CHAPTER 17

Sediment on the Moloka‘i Reef

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Sediment is an important, natural component of coral reef systems. Sand and silt particles derived from organic growth and erosion are a major constituent of reefs, filling in framework voids, channels, and holes. Aggregations of particles constitute microhabitats for microfauna. In excessive amounts, however, sediment can lead to degradation of a reef. Fine particles that are suspended in the water column block light and decrease levels of photosynthesis. Particles settling on coral surfaces interrupt feeding patterns and cause corals to expend valuable energy to slough off the sediment. More importantly, even a thin deposit of sediment on hard surfaces eliminates potential recruitment sites for larvae. When mobilized, sediment can abrade coral tissues. The net result of excessive sediment on reefs is reduced calcification, reduced recruitment, altered species composition, shallower depth distribution limits, and a loss of biodiversity (Fabricius, 2005).

As noted in the preface to this volume, the south Moloka‘i coral reef has been recognized as an area of excessive sedimentation for many years; indeed, mangroves were introduced at Pālā‘au in 1902 to combat that problem. This chapter describes the sources, composition, and distribution of sediment on the reef and discusses its transport and ultimate fate. Companion chapters by Bothner and others and Ogston and others (this vol., chaps. 19 and 20, respectively) address related aspects of sediment accumulation and suspension on the reef.

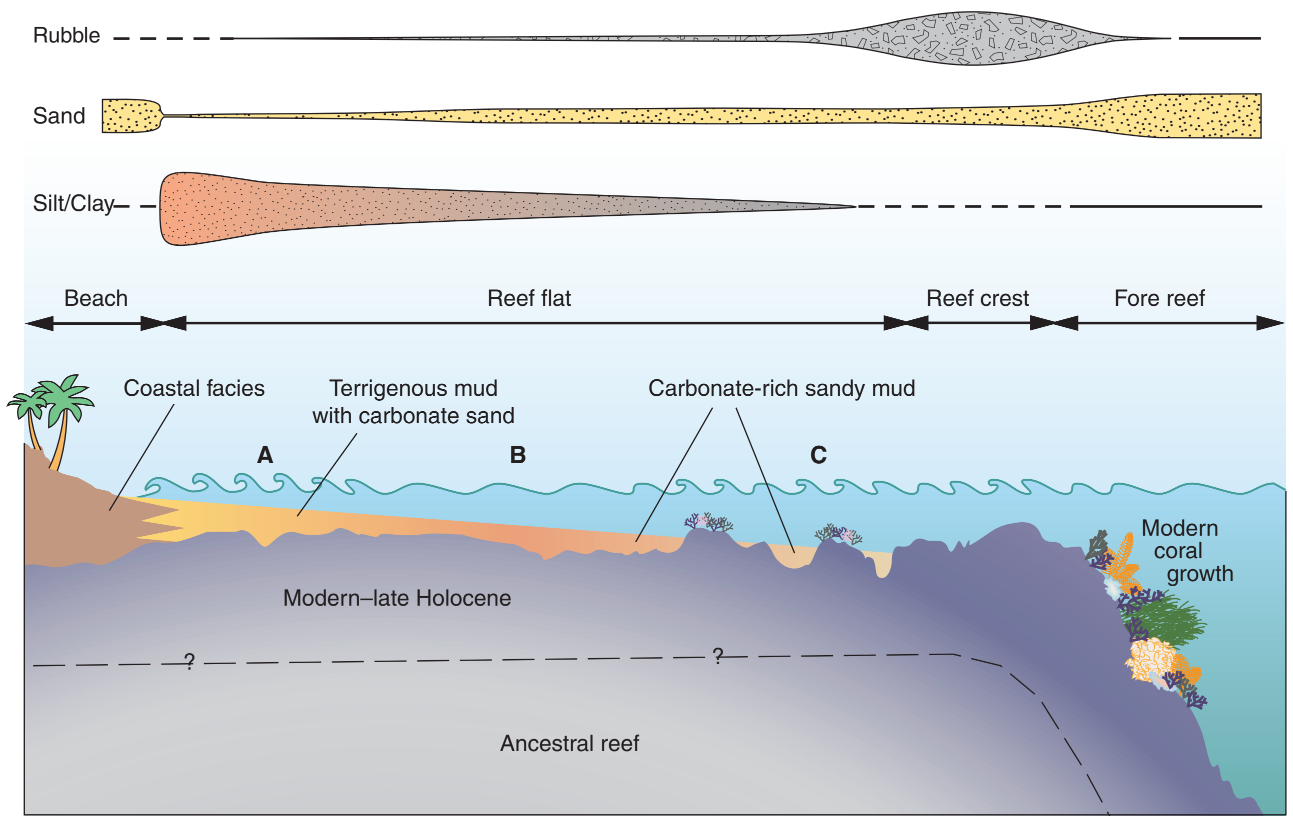

Figure 1. Cross section of the south Moloka‘i reef system showing the transition from the sediment-covered inner reef flat to the coral-rich fore reef. The relative abundances of rubble, sand, and mud are shown schematically from the beach across the reef flat and reef crest onto the fore reef. A, B, and C mark the approximate locations of samples described in figure 2. The age of the ancestral reef is late Pleistocene (oxygen isotope stage 5e, approximately 120,000 years before present).

Sources of Sediment to the Reef

Sediment accumulates on Hawaiian coral reefs, usually in minor amounts, through two natural processes: (1) erosion of the adjacent island surface and transport onto the reef and (2) production of sediment on the reef itself by breakdown of organic materials and bioerosion. Materials from the adjacent island are derived by physical and chemical breakdown of parent basaltic lava flows into particles. These land-derived, or terrigenous, grains typically form in a variety of sizes from sand (2.0 to 0.063 mm) to silt (0.063 to 0.004 mm) to clay (<0.004 mm). The weathered grains are commonly red-brown in color from the oxidation of iron in minerals, and organic matter incorporated with the grains also contributes to the red-brown color of the island’s soils. Silt and clay particles can adsorb chemical compounds, including nutrients and pollutants, onto their surfaces and thereby transport them to the reef environment.

The weathered products in soils vary in size from fractions of a millimeter to as much as a meter. Under natural conditions, soil particles are transported to the reef by a two-step process, starting with infilling of hillside gullies by water flow and landslides. Particles are subsequently carried to stream mouths and small coastal deltas by channelized and overland flows during heavy rains. Slope, soil thickness, and climate are important natural factors influencing the volume of water and the amount and character of sediment flowing onto the reef, but there is ample evidence that human activities also have a strong influence on water and sediment yield (Guilcher, 1985; Bryant and others, 1998; Hughes, 2003). For example, loss of vegetation and root structures, which hold the soil in place, because of fires, grazing, agriculture, and other activities can markedly increase stream flows and the amount of sediment that is eroded from the land surface (Van Vuren and others, 2001; Warne and others, 2005; see also Roberts and others, this vol., chap. 14).

On the reef itself (fig. 1), sediment is produced by the breakdown of coral, coralline algae, and other marine organisms. Sediment here is also produced in a variety of sizes from rubble (>2 mm) to sand to silt and clay, and the grains are almost uniformly light in color—white, cream, or tan. All of the sediment is produced initially by organic growth, some of which converts rapidly to sediment particles (for example, one-celled animals, such as foraminifers, and small algae, such as *Halimeda* spp.) Shells of macroinvertebrates (such as snails) and the hard limestone structure of the reef are slowly converted to sand and smaller particles by wave forces and by grazing fish and invertebrates.

