CHAPTER 19

Sediment Mobility Along Molokaʻi's Fringing Coral Reef: Evidence From Sediment Traps

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There is concern about the potential negative impact of suspended sediment and sedimentation on the health of the coral reef off Molokaʻi (Roberts, 2001; Jokiel and others, 2004). To gain information about the composition and quantity of sediment that was being transported within the reef system, we deployed a series of sediment collection tubes on the reef (fig. 1) as described in Bothner and others (2006). We were interested in characterizing the material collected in traps during and after flood events associated with Kona storms to determine how much land-derived material was transported to the fore reef where coral growth was most active. By analyzing sediment collected in traps and wave-stress data, we sought to improve understanding of the frequency, cause, and relative intensity of sediment mobility/resuspension events within the Molokaʻi fringing reef system. We also analyzed potentially toxic metals and magnetic properties of the trapped sediment.

We found evidence of land-derived sediment moving throughout the reef system. This material had low concentrations of toxic metals and, in some areas, had distinctive magnetic properties that may reflect different sources of the land-derived sediment. Time-series traps with a temporal resolution of 4.5 days showed that during Kona storms and significant floods, the sediment collection rate increased by as much as 1,000 times compared to nonstorm intervals. The sediment collection rate increase was related to resuspension of existing sediment by Kona storm waves rather than higher fluxes of flood-derived sediment. The similar composition of trapped sediment collected before, during, and after the Kona storms indicated that when a major flood is accompanied by high waves, the land-derived sediment has a low potential for burying coral on the fore reef.

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Trapping Sediment

Two types of sediment traps were used. The simpler tube trap (fig. 2) consisted of a 60-cm-long (23.6 in), clear plastic tube having an internal diameter of 6.7 cm (2.6 in). A baffle of "honeycomb-like" cells (diameter 0.5 cm/0.2 in, length 7.6 cm/3 in), consisting of resin-coated fiber and treated with anti-fouling paint, was placed in the top of the sediment traps to reduce turbulence and to prevent fish occupation. The tube trap openings were at 0.6 meters above bottom (mab) (2 ft), except on the shallow reef flat where they were 0.3 mab (1 ft). Reproducibility of the collection-rate measurement by tube traps was evaluated by setting duplicate traps on seven occasions. The average difference in collection rate between pairs was 11 percent.

The programmable time-series trap (fig. 3) had a 20-cm (8 in) internal-diameter collection cylinder with an overall length of 75 cm (30 in). The cylinder opening was 1.3 mab (4 ft). A funnel, within the cylinder, directed

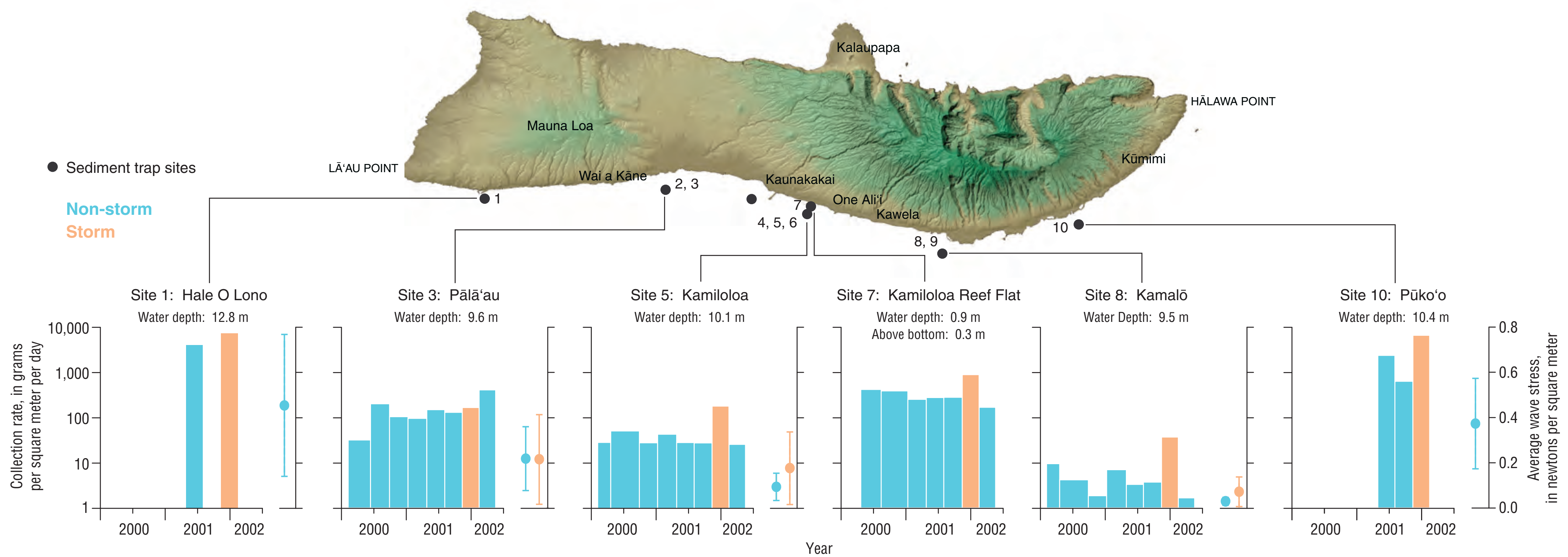


Figure 1. Location of sediment traps along the south shore Molokaʻi reef, along with collection rates (bars, log scale) during successive roughly three-month periods. Collection rates from nonstorm periods are shown in blue, and data from the deployment period containing Kona storms are shown in orange (scale at left). Average wave-induced bottom stress is shown in corresponding colored dots alongside the graphs (scale at right); bars show plus and minus one standard deviation. Higher bottom stress at the wave-exposed east and west ends of the reef, and lower bottom stress in the more protected central area, explain the regional differences in collection rate. High bottom stress during Kona storms generated higher collection rates at most locations. See text for details.

