alteration) history of the sediment in the cores have been analyzed, and interpretations have been made of the depths and environments in which they were formed and subsequently altered. Radiometric dating of the calcium carbonate skeletal remains within the reef (coral, coralline algae, *Halimeda*, echinoderms, and molluscs), using the isotopic decay rates of radiocarbon ($^{14}$C) and/or uranium series ($^{230}$Th/$^{234}$U), enables reef accretion histories to be developed. Corrections to these reef accretion records accounting for differential island movements and adjustments for their habitat (depth) zonation allows estimation of past sea-level positions and construction of a history of sea-level rise.

## Postglacial Sea Level and its Impact on Hawaiian Reef Development

The interaction of sea-level rise, wave exposure, and the morphology and composition of the sea floor strongly control the location, timing, and eventual development of Hawaiian reefs. This has been especially true during the Holocene on O‘ahu and Moloka‘i, as postglacial sea level rose to its present position over relatively stable and mature shelf systems. The O‘ahu shelf is marked by steep walls at 55 m and 24 m (180 ft and 79 ft) below modern sea level, and it is now thought that the shelf at these depths is composed of fossil limestone formed before the Holocene (Fletcher and Sherman, 1995; Sherman and others, 1999). The depths at which notches have been cut into these walls correspond to depths at which hypothesized abrupt eustatic sea-level rise events began at ~11,500 and ~8,000 years ago (fig. 2), though the exact origin of the notches is difficult to conclusively document. Rapid sea-level rise over this stepped topography resulted in varied reef response. Some reefs were likely abandoned offshore of these walls, where corals could not keep pace with sea-level rise. Other locations witnessed the formation of sequences of back-stepping reef tracts where the walls were more gradually sloping, such as at Hale O Lono (Engels and others, 2004; Engels and Fletcher, this vol., chap. 4). Radiometric dating of drill-core samples indicate that the fringing reefs we observe today above the wall at 24-m depth initiated coral growth between 9,000 and 8,000 years ago, with greater vertical development where wave exposure is low.

The longer reef-accretion records developed so far in Hawai‘i show that between ~8,400 and 8,000 years ago, an abrupt transition in coral community occurred, with shallow-water corals and coralline algae rapidly replaced by deep, calm-water corals (fig. 5). The difference in the representative depth zones of the shallow-water assemblages (water depths of ~2–3 m or ~6.6–10 ft) and the deep-water assemblages (water depths of ~14 m or 46 ft) suggests a rapid drowning of as much as ~11–12 m (~36–39.3 ft). A rapid sea-level jump is also noted in Caribbean coral-accretion records (Blanchon and Shaw, 1995) and may be related to the preservation of an erosional notch circling O‘ahu at a depth of 24 m (79 ft) (Fletcher and Sherman, 1995). The full range of impacts of this abrupt sea-level rise event on reef development around the entire Hawaiian Islands has yet to be determined. Recently, a study of a reef tract at 150-m depth off the Island of Hawai‘i showed that a shallow-water coral community was abruptly replaced by a deep-water coralline algae community between 15,000 and 14,000 years ago (Webster and others, 2004). This history is consistent with rapid drowning during Meltwater Pulse 1A (14,500 years ago, see fig. 2). It also illustrates the importance of the combined effect of subsidence and episodic sea-level rise on limiting the ability of corals to maintain their position within the photic zone and continue accretion.

