The Coral Reef of South Moloka‘i, Hawai‘i

Portrait of a Sediment-Threatened Fringing Reef

Scientific Investigations Report 2007-5101

U.S. Department of the Interior
U.S. Geological Survey

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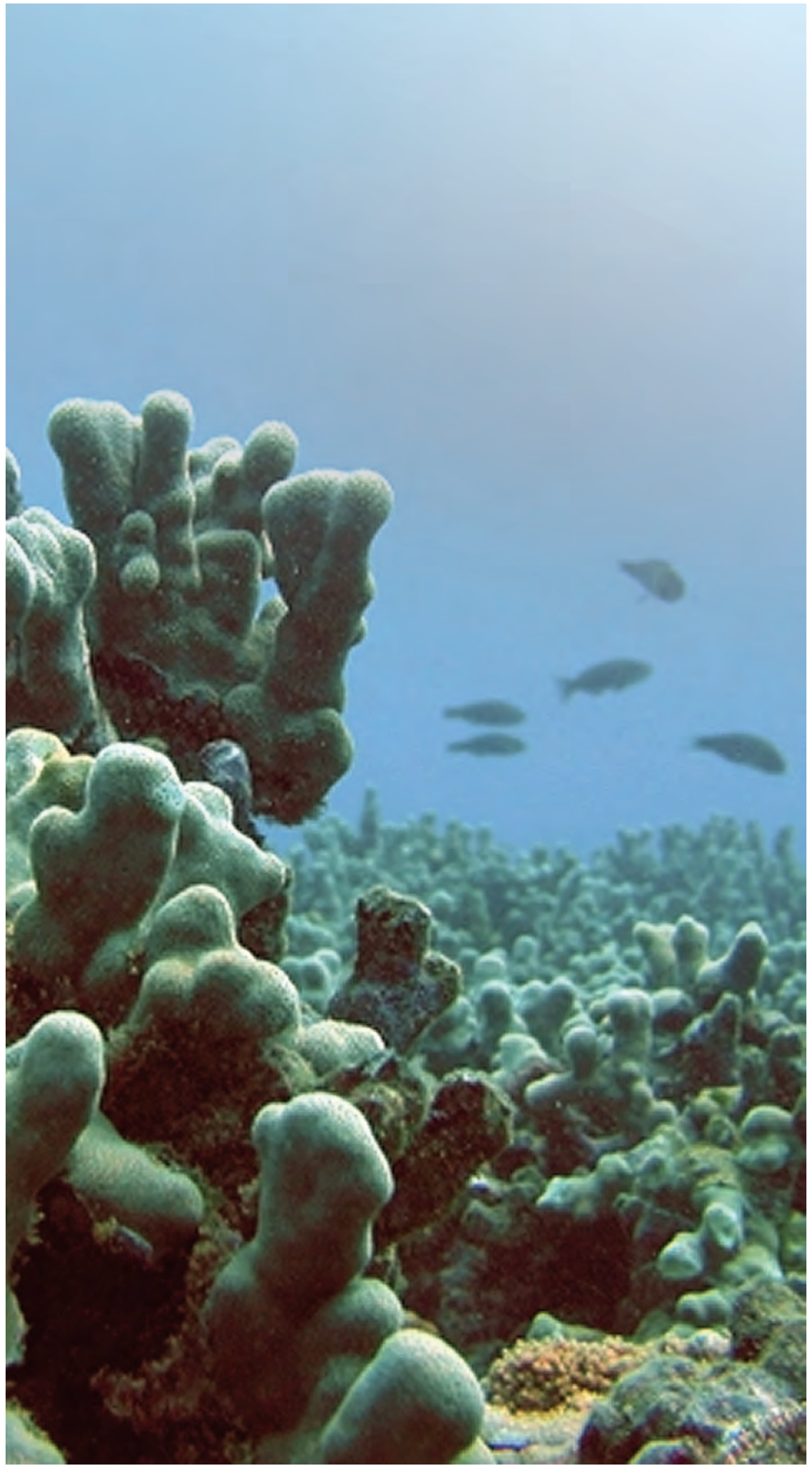
Edited by Michael E. Field, Susan A. Cochran, Joshua B. Logan, and Curt D. Storlazzi



Scientific Investigations Report 2007–5101

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CONTENTS

INTRODUCTION

EVOLUTION OF THE SOUTH MOLOKA‘I FRINGING REEF

CHARACTER OF THE SOUTH MOLOKA‘I FRINGING REEF

NATURAL CHANGE TO THE MOLOKA‘I REEF

RIDGE-TO-REEF: SEDIMENT SHED FROM THE ISLAND

IMPACT OF SEDIMENTATION ON THE MOLOKA‘I REEF

SUMMARY

FOREWORD

Moloka‘i, with the most extensive coral reef in the main Hawaiian Islands, is especially sacred to Hina, the Goddess of the Moon. As Hinaalo, she is the Mother of the Hawaiian people; as Hinapuku‘a, she is the Goddess of Fishermen; and in the form Hina‘opuhalako‘a, she is the Goddess who gave birth to coral, coral reefs, and all spiny marine organisms. Interdependence between the reef’s living resources, the people, and their cosmology was the basis for management of Moloka‘i’s coastal waters for over a thousand years.

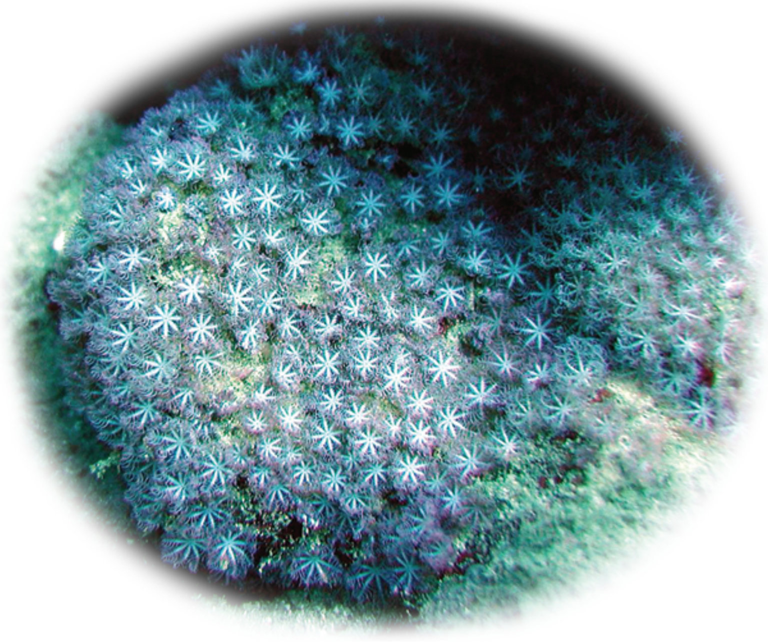
The ancient residents of Moloka‘i built the greatest concentration of fishponds known anywhere, but their mastery of mariculture, something needed now more than ever, was lost after near genocide from exotic Western diseases. Subsequent destruction of the native vegetation for exotic cattle, goats, pigs, sugar cane, and pineapple caused soil erosion and sedimentation on the reef flat. This masterful volume clearly documents that soil washing into the sea is the major threat to the reef today. Abandoned fishponds, choked with sediment, now act as barriers and mud traps, making damage to corals less than it would otherwise would have been.

The role of mud and freshwater from land in preventing coral reef growth, clearly articulated in Charles Darwin’s first book, The Structure and Distribution of Coral Reefs, is the major theme of this book. All around the tropics, coral reefs have died from huge increases in terrestrial sedimentation that resulted from destruction of hillside forests for cash-crop agriculture and pastures in the colonial era, especially in Latin America, Asia, and the islands of the Caribbean and Indo-Pacific. It is obvious that one cannot manage the coastal zone as a unit separate from the watersheds that drain into it. Yet there has been surprisingly little comprehensive scientific study of these impacts.

In this landmark volume, U.S. Geological Survey researchers and their colleagues have developed and applied a remarkably integrated approach to the reefs of Moloka‘i, combining geology, oceanography, and biology to provide an in-depth understanding of the processes that have made these reefs grow and that now limit them. They have joined old fashioned natural history of marine animals and plants with study of the geological evolution of the island, hydrology, meteorology, and land-use history, to an arsenal of new methods of remote sensing, including aerial photography, laser ranging, infrared thermal mapping, seismic reflection, in-situ instrumentation to measure chemical parameters of water quality, and direct measurements of the physical driving forces affecting them—such as wave energy, currents, sedimentation, and sediment transport. They provide a level of documentation and insight that has never been available for any reef before.