Figure 2. Tube trap at site 3 on coral ridge at start of deployment. Water depth is 9.6 m (31.5 ft).

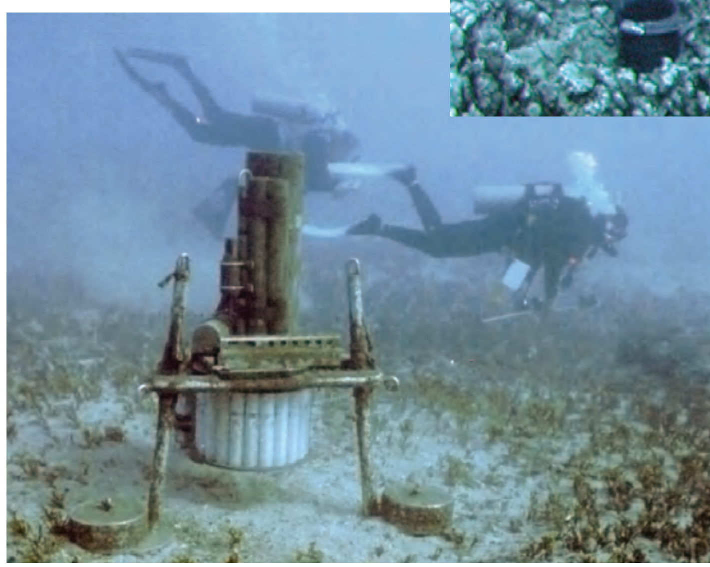


Figure 3. Time-series sediment trap at 11.5-m (37.7 ft) water depth off Kamiloloa.

settling particulate material into one of 21 plastic bottles (500 ml/17 oz each). A carousel rotated a new sampling bottle under the funnel after a period of about 4.5 days (McLane Research Laboratories, Inc., 2004), providing a detailed temporal resolution of collection-rate variability. Time-series traps were positioned at Kamiloloa (site 4) and Pālā'au (site 2) at about 12-m (39 ft) water depth.

Self-contained wave gauges were deployed at six locations, which were also occupied by sediment traps, to provide co-located measurements of wave heights and wave periods for estimating wave-induced near-bed shear stress. Details of sampling and analytical techniques are provided in Bothner and others (2006).

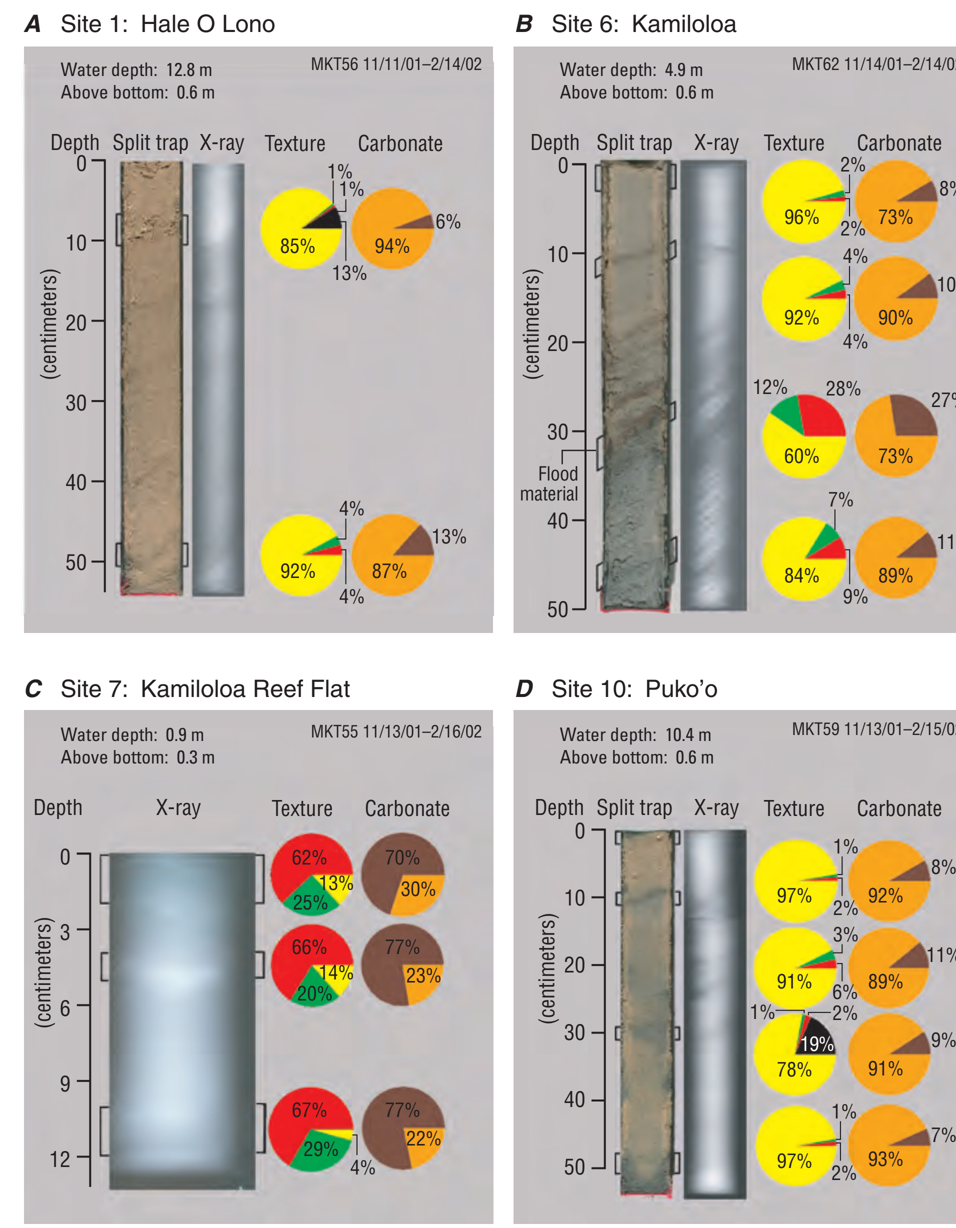
We emphasize that sediment traps in this study provide only a relative measure of sediment mobility/resuspension. This limitation exists because the efficiency of traps for collecting particles and the degree of biasing in favor of the more rapidly settling particles have not been quantified in areas influenced by large surface waves. We also define the rates determined by using sediment traps in this environment as "collection rates" rather than "sedimentation rates." The term "collection rate" is used because particles settling into a well-designed trap encounter significantly lower turbulence than particles falling onto the reef surface, where they may be resuspended and removed as the next wave passes. For these reasons traps do not measure net sediment accumulation in this setting.

