

## Light, Calcification, and Carbonate Sediment Production on the Moloka'i Reef Flat

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There are many variations in how people perceive and define what are commonly called coral reefs. One widely accepted definition of coral reefs is that they are geological structures built by the accumulated skeletal remains of corals and other organisms that live on the reef surface. The reef on south Moloka'i is an excellent example of this definition and is discussed in this chapter. Another definition for coral reefs focuses on the marine biological communities that have reef-building potential, regardless of whether or not those communities are presently building reefs. The coralline algae and coral-rich areas on basalt boulders along portions of the Kona coast of Hawai'i are an example of this biological definition. However, these coral areas are not considered reefs in the geological sense. Grigg (1998) and Engels and others (2004) have pointed out areas of O'ahu and Moloka'i where reef accumulation is limited by wave action. To further complicate things, coral reefs may be considered relict, meaning the structure remains long after the animals and plants that built them were replaced by marine communities that are not reef building. Portions of the reef in Kailua Bay, O'ahu, are examples of this third type (Grossman and Fletcher, 2004).

These three types of reefs may sometimes be differentiated on the basis of geomorphic observations. Often, however, it may be difficult to determine when a reef has reached senility and stopped generating sediment. The ability of coral reef communities to accumulate sediments and build reefs depends on the rate of sediment production versus the rates at which these sediments are transported or dissolved from the reef. Although reef building may seem obvious (the very presence of a coral reef attests to the dominance of deposition over erosion and dissolution), perceiving what is actually occurring now may be difficult. It is easier to evaluate the cumulative results of these processes over millennia than it is to measure short-term rates—those on time scales of decades to centuries. These short-term rates have become more important in light of the present-day crisis of coral reef ecosystems (Bellwood and others, 2004). Here we describe some short-term measurements and observations that focus on the ability of the benthic marine community of the Moloka'i reef flat to continue producing reef structure.

### Setting

The fringing reef on the south shore of Moloka'i is characterized by several gradients across the kilometer-wide reef flat. Seaward from the shore, water depth increases from 0 to about 2.5 m, wave energy increases, and turbidity decreases toward the reef crest (Ogston and others, this vol., chap. 20; Ogston and others, 2004; Presto and others, 2006). One of the most important gradients is the percentage of coral cover. Coral cover increases from 0 percent along the shore to as much as 40 percent at the reef crest, although it is patchy along the outer margin of the reef flat. Seaward of the reef crest, coral cover in the fore reef may be as great as 50 to 80 percent in water depths of 5–10 m (Rodgers and others, 2005). The increase in coral cover is inversely related to the amount and type of suspended sediment, which in turn affects turbidity, water clarity, and irradiance. The silt and clay fractions of inner reef-flat sediments contain as much as 80 percent terrigenous sediment and are typically dark red-brown in color. The terrigenous sediment is preferentially resuspended

because it is finer grained than carbonate sediment (Field and others, this vol., chap. 17; Bothner and others, 2006). Several hundred meters offshore, the sediments are almost 100 percent carbonate, white or slightly tan in color. This color change is apparent on aerial photographs of the reef (fig. 1). Also apparent in figure 1 are dark streaks across the reef flat, which are composed of skeletal sand, gravel, pebbles, and cobbles (Wentworth, 1935), collectively referred to as rubble, much of which is colonized by benthic algae and coral. A gradient exists in colonization, the nearshore rubble being dominated by fleshy macroalgae and that on the seaward flat dominated by turf algae, live coral, and coralline algae.

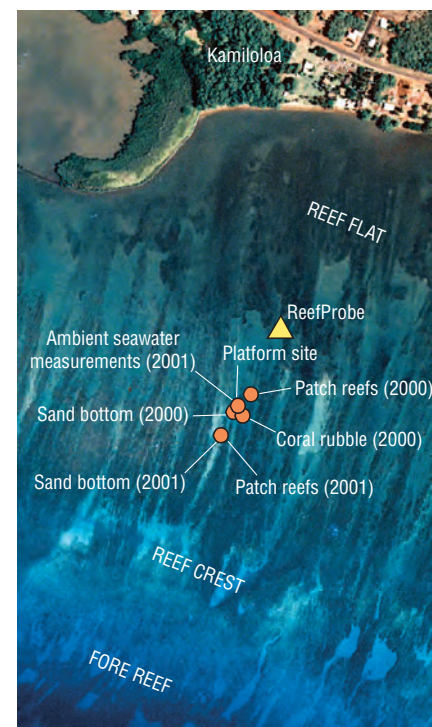
On the outer reef flat, corals, calcareous algae, and other photosynthetic organisms fix carbon into organic tissues and calcium carbonate skeletons. The metabolism of bottom organisms can be monitored by carefully measuring chemical changes in seawater that result from photosynthesis, respiration, and calcification. These changes can be readily detected in seawater on the reef flat, but quantitative evaluation of metabolism rates requires measurements in a known volume of water. For this purpose, a clear plastic chamber, the SHARQ (Submersible Habitat for Analyses of Reef Quality) was deployed on the reef flat (Yates and Halley, 2003).