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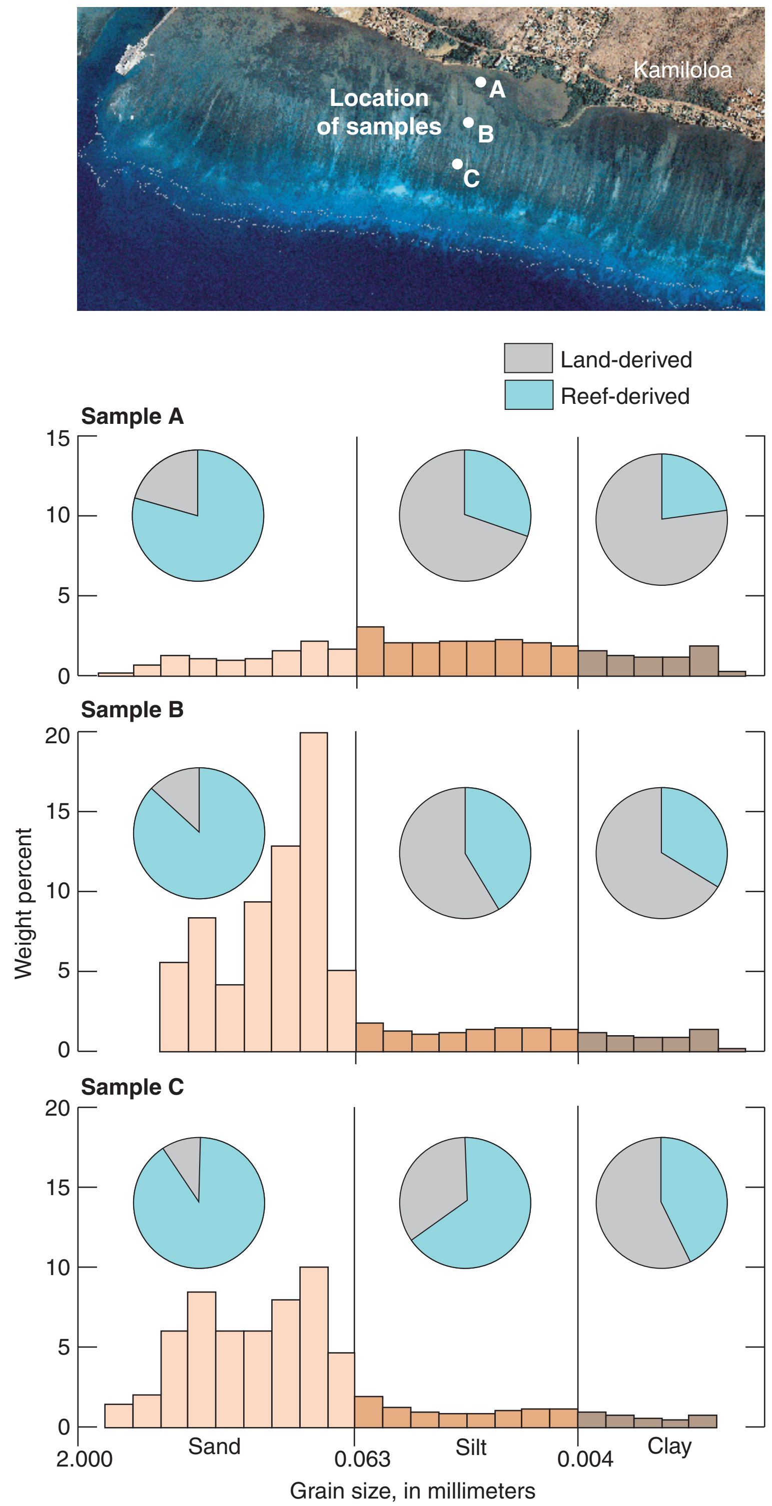


Figure 2. Size and composition of three typical sediment samples from the south Moloka‘i reef flat; the rubble fraction is not shown. The land-derived (terrigenous) and reef-derived (carbonate) fractions were determined by HCl acid solution, a standard laboratory procedure. Note: the x-axis is a decreasing logarithmic scale, converted to millimeters from the phi (*ϕ*) sizes commonly used by geologists.

Composition of Sediment on the Reef and its Significance

Particle Sizes and Their Origin

Sediment on the south Moloka‘i reef consists of rubble, sand, silt, and clay. Because of their small mass, both silt and clay are easily suspended and transported by water; together they are referred to as mud (see Folk, 1974, and Folk and Ward, 1957, for definitions of particle sizes and their measurement). Rubble, sand, and mud occur in changing abundances across the reef in response to available sources as well as to wave and current forces that transport and sort the materials. The south Moloka‘i beaches are in a low- to medium-energy setting, and most beach deposits incorporate only minor amounts of mud in a dominantly sand environment. The inner reef flat is dominated by mud, with significant quantities of sand. Reef-flat sediment becomes coarser in a seaward direction, with increasing amounts of sand and rubble and decreasing amounts of mud toward the reef crest. Sediment on the fore reef is dominantly sand, with only very minor amounts of mud present.

The composition of sediment similarly changes in a cross-reef fashion. Sand and rubble throughout the reef are largely reef-derived, whereas mud is clearly derived from both the reef and the land. These cross-reef trends are illustrated in the diagram in figure 1. With few exceptions, sand is composed of mostly calcium carbonate (reef-derived) grains. Values are 80 to 95 percent on the reef flat and consistently higher than 90 percent on the fore reef. The mud (silt and clay) fractions are quite different. On the inner reef flat, the mud is mostly land derived (only 10 to 20 percent calcium carbonate) and the balance between land-derived and reef-derived gradually and persistently shifts towards the outer reef flat (fig. 2).

Calhoun and Field (2008) evaluated cross-reef changes in calcium carbonate by analyzing sediment samples from the beach to the fore reef just east of the Kaunakakai Wharf (fig. 3). All their analyses show a clear trend of decreasing land-derived content and increasing reef-derived content, as indicated by increasing calcium carbonate content, in sediment across the reef**.** The changes are approximately linear for both silt and clay. The reef-derived content steadily increases seaward across the reef and stabilizes at its maximum value at 500 to 650 m (1,640 to 2,133 ft) from the shoreline. The reef-derived content of the sand fraction likewise increases with distance from the shoreline, reaching its maximum value at approximately 400 m (1,312 ft) from shore. Overall, there is an unmistakable pattern of reef-derived content of sediment increasing with distance from shore until a maximum is reached between 400 and 650 m offshore. As terrigenous sediment enters the reef at point sources, the consistency of this pattern for many kilometers along the shoreline suggests that sediment transport occurs in a shore-parallel direction as well as an onshore-offshore direction.