In addition to the relative measure of sediment mobility, the traps provided sufficient material for analysis of temporal variability in sediment properties. Some tube traps were X-rayed at the Kaunakakai Hospital to identify layers of different sediment density and grain size. Concentrations of heavy metals in trap samples were determined by using inductively coupled plasma mass spectrometry after the sediments were completely dissolved in strong acids (Lamothe and others, 1999). Magnetic properties of the sediment samples also were measured following the methods of Thompson and Oldfield (1986) in order to evaluate the characteristics and abundance of magnetic minerals, such as magnetite, a common component of island rocks and soils.

Sediment Collection Rate: How it Varies Along the Reef

Tube Trap Collection Rates

The three-month average sediment-collection rates indicate regional variations in sediment mobility (fig. 1). The orange bar in each graph shows collection rates during the period that included the Kona storms



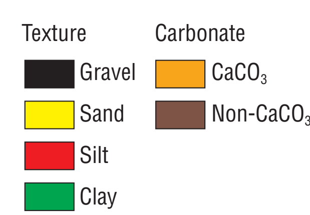


Figure 4. Characteristics of sediment trapped during the deployment in which Kona storms occurred. Traps were X-rayed, split, and photographed. Selected layers were analyzed for sediment grain size and for calcium carbonate content. Traps shown in *A*, *B*, and *D* were full when recovered. *A*, The exposure to large waves at this location accounts for collection of sandy sediment composed predominantly of reef-derived carbonate. *B*, The appearance and composition of the layer at 31–34 cm (12–13 in) (sampled parallel to layer boundaries) indicates that land-derived material was transported in a pulse to this fore-reef location. *C*, The trapped sediment from the reef flat contained the highest noncarbonate fraction and the highest silt and clay percentages observed. Floods accompanying the Kona storms increased the inventory of land-derived fine-grained sediments on the reef flat. *D*, No increases in land-derived sediment were observed at this location. The consistently high percentage of coarse-grained carbonate sediment reflects the frequent exposure to high waves.

of November 2001 and January 2002. Those storms brought exceptionally high waves and wave-induced bottom stresses (orange dots and error bars) to most areas along the fore reef and flooding rains to the normally dry south side of Molokaʻi.

During the tube trap deployment that included the period of Kona storms, the three-month collection rate along the fore reef averaged about 10 times higher than collection rates during prestorm deployment periods but showed considerable variability (fig. 1). Tube trap collection rates influenced by Kona storms increased from 1.3 times higher at Pālāʻau (site 3) to 39 times higher at Kamalō. The tube traps at Hale O Lono (site 1) and Pūkoʻo (site 10) were full at the time of recovery, so the sediment collection rates during the storms were minimum estimates, yet they represent the highest rates observed (>7,400 g/m^2/day or 1.5 lbs/ft^2/day and >6,400 g/m^2/day or 1.3 lbs/ft^2/day, respectively; fig. 1).

A comparison of sediment collection rates and wave-induced bottom stress during deployment periods without Kona storms (blue dots and error bars, fig. 1) supports our assumption that collection rates are influenced primarily by waves. The average collection rates in tube traps were highest at Hale O Lono and Pūkoʻo, on the wave-exposed western and eastern ends of the reef, and lowest at Kamalō. Sediment collection rates were intermediate at Kamiloloa and Pālāʻau. Variations in average bottom stress have the same spatial pattern.

The influence of wave-induced bottom stress on sediment collection rate is evident in the comparison of results from two tube traps at different depths (4.9 m/16 ft and 10.1 m/33.1 ft) on the same type of bottom at Kamiloloa. The shallower tube trap collected sediment at a rate 28 times higher than the collection rate of the deeper tube trap, reflecting wave-induced bottom stress that was about three times higher than at the deeper site.

The collection rate also depends on sediment availability. At Pālāʻau, one tube trap was on a coral spur (site 3) at 9.6-m (31.5 ft) water depth that was covered by 95 percent living coral with, at most, a dusting of fine sediment, except in deep crevices of the reef surface. A second tube trap was approximately 12 m (39.4 ft) away from the first tube trap, at 12.6-m (41.3 ft) water depth, in a channel (site 2) floored by freshly rippled sand, an indication of active sediment movement. Although the bottom stress on the coral spur is considerably higher because of shallower water, the collection rates were only one third of those measured in the sand channel where there is an abundant near-by source of sediment.

