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Sedimentation processes in a coral reef embayment: Hanalei Bay, Kauai

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ABSTRACT

Oceanographic measurements and sediment samples were collected during the summer of 2006 as part of a multi-year study of coastal circulation and the fate of terrigenous sediment on coral reefs in Hanalei Bay, Kauai. The goal of this study was to better understand sediment dynamics in a coral reef-lined embayment where winds, ocean surface waves, and river floods are important processes. During a summer period that was marked by two wave events and one river flood, we documented significant differences in sediment trap collection rates and the composition, grain size, and magnitude of sediment transported in the bay. Sediment trap collection rates were well correlated with combined wave-current near-bed shear stresses during the non-flood periods but were not correlated during the flood. The flood's delivery of fine-grained sediment to the bay initially caused high turbidity and sediment collection rates off the river mouth but the plume dispersed relatively quickly. Over the next month, the flood deposit was reworked by mild waves and currents and the fine-grained terrestrial sediment was advected around the bay and collected in sediment traps away from the river mouth, long after the turbid surface plume was gone. The reworked flood deposits, due to their longer duration of influence and proximity to the seabed, appear to pose a greater long-term impact to benthic coral reef communities than the flood plumes themselves. The results presented here display how spatial and temporal differences in hydrodynamic processes, which result from variations in reef morphology and orientation, cause substantial variations in the deposition, residence time, resuspension, and advection of both reef-derived and fluvial sediment over relatively short spatial scales in a coral reef embayment.

1. Introduction

Hermatypic coral reefs typically grow in relatively clear, oligotrophic waters. Land use practices such as agriculture, overgrazing, and urban development lead to significant alterations in the quantity and quality of sediment delivered to the coastal ocean and coral reefs (e.g., McCulloch et al., 2003). Terrestrial sediment runoff in developed coastal regions may also include nutrients, fertilizers, pesticides, herbicides, metals, and pathogens, and although the effects of sediment-associated contaminants on marine ecosystems may be significant (e.g., Harrington et al., 2005; Jones, 2005), the ecosystem impacts and sediment-toxicity guidelines are not well constrained for many compounds (e.g. Bjorgesaeter and Gray, 2008). By itself, fine-grained terrestrial sediment can increase turbidity, which in turn, decreases light available for photosynthesis and can create physiological stress or even coral mortality (Marszalek, 1981; Buddemeir and Hopley, 1988; Acevedo et al., 1989; Fortes, 2000; Phillip and Fabricius, 2003; Piniak, 2007; Piniak and Brown, 2008). Under conditions that permit sediment accumulation, corals can be additionally stressed due to the allocation of energy required to remove sediment particles, sites for new coral recruitment can be eliminated, and coral colonies can be buried (e.g. Rogers, 1990; Fabricius, 2005).

The studies by Marszalek (1981) and Ogston et al. (2004) and the syntheses by Rogers (1990), Phillip and Fabricius (2003), and Fabricius (2005) note that the magnitude and duration of turbidity and sedimentation play a significant factor in the ecological response of both individual corals and coral reef ecosystems. Phillip and Fabricius (2003) and Fabricius (2005) also noted that an important factor contributing to the level of degradation caused by a given stressor is the level of exposure, which is a function of the stressor's concentration and residence time, both of which are influenced by hydrodynamic processes. A number of studies have investigated sediment delivery by rivers (e.g., Milliman and Syvitski, 1992) and sediment dynamics in river plumes (e.g., Geyer et al., 2000; Warrick et al., 2008). These have primarily focused on the influence of physical forcing and flood dynamics on balance between freshwater buoyancy and sediment settling in the coastal zone.

Wolanski (1994), Fabricius and Wolanski (2000), and Wolanski et al. (2003) have conducted detailed investigations of fine-grained sediment delivery by river plumes to coral reef environments. These

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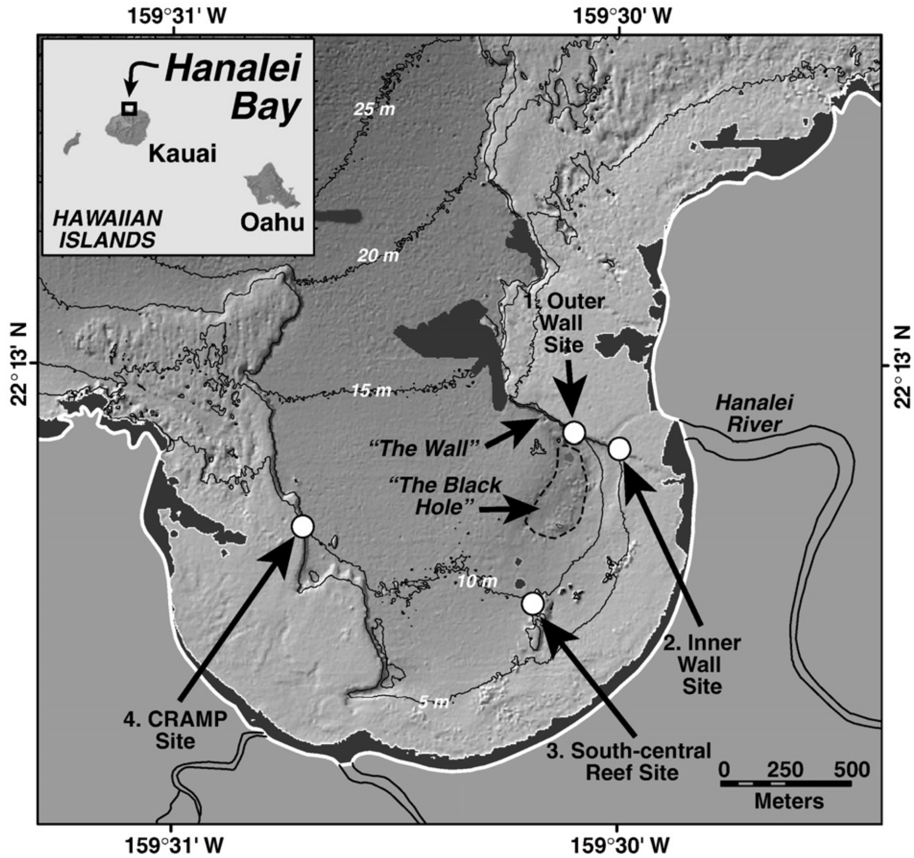