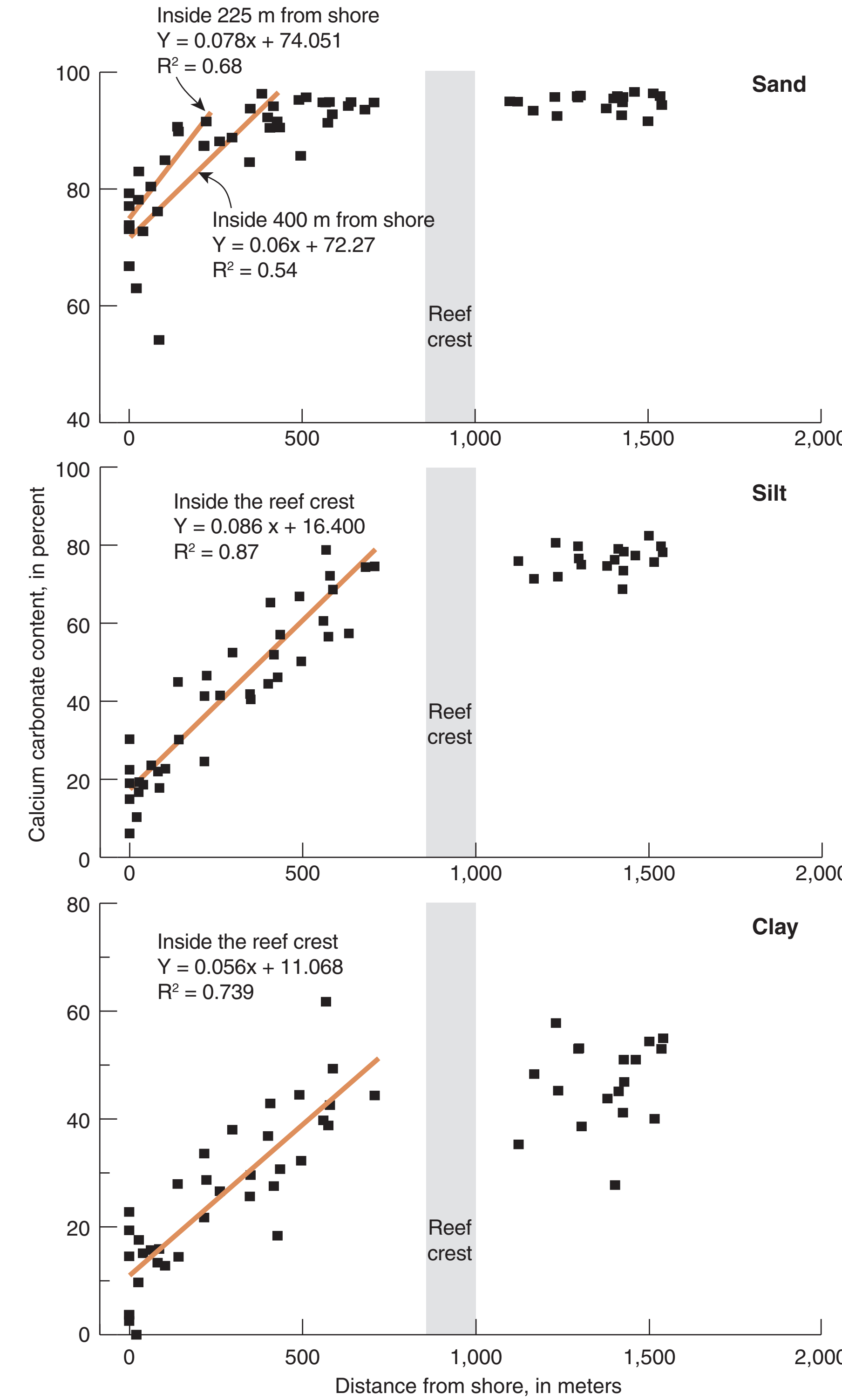
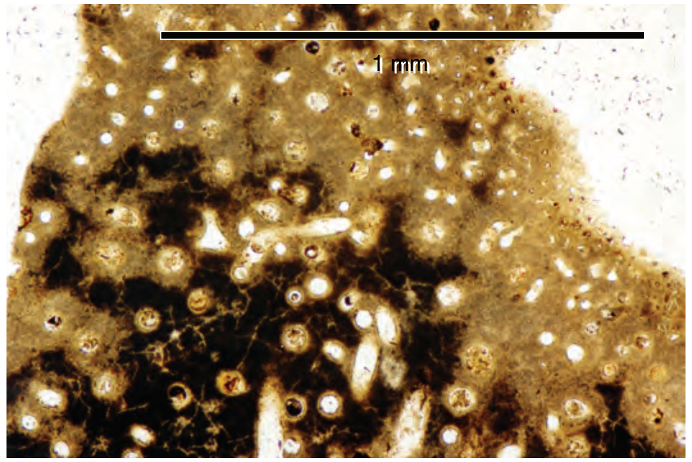


Figure 3. Calcium carbonate content of sand, silt, and clay fraction. The calcium carbonate contents increase with distance from the shoreline, reaching their fore-reef levels at approximately 400 m (1,312 ft) for sand, 500 m (1,640 ft) for clay, and 650 m (2,133 ft) for silt.

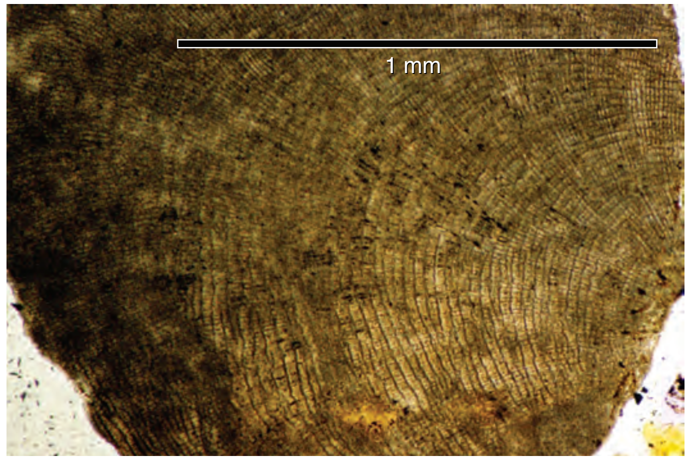
Figure 4. Photomicrographs of sand grains of various origins from sediment on the south Molokaʻi reef (Calhoun and Field, 2008).

A sand grain (left center) derived from a fragment of a calcium carbonate mollusc shell. Molluscs (for example clams and snails) make up a significant portion of the invertebrate fauna on reefs. On the Molokaʻi reef, molluscan fragments account for approximately 6 percent of the sand along the beach, 4 percent on the reef flat, and 4 percent on the fore reef.

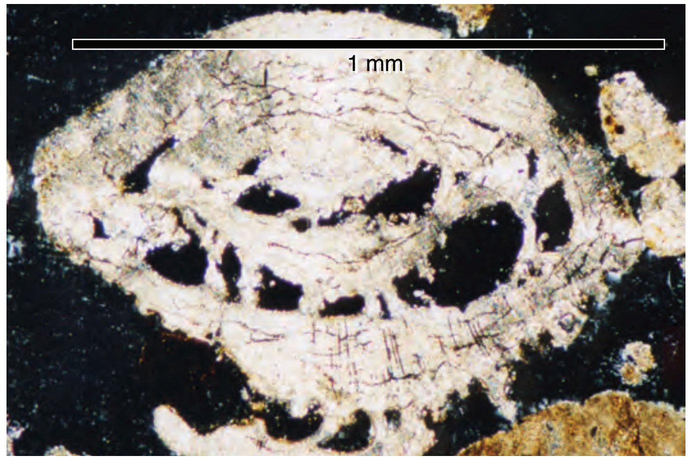


A sand grain derived from a fragment of a *Halimeda* plate. *Halimeda* are algae having a calcium carbonate center that is released to the reef as a sand-size particle when the algae die. On the Molokaʻi reef, *Halimeda* grains account for approximately 6 percent of the sand along the beach, 4 percent on the reef flat, and 9 percent on the fore reef.

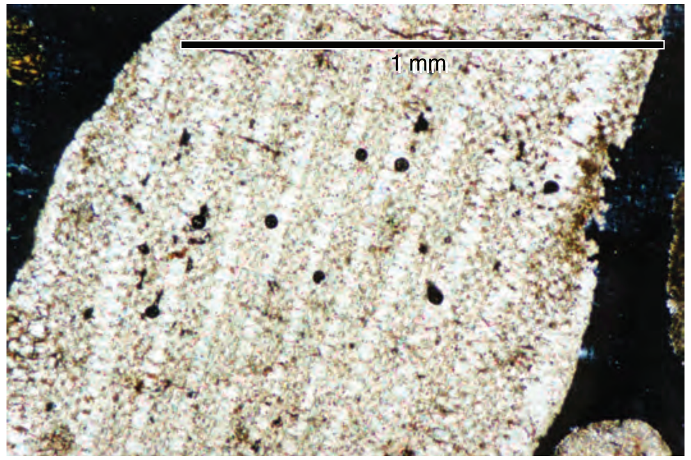
A sand grain derived from a fragment of coral. The calcium carbonate (coral) part of the grain is the light-colored areas; the darker material is sediment that has infilled holes in the grain. Corals are eroded (most commonly when the colony dies) by both physical processes, such as wave forces, and biologic processes such as grazing by fish and boring by invertebrates. On the Molokaʻi reef, calcium carbonate coral fragments account for approximately 11 percent of the sand along the beach, 12 percent on the reef flat, and 16 percent on the fore reef.