On the reef flat (fig. 1, site 5), high collection rates are related to the combination of a large inventory of fine-grained sediment, shallow water, trade-wind waves, and occasional long-period ocean swell, particularly at high tide (see Ogston and others, this vol., chap. 20, for further discussion about trade-wind waves and transport).

Composition of Material in Tube Traps

The Kona storms completely filled some of the tube traps, providing sufficient sediment volume to identify and sample individual layers by using X-rays of the whole tube trap and photographs of split tube-trap samples.

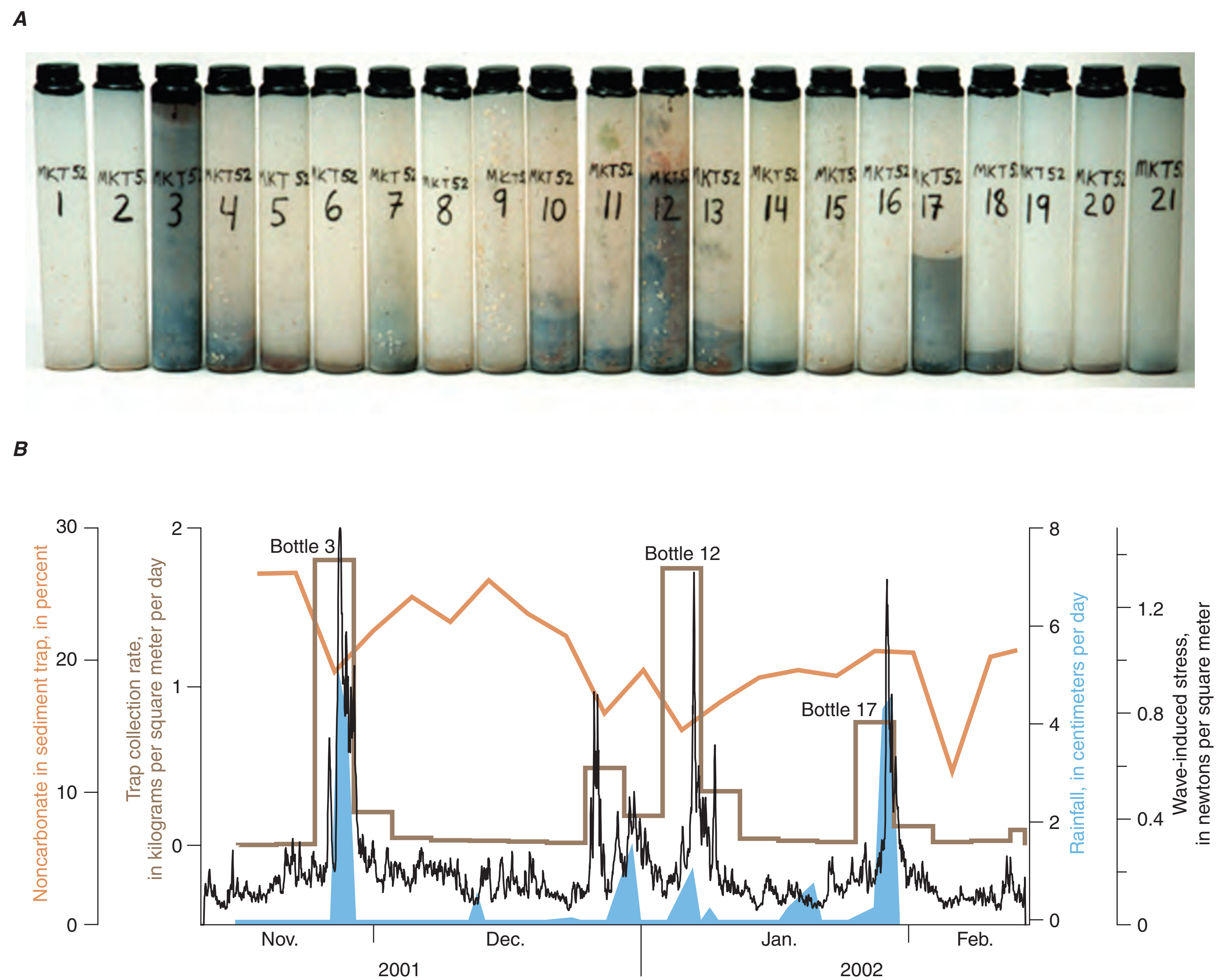


Figure 5. Sediment collection at Pālāʻau at 12.6 m (41.3 ft) water depth. *A*, Photograph of sample bottles with various amounts of gray sediment collected at Pālāʻau during successive 4.5-day intervals between November 15, 2001, and February 14, 2002. *B*, Plots of trap-collection rate, rainfall, wave-induced bottom stress, and percentage of noncarbonate sediment trapped during the deployment off Pālāʻau between November 15, 2001, and February 14, 2002.