A remarkable feature of this book is that it is aimed at the people of Moloka‘i to inform them of what is happening to their reef and what they might do to preserve their vital resources. The scientific data and interpretations are expressed in unusually clear and comprehensible language, free of the professional jargon that makes most technical publications impenetrable to the public that most needs to know about them, yet without loss of scientific rigor.

Here readers will see clearly explained the whole path of soil loss, from the impacts of wild pigs and goats at higher elevations, deforestation of the hills for cattle pasture at lower levels, and denudation of low lands for cash crops. The resulting biological impoverishment has bared the soils, which wash away in flash storms, smothering the inshore reefs, whose growth was already limited because they had grown right up to sea level. The data in this book show that the mud doesn’t get far if it is washed into the sea during a big storm with heavy waves. Afterwards this mud keeps getting stirred up by every succeeding storm, spreading and affecting corals over wider areas until it is finally washed out of the system—and that only happens if there is no more new mud washing onto the reef.



I saw this myself a few years ago in Pila‘a Bay on Kaua‘i, where a bulldozed hillside of abandoned sugar cane fields had slumped right on top of a coral reef following exceptional rains. Years later, the algae species were zoned in a way that clearly mapped the distribution of nutrients washed into the bay, most likely from fertilizers bound to the eroded soils. That pattern closely mimics, on a small scale, that shown in Moloka‘i in this volume, where the inner reef is covered with algae, zoned by species in a way that points to land-based sources of nutrients, while the outermost reef slope is still coral dominated, and the deep algae seem to indicate deep-water nutrient upwelling.

What of the future? The Hawaiian Islands have been exceptionally fortunate to be spared the worst coral heatstroke death from high temperatures, at least to date. So far, the worst global warming impacts have luckily been small in this region, and the small number of people on Moloka‘i has kept population densities, and sewage pollution, low compared to the more developed islands. Nutrients from years of sugar and pineapple fertilization, and the washing of this soil onto the reefs, show clear influences on the pattern of algae on the reef. Even at very low levels of nutrients, well below that which drives algae to smother and kill coral reefs, more algae is present. Soil erosion control is therefore the key to better management of both nutrients and turbidity on Moloka‘i reefs. To that end land management actions mentioned in this book, such as suppressing wild fires and eliminating wild goats and pigs, could be made even more effective if supplemented by active erosion control using plants whose roots bind the soil effectively in place. Through all of these efforts, Hina and the people of Moloka‘i could be happy again!

Thomas J. Goreau, Ph.D.
President, Global Coral Reef Alliance

PREFACE

Two themes pervade this publication. One is the beauty, grandeur, and majestic resource that the fringing coral reef off south Moloka‘i represents to the people of Moloka‘i and Hawai‘i—and indeed to people everywhere. The other theme is the threats that face that same reef.

Hawaiian reefs, like other reefs worldwide, harbor an incredible diversity of plant and animal life, and that richness is reflected in the cultural traditions of native peoples and in prosperity from tourism. However, coral reefs are in decline worldwide (Hughes and others, 2003a), and Hawai‘i and Moloka‘i are no exception. An abundance of land-derived silt has washed from Moloka‘i's slopes and threatens the health of the island's reef by blocking light and choking the reef inhabitants. Conditions on Hawai‘i's reefs vary from island to island and location to location (some areas show signs of improving), and the causes of degradation are both natural and human induced. Natural disturbance by large waves is being exacerbated by increased sediment runoff. Islands erode by natural processes, but the activities of humans—deforestation, agriculture, cattle and sheep farming, introduction of feral grazers, increased wildfires, construction —often cause the release of sediment at higher rates than occur naturally. Nowhere is this more evident than on the island of Moloka‘i. In 1979—a full two decades before U.S. Geological Survey (USGS) scientists visited Moloka‘i to study sediment on the reef—the famous ocean explorer Jacques-Yves Cousteau wrote:

> One of the most serious dangers to coral reefs is sedimentation. This threat is dramatically illustrated in Hawaii. With the arrival of Westerners, upland soil was plowed for sugar cane and pineapple. The impact of the resulting erosion has been tragic. Since 1897 the shoreline of Molokai has advanced as much as a mile and a quarter across the reef flat. Elsewhere off Molokai, the reef is overlaid with four to 27 inches of red-brown silt. (Cousteau, 1985, p. 191)

It is noteworthy that of all the troubled reefs in the world, Cousteau singled out Moloka‘i as the example for sedimentation on reefs.

Starting in 1999, the USGS, along with university and agency partners, initiated a study to map the reef off south Moloka‘i and describe the coral, analyze the sediment, and measure the processes that suspend and transport sediment on the reef. This publication reports the results of those endeavors.

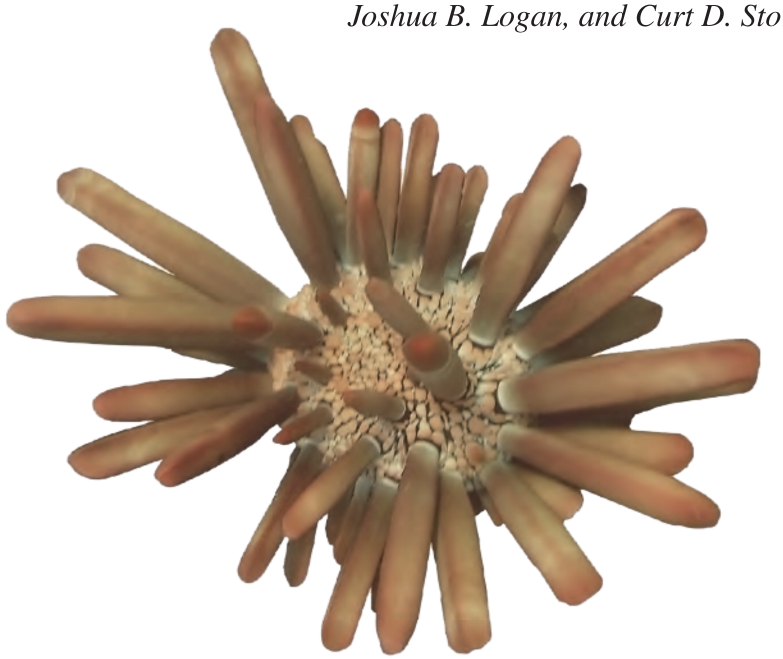
The importance of identifying and monitoring the effects of land-based pollution has become crucial within the United States, as evidenced by priorities set by the U.S. Task Force on Coral Reefs. One of the key topics in the April 2004 Report of the U.S. Commission on Ocean Policy (U.S. Commission on Ocean Policy, 2004) is the need for “an ecosystem and watershed-based management” approach to ocean pollution, and that report highlights “the astounding decline of coral reef ecosystems” and “an urgent need to address the identified, major factors causing coral declines.” In Hawai‘i, local representatives of the U.S. Coral Reef Task Force specifically developed and established a Local Action Strategy (LAS) and steering committee to address land-based sources of pollution and their impact on reefs. The LAS is essentially a locally-driven roadmap for collaborative and cooperative action among Federal, State, and nongovernmental partners to identify and implement priority actions needed to reduce key threats to valuable coral-reef resources. In the state of Hawai‘i, Moloka‘i was designated one of the key LAS sites. To protect and sustain coral reefs, broad understanding of the processes involved is necessary — how sediment is derived in upland regions, how it is transported through the watershed, and its fate on the reef. Many positive signs indicate that science and management are embracing that need for understanding.

This volume supports and augments those goals through presentation of new information on the behavior and fate of sediment on the Moloka‘i coral reef. The following chapters discuss the evolution of the reef, the natural processes that affect the reef, and the role of sediment in inducing change on the reef. This information is intended to help make decisions—on Moloka‘i and elsewhere — that can lead to sustaining healthy reefs.

We hope this volume will be of benefit first and foremost to the people of Moloka‘i. The fringing coral reef bordering the south shore of their island is perhaps the most magnificent coral reef in the Hawaiian Island chain. In addition to its intrinsic value as an important ecosystem, the reef holds a rich heritage of cultural and historical associations and meanings for the island residents. Today the Moloka‘i reef is at a crossroad—the evidence of damage from heavy land use is clear, and yet procedures for its protection through improved land-use practices are already underway. It is the people of Moloka‘i who will ultimately decide the fate of their coral reef. Measures to decrease sediment runoff, control fish collection, and establish protected zones are all actions they can take to help preserve the reef.