### Methods

In February 2000 and July 2001, using platforms as field laboratories, we made chemical measurements in water from the SHARQ chamber that was deployed over areas of the reef flat and in ambient reef-flat water on the outer reef flat (fig. 2). The chemical measurements were used to calculate metabolic activity of the reef. Details of measurement parameters and intervals may be found in Yates and Halley (2003, 2006a). Measures of reef-flat productivity were collected over four bottom types: sand, rubble, 10-percent coral cover, and 22-percent coral cover. These areas typify the bulk of the outer reef flat (Rodgers and others, 2005). The platforms served as 24-hour observatories from which to measure metabolic activity on the reef flat in general (ambient measurements) and of the community of organisms living within the SHARQ in particular.

### Results

In general, the very shallow nearshore water exhibits more extreme temperatures near the sea floor than deeper water located farther offshore near the



**Figure 1.** Aerial photograph of a portion of the Moloka'i reef flat at Kamiloloa showing SHARQ chamber sampling locations (red dots) for this study in 2000 and 2001. The samples were collected in an area approximately 200 m landward of the reef crest and 300 m seaward of the ReefProbe (yellow triangle), a small instrumented tripod (see Ogston and others, this vol., chap. 21, for more information on the ReefProbe). Instruments to measure ambient seawater were housed on the field laboratory platform.