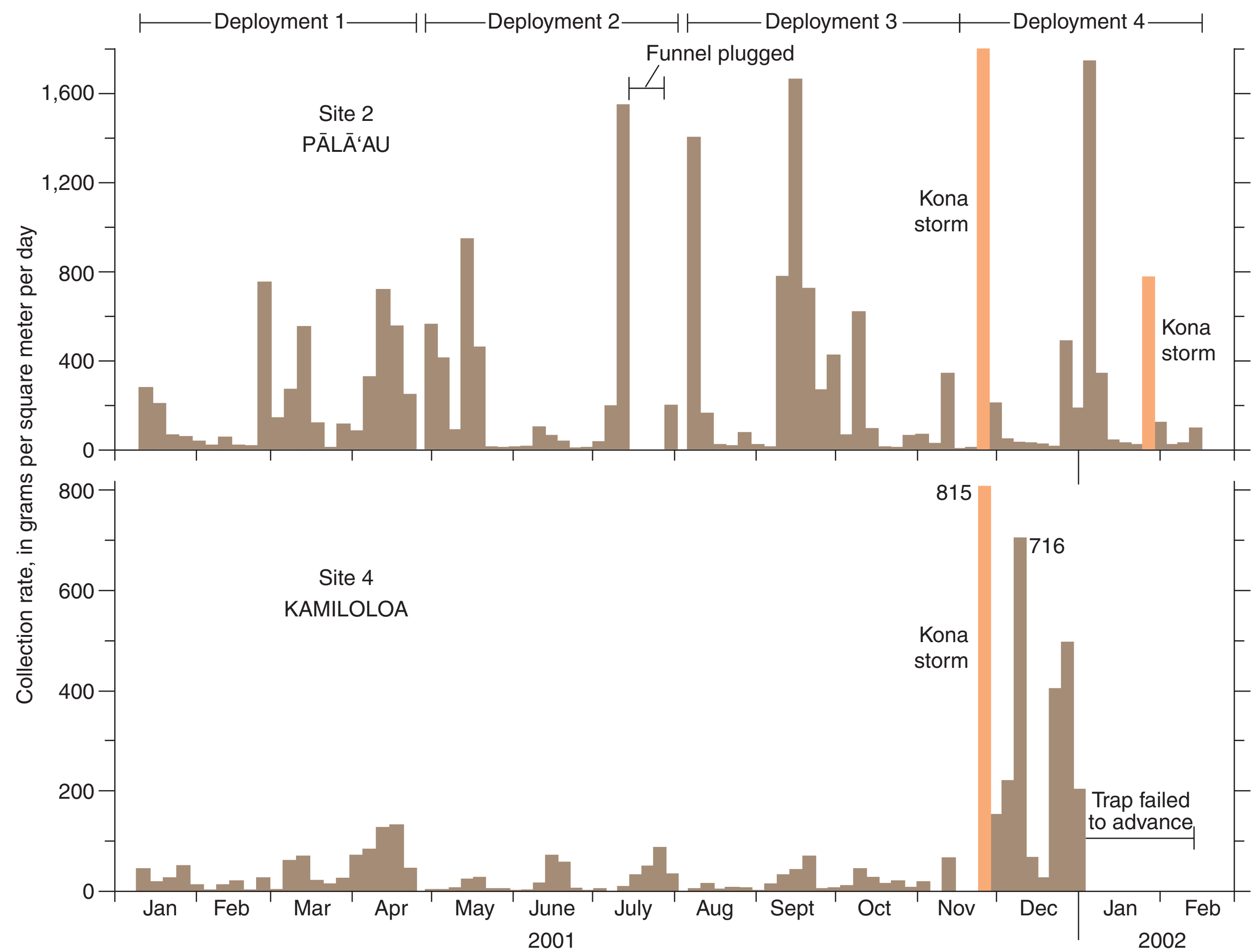


Figure 6. Collection rates determined in time-series traps were consistently higher at Pālā'au (top) than at Kamiloloa (bottom) in response to higher wave-induced bottom stress. Orange bars represent intervals during which Kona storms occurred. The similarities in timing of many peaks in collection rate at these two locations indicate that wide areas of the reef are affected by the same wave events.

Selected horizons were analyzed for texture (grain size) and carbonate content (fig. 4).

On the reef flat off Kamiloloa, the sediment trapped during the Kona storm period had the highest noncarbonate fraction (76 percent), indicating a land source, and the highest percentage of silt and clay (90 percent) in this study (fig. 4*C*). The 76-percent noncarbonate value was significantly above the 60-percent prestorm average and the 58-percent single poststorm value. These percentages are consistent with the hypothesis that land-derived mud is delivered to the south Moloka'i reef flat during the floods that typically accompany Kona storms (Ogston and others, 2004; Field and others, this vol., chap. 21).

Farther offshore of Kamiloloa, the flood signal also was measurable. The sediment tube trap on the fore reef at 4.9-m (16 ft) water depth, 100 m (328 ft) seaward of the reef crest (site 6), had a distinct horizon at 31–34 cm (12–13 in) that was visible in the trap X-ray and in the photograph of the split-trap sample (fig. 4*B*). The steep dip of this horizon, and other horizons that were nearly parallel to it, may result from a slight tilt of the trap from vertical (typically <10°) during deployment that would allow particles to preferentially accumulate along one side of the tube trap. The 31–34-cm horizon had significantly higher amounts of silt and clay (40 percent), noncarbonate particles (27 percent), and magnetite particles than other horizons in the trap. Although it is not possible to assign dates to deposits within the tube trap, we interpreted this horizon as a pulse of land-derived material that was transported over the reef crest and deposited in the trap during or after the storm (Field and others, this vol., chap. 21). Compared to a horizon deposited at 45–48 cm (18–19 in), percentages of both mud and noncarbonate particles in the 31–34-cm horizon increased by a factor of 2.5, and the percentage of magnetite particles (another indicator of land-derived material) increased by a factor of 4.5. This is the best example of presumed flood material that accumulated in tube traps beyond the reef crest.