We hope this publication will also be of value to all coastal people living harmoniously with neighboring coral reefs. Some of the causes of reef degradation are global, but many remain local. It is largely through local decisions and local actions that protection of coral reefs can be assured for future generations.

Michael E. Field, Susan A. Cochran,
Joshua B. Logan, and Curt D. Storlazzi



ACKNOWLEDGMENTS

The information presented in this volume derives largely from research undertaken by the U.S. Geological Survey (USGS) to meet one of its principal goals—to establish the geologic framework of ecosystem function and structure. Some of the research was supported by our partners at the University of Hawai‘i and the National Oceanographic and Atmospheric Administration (NOAA). All of the authors and editors fully recognize that the success of their studies resulted in very large measure both through the technical expertise provided by our colleagues in Hawai‘i and on the mainland and from the assistance and friendship of the people of Moloka‘i.

Our studies benefited greatly from the advice, assistance, and knowledge of the land and reef shared by Moloka‘i residents. There are many friends on Moloka‘i to acknowledge, but most certainly at the top of the list is Captain Joe Reich, owner of the *Alyce C*, whose keen eye and understanding of the waves, wind, and the reef itself made for safe and productive experiments time after time after time. We could not have done it without you, Joe.

Among the many people who assisted us, we wish to thank in particular the following. Ed Misaki of the Nature Conservancy, Debbie Kelley and Sheila Cox of the USDA, and the members of the Moloka‘i Watershed Advisory Group collaborated in our studies. Lyndon and Janis Dela Cruz assisted with data collection, instrument maintenance, and other last-minute duties beyond the call of friendship. Harbormaster Bernie Straehler, Young Brothers manager Al Ranis, and the rest of the employees at Young Brothers stored our mountains of gear and allowed us temporary workspace at times over the years. Aka and Porter Hodgins assisted with additional transportation and storage of fieldgear. The late Bill Kapuni filled numerous scuba tanks for us over the years, and we're glad he was able to share his mana‘o with us. Roland (Rolly) Moran provided boats, motors, and the uncanny ability to repair anything or have any obscure part one might need on a small island. Sam Rawlins taught us "crazy professors" about fishponds. Mervin Dudoit assisted with small-boat work. Jerry Johnson took our team under wing and introduced us to many folks on the island. Moloka‘i General Hospital provided us with x-rays of cores. The staff members of Hotel Moloka‘i, Moloka‘i Shores, Moloka‘i Vacation Rentals, and Moloka‘i Fish and Dive were always helpful, as were Moloka‘i residents Bill Feeter, Donna Haytko-Paoa, Yolanda Reyes of Moloka‘i Ranch, and finally, the FedEx drivers who carted our endless boxes of instruments and gear.

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This volume contains contributions from many authors on diverse and complex topics, and this combination makes smoothness and consistency between chapters inherently difficult. Peter Stauffer and David Jones were responsible for editing and melding the contributions into a single volume. They were extremely helpful and, in our view, successful in doing so. The individual chapters have also benefited measurably from superb, thoughtful suggestions by the following colleagues, and we thank them for their patience and advice:

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Captain Joe Reich and his boat, *Alyce C.*

Introduction

View of south Molokaʻi, looking eastward from hills above Hale O Lono.


View south from Moloka‘i Shores condominium complex. The island of Lana‘i is in the background.

INTRODUCTION

The South Moloka‘i Reef: Origin, History, and Status

Michael E. Field[1], Susan A. Cochran[1], Joshua B. Logan[1], and Curt D. Storlazzi[1]

Moloka‘i is the fifth youngest island in the long chain of volcanoes and volcanic remnants that compose the Hawaiian archipelago (fig. 1). The archipelago extends from the Island of Hawai‘i (the “Big Island”) in the southeast past Midway Island, to Kure Atoll in the northwest, for a total distance of about 2,400 km (1,500 mi). Beyond Kure Atoll, the chain continues as a series of submerged former islands known as the Emperor Seamounts, which extend to the Aleutian Trench off the coast of Alaska. Evolution of the entire Hawai‘i-Emperor volcanic chain represents a time span of nearly 80 million years (Clague and Dalrymple, 1989). The volcanic chain is a result of gradual and persistent movement of the Pacific lithospheric plate (the sea-floor crust and rigid uppermost part of Earth's mantle) over a deep fracture (or hot spot) that extends down to the astenosphere, a less rigid part of the mantle (fig. 2). Plumes of molten lava flowed onto the sea floor, repeatedly creating massive shield volcanoes that exceed 10,000 m (33,000 ft) in relief above the surrounding sea floor. The growth of each volcano is a process that takes half a million years or more to construct most of its mass through sequential volcanic phases—submarine, explosive, and subaerial—of shield growth.

Once formed, each massive island volcano is carried northwestward on the Pacific tectonic plate at rates of 8.6 to 9.2 cm/yr (Clague and Dalrymple, 1989). The postshield processes of alkalic volcanism, subsidence, landslides, rejuvenated volcanism, weathering, sediment deposition, and reef growth have all markedly influenced each volcano’s present-day shape. Subsidence of each island is rapid at first (rates of 2 mm/yr or more; Moore and Campbell, 1987; Moore and Fornari, 1984; Campbell, 1986) in response to the extraordinary weight of large volumes of lava loaded onto the crust. As each island cools and slides northwestward with the sea-floor crust, it continues to subside at decreasing rates, down to the order of 0.02 mm/yr (Detrick and Crough, 1978). The sheer volume of rock that accumulates at each volcano ultimately leads to failure and partial collapse—each island has had spectacular landslides that are amongst the largest on earth (Moore and others, 1989). The large areas of irregular topography on the sea floor around the islands (for example, north of Moloka‘i and northwest of O‘ahu) attest to the magnitude of these events (fig.1).

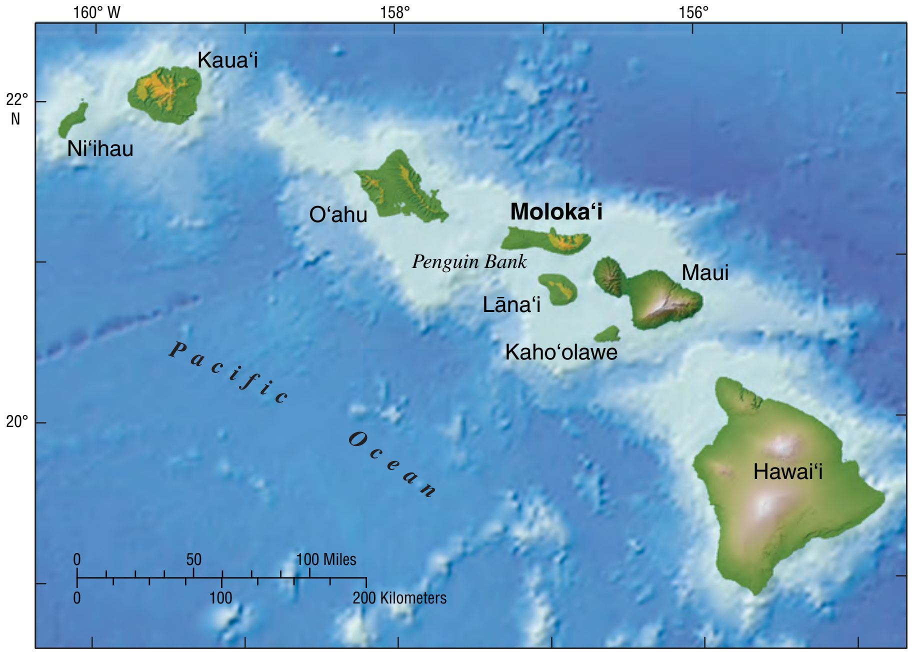

Figure 1. Physiographic map of the eight main Hawaiian Islands, which are the most recent additions to the approximately 2,400-km (1,500-mi) -long Hawaiian chain of islands, atolls, and pinnacles that extends from the Island of Hawai‘i (the “Big Island”) northwest to Kure Atoll. Moloka‘i formed between 2.0 and 1.7 million years ago and is the fifth youngest in the line of more than 107 volcanic edifices in the Hawaiian chain (Clague and Dalrymple, 1989). Only the volcanoes forming Lāna‘i, Maui, Kaho‘olawe, and Hawai‘i are younger.