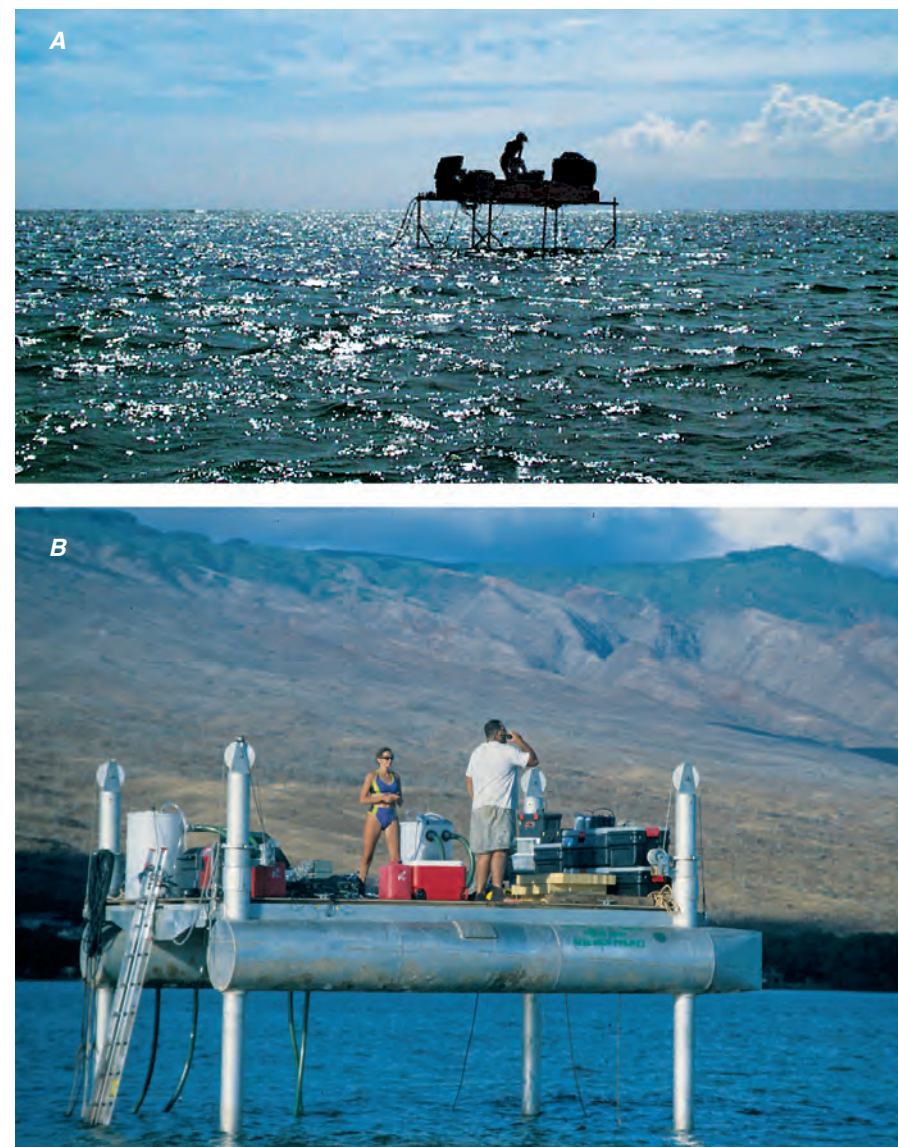


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reef crest—colder at night and warmer in the afternoon (fig. 3). High tides have a secondary effect, bringing warmer surface seawater from offshore to the reef crest area at night but having little effect inshore. Although these temperature differences are small, only a degree or two, the difference can become critical for coral bleaching, which can be induced by small temperature increases (Jokiel and Brown, 2004).

Light measurements taken at the ReefProbe (a small instrumented tripod; see Ogston and others, this vol., chap. 20, for more information) site on the reef flat (fig. 1) indicate that about 87 percent of the available surface light reaches the sea floor at this location (fig. 4). At this shallow site (water depth 1.2 m), neither the turbidity nor tidal fluctuations affect light penetration enough to inhibit photosynthesis. Figure 5 illustrates light penetration at



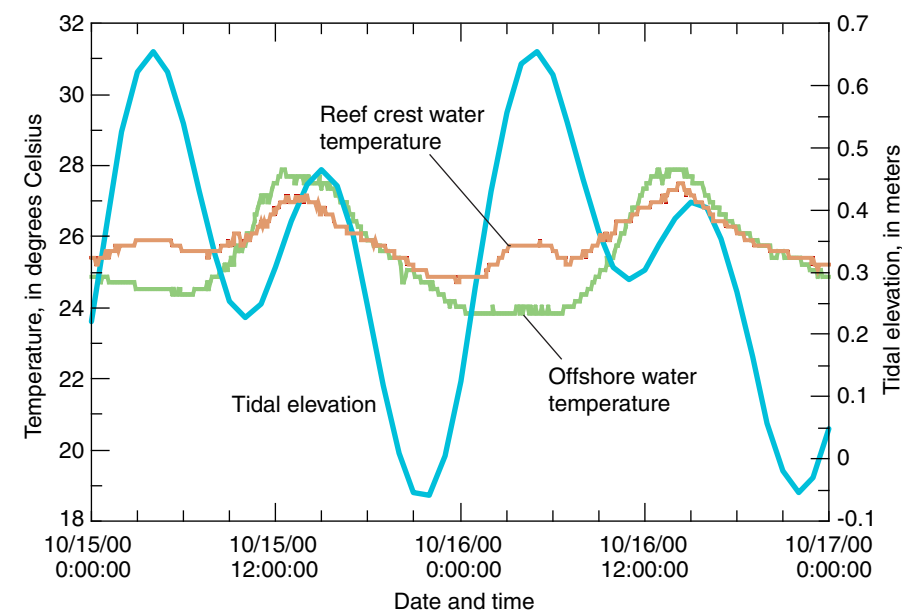
**Figure 2.** Platforms were erected on the reef flat and used for SHARQ support systems and as a field laboratory. *A*, Scaffolding with a plywood top used during February 2000. *B*, The University of Hawai'i drill platform used during July 2001.

the platform site (fig. 1) in about 2.2 m of water. At this location, afternoon light is reduced by as much as 35 percent. However, even with a 35-percent reduction through the water, sufficient light for photosynthesis reaches the bottom (Yates and Halley, 2000).