Fig. 1. Map of the study area with locations of the bottom-mounted instrument packages employed for long-term sampling. The CRAMP Site [4] refers to a permanent monitoring site of the Coral Reef Assessment and Monitoring Program by the University of Hawaii. The bathymetry is shaded by depth and the isobath interval is 5 m; gaps in the data are denoted by black regions. Inset: Location of the study area in relation to the main Hawaiian Island chain.

studies have shown the importance of the phasing between sediment delivery and oceanographic forcing (waves, currents, etc), differentiating between the effects of high suspended sediment concentrations (SSCs) in the water column due to wave resuspension versus those due to settling of a flood plume. Our study was designed to expand on their contributions and link the observed forcing and SSCs to seabed sediment dynamics and identify the long-term effects of the floods on benthic coral communities. Systematic studies that couple hydrologic, oceanographic, and geologic data on the fluvial delivery, deposition, and persistence of terrestrial sediment are needed to better understand the complete impact of river floods on coral reef environments.

The goal of this study was to better understand the sediment dynamics in a coral reef-lined embayment influenced by ocean surface waves and river floods, and quantify the processes controlling sediment residence time and dispersal. Four fixed instrument packages were deployed to make *in situ* time-series measurements of waves, winds, currents, and sediment dynamics. These data were supplemented by sediment sampling to provide information on spatial variability in sediment physical and chemical properties. The measurements document the complex interactions between waves, tides, mean currents, and river floods that drive sediment dynamics in a reef-lined embayment and these processes' contributions to suspended sediment concentrations (SSCs) and net sedimentation. The implications of these results for coral reef health and the application of sediment traps to coral reef studies will also be addressed.

2. Study area

This study focused on sediment dynamics in Hanalei Bay, an embayment approximately 4.4 km^2 on the north shore of the island of Kauai, Hawaii, USA. (Fig. 1). The floor of Hanalei Bay consists of marine carbonate sediment mixed with siliciclastic material derived from the basaltic highlands of the Hanalei River basin (Calhoun et al., 2002). The center of the bay is largely free of coral reef substrate, with a relatively flat sandy sea floor at a depth of approximately 10 m. In the eastern portion of the bay, approximately 500 m from the river mouth, there is a broad (200–400 m wide) depression 2 to 5 m deep (water depth ~12–15 m) known locally as the "Black Hole" because dark, fine-grained, organic-rich suspended sediment often obscures visibility; the seabed throughout the rest of the bay is primarily fine to medium sand (Calhoun and Fletcher, 1999; DeFelice and Parrish, 2001).

The physical environment offshore of the bay during the summer is dominated by northeasterly trade winds that generate wave heights of 1 to 3 m with periods of 5 to 8 s (Moberly and Chamberlain, 1964). Winter conditions, typically beginning in October and extending through March, are characterized by North Pacific swell that produces wave heights of 3 to 6 m with periods of 10 to 18 s that approach the bay generally from the northwest. The bay has a mixed, semi-diurnal microtidal regime, with the mean daily tidal range approximately 0.6 m and the minimum and maximum daily tidal ranges are 0.4 m and 0.9 m, respectively; circulation is generally sluggish, with mean current speeds on the order of 0.02 ± 0.02 m/s (Storlazzi et al., 2006). The fringing reefs that line Hanalei Bay's eastern and western sides range in depth from 3 m to 20 m and host coral communities that are considered relatively healthy (Friedlander et al., 1997, 2005).

The 25 km-long Hanalei River, one of the largest rivers in the Hawaiian Islands in terms of water discharge, drains an area of 54.4 km^2 before flowing into the eastern corner of Hanalei Bay. Its north-facing drainage basin consists of steep-walled, heavily vegetated volcanic ridges and fluvial gorges that drain the island's 1500 m-high central mountains, where rainfall commonly exceeds 10 m/yr.