The normal processes of surface erosion and stream runoff modify volcano slopes early in an island’s history. Those processes, along with development of soils, which occurs relatively quickly in humid volcanic terrain, lead to transport and deposition of sediment in alluvial fans, flood plains, and narrow coastal plains. The final process in island shaping is the establishment of coral reefs in shallow waters that are protected from large waves. Corals colonize exposed rock surfaces very quickly (Grigg and Maragos, 1974; Grigg, 1983), and it is likely that they become established early in the evolutionary history of each island. The development of coral reefs—the massive limestone structures capped by a living ecosystem that border many Hawaiian Islands—takes much longer (Grigg, 1987). Each reef is a thick (meters to tens of meters) packet of reefal limestone that likely accumulated over multiple stages of sea-level shifts (Grossman and others, 2006; Grossman and Fletcher, 2004; Sherman and others, 1999). In most locations in Hawai‘i, modern coral cover is only a thin living veneer on top of older reef structures that formed during an earlier time under different conditions (Grigg, 1983, 1998)

Moloka‘i—Making of a Unique Island

Despite the similarity in origin and physical processes that it shares with the other Hawaiian Islands, Moloka‘i is unique in many ways. Its marked east-west orientation and its relatively storm- and wave-protected south shore are two important factors that have contributed to development of a spectacular coral reef that is perhaps the most extensive and continuous fringing reef in the Hawaiian chain.

In its original configuration, Moloka‘i was part of a very large island (Maui Nui) that included Lāna‘i, Maui, Kaho‘olawe, and Penguin Bank (fig. 1). As the massive, contiguous island subsided, Moloka‘i, Lāna‘i, and Penguin Bank became an island separate from the others about 300,000 to 400,000 years ago (Juvik and Juvik, 1998). Penguin Bank eventually submerged, and Lāna‘i and Moloka‘i became separated by a small chan-

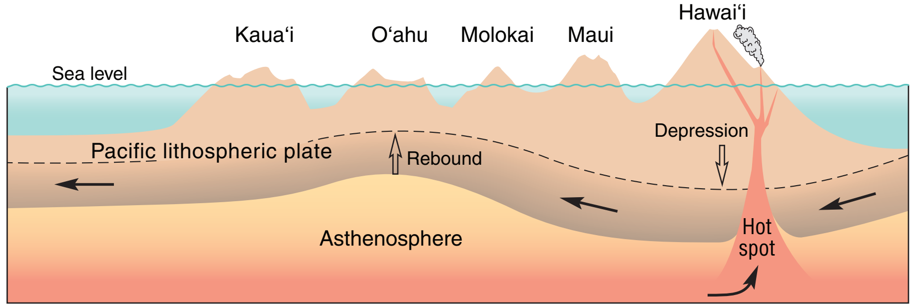

Figure 2. Diagram illustrating the formation of the Hawaiian volcanoes by the eruption of lava rising from a “hot spot”—a thermal plume emanating from deep in the Earth’s mantle. As the Pacific Plate of the lithosphere moves northwestward at rates of about 9.0 cm/yr (3.5 in/yr), a new volcano forms over the hot spot every 100,000 to 500,000 years. Vertical arrows show the depression of the lithosphere under the island of Hawai‘i from the weight of newly formed volcanic edifices and the subsequent rebound of the lithosphere (as shown under O‘ahu) surrounding the depression.

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[1] U.S. Geological Survey Pacific Science Center, 400 Natural Bridges Dr., Santa Cruz, CA 95060

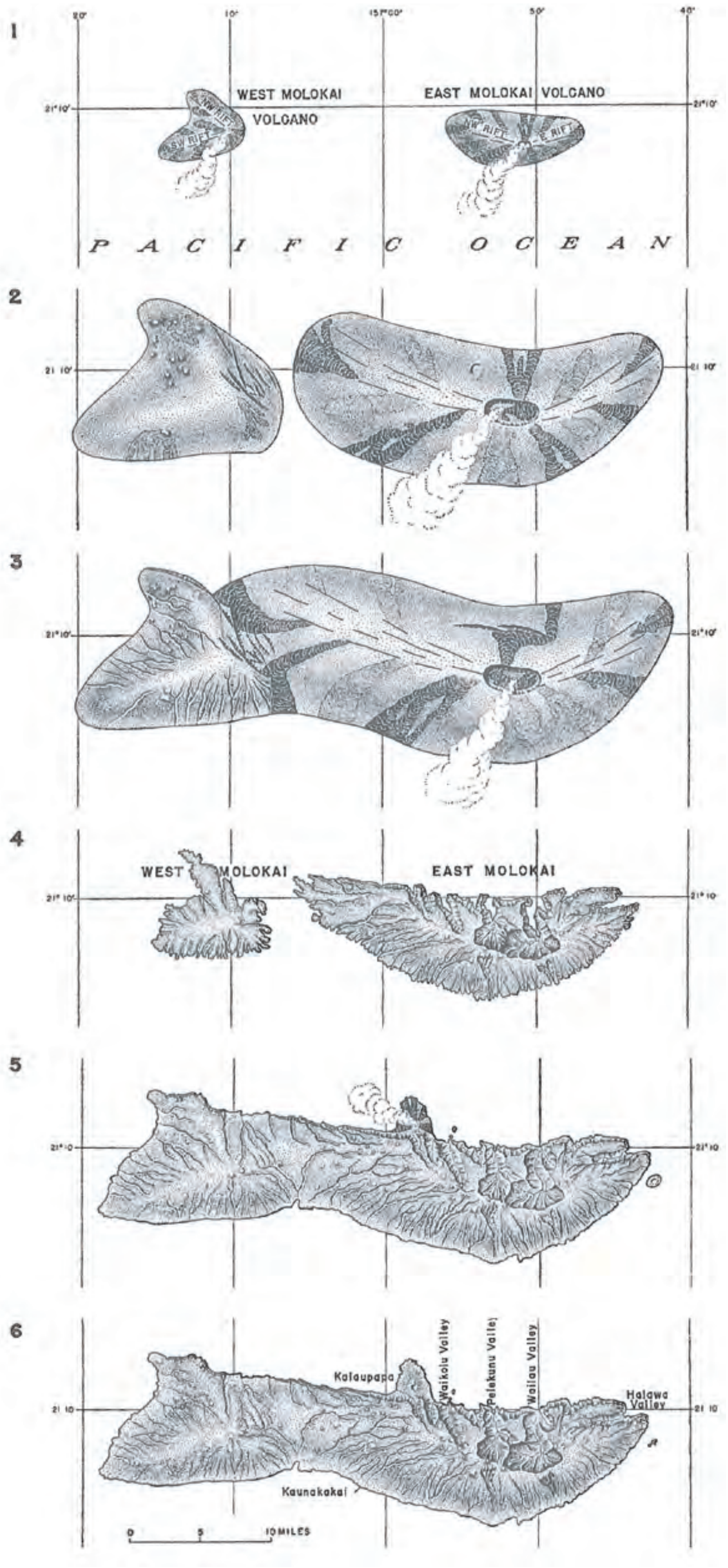


Figure 3. Original drawings from Stearns and Macdonald (1947; reproduced in Stearns, 1966) showing the development of the island of Moloka‘i. Stages 1 through 3 show the two volcanoes forming between 1.9 (west) and 1.75 (east) million years ago and converging to form a single, overlapping volcanic ediface. Stearns and Macdonald thought that the two volcanoes were isolated later by rising sea levels associated with an intergalcial period (stage 4 in the diagram). Long after Moloka‘i was formed, posteruptive volcanism produced the Kalaupapa Peninsula (stage 5). Stage 6 shows the island as it exists today. Stearns and Macdonald’s work was published before anyone had inferred that giant landslides formed the pali on the north side of the island (see, for example, Moore and others, 1989), and so that episode is missing from their scenario.

nel about 100,000 to 200,000 years ago (Juvik and Juvik, 1998). The two islands were attached to each other by an isthmus on multiple occasions and as recently as 8,000 years ago, during periods of low sea level associated with global continental glaciations (Grigg and others, 2002).

Moloka‘i was built by two distinct volcanoes, west and east Moloka‘i, that formed about 1.9 and 1.76 million years ago, respectively (Clague and Dalrymple, 1989). The formation of the west Moloka‘i shield volcano (Mauna Loa) at 1.9 Ma (million years ago) was followed by a postshield phase of eruption from 1.8 to 1.75 Ma that capped the caldera (large crater at the summit of the volcano, fig. 3; Stearns, 1966). The east Moloka‘i volcano (Wailau) formed about 1.76 Ma, and it too was capped by postshield volcanic flows (1.5 to 1.35 Ma) and a rejuvenated phase of eruptions at about 0.57 to 0.35 Ma (fig. 3; Juvik and Juvik, 1998). The geology of Moloka‘i, as originally mapped by Stearns and Macdonald (1947; fig. 4), illustrates the island’s evolution by a series of distinct, sequential events: (1) formation of the west Moloka‘i volcano, (2) formation of the east Moloka‘i volcano through two sequences of volcanism, (3) formation of the high sea cliffs (pali) of the north coast by a gigantic landslide, (4) formation of a small shield volcano and caldera forming the Kalaupapa Peninsula, and (5) erosion of the volcano slopes and deposition of alluvium in channels, fan deltas, and coastal plain deposits (Stearns, 1966; Stearns and Macdonald, 1947; Walker, 1990).