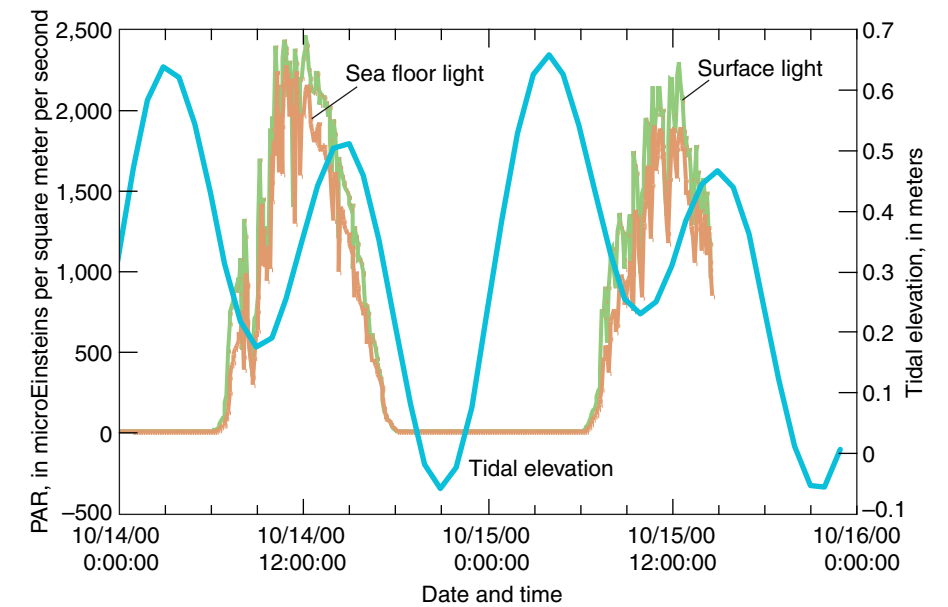
The plants and animals of the reef derive their energy through photosynthesis and respiration. During the day, the Moloka'i reef is dominated by photosynthesis, a process that consumes carbon dioxide and produces oxygen. The daytime rate of photosynthesis is greater than the rate of respiration by nonphotosynthetic organisms, so oxygen accumulates in the water. At night, photosynthesis stops and the underlying rate of respiration is revealed by the consumption of oxygen and the production of carbon dioxide. This cycle repeats every 24 hours, and these two processes are roughly in balance over weeks and years (fig. 6A).

The increased carbon dioxide at night reacts, in turn, with seawater to make an acid, called carbonic acid, and lowers the pH of the seawater. The nightly decrease in pH is not perfectly correlated with decreases in dissolved oxygen, but the daily cycle in pH is apparent on the outer reef flat (fig. 6B). Although the illustrated cycles were measured in the SHARQ, similar pH shifts were observed in ambient water at the platform site. These shifts seem small, about half a pH unit, but they are sufficient to cause the dissolution of carbonate minerals at night (Yates and Halley, 2006a)

Algae, in one form or another, occupy the entire surface of the Moloka'i reef flat (Smith and others, this vol., chap. 8). There are (1) symbiotic algae (termed “zooxanthellae”) in the tissues of corals, foraminifera, and some mol-



**Figure 3.** A 48-hour record (October 15 to 17, 2001) of tide and temperature on the inner and outer Moloka'i reef flat. Tide range (blue line) is about 0.7 m during this period. Water temperature 50 m offshore (green line) shows a daily cycle, with a range of 4°C and maximum temperatures in the afternoon. Water temperatures at the reef crest (orange line) have a range of 2°C, with a maximum in the afternoon and a secondary maximum at high tide.



**Figure 4.** A 48-hour light and tide record (October 14 to 16, 2001) at the Reef-Probe location. Light measurements are of photosynthetically active radiation (PAR) measured in microEinsteins. Light reaching the sea floor (orange line) is only slightly reduced from surface light (green line) at this shallow water depth (1.2 m). During this period, tide range (blue line) was 0.7 m.

lusk; (2) calcareous macroalgae (such as *Halimeda* sp. and *Porolithon* sp.); (3) fleshy (noncalcareous) macroalgae (such as *Dictyosphaeria* sp. and *Caulerpa* sp.); (4) the ubiquitous turf algae, a community of microscopic species creating a fuzz on hard surfaces; and (5) endolithic algae, microscopic forms that bore into and live below the surface of rocks and sand. The distribution of these photosynthetic organisms, together with the amount of light that reaches them during the day, controls the amount of oxygen produced on the reef flat. Higher plants, such as seagrass, also contribute to photosynthesis, but they are sparse on the Moloka'i reef flat and do not form the extensive meadows that are characteristic of reef areas in the Caribbean.