The tube trap at site 6 is in an anomalous region, about 6 km (3.7 mi) in length, along the reef crest where live coral coverage is <12 percent, as compared to 80–90 percent elsewhere (Jokiel and others, this vol., chap. 5). Ogston and others (2004) and Storlazzi and others (2004) note that this anomalous region is exposed to elevated suspended-sediment concentrations resulting from resuspension and offshore transport of reef-flat material by trade-wind waves, swell, and local circulation. These authors point out, however, that a causal linkage between offshore sediment transport and the low coverage of living coral in this region has not been confirmed. The compositional tube trap results suggest that sediment from the reef flat can be transported across the reef crest to the fore reef in this region and may impact coral health.

Tube traps from Hale O Lono and Pūko'o were completely filled during the deployment that included periods of Kona storms, and therefore the collection-rate estimates constitute a lower limit (at least 7,400 g/m^2/day and 6,400 g/m^2/day, respectively). The texture of the trapped sediment at these sites is >78 percent sand, and the carbonate contents within both tube traps fall between 87 percent and 94 percent, indicating a consistent predominance of reef-derived material in each horizon selected. There was also no evidence of increased land-derived material from visual or X-ray assessment of trapped sediment. At both sites gravel-size particles were collected in the tube traps, indicating periods with significant resuspension.

How Sediment Collection Varies with Time

The storm of November 27–28, 2001, generated the highest rainfall (>4 cm/day or 1.6 in/day) and the highest wave-induced bottom stress during the 14-month study (fig. 5*B*). The sediment collection rate at Pālā'au during the 4.5-day period that included the November storm (fig. 5*A*, bottle 3) was also the highest recorded. We used percent noncarbonate to determine the relative importance of reef and land as sources of material trapped before, during, and after the storm. At Pālā'au we found that the percent noncarbonate in storm and poststorm samples was equivalent to, or

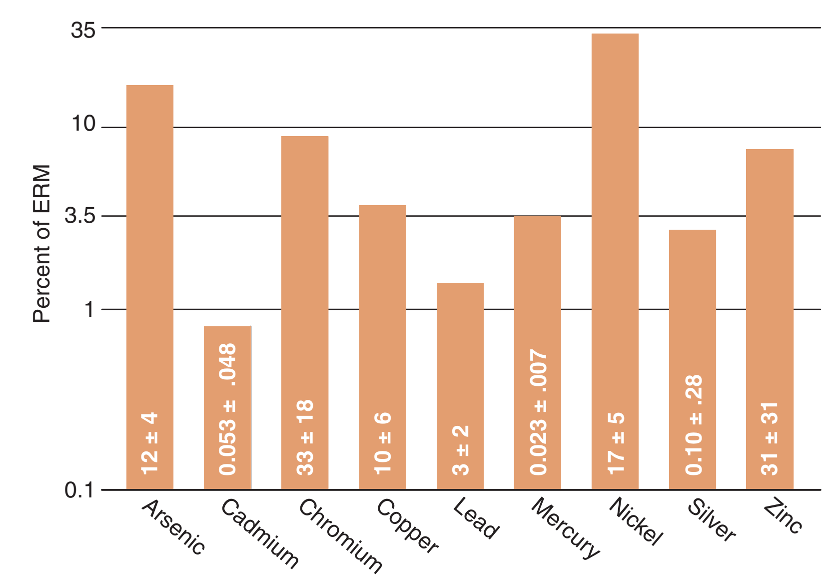


Figure 7. Histogram showing the average metal concentration (in parts per million, mean ±one standard deviation) in sediments trapped off south Moloka'i as a percentage of the Effects Range-Median (ERM), a guideline for sediment toxicity (Long and others, 1995).

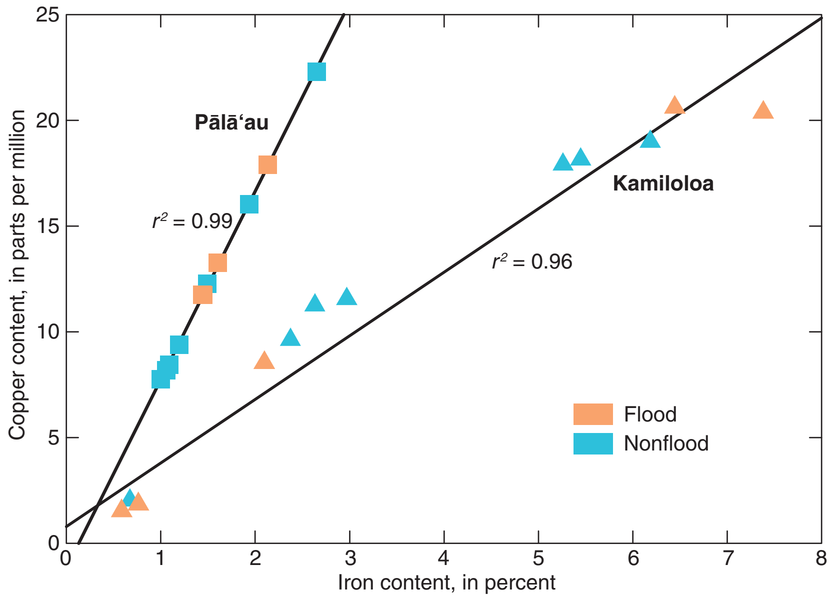


Figure 8. Concentrations of iron (percent dry weight) and copper (parts per million = µg/g) are highly correlated within trap samples from Pālā‘au and Kamiloloa. Samples collected during flood periods (orange) plot on the same line as those collected during non-flood periods (blue). These data suggest that the source of land-derived material in traps is different for each site but was not changed by the floods.