The narrow shape of the island and the very high (nearly 1,200 m or 3,900 ft) pali on the northern side of Moloka‘i—among the highest sea cliffs in the world—resulted from a catastrophic landslide following the construction of east Moloka‘i volcano. The landslides that characterize the volcanoes of the Hawaiian chain are some of Earth’s largest, and among the Hawaiian slides, the Moloka‘i slide (named the Wailau Slide) is one of the largest (Moore and others, 1994). A large part of the island collapsed, scattering huge volcanic blocks (as much as 6 km, or 4 mi, in diameter) and debris more than 150 km (90 mi) across the sea floor (Moore and others, 1989). Following the landslide, rejuvenated volcanism created the low-relief Kalaupapa Peninsula that abuts the cliffs of north Moloka‘i. The island of Moloka‘i today has a shape reflecting these formative processes (fig. 5).

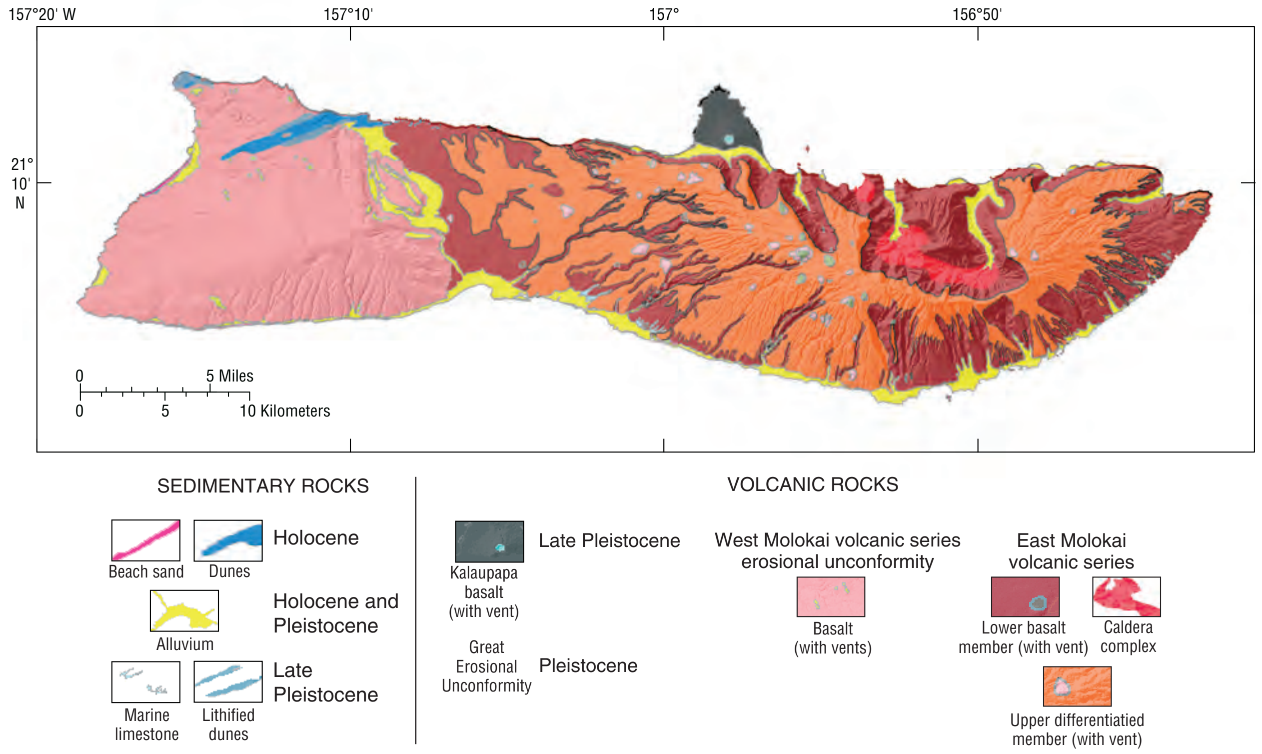


Figure 4. Geologic map of Moloka‘i, from Stearns and Macdonald (1947). Distinguishing features of the geology include the distinction between the west Moloka‘i (Mauna Loa) volcano (pink) and the layered lava flows that constitute the east Moloka‘i (Wailau) volcano (orange and rust brown), the posteruptive volcanism (dark grey) that formed the Kalaupapa Peninsula against the base of the north pali (following the giant landslides that formed those sea cliffs), and the alluvium (light green) that forms a thin band of coastal and deltaic deposits along the south coast.

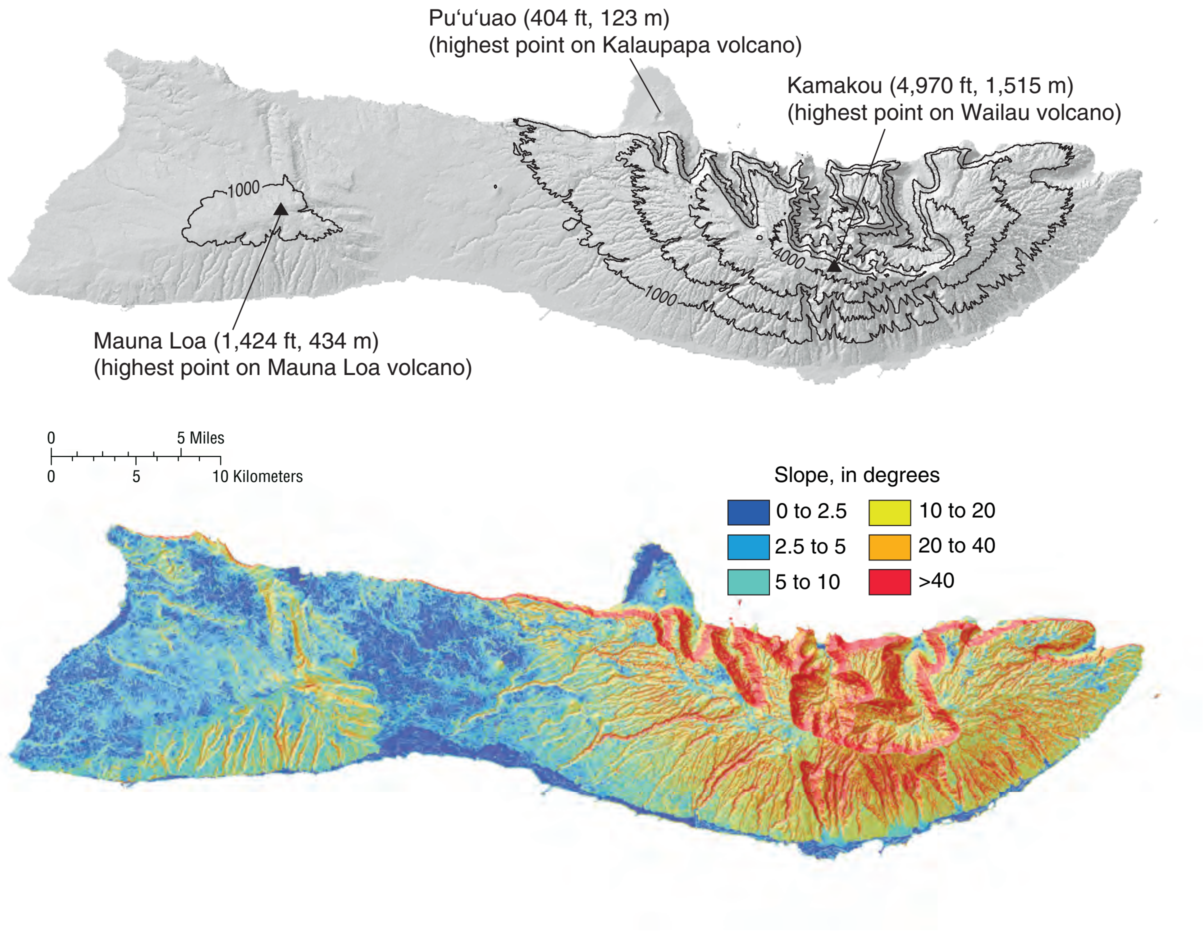


Figure 5. Maps showing the topography and steepness of slopes on the island of Molokaʻi. The island is dominated by two volcanoes: Mauna Loa on the western side of the island and Wailau on the eastern side. The topographic map (top) shows the dominance—in both area and relief—of the Wailau volcano (east) over the Mauna Loa volcano (west). Mauna Loa has the gently sloping shield shape characteristic of Hawaiian volcanoes. Wailau, in contrast, has areas of steep-sided valleys and some of the highest seacliffs in the world on its northern edge. These seacliffs resulted from a giant landslide, among the largest on Earth, which bisected the Wailau volcano, leaving debris on the sea floor more than 150 km (90 mi) to the north. The Kalaupapa Peninsula is the most recent volcanic addition to the island, having been formed by eruptions subsequent to the giant landslide. The caldera of Kalaupapa (large crater at its summit) is now the site of a brackish lake nearly 240 m (800 ft) deep. On the slope map (bottom), steeply sloping land is shown in red and gently sloping land is shown in blue. The map highlights the relatively low slopes that characterize the west volcano and the Hoʻolehua saddle between the volcanoes. The steepest slopes occur on the pali on the north shore and in the deeply incised gulches on the large east volcano. The maps were derived from a U.S. Geological Survey 10-m digital elevation model (DEM).