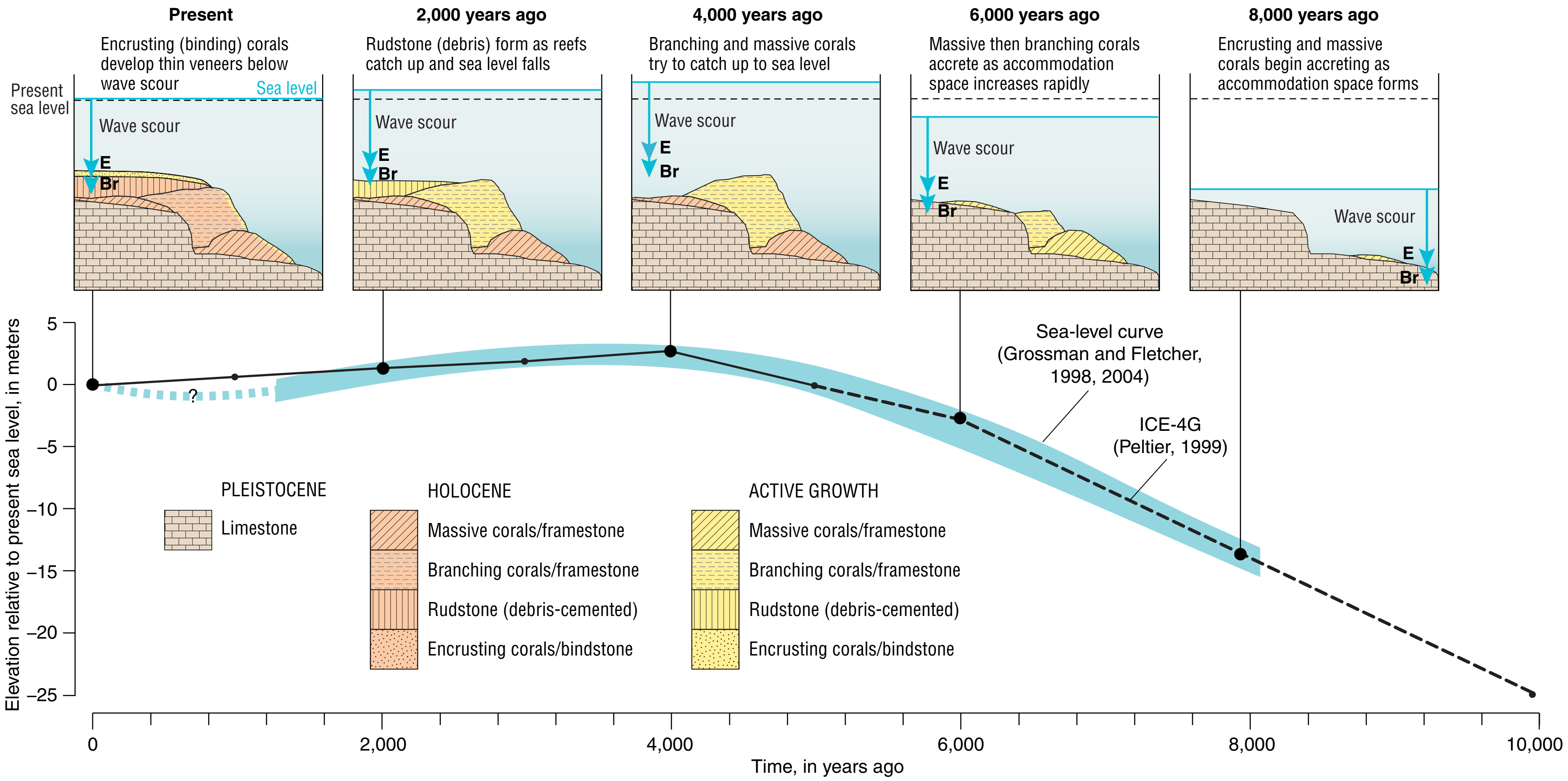

**Figure 5.** Model of Holocene reef development (after Grossman and Fletcher 2004; Grossman and others, 2006) in relation to accommodation space. Accommodation space for reef accretion is controlled by erosive forces, including wave scour, and occurred throughout the Holocene largely below the rising sea level (Grossman and Fletcher, 1998, 2004; Peltier, 1999). Blue band is Hawaiian sea-level curve of Grossman and Fletcher (1998, 2004). Black dashed line is predicted sea level from the ICE-4G model of Earth's lithospheric and sea-level response to deglaciation (Peltier, 1999). Blue arrows in time plots of reef accretion show the depths at which wave scour controls encrusting coral/bindstone (E) and branching coral framestone (Br) accretion based on modern coral ecology (Grigg, 1983; Grossman, 2001). Early Holocene reef accretion began between 9,000 and 8,000 years ago with encrusting bindstone and early massive coral framestone development. At 6,000 years ago, massive and branching coral framestones were rapidly accreting following modest rates of sea-level rise. At 4,000 years ago, as sea level stabilized above present, branching coral framestone development on open coasts slowed as it filled the accommodation space set by sea level and wave scour (approximately ~14 m or ~46 ft below sea level). Vertical reef accretion was largely replaced by lateral reef development. At 2,000 years ago, as sea level fell from the mid-Holocene sea level highstand (~3,500 years ago), reef tops were eroded, which furnished debris that accumulated across the reef as rudstone and became bound by cement and algae. In the most recent time period with sea level rise, encrusting coral bindstones formed thin veneers on top of rudstones or older fossil reef.

From analyses of the current inventory of coral core samples in Hawai‘i, we have determined that modern reefs began to develop with encrusting and massive framestone accretion between 9,000 and 8,000 years ago (fig. 5) as sea level inundated the insular shelves (framestone is limestone that is organically bound by coral skeletal growth). These encrusting and massive framestone facies (body of rock with specific characteristics) are dominated by *Porites lobata* and *Monitpora capitata* corals and *Porolithon onkodes* and *P. gardineri* coralline algae. Rapid rates of eustatic sea-level rise between 8,000 and 6,000 years ago allowed extensive units of branching coral framestone to accrete, outpacing massive and encrusting coral forms, as the reef community strove to catch up with sea level position. During this time, thick sequences of branching *Porites compressa* created reef strata between 3 and 10 m thick, generally in areas protected from waves. *P. compressa* also grew in wave-exposed settings because rapid sea-level rise expanded accommodation space (space for corals to grow below the depth of wave scour). In shallower areas, massive and encrusting coral framestones accumulated at rates lower than for branching coral framestone because of wave-induced bottom shear stress.

As the melting of the last great ice sheets ended about 6,000 years ago, the rise of eustatic sea level slowed and sea level eventually stabilized. It is thought that eustatic sea level reached its present position between 6,000 and 5,000 years ago and that it has remained relatively static since. This stabilization of sea level is thought to have altered the environmental conditions for reef growth and, consequently, the types of reef facies that developed. Coral sequences identified in core samples show a transition from deeper, calmer water corals to shallower, more wave-tolerant corals between 5,000 and 4,000 years ago, consistent with the interpretation that reef growth and sea-level stabilization brought about a change to shallower, more energetic conditions as reef tops caught up to sea level and shoaled into the zone of active wave scour. By about 4,000 years ago vertical reef framestone accretion nearly terminated, and since 3,500 years ago lateral framestone accretion has outpaced vertical framestone accretion. Vertical accretion since 3,500 years ago has been largely restricted to the development of coral gravels (rudstones), through the accumulation and cementation of eroded reef fragments and sediment, and the formation of thin veneers of encrusting corals (*Porites lobata*, *Montipora capitata*, *M. patula*) and coralline algae (*Porolithon onkodes*) that form bound layers of thin-bedded carbonate (bindstone). Exceptions to this pattern occur where reefs have developed in settings protected from large open-ocean swell.