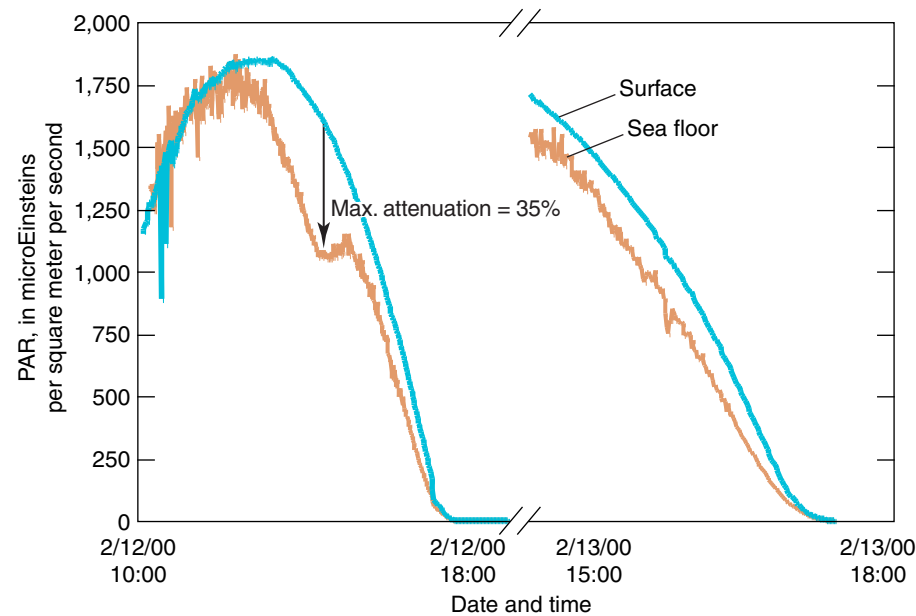
Bacteria and animals respire, consuming oxygen both day and night. Researchers who have studied reef productivity assume that respiration is constant both day and night (Marsh and Smith, 1978; Carpenter, 1985). This may not be the case, because some animals are more active during the day, some at night. However, the assumption may be a good approximation because (1) day/night animal activity and respiration offset each other; or (2) the system may be dominated by bacterial respiration that is little affected by light and dark. Unfortunately, there are very few studies of respiration in carbonate sediments, and the existing generalizations are predominately based on clastic coastal sediments (Middelburg and others, 2005). In practical terms, respiration is often measured in the field as the rate of oxygen consumption at night. Daytime measurements of oxygen production reflect oxygen produced by photosynthesis minus that consumed by respiration. Thus, daytime measurements are net measures of photosynthesis. For gross photosynthesis rates, the amount of oxygen consumed by respiration at night is added to the net (day) rate, with



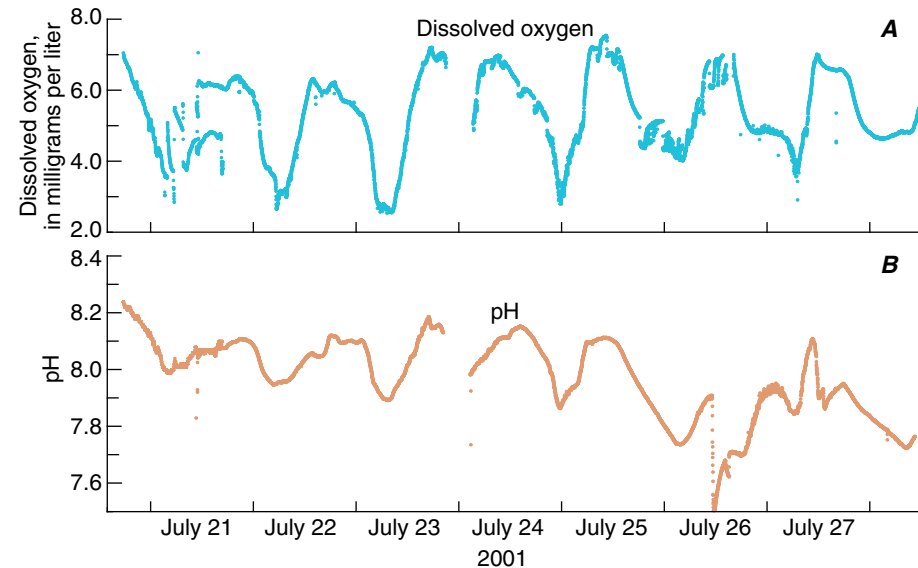
the assumption that respiration rates during the day are similar to respiration rates at night.

Photosynthesis rates, as a function of sea-floor light, for four bottom types on the outer reef flat (sand, rubble, 10-percent coral cover, and 22-percent coral cover) are shown in figure 7. These rates are determined from within the SHARQ enclosure, which excludes gain and loss of oxygen and carbon dioxide from the atmosphere or from water flow across the reef flat. As expected, photosynthesis was detected in all four bottom types and increases in the order: sand, rubble, 10-percent coral cover, and 22-percent coral cover. Linear approximations show that for a given increase in light, the increase in photosynthesis in 22-percent coral cover is four times that in sand. It is also interesting to note that the rate of photosynthesis on rubble bottom is three times greater than on sand. This occurs because the rubble is more stable than sand and supports a more abundant growth of macro- and microalgae.