Molokaʻi Today: Climate, Land, and the Reef

Seasons, Trade Winds, and Rainfall

Early Hawaiians recognized only two six-month seasons, "kau," when the weather was warmer and the trade winds blew steadily, and "hoʻoilo," when the weather was cooler and the trade winds were less consistent (Western Region Climate Center, 2006). Weather analysts today recognize these two seasons with a slight modification: the winter season, hoʻoilo, is seven months (October through April) and the summer season, kau, is only five months (May through September). Rainfall, wind, and storm patterns are quite different for the two seasons. The summer season is warmer, drier, and dominated by northeast trade winds, and widespread rainstorms are rare. In the winter season, temperatures are cooler, trade winds diminish, and low-pressure storm systems bring rain. Each of these two seasons is influential in shaping the land and transporting sediment to the ocean.

Summer Patterns: Persistent Trade Winds and Low Rainfall

The persistent trade winds that blow in a general east-to-west direction are one of the most prominent circulation patterns in the Earth's atmosphere. In the tropical Pacific north of the equator, the trade winds blow from the northeast from a region of high pressure known as the Pacific Anticyclone (or Pacific High). The center of this high-pressure system is typically located well north and east of the Hawaiian Islands. The Pacific Anticyclone moves with the seasons, reaching its northernmost position in the summer. This brings the main part of the trade winds across Hawaiʻi from May through September, during which time they blow 80–95 percent of the time (Western Region Climate Center, 2006; fig. 6). Trade winds have relatively high moisture content, which yields frequent showers on the windward coasts and at higher elevations but leaves the leeward coasts (south and west) dry. This pattern is clearly depicted by a map of the distribution of annual rainfall on Molokaʻi (fig. 7). Only a relatively small amount of rainfall occurs during the summer months on the leeward coasts, as shown by a 12-year rainfall record from Kaunakakai (fig. 8).

There is often a strong daily variation in wind direction and speed around the islands because of the increased solar heating of the islands relative to the ocean. By late morning or early afternoon, the sun's rays typically heat the island and the overlying air mass to the point that the air rises, drawing in more cool air off the sea. This daily intensification of onshore winds during the daytime is often referred to as a "sea breeze." Conversely, at night, as the island cools relative to the ocean, the overlying air mass cools and sinks, causing offshore flow. Thus, whereas out on the open ocean the winds may blow steadily at 10 km/h (6 mi/h), they might exceed 20 km/h (12 mi/h) off Molokaʻi's south coast during the day and be less than 3 km/h (2 mi/h) at night.

Tropical storms and hurricanes are infrequent events that generally occur during the summer and early fall. Hurricanes are rare in Hawaiʻi (only two have made landfall in the past 24 years), but even if they do not make landfall in Hawaiʻi, they may pass close enough to the island chain

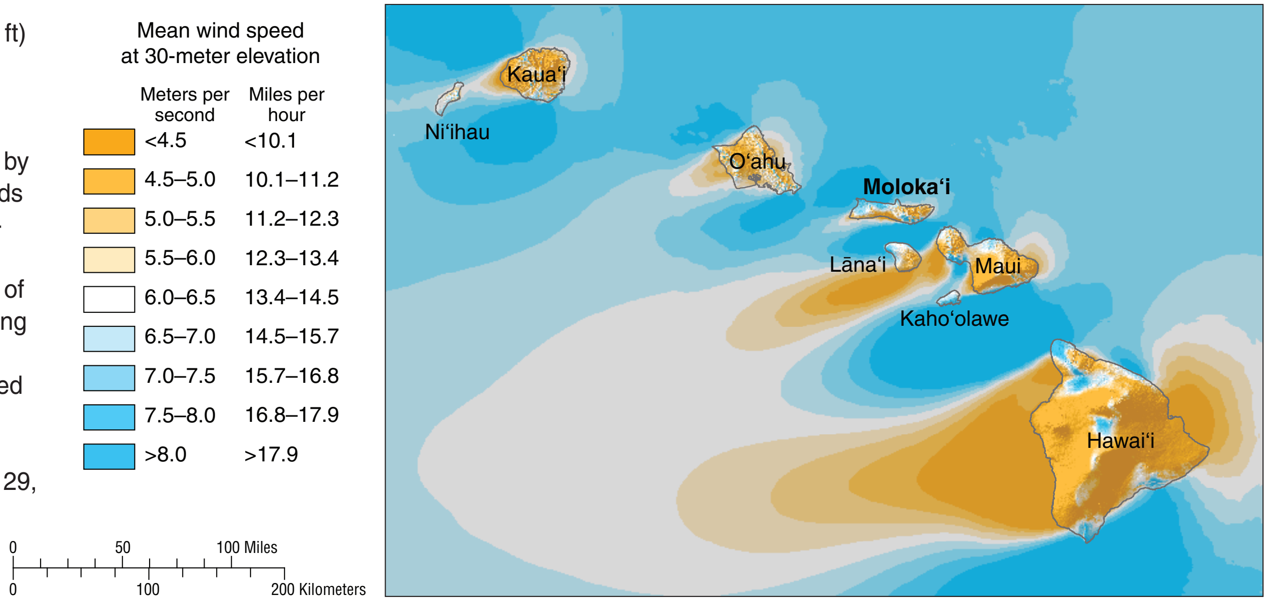


Figure 6. Map showing mean wind speed 30 m (100 ft) above the surface for the region of the eight main Hawaiian Islands. Note the large variability in wind speed around the islands, in particular the greater speeds in the channels between the islands, caused by topographic steering. In this region, mean wind speeds over the ocean are highest during the summer trade-wind period. During May through September, winds over the ocean exceed 20 km/h (12 mi/h) 50 percent of the time and are dominantly out of the northeast. Along the south Molokaʻi coast, trade winds approach the shoreline from the southeast because they are steered around the east Molokai volcanic cone (1,500 m or 4,970 ft high). Data from AWS Truewind (http://www.awstruewind.com/wind-view.cfm, last accessed April 29, 2008).