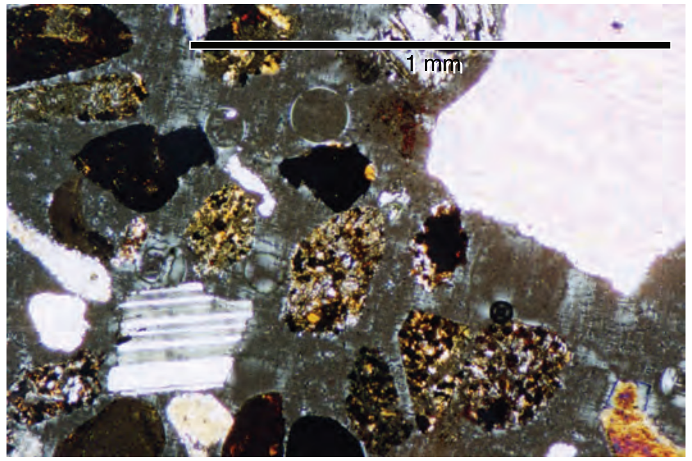
A sand grain derived from a fragment of calcium carbonate coralline algae. Coralline algae, like coral, are a major contributor to the reef framework, and their high abundance leads to a corresponding high abundance of derived sand grains. On the Molokaʻi reef, grains derived from coralline algae account for approximately 34 percent of the sand along the beach, 18 percent on the reef flat, and 22 percent on the fore reef.



A sand grain consisting of the shell of the common one-celled organism called a foraminifer (foram for short). Forams are abundant throughout the reef habitat, from the reef flat to sand channels to fore reef. On the Molokaʻi reef, forams account for approximately 4 percent of the sand along the beach, 1 percent on the reef flat, and 4 percent on the fore reef.



A sand grain derived from an echinoid shell (probably an urchin). Urchins are another common type of invertebrate on coral reefs. Their thin calcium carbonate shells are easily broken into sand-size particles after death, and their distinctive shell structure makes them readily identifiable with a microscope. On the Molokaʻi reef, echinoid grains account for approximately 1 percent of the sand along the beach, 1 percent on the reef flat, and 2 percent on the fore reef.



A sand grain (occupying the entire field of view) derived from volcanic deposits on land. These types of grains are formed by weathering of volcanic rocks and transport to the reef by streams. They are the only type of sand grain on the reef not derived from the reef itself. On the Molokaʻi reef, the abundance of volcanic grains along the beach and reef flat varies markedly, being approximately 13 percent of the sand along the beach, 22 percent on the reef flat, and only 1 percent on the fore reef.

Figure 5. Composition of beach sand on south Moloka‘i. The principal components are coralline algae, chemically altered (micritized) carbonate grains, terrigenous grains, and coral. Foraminifers and *Halimeda* are locally abundant along west Moloka‘i. Similarities between these samples and those found on the reef flat (fig. 6) suggest sediment exchange between the two environments (see text for explanation). Streams draining to the south side of Moloka‘i shown in blue.

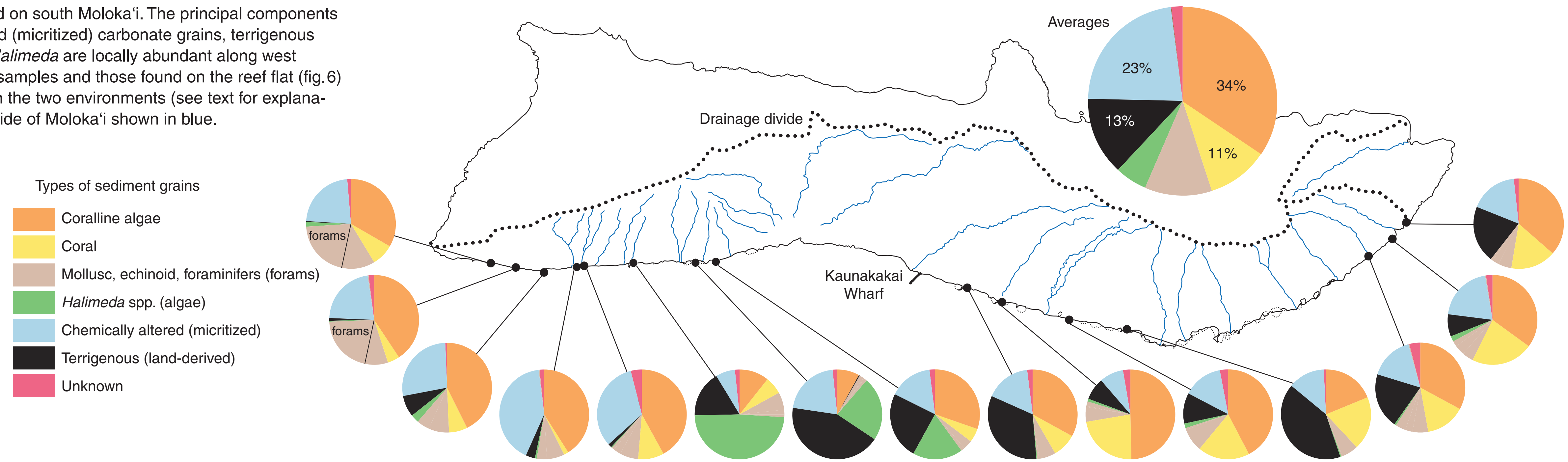


Figure 6. Composition of reef-flat sand on the south Moloka‘i reef. The most important components are chemically altered (micritized) carbonate grains, terrigenous grains, coralline algae, and coral. Streams draining to the south side of Moloka‘i shown in blue.