The depths and times of formation of these reef facies transitions are consistent with the influence of wave scour during the sea-level history of Hawai‘i. Large waves that reach Hawai‘i’s shores are generated during the year from north and south Pacific swell and from tropical storms (see Storlazzi and others, this vol., chap. 11). These waves induce erosive forces that break coral, transport sediment, and alter reef development and community structure at depths reaching 10–14 m (Grigg, 1983; Storlazzi and others, 2003; Grossman and Fletcher, 2004; Storlazzi and others, 2005). As a result, on the stable islands of Kaua‘i, O‘ahu, and Moloka‘i reef framework development slowed and, where exposed to long-period, large open ocean swell, reef framework accretion terminated altogether ~4,000 years ago as reefs caught up with sea level and the destructive forces of wave energy limited their vertical accretion (Engels and others, 2004; Grossman and Fletcher, 2004). In central southern Moloka‘i, however, drill core studies show that framestone continues accreting today (Engels and others, 2004; Jokiel and others, this vol., chap. 5). This is likely because of dissipation of wave energy by wave-ray divergence and/or sheltering by the nearby islands of Lana‘i and Kaho‘olawe. (see Storlazzi and others, this vol., chap. 11, for a further discussion about waves on Moloka‘i). An additional factor that may have caused reefs to stop accreting may be a change in the climate regime about the same time (5,000 years ago) that led to increased north Pacific swell associated with especially strong El Niño years (Rooney and others, 2004).

A unique aspect of middle to late Holocene sea level (5,000 to 2,000 years ago) was a lowering of equatorial sea level in the Pacific (Fletcher and Jones, 1996; Grossman and Fletcher, 1998; Grossman and others, 1998) associated with shifts in Earth’s gravity field following the removal of glacial ice loads in the high latitudes. Sea level fell 1 to 2 m around Pacific islands, contributing to the shoaling of reef flat environments and causing a reduction in water circulation and wave energy landward of the reef crest. Fringing reefs throughout Hawai‘i experienced shallowing and the shift of coral growth to deeper water on the fore-reef slopes. Back-reef environments tended to collect fine sediment throughout the late Holocene as a result, while active coral growth shifted offshore.

Historical tide-gauge measurements show that global sea-level rise over the past 100 years has ranged from 1 to 3 mm/yr and may be accelerating (Douglas, 1991; Douglas and others, 2000). These rates are an order of magnitude greater than rates characterizing the past 5,000 years. This rise is thought be forced by global warming and the associated thermal expansion of surface waters (“steric” effect). Recent studies suggest, however, that retreat of alpine glaciers, especially because of disproportionate warming of the high latitudes, is adding to the observed rise. For coral reefs this would seem beneficial, adding more vertical accommodation space under the water’s surface for new growth. This may in fact be the case in Hawai‘i, where we often observe high coral cover in shallow wave-exposed environments, although most of this reef cover is composed of encrusting corals and coralline algae that are better suited to high wave stresses. The realization that these are thin covers on fossil (5,000 to 3,000 years old) substrates suggests that they are transient features and perhaps of only recent (<100 years) origin owing to the last century of sea-level rise.

## Summary

Sea level directly influences reef development, and in Hawai‘i it has played a primary role in the initiation, structural development, and community composition of Holocene reefs. Significant reef development occurred around Kaua‘i, O‘ahu, and Moloka‘i beginning between 9,000 and 8,000 years ago as postglacial sea-level rise inundated island flanks. Evidence of abrupt rises in sea level, including one at ~8,000 years ago, is preserved in the reef as rapid transitions from shallow-water coral and coralline-algal communities to deep-water coral assemblages. The vertical accretion of deep-water assemblages slowed and ultimately terminated about ~5,000 to ~3,000 years ago as sea level stabilized, and the reefs themselves altered their growth habits as they grew into the shallow depths zones above 14 to 10 m. At these depths, waves influenced reef community composition toward more wave-tolerant species and significantly limited new vertical reef development. This has resulted in a narrow depth window for Holocene reef growth and has limited major reef accretion to protected settings in deeper water and sheltered embayments. The possibility of increased wave impact associated with a change in climate ~5,000 years ago is being tested to explore its role on reef development along with sea-level history. Modern thin encrusting reef communities appear to be transient features less than 100 years old that are scoured off the sea floor periodically by massive swell events, leaving a fossil shelf exposed at the surface. Reef development history may be significantly different on Maui and Hawai‘i in response to higher rates of relative sea-level rise and the continued addition of accommodation space as those islands actively subside.

Suggested citation:

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