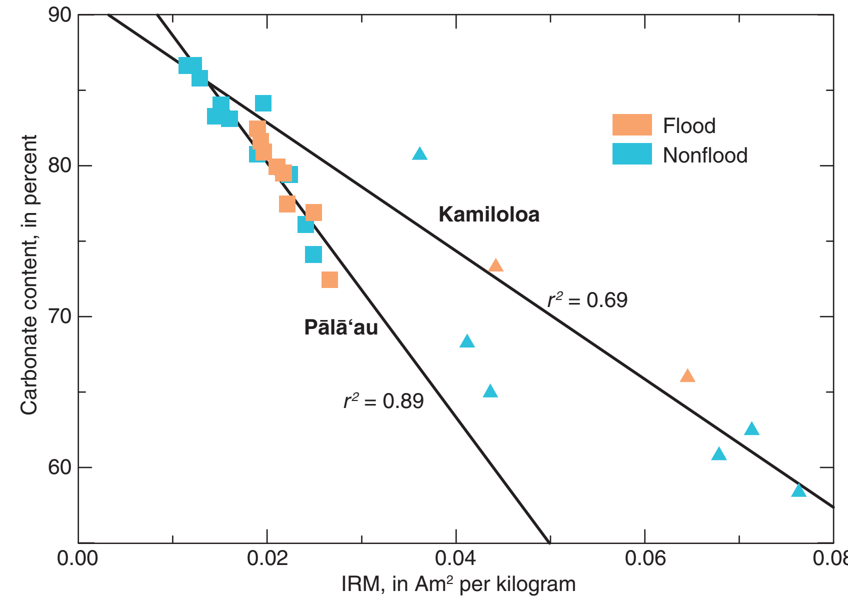


Figure 9. The different regression lines for isothermal remanent magnetization (IRM in units of ampere meter squared per kilogram) versus percent calcium carbonate in trap samples from Pālā‘au and Kamiloloa indicate a higher magnetite content in the land-derived fraction of Kamiloloa traps. Data from flood periods (orange) plot with the same slope as data from non-flood periods (blue). These trends provide further evidence that floods did not significantly alter the composition of trapped sediment.

lower than, the prestorm average of 24 ± 2 percent (fig. 5*B*). We concluded, therefore, that the high sediment collection rates during this period were due primarily to wave-induced resuspension of bottom sediment at the trap site and that the composition of mobile sediment collected in this trap was not changed as a result of the flood.

At the Kamiloloa fore-reef site (site 4, water depth 11.5 m/37.7 ft), the percent noncarbonate in time-series trap samples increased from 34 ± 2 percent during prestorm periods to 39 ± 2 percent during poststorm periods of comparable wave-induced bottom stress (data not shown). This magnitude of increase is considerably less than observed in tube traps from the Kamiloloa reef flat (fig. 4*C*) or from the 31–34-cm horizon in the tube trap at 4.9 m (fig. 4*B*), implying that material introduced during the flood period was not easily identified beyond the reef crest.

The low variability in percent noncarbonate in sediment collected by traps suggests that there is a low potential for flood-derived sediment to bury or smother coral on the fore reef off Moloka‘i when floods are accompanied by high waves. The potential for settling particles to be retained in sediment traps is much greater than on the exposed surface of the coral reef where wave-induced turbulence may cause settling particles to be removed by successive waves. The observation that flood-derived material does not accumulate in fore-reef traps in sufficient quantity to significantly change composition indicates that this material is unlikely to accumulate on the adjacent surface of living corals. However, the consistent presence of land-derived material in all traps is evidence that terrestrial sediment is passing through the system, thus possibly having an influence on reef health.

The time-series sediment traps at Pālā‘au and Kamiloloa (fig. 6) provide two pieces of new information. First, the collection rates are consistently higher at Pālā‘au than at Kamiloloa—about 10 times higher during deployments 1–3 and about 2 times higher during deployment 4. There are consistent relative differences in wave-induced bottom stress at the two locations. Average bottom stress at Pālā‘au is higher than at Kamiloloa by about 2 times during deployments 1–3, but higher by only 20 percent during deployment 4.

Second, the timing of collection events is similar at Pālā‘au and Kamiloloa, which indicates that wide areas of the reef are impacted by the same wave events. There were 16 peaks in the collection-rate record at Kamiloloa (fig. 6) when time-series traps at both locations were operating properly. Of these 16 peaks, the timing of 8 peaks matches exactly with the timing of peaks at Pālā‘au. For 6 additional peaks, the timing at the two locations agrees within one interval.

Concentrations of Metal Collected in Traps

The concentrations of metals in trapped sediment were low (fig. 7) compared to sediment-quality guidelines that are often used to assess potential toxicity of coastal sediments. These guidelines, known as the Effects Range-Median (ERM), are the metal concentrations above which toxic effects in marine organisms were observed in approximately 50 percent of reviewed studies (Long and others, 1995). Low concentrations of heavy metals are not surprising, because there are no mining or metal-related industries on Moloka‘i, and there are no ocean outfalls for sewage. Sewage from the town of Kaunakakai (940 m^3/day from a population of 2,700) undergoes secondary treatment, with disposal of dry sludge to a landfill and discharge of treated effluent into injection wells. Impacts from potential migration of ground water from these injection wells or from others used by private septic systems outside of Kaunakakai have not been observed (John Souza, Department of Waste Water Reclamation, Moloka‘i, oral commun., 2004).