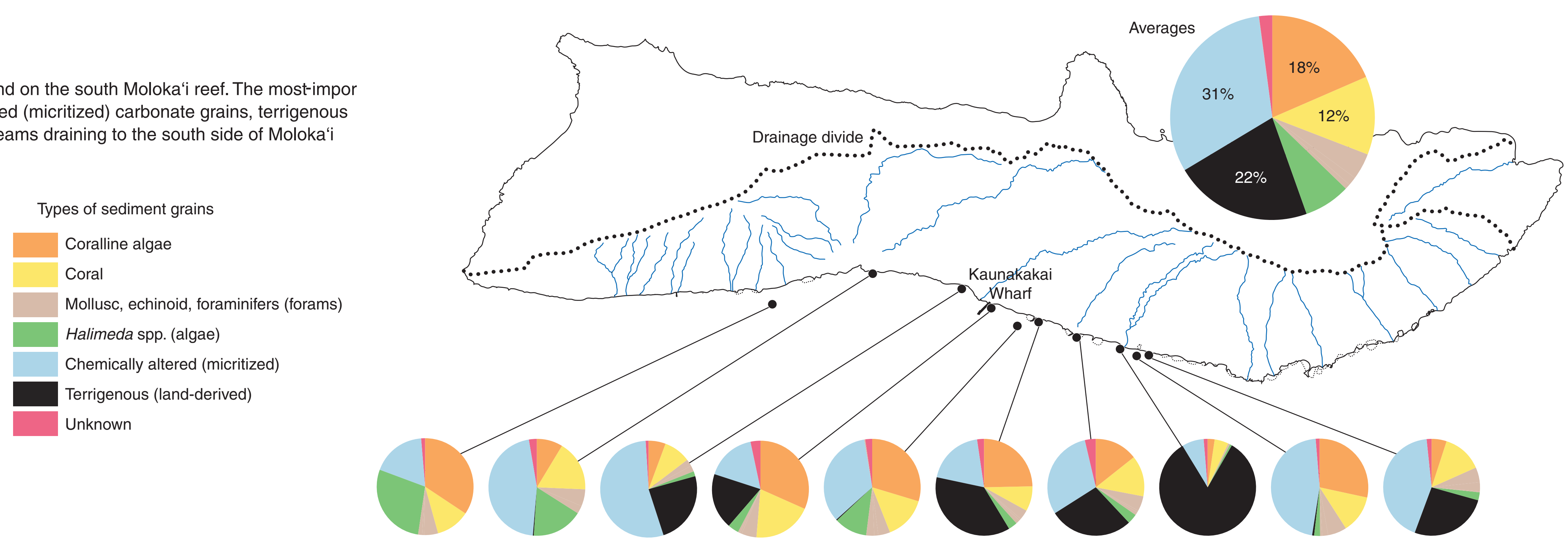
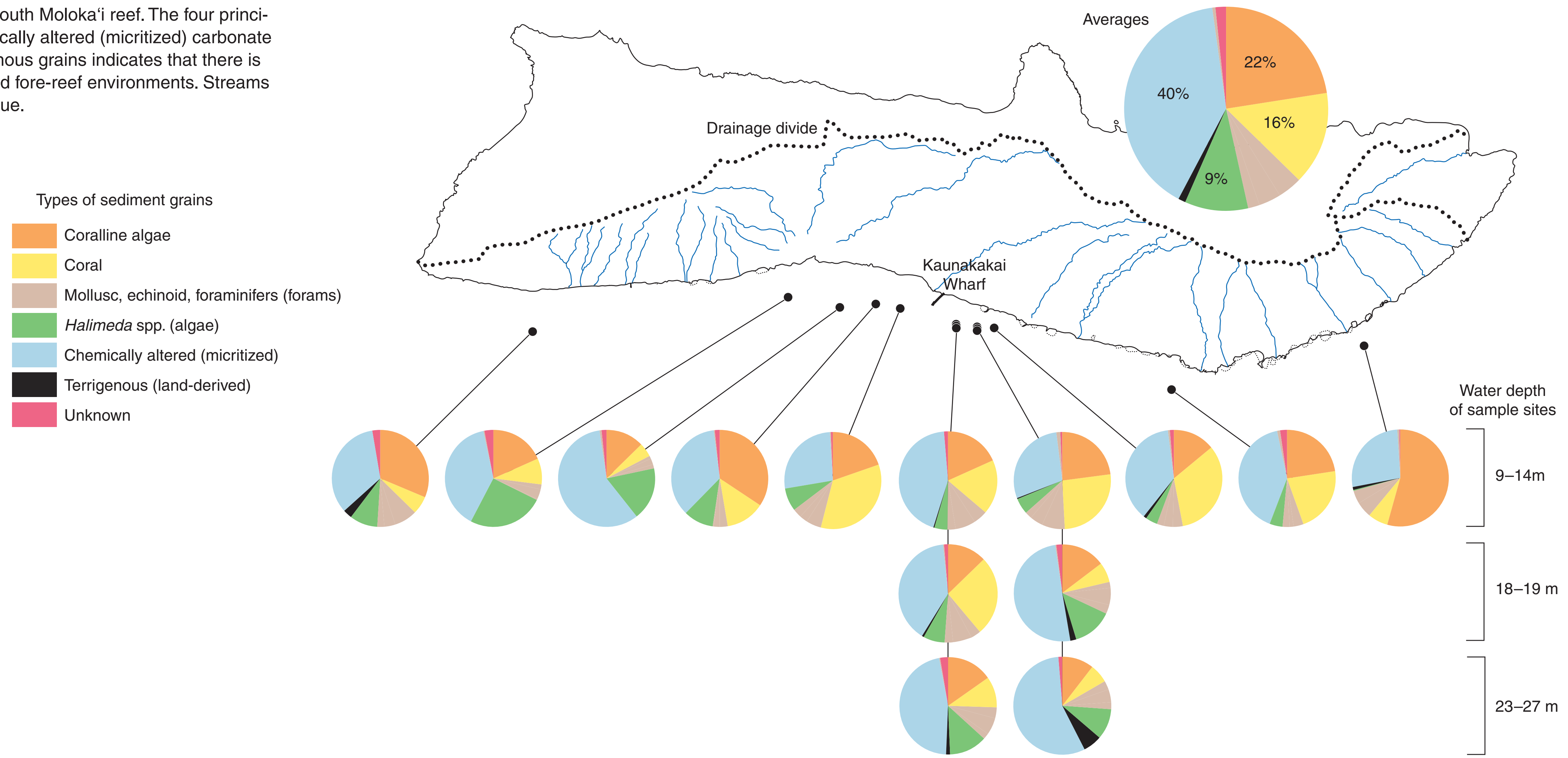


Figure 7. Composition of fore-reef sand on the south Moloka‘i reef. The four principal components are coralline algae, coral, chemically altered (micritized) carbonate grains, and *Halimeda*. The scarceness of terrigenous grains indicates that there is little sediment exchange between the reef-flat and fore-reef environments. Streams draining to the south side of Moloka‘i shown in blue.



Sand Composition as an Indicator of Source

Studies examining the composition and distribution of individual sand grains elsewhere in Hawai‘i have been useful for understanding the major sources of sand and providing information about long-term transport history (Harney and others, 2000; Calhoun and others, 2002; Harney and Fletcher, 2003). The sand-size fraction of south Moloka‘i beach and reef sediment, recently studied by Calhoun and Field (2008), is composed of both marine biogenic-carbonate grains and terrigenous grains from the Moloka‘i volcanoes. As described above, contribution of sand from land sources is evident in beach and inner reef-flat deposits, but less so in outer reef-flat deposits and particularly fore-reef deposits. Calhoun and Field (2008) noted that coralline algae, coral, chemically altered (micritized) carbonate grains, and terrigenous grains are the most common components of sand along the south Moloka‘i fringing reef, and their proportions vary depending on location. Other important contributors, usually in minor amounts, are molluscs, *Halimeda* spp., foraminifers, and echinoderms. Photomicrographs of most of these grain types are shown in figure 4.

The distribution of the principal components of the sand in beach, reef-flat, and fore-reef deposits is shown in figures 5, 6, and 7. On south Moloka‘i beaches, the most abundant sand grains are coralline algae (34±11 percent), chemically altered carbonate grains (23±10 percent), terrigenous grains (13±13 percent), and coral (11±7 percent), as shown in figure 5. The higher abundance of terrigenous grains on the eastern beaches (20±13 percent) compared to the western beaches (5±5 percent) probably results from the higher rates of sediment influx to the coast from east Moloka‘i relative to west Moloka‘i because of higher rainfall and steeper gradients (Field and others, this vol., Introduction). On the reef flat, the most abundant sand grains are chemically altered carbonate grains (31±16 percent), terrigenous grains (22±26 percent), coralline algae (18±13 percent), and coral (12±4 percent) (fig. 6). Note that sand is a dominant grain type of the beaches and fore reef, but it makes up less than 50 percent of the sediment on the reef flat. Thus the total sediment composition may be quite different from that illustrated in figure 6, for only the sand-size fraction was used in those analyses. Seaward of the reef crest on the fore reef, chemically altered grains are the dominant component (40±10 percent), and particles of the calcareous green algae *Halimeda* (9±6 percent) become the fourth principle grain type (fig. 7). Terrigenous grains are largely absent from the fore reef, with only one location having more than 5 percent.