The data presented in figure 7 also indicate that photosynthetic saturation is not reached on the Moloka'i reef flat. Saturation occurs when photosynthesis remains constant with increased light intensity. Maximum photosynthetic rates ( $P_{max}$ ) are well known for corals and algae, but it is also known that these organisms can adapt to changed light conditions within days and weeks (Anthony and Huegh-Gulberg, 2003). The community-level measurements of this study do not show evidence for saturation, nor do they suggest any deviation from linearity. These communities become productive (net oxygen production) at about two to four times the light intensity required by corals elsewhere in the Pacific. For example, net oxygen produc-



**Figure 5.** Partial 48-hour light record from coral-rubble SHARQ site in February 2000. Light (PAR, photosynthetically active radiation) reaching the sea floor (brown) is more reduced from surface light (blue) in the deeper water (2.2 m) at this study site. Windy conditions and increased turbidity on the afternoon of February 12, 2000, reduced surface light by as much as 35 percent. The calmer afternoon of February 13 reduced sea-floor light by only about 10 percent.



**Figure 6.** Daily cycles of dissolved oxygen and pH record for the Moloka'i reef flat, July 20–28, 2001. The daily metabolic activities on the reef flat induce chemical changes in the overlying water. Erratic nature of these cycles is partially due to variations in light, wind, and other naturally occurring conditions. Breaks in data are due to equipment failure during inclement weather. *A*, Daily variation in dissolved oxygen dominated by daytime photosynthesis and nighttime respiration. *B*, Daily variation of pH dominated by photosynthetic consumption and respiratory production of carbon dioxide.

tion begins at about 500 microEinsteins on the outer reef flat, compared to 125 to 250 microEinsteins for corals along the Great Barrier Reef (Barnes and Chalker, 1990).

Calcification in corals and calcareous algae is enhanced by photosynthesis (Barnes and Chalker, 1990). In reef settings, calcification rates are indicated by alkalinity changes in seawater (Smith and Key, 1975). Alkalinity decreases during calcification and increases during calcite or aragonite dissolution. As with many other parameters, alkalinity exhibits daily cycles on the reef flat, decreasing during the day and increasing at night. Summing alkalinity changes through a 24-hour cycle provides an estimate of net calcification or dissolution. On the basis of our limited data, the four bottom types all show evidence of calcification during the day and dissolution at night. Sand and rubble areas show net dissolution. Sandy sea floor with 10-percent live coral cover shows net dissolution or net sediment production, depending on location and time of year. Sandy sea floor with 22-percent live coral cover shows net sediment production (Yates and Halley, 2006a).