The concentrations of most heavy metals correlate with concentrations of iron, one of the main elements in Moloka‘i’s red soils, indicating they are associated with the land-derived fraction of the trapped sediment. For example, a strong correlation of copper and iron exists for tube trap samples from Pālā‘au and Kamiloloa (fig. 8). The different slopes suggest a different composition and source of the land-derived material collected at the two trap sites. The range of metal concentrations reflects variable dilution by reef-derived carbonate sediment. In figure 8, flood-period data are shown in orange, preflood and postflood data are shown in blue. The indistinguishable copper/iron ratio during flood and nonflood periods indicates that the land-derived material had a consistent composition (and source) throughout the study period that was not changed by the floods.

Magnetic Properties of Trapped Sediment

The magnetic properties of the trapped sediment provide additional evidence of land-derived material at all locations along the reef, with no change in composition following Kona storms. Magnetite, a mineral present in rocks and soils of the Hawaiian Islands, is detected by using isothermal remanent magnetization (IRM; Thompson and Oldfield, 1986) and was found in all the samples of trapped sediment. The IRM findings indicate that land-derived magnetite makes up a measurable fraction of the actively mobile sediment throughout the reef system. IRM increases linearly as calcium carbonate decreases at both Kamiloloa and Pālā‘au fore-reef sites, but with different slopes (fig. 9). These linear but different relations are interpreted to be mixing lines between the reef-derived carbonate sediment and two different land-derived sources. The source at Kamiloloa has a higher concentration of magnetite than the source at Pālā‘au.

The linear relations in figure 9 include storm and nonstorm samples on the fore reef. There are no significant or consistent increases in IRM (magnetite) relative to carbonate in trap samples collected during or after storms. This indicates that the Kona storms did not markedly increase the land-derived component of suspended sediment relative to the reef-derived component captured by traps on the fore reef. This conclusion is supported by the nearly uniform noncarbonate percentage in prestorm and poststorm samples.

A Summary of What the Sediment Traps Show

Land-derived sediment was a measurable component of sediment-trap material at all trap sites, but it was not collected in large amounts on the fore reef. The consistent distribution of land-derived sediment indicates that fine-grained terrestrial material is constantly moving through the Moloka‘i reef system.

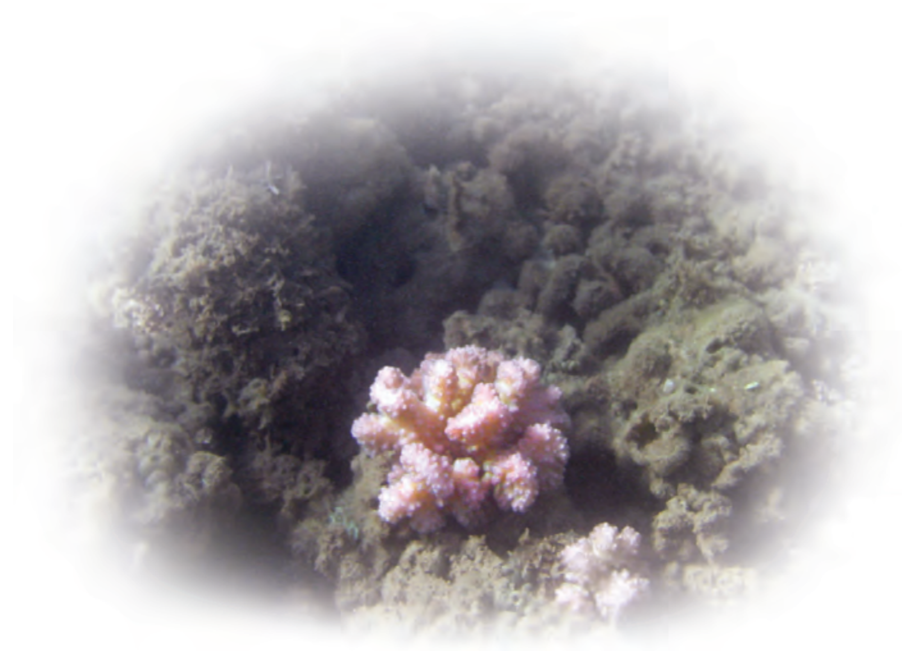
Following the Kona storms and floods beginning in late November 2001, we measured a significant increase in the land-derived fraction of trapped sediment on the reef flat at Kamiloloa, and a much weaker “flood signal” at sites on the fore reef at 4.9-m and 11.5-m water depth. At other sites along the fore reef (10–13 m water depth) there was an increase in the quantity of trapped sediment during Kona storms, but no corresponding increase in the land-derived fraction.

These patterns indicate that when a major flood is accompanied by high waves, the land-derived sediment has a low potential for burying or smothering coral on the fore reef. However, one potential impact of flood-derived sediment could be periodic high turbidity and reduction in light needed for photosynthesis by algae in coral.

We observed consistent regional differences in the relative magnitude of sediment-collection rates that correlated with spatial variations in wave-induced bottom stress. Regional differences in sediment-resuspension intensity reflect the greater wave exposure on the western and eastern ends of the reef, and the more tranquil central region that is sheltered by neighboring islands and by Moloka‘i itself.

The time-series traps with 4.5-day resolution revealed that Kona storms increased the collection rate by more than 1,000 times compared to nonstorm intervals. Good agreement was observed in the timing of peak resuspension events measured in time-series traps at two locations 12.3 km apart. This observation indicates that the same wave events cause resuspension along wide areas of the fore reef.

The concentrations of heavy metals in the trapped sediment within the reef system off Moloka‘i are well below Effects Range-Median (ERM) sediment guidelines for toxicity (Long and others, 1995). Specific guidelines for metal concentrations in sediments keyed to health of coral, however, do not yet exist. The copper/iron ratios in trapped sediment may be another index, similar to magnetic signatures, which may identify different source areas of land-derived material to the reef system.



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