Halimeda spp., foraminifers, and molluscs are locally important contributors to the sand-fraction components in all environments. In some areas, *Halimeda* spp. reaches almost 50 percent of the total sample, foraminifers just over 20 percent, and molluscs just over 10 percent. Small amounts of echinoderm fragments (<4 percent) and bryozoans (<1 percent) are also found along south Moloka‘i.

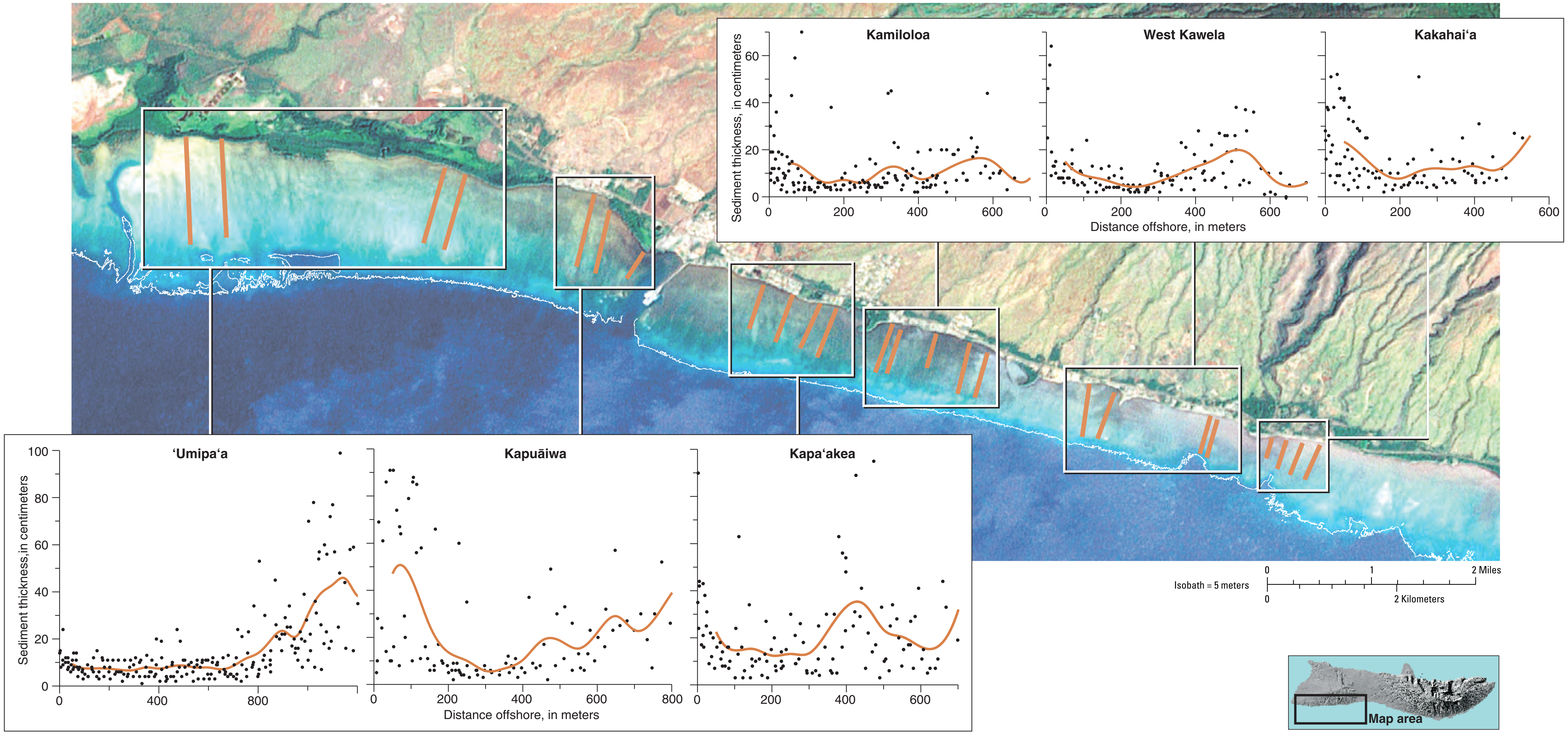


Figure 8. Sediment thickness on the Moloka‘i reef flat. Red lines on map show locations of sampling transects. Red lines on graphs are best-fit averages. Sediment thickness off **Kakahai‘a**: The thick sediment within 100 m (328 ft) of the shoreline is a reflection of the proximity of Kawela Gulch and the large quantities of land-derived mud that are transported to the coast during Kona storms. This location is one of the few places where the average sediment thickness is consistently greater than 10 cm (3.94 in). The lack of very high values on the central reef flat (400–600 m/1,312–1,969 ft from shore) is due to a general lack of holes for the sediment to accumulate in. Sediment thickness off **West Kawela**: Terrigenous mud derived from Kawela Gulch, mixed with reef sand, accumulates in deposits 10–20 cm (3.94 –7.87 in) thick on the inner reef flat. The deposits thin in a seaward direction to their lowest values about 220 m (722 ft) from the coast, then farther seaward show high variation caused by irregular reef topography. Sediment thickness off **Kamiloloa**: Here, as at locations farther east, the inner reef flat is covered by sandy mud several centimeters to 20 cm in thickness. The deposits rapidly thin seaward, reaching their lowest values between 100 and 200 m (656 ft) from shore. Variable thicknesses farther seaward reflect the irregular reef topography. Sediment thickness off **Kapa‘akea**: This area is the “downstream” portion of the Moloka‘i reef flat, in that prevailing currents transport sediment from Kawela and Kamalō regions west to this area, where further transport is effectively blocked by the Kaunakakai Wharf (Ogston and others, this vol., chap. 20). Sediment thickness is highly variable, but overall average values are the highest (>15 cm/5.91 in) on the reef flat 400–600 m from shore. Sediment thickness off **Kapuāiwa** coconut grove: This section of the coast has undergone erosion and is embayed; consequently, the inner reef flat is very broad. The reef flat is generally protected from large waves and strong currents from the east by the Kaunakakai Wharf. The inner reef flat is exposed at low tide; consequently there is little space available for additional sediment deposition. Thickness values near the shoreline range from 5 to >90 cm (35.43 in) and show the greatest range of any location. Between 200 and 350 m (1,148 ft) offshore, the sediment is generally <10 cm thick but farther seaward is again highly variable because of irregular reef topography. Sediment thickness off **‘Umipa‘a**: The ‘Umipa‘a reef flat (just east of Pālā‘au) has greater wave exposure and limited sediment sources at present relative to areas farther east, consequently sediment deposits on the inner reef flat are typically less than 15 cm thick. An abundance of reef-derived sediment here provides for consistent thickness values of several centimeters to 15 cm for a distance of 700 m (2,297 ft) offshore. Further seaward, the values become highly variable because of the irregular reef topography.

Sediment Patterns on the Reef Flat

Sediment is nearly ubiquitous on the Molokaʻi reef flat. Because of the apparent degradation of coral habitats on the reef flat, emphasis was placed on measuring both the sediment cover and the particles in suspension across the reef. The type of sediment and its distribution across the reef provides important information about the processes at work and the recent history of the reef. To measure sediment thickness on the reef, a marked steel rod was pushed into the substrate along transects between Kamalō on the east and the old Kolo Wharf on the west. Data were collected roughly every 20 m (65 ft) on each of 38 shore-normal transects from the beach offshore for distances of 600 to 1,200 m (1,969 to 3,937 ft), depending on water depth. The results of the systematic profiling have been grouped into six areas between Kamalō and Pālāʻau; each area includes measurements made along 3 to 5 transects (fig. 8).