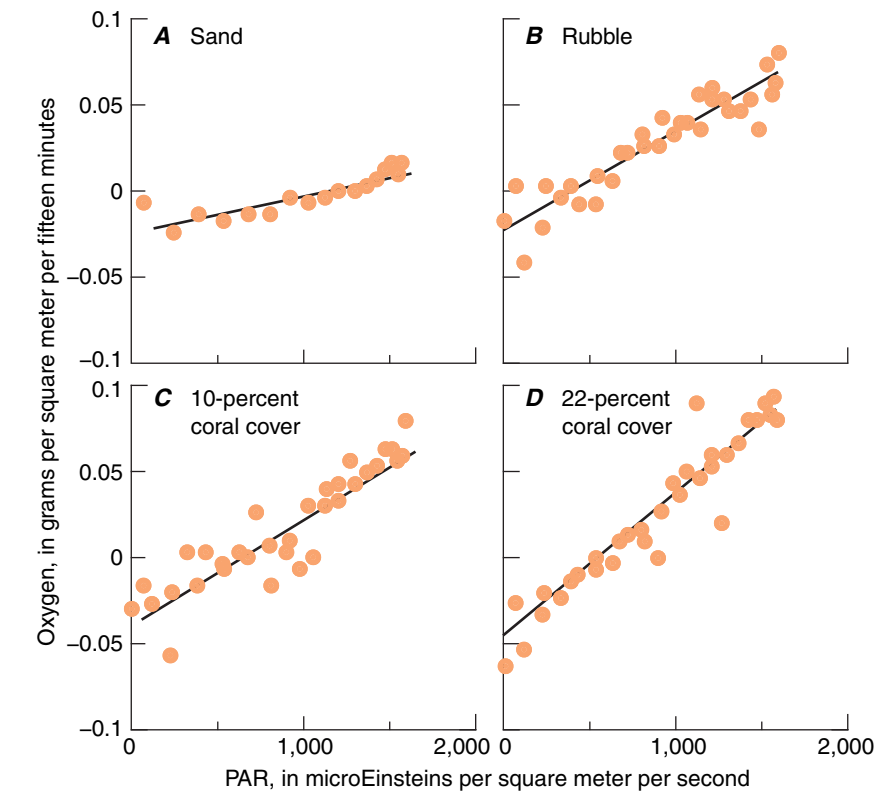
## Discussion

### Suspended Sediment: Light Versus Loading

As pointed out by Rogers (1990) and Ogston and others (2004), corals are generally not found in areas where suspended sediments exceed 10

mg/L, and greater concentrations are injurious to corals. The measurements made at the ReefProbe site, 300 m landward of the platform site, indicate that suspended sediment in excess of 10 mg/L is common during high tides on windy afternoons and evenings (Ogston and others, 2004; Presto and others, 2006). Storlazzi and others (2004) found that hourly mean concentrations often exceeded 5 mg/L and some individual measurements exceeded 40 mg/L. Rodgers and others (2005) found no coral growing shoreward of this position.

It appears that the ReefProbe location represents the approximate level of sediment stress that excludes coral growth. Yet even at this highly turbid site, the shallow water allows more than 500 microEinsteins to reach the bottom for most of the day (fig. 4). Therefore, it seems unlikely that light attenuation is preventing coral growth. More likely, the physical loading of coral surfaces with fine sediment, and the energy required to keep these surfaces clean, is beyond the capability of these photosynthetic organisms to overcome. In this way, turbidity limits coral growth to 400 m offshore and beyond, the distance that Rodgers and others (2005) found coral growth. It is interesting to note that even on the outer reef flat, living corals must continually shed significant amounts of sediment. Living corals are the only sediment-free surfaces on the reef flat. Dead coral and algae are quickly covered with a thin veneer of brown



**Figure 7.** Photosynthetically active radiation (PAR) and oxygen ( $O_2$ ) production on the Moloka'i reef flat. These graphs show the relationships between available light and photosynthesis or respiration for sand (*A*), rubble (*B*), 10-percent coral cover (*C*), and 22-percent coral cover (*D*). Note that net respiration (negative values) changes to production (positive values) at 0 on the left (vertical) scale.

sediment, giving most of the reef a drab and dirty appearance (Field and others, this vol., chap. 17, fig. 10).

### Coral Cover and Productivity

Aerial photos show the patchiness of coral growth on the Moloka'i outer reef flat. The patchy distribution is reflected in the transect data of Rodgers and others (2005), who recorded coral cover from 1 percent to over 40 percent at the outer (550 m and 700 m) stations of their survey transects across the reef flat. These coral patches, along with areas of rubble and sand, are organized into fuzzy elongate stripes, meters to tens of meters wide and hundreds of meters long, roughly perpendicular to the shore. Storlazzi and others (2003) and Storlazzi and others (2004) recognize these features as “ridge and runnel” structures, similar to the “ridge and furrow” structures of Grand Cayman as described by Blanchon and Jones (1995). However, the ridges and furrows of Grand Cayman are erosional features as much as 10 m deep in sculptured bedrock (Blanchon and Jones, 1995, 1997). On Moloka'i, ridges are depositional, formed by in-place growth of coral and subsequent binding by algae and other organisms. As seen from above, the dark stripes are irregular and anastomizing, consisting of coarse sand and rubble covered by algae landward, but of increasing amounts of live coral seaward. From the SHARQ measurements, patches with 10 to 20 percent or greater coral cover are net sediment producers. Although dissolution may be occurring at night, there is excess sediment being produced that may be transported across and along the reef flat, to the beach, or, in the opposite direction, to the fore reef. Areas with less than approximately 10 percent coral cover are losing carbonate sediment through dissolution. Rodgers and others (2005) estimate overall coral cover on the outer reef flat to be less than 10 percent. From these estimates we suggest that the reef flat as a whole is not producing sediment sufficient for net accumulation or transport out of the system. Rather, the flat is largely a relict feature, with only a thin layer of modern sediment. Modern sediments on the reef flat and crest may have accumulated during a brief but significant sea-level highstand that occurred in Hawai'i during the late Holocene (Grossman and Fletcher, 1998; Grossman and others, 1998). These sediments may overlie an older, possibly Pleistocene, edifice similar to the reef flat along southern O'ahu that was cored and dated at Mamala Bay (Grigg, 1998).