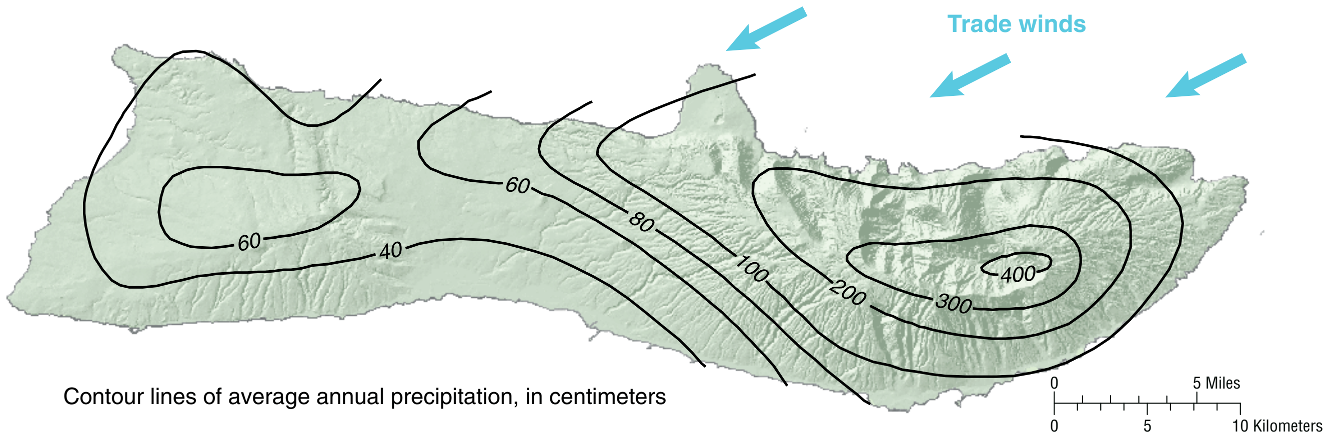


Figure 7. Map showing the distribution of annual rainfall on Molokai. The highest elevations on the eastern half of the island receive more than 400 cm (160 in), and the amounts decrease to the south and west, reaching annual values of less than 40 cm (15 in) along coasts on the western part of the island. Molokai and the other main Hawaiian Islands lie within the trade-wind zone, an area of prevailing easterly surface winds caused by global atmospheric circulation. When these warm, moisture-laden winds meet the island's volcanic mountains, they are forced to rise abruptly and cool. The moisture then condenses to form clouds and precipitates out of the atmosphere in the form of rain. This phenomenon is evident in this map showing the average annual rainfall: most precipitation occurs on the windward, northeastern portion of the island, where high elevations and steep watersheds are found. Much of the southern and western portions of the island receive little rainfall by comparison, because they are blocked from the moisture-bearing wind by the volcanic cone to the east. This accounts for the drier climate found in Kaunakakai and other areas on the south coast. This map was derived from the Hawaii Statewide Planning and Geographic Information System Program (Giambelluca and others, 1986).

to generate heavy rains, high winds, and great waves on the coasts (fig. 9; Fletcher and others, 2002).

Winter Patterns: Decreased Trade Winds and Occasional Storms

From October through April, Hawai‘i is located to the north of the main trade-wind belt. During the winter the trades still blow across the islands, though only 50-80 percent of the time and with wind speeds that exceed 20 km/h (12 mi/h) only about 40 percent of the time. It is during the winter season that light, variable winds are most common, as are occasional very strong winds. The high Hawaiian volcanic mountains have a pronounced topographic effect on the winds, both in winter and in summer, funneling the winds through the channels between the islands and causing the local wind speeds to be much higher than those observed over the open ocean (fig. 6).

Major storms occur most frequently between October and March, bringing heavy rains often accompanied by strong winds. The rainfall record from Kaunakakai (fig. 8) shows the increase in rain in the winter months. Three main classes of disturbances produce major storms. Cold fronts sweep across the islands, bringing locally heavy showers and gusty winds. Low-pressure systems, known locally as Kona storms, bring widespread heavy rains, often accompanied by strong winds from the south or west. Hurricanes strike the islands infrequently but can result in major impacts to coasts and reefs when they arrive.

Drainage Patterns and the Making of an Ahupua‘a

The southern slopes of Moloka‘i are dominated by a series of elongate, shallow-to-deep gulches that are important for the transport of soil from island slopes to the coast; they are also are important to the cultural traditions of native Hawaiians. More than 80 individual gulches reaching to the south coast can be identified on topographic maps of Moloka‘i (fig. 10). The gulches range from tens to hundreds of meters in width and meters to tens of meters in depth; a few are more than 100 m (330 ft) deep. The longest gulches (for example, Kaunakakai, Kawela, Kamalō) emanate from the higher east Moloka‘i volcano. In general, gulches on the south slope of the west Moloka‘i volcano are shorter, narrower, and shallower. The prominence of the gulches on the southern slope of the east Moloka‘i volcano results from three factors that influence stream incision: the greater height of the volcano, its steeper slopes, and the higher rainfall amounts than on the west Moloka‘i volcano.

The early Hawaiians used a complex system of land division and management based on the natural form and boundaries of island watersheds. Islands were subdivided into wedge-shaped parcels, or "moku," extending from the mountain crest to the shoreline. Each moku was subdivided into smaller wedge-shaped parcels, termed "ahupua‘a," which followed the shapes of the watersheds; each had resources that were managed in a way to be self-sustaining (Roberts, 2001). These resources included upland trees, fertile lands for taro production, and coastal areas for salt and fish. Early Hawaiians recognized that effective sustainability of the ahupua‘a required management of the resources and restrictions on the plants and fish that could be harvested, as well as restrictions on the seasons during which they could be harvested. This recognition of the connectivity and interdependence of the different parts of the ahupua‘a—upland ridge, stream valley, coastal area, and reef—is as valid today as it was centuries ago.

A key component of the ahupua‘a was the construction of coastal fishponds to raise fish (Faber, 1997). Ancient fishponds are a part of the coastal landscape in Hawai‘i, and particularly so on Moloka‘i's south shore, where they number more than 60, the greatest number for any comparable area in the State. The fishponds, constructed between the 13th and 15th centuries

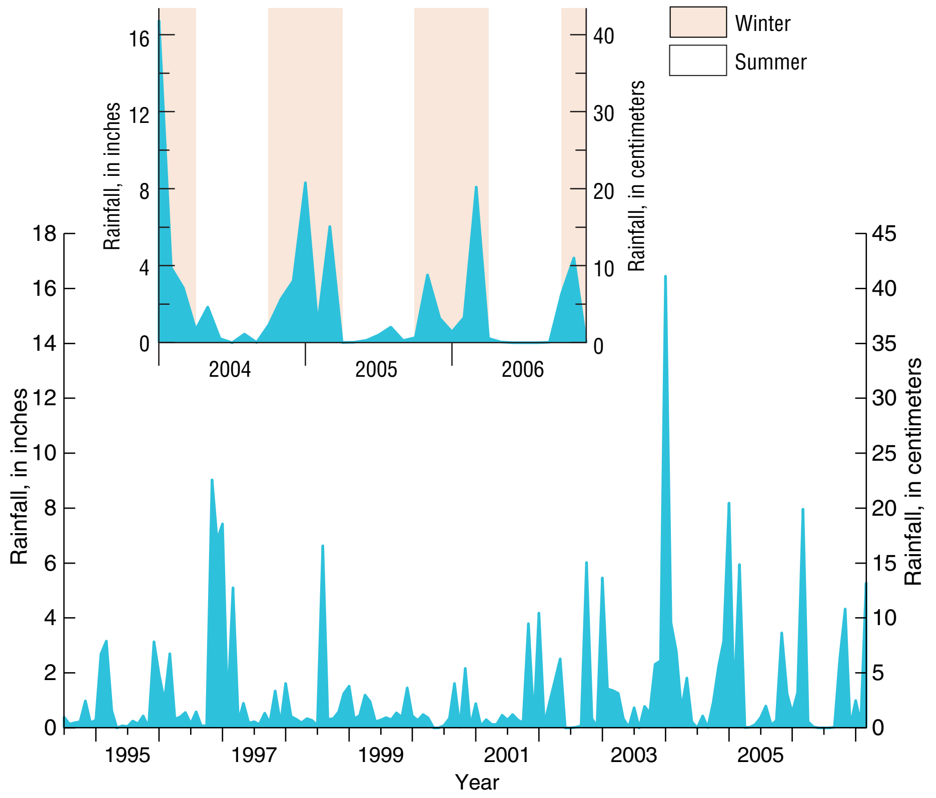


Figure 8. Graph showing monthly rainfall between July 1994 and January 2007 as recorded by a rain gauge at Kaunakakai on Moloka‘i's south coast. Note the distinctly different rainfall patterns between the winters (October through April) and the summers (May through September). Rainfall in the summer is derived from the trade winds and typically is less than 5 cm (2 in) per month. Winter periods, however, derive rain from north Pacific low-pressure systems and commonly yield 15 cm (6 in) or more per month. The inset graph for 2004 through 2006 shows clearly this pattern of most rain occurring in winter periods (brown bars) and little rain occurring in most summer periods.