The thickness of sediment on the reef flat is generally less than 1.0 m (3.3 ft), less than 0.5 m (1.6 ft) in most places. These low values reflect two important characteristics about the Molokaʻi reef flat: the shallow depth of holes and channels in which sediment can accumulate and the overall shallow nature (<2 m/6.6 ft) of water depth on the reef flat, which inhibits accumulation of thick sediment bodies. The sediment that has accumulated, and that continues to accumulate, on the south Molokaʻi reef flat is highly variable in thickness. The variations on the mid to outer reef flat are due in large part to the irregularities of the subsurface ancestral reef pavement—sediment collects in holes and low areas between coral ridges and is swept away from high areas. On the inner reef flat, sediment thickness is influenced by the availability of terrigenous mud and the presence (or absence) of wave stresses sufficient to remove the sediment. Thus the inner reef flat in small embayments and between large native Hawaiian fish ponds along the coast between Kamalō and Pālāʻau is typically buried by tens of centimeters of sandy terrigenous mud, whereas less protected areas are mantled by only 2 to 5 cm (0.79 to 1.97 in). The only locations where sediment is absent are (1) broad, shore-parallel rock surfaces on the inner reef flat and (2) elongate, shore-normal coral ridges on the outer reef flat. The rock surfaces on the inner reef flat are smooth, slightly shallower than adjacent areas, and mostly algae covered (see Cochran, this vol., chpt. 9). On the mid to outer reef flat, raised shore-normal ridges support coral growth and accretion at low (<10 percent) and moderate (10–50 percent) coverage levels (Rodgers and others, 2005).

The distribution of sediment across the reef flat is variable, but there are three noteworthy trends:

- Sediment on the innermost reef flat (1–100 m/3.3–328 ft from shore) is commonly on the order of 20 cm (7.87 in) thick, and these deposits are dominantly terrigenous mud. Actual thicknesses are typically 10 to 20 cm (3.94 to 7.87 in). Some of the greatest thicknesses (40 cm/15.75 in) occur in depocenters between fish ponds (where low energy inhibits removal processes) or inside of partially destroyed fish ponds (for example, Kakahaiʻa).

- Sediment deposits tend to thin seaward from the shoreline to values of 5 cm or less several hundred meters offshore and are only a few cm thick—or absent entirely—on top of smooth, raised rock surfaces.

- Sediment thicknesses are highly variable on the mid and outer reef flat (50 cm/19.69 in variations are not uncommon). Much of this variation is due to admixtures of terrigenous mud and reef-derived sand and rubble infilling low areas.

Transport and Fate of Sediment on the Molokaʻi Reef

The variations in composition indicate that the origin and transport of sand on beach and inner reef-flat environments are effectively separated from production and transport on the fore reef. The fore reef is the zone of high biological productivity and therefore also of sand production. Despite this productivity, and because of the physical isolation of the live reef created by the broad, shallow reef flat (see images in Field and others, this vol., chap. 2), the narrow to nonexistent beaches of south-central Molokaʻi have very limited sources available for natural replenishment.

On the south shore of Molokaʻi, beach sand and reef-flat sand are similar in both composition and relative abundance of coralline algae, chemically altered (micritized) carbonate grains, terrigenous grains, and coral. The similarity in composition and abundance suggests that sediment is exchanged between the beach and the reef flat and that beaches therefore are locally supplied by adjacent reef-flat productivity. Sand on the fore reef is distinctly different in composition in several regards, including the absence or near absence of land-derived terrigenous grains. Sand appears to be locally generated on the fore reef, seaward of the reef crest. Locally derived calcareous green algae, *Halimeda* spp., are the fourth most abundant sand component on the fore reef. The near-absence of land-derived sand grains on the fore reef indicates that sand is not being transported from the shoreline and across the reef flat in significant quantities to the fore reef. The silt and clay fraction of fore-reef sediment similarly lacks a significant land-derived component.

The reef-derived portion of the sand, silt, and clay fractions increases with distance from shore, reaching maximum value midway across the reef flat (fig. 3). The land-derived fraction is larger close to shore, perhaps indicating sediment trapping. Low productivity of reef sediment on the inner reef flat also partially explains why the relative portion of land-derived sediment is high there. On the Molokaʻi inner reef flat, only minor production of grains by corals and coralline algae occurs (fig. 4), probably because of the combined effects of low coral cover and chronic turbidity from entrained mud. Living coral colonies and encrusting coralline algae on the outer reef flat and reef crest make up 10 percent to 30 percent of the substrate, thus leading to higher production of calcium carbonate grains in these areas than on the relatively barren inner reef flat. Equal abundances of reef-derived sand grains on both sides of the reef crest indicate that sediment exchange occurs across the reef crest. Thus the wide reef flat is more effective than the reef crest itself as a physical barrier to sand movement.

The Mud Factor

Our studies on the Molokaʻi reef clearly indicate that different size fractions have different transport patterns. Mud is more mobile than sand and is resuspended frequently (often daily; see Ogston and others, this vol. chap. 20). The observations of sediment thickness, combined with the measurements of particle size and carbonate content, show that land-derived mud is a dominant component on the inner reef flat, decreasing in content seaward across the reef flat. Little land-derived mud is present on the reef crest or fore reef, indicating either that little mud is transported to these environments or that it is not retained there. Bothner and others (2006; this vol., chap. 19) discuss the amounts and composition of mud collected on the fore reef and conclude that fine-grained sediment is moving through the system but only minor amounts are retained on the fore reef. Whether the mud particles bypass the outer reef entirely, or are deposited for a short time is not clear. What is evident is that the

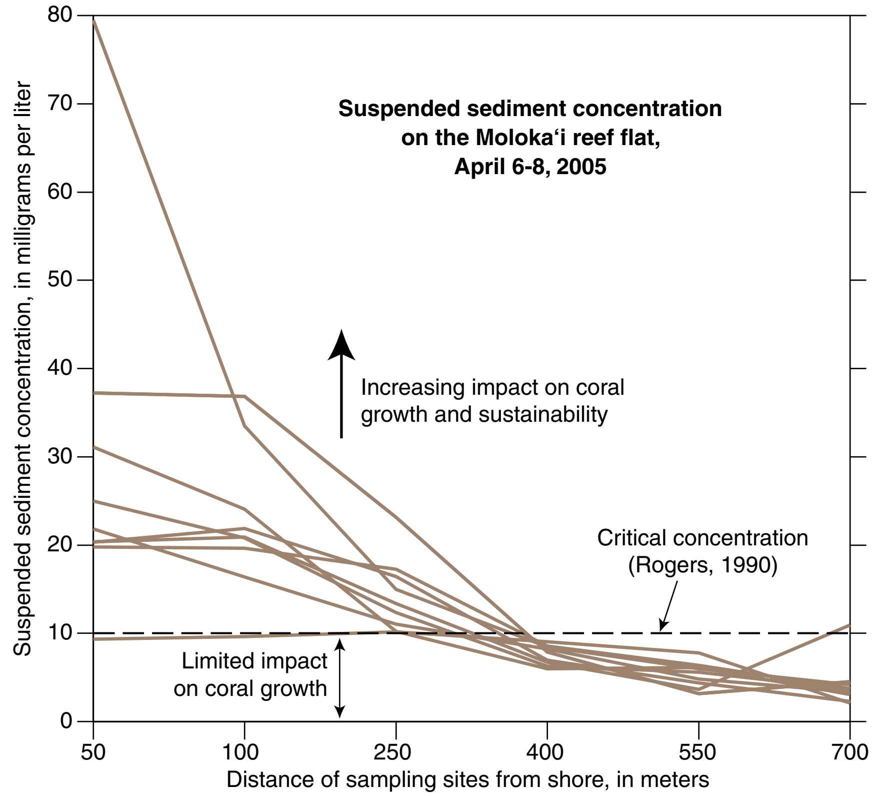


Figure 9. Diagram of suspended sediment concentrations across the reef flat between Kamalō and the Kaunakakai Wharf measured at 1-mile intervals along the shore in April 2005. All of the profiles show high levels of suspended sediment (typically 10 to 40 mg/L and higher). The values steadily decrease to about 5 to 10 mg/L at a distance of 400 m (1,312 ft) from the shore. One profile is consistently higher than other profiles; its position is just west of the mouth of Kawela Gulch, where large amounts of terrestrial sediment are deposited during storms. A concentration of 10 mg/L, based on the work of Rogers (1990), is commonly accepted as sufficient to affect corals, although many factors, such as land-derived content, duration, and particle size, also affect coral growth and survivability.