### Reef-Flat Extension

Although much of the Moloka'i reef flat may be relict, two areas are actively accreting. First, within the reef flat proper, large patches of coral growth must be net producers (>20 percent coral cover). In addition to the larger patches of coral, the “blue holes” on the reef flat are surrounded by coral fringes actively growing into these solution features. This active coral growth is similar to that on the fore reef and creates steep (45°) walls, from

which colonies tumble down slope to form an apron of talus and sediment. The blue holes are sedimenting rapidly (geologically speaking) and adding to the reef flat as the depressions fill in.

Secondly, the fore reef (5 to 20 m deep) is another area of spectacular coral growth. Although coral growth is sparse immediately off our fore-reef study site, elsewhere the fore reef is characterized by meadows of 50 to 80 percent coral cover. Accretion has been studied by coring at two areas on the western end of the Moloka'i reef (Engels and others, 2004). At the extreme western end of the island accretion has been prevented since the mid Holocene by high wave energy associated with northern swells. At Hikauhi farther east, where the island protects from those swells, Engels and others (2004) documented vertical accretion rates of 3 to 5 mm/yr. Given the fore-reef slope of about 5° (1:11), this accretion rate translates to an addition of 30 to 50 m of reef flat per 1,000 years. These rates are comparable to reef growth in the equatorial Pacific and Indian Oceans, for example at Mauritius, where Montaggioni and Faure (1997) documented rates of 4.3 mm/yr. The entire fore reef of south Moloka'i may not be accreting as quickly as the Hikauhi area, but much of it is characterized by more than 50 percent coral cover and is actively building seaward.

Relating measures of reef growth and sediment production over different spatial and temporal scales remains a challenge for biologists and geologists. On small spatial scales, rates of dissolution and calcification can be measured almost instantaneously, on time scales of minutes to weeks. Using repetitive measurements, these geochemical measurements can be scaled to describe seasonal changes (Atkinson and Grigg, 1984). Addressing longer timescales in this way has proven prohibitively expensive, but a new generation of sensors may allow repetitive monitoring over years to decades (Berkelmans and others, 2002).

Sediment production and accumulation in reefs and related carbonate sedimentary environments continues to be an active area of research, often approached within the framework of a sediment budget (Hubbard and others 1990; Harney and Fletcher, 2003; Yates and Halley, 2006b). These studies, typically with a timescale of a few thousand years, allow some estimates to be made of long-term sedimentation rates. More often than not, however, important aspects of these sediment budgets remain unconstrained—dissolution or transport for example—and closure of the budget remains out of reach. It continues to be a challenge to relate short-term measurements of sediment production to larger scales of time and space. Examples of studies approaching this challenge are the summaries by Bosscher (1992) and Smith (1995) that expand carbonate-sediment production estimates to a global scale and throughout geologic time, respectively. It seemed intuitive to Darwin (1842) that his short-term observations of coral growth and the geometry of reefs could explain their growth and accumulation over geologic time. However, 150 years of research have left us with an incomplete understanding of the structural make-up of reefs (Braithwaite and others, 2000). Continued studies of reefs like the Moloka'i fringing reef bring us closer to a more complete knowledge of coral-reef growth and the factors that affect them.

### Summary

The reef flat along the south shore of Moloka'i is an example of a reef area that might be said to have reached senility. By “senility” we do not mean that the reef is entirely dead, or relict. Rather, it supports some coral growth but not enough to accumulate sediment across broad areas of the flat. Inhibited by an influx of sediment from the island, live coral cover now is insufficient to maintain reef structure on the reef flat. Sufficient light is available for coral growth, but calcium carbonate production is likely limited by other factors, such as sediment loading and diminished settlement of young corals. Although those areas with more than about 10-percent coral cover (larger patches of coral on the flat) are net sediment producers, the flat as a whole maintains less than 10-percent coral cover.

In contrast, large areas of the fore reef are extremely productive, with coral cover approaching or exceeding 50 percent. These areas are rapidly producing reef structure, and in some locations vertical accretion rates of 3 to 5 mm/yr have been verified by drilling. These rates, together with fore-reef geometry, indicate that the reef flat is growing seaward on the scale of a few meters per century. The reef flat as a whole is growing outward, but not upward. It will slowly widen, but sediment thickness will not deepen significantly if major changes do not alter current patterns of coral growth.



Suggested citation:

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