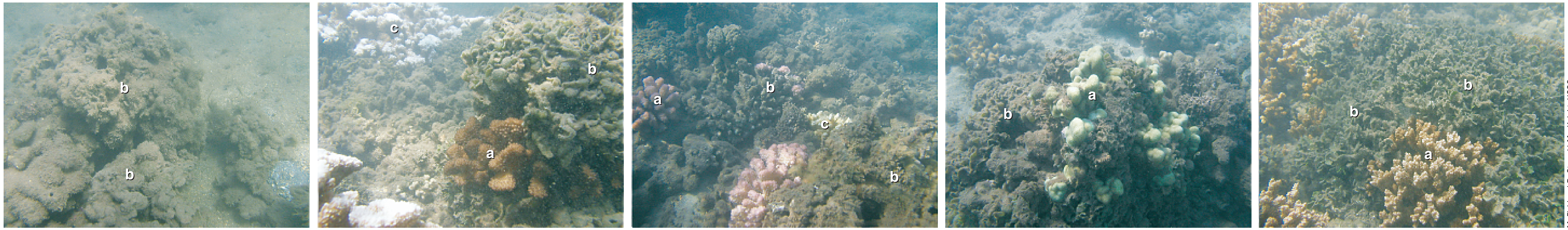


Figure 10. Photographs from the Moloka‘i reef flat (Kakahai‘a and Kamililoa) showing the abundance of sediment-covered macroalgae overgrowing—and in some instances smothering—live colonies of *Pocillopora meandrina, Porites* spp., and *Pocillopora damicornis*. These photos were taken in May 2002 following a winter in which large amounts of sediment were washed onto the reef. The sediment seemed to trigger an algal bloom, which in turn led to more sediment trapping. Each individual macroalgae clump on the Moloka‘i reef flat traps and holds nearly 4 g of sediment (Stamski and Field, 2006). Few live colonies (a) are evident in the photographs; most are covered by algae and sediment (b) or bleached and dead (c).

residence time of land-derived mud on the fore reef is minimal under present-day conditions. Changes to the reef due to increased sediment yield from the land or increased storage capacity because of local sea-level change or other factors could alter pathways such that land-derived mud could become more, or less, abundant on the coral-rich fore reef in coming years.

More important at present is the excessive amount of land-derived mud on the inner reef flat. Sediment is 5 to 10 cm thick across tens of square kilometers. That sediment is at least half mud in many places, and most of that is land-derived in origin (fig. 2). The persistency of the mud over years of monitoring the reef indicates a long residence time, probably resulting from a slow flushing process. Although the mud is very mobile and results in high turbidity levels on a daily basis, the amount that is transported across the reef appears to be minor relative to along-reef transport and residency on the inner reef flat. Fine-grained sediment is introduced only episodically to the Moloka‘i reef (Field and others, this vol., chap. 21). Once it is deposited, however, the relatively weak wave stresses and the coast-parallel transport that characterizes the reef are not efficient at dispersing the mud.

Mud in Suspension

As pointed out by Ogston and others (2004) and Storlazzi and others (2004), the combination of waves generated by trade winds and tide levels above median height generate wave stresses that are sufficient to resuspend mud particles on the shallow reef flat. These conditions exist on most days of the year, leading to chronic conditions of high turbidity. In 2005, a study of turbidity was conducted on the Moloka‘i reef flat to examine the concentration of suspended sediment across the reef flat and along the coast between Kamalō and the Kaunakakai Wharf. Some of the preliminary results, shown in figure 9, follow the findings of Presto and others (2006). Turbidity levels are consistently high (typically 20 to 40 mg/L and higher) near the coast and decrease markedly to concentrations of 5 to 15 mg/L mid-way across the reef flat (400 m/1,312 ft from shore). Further, the content of the suspended sediment changes. Presto and others (2006) show that the sediment is dominantly land-derived (>90 percent) close to shore; these values decline steadily across the reef flat to values of ~75 percent at distances of 500 m. On the outermost reef flat, the amount of land-derived sediment in suspension is only about 10 percent.

Mud Fallout and Algal Trapping

One interesting result of the daily resuspension of mud on the reef flat is the resulting daily deposition when winds abate and/or the water level drops at low tide. The sediment is deposited in thin layers over hard surfaces (thereby limiting recruitment) and over live coral and macroalgae (fig. 10). A study by Stamski and Field (2006) showed that macroalgae trapped an average of 1.26 g of sediment per gram of dry weight biomass. Individual macroalgae weigh on average about 3 g and are very abundant on the inner reef flat. The sediment trapped by macroalgae is dominantly land-derived mud (nearly 60 percent). Stamski and Field estimate that about 310 metric tons of sediment were retained by macroalgae across 5.75 km^2 (spread evenly, that equates to roughly 54 g/m^2). It seems likely that most of the particles attached to the macroalgae remain affixed until decay of the algae, at which time the particles reenter the sediment reservoir on the inner reef flat. Thus macroalgae are an important factor in sediment retention and the overall sediment budget for the reef.

Summary

Sediment is a natural part of coral reefs, especially those bordering high islands such as those of the Hawaiian archipelago. However, it is clear from even a cursory examination of photographs that the amount of sediment, and of mud in particular, on the south Moloka‘i coral reef is large compared to similar reefs elsewhere.

At present, the fore reef exists in a near-natural state with regard to sediment. Nearly all of the sediment is sand size and locally derived from the reef by natural processes. The sand is concentrated in pukas (holes) in the reef, in channels and grooves, and within the framework of the reef. The only exception to this overview is the area east of Kaunakakai Wharf, where coral is essentially absent in a small zone that extends from the reef crest (3-m water depth) to the base of the fore reef (28-m water depth). This zone is mantled by thin layers of sand that are periodically mobilized by the long-period swell, and this movement likely inhibits coral recruitment and recovery. There is limited evidence that mud from the land and reef flat is deposited only temporarily on the fore reef. However, continued sedimentation in excessive amounts, now largely confined to the reef flat, has the potential to reach the fore reef in larger amounts and impact reef health and sustainability.

Sediment quantities derived from adjacent island slopes increased substantially in the late 1800’s, largely a result of the changes that occurred in the watersheds, as described by Roberts and others (this vol., chap. 14); changes in the watersheds continue today. Much of the land-derived terrigenous sediment is stored on the Moloka‘i reef flat between Kamalō on the east and the Pālā‘au embayment on the west. Farther east and farther west from those locations, reef-flat sediment generally contains markedly less mud, and most of the sediment is reef-derived. This is a result of two factors: less mud is entering the reef in those locations, and the processes of mud removal are more efficient because of oceanic swell (south and west) and direct exposure to deep-water trade wind waves (east).

Between Kamalō and Pālā‘au the reef flat is mantled with sediment that ranges from 0 to >50 cm in thickness. Most of the inner reef flat is covered by 5 to 15 cm (2.0 to 5.91 in) of sediment, in which land-derived mud is a dominant component. Sediment is resuspended on almost a daily basis and through this process blocks light, covers recruitment sites, and mantles coral. Large amounts are trapped by the abundant macroalgae (nearly 4 g per clump of macroalgae). Thickness of the mud has not changed significantly since at least 1999, indicating that despite the daily resuspension and transport events, much of the mud fraction is retained on the inner reef flat.

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