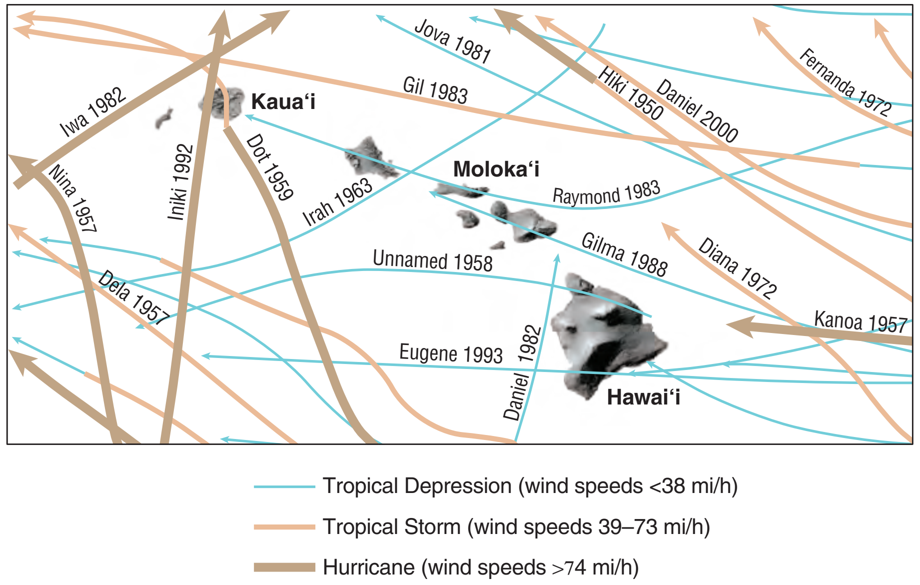


Figure 9. Tracks of major tropical storms that have affected the eight main Hawaiian Islands since 1945. Tropical storms are categorized by their measured wind speed, based on a 1-minute average. A tropical depression has wind speeds that are less than 38 mi/h. A tropical storm has wind speeds from 39 to 73 mi/h. A storm is categorized as a hurricane once the wind speeds reach 74 mi/h. The last major hurricane to strike the islands was Hurricane Iniki in September 1992. Data from the Pacific Disaster Center (http://www.pdc.org/geodata/world/stormtracks.zip, last accessed April 29, 2008).

(Summers, 1964; fig. 11), played an important role in early Hawaiian life. Today they remain important cultural landmarks, and because of their large number and large size (many are tens and even hundreds of acres) they exert an influence on coastal processes.

Fishpond walls were built with basalt and limestone boulders on the shallow submerged limestone surface of the reef flat in water less than 1 m (3 ft) deep (fig. 12). The walls measured 1 to 6 m (3–20 ft) wide and 0.6 to 2 m (2–6 ft) high, and could be hundreds of meters long. Some of the fishponds (referred to as “loko kuapā”) were entirely enclosed except for a slotted gate (“makaha”) that allowed small fish to enter but restricted them from leaving when they increased in size. Other fishponds (“loko ‘ume iki”) had low walls that were submerged at high tide; walled lanes led into and out of the ponds. Hawaiian pond builders, recognizing the dominant east-to-west wind and current patterns, particularly on the eastern part of Moloka‘i, placed the lanes leading into the ponds on the eastern side and the lanes leading out on the western side.

Today, these ancient fishponds influence the coastal environment in several ways. Fishponds are natural accumulation sites for sediment, both that which is discharged directly from stream mouths and silt settling from turbid waters on the Moloka‘i reef flat. Once deposited, the sediment tends to remain in the fishponds (early Hawaiians cleaned the ponds with bamboo rakes) and plants gain a foothold. Mangroves have migrated along the south coast from their originally introduced location at Pālā‘au and taken hold in many fishponds. Once established, mangroves increase the sediment-trapping efficiency of the pond, which then tends to fill more quickly, creating more area for plant growth. A second effect of ponds is the steering of coastal currents by the massive stone walls that extend out onto the reef flat. Two recent studies (Presto and others, 2006; Calhoun and Field, 2008) have shown that coastal flow of water and transport of sediment follow the lobate shape of the ponds; silt is more easily trapped in the spaces between protuberant ponds (see fig. 11). The residents of Moloka‘i have made several valiant efforts to restore selected fishponds to their original condition. Through State funding, the Waialua Fishpond project demonstrated, with very strenuous volunteer labor, the feasibility of restoring two fishponds at Waialua (State of Hawai‘i Department of Lands and Natural Resources, undated).

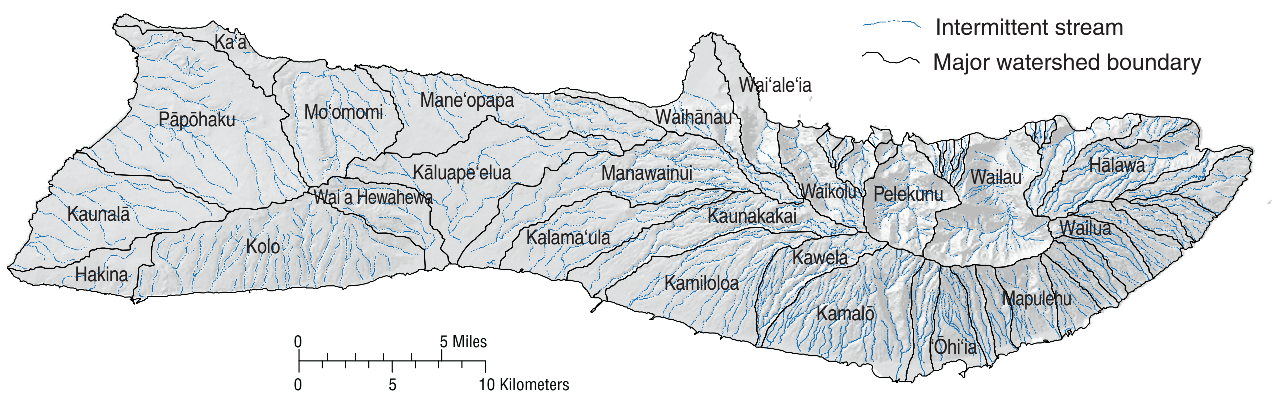


Figure 10. Stream drainages and major watersheds on Moloka‘i. With the exception of the streams that drain the wet northeastern valleys, the majority of streams on Moloka‘i are fed only by surface runoff and therefore flow intermittently—during periods of high precipitation. When heavy rainfall events occur, many of the streams are subject to rapidly increasing flows and flooding. These high flows are a hazard to people and property, and they also deliver high concentrations of sediment to the coral reef. This map was derived from the Hawai‘i Statewide Planning and Geographic Information System Program (Giambelluca and others, 1986).

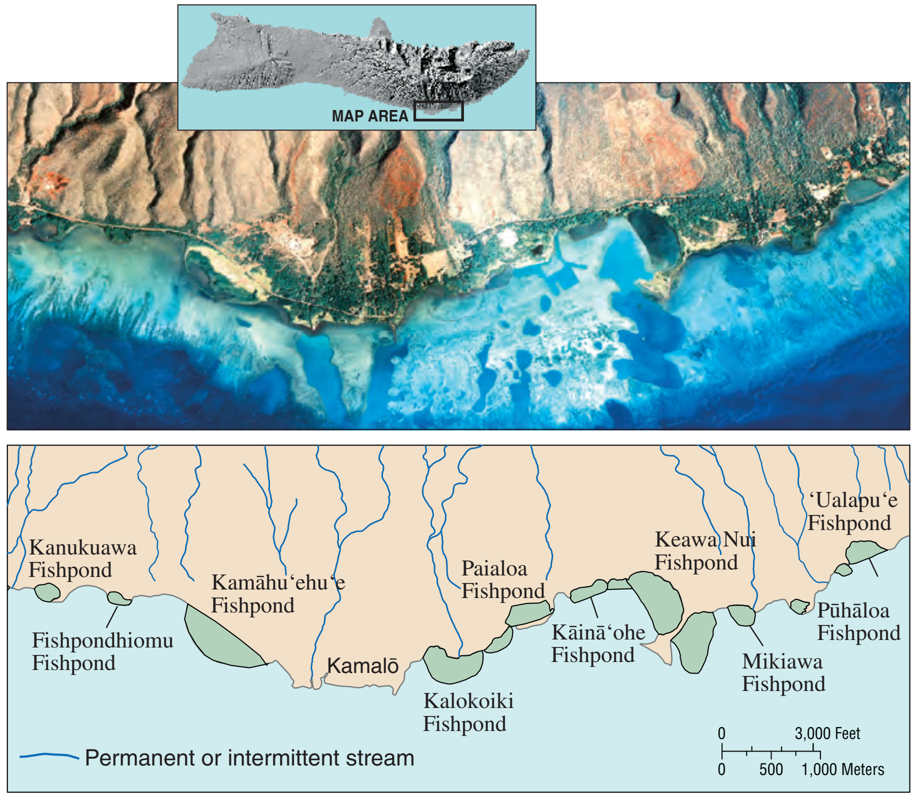


Figure 11. Aerial photograph and interpreted map of part of the south Moloka‘i coast, showing the abundance of fishponds. Most of the fishponds are partly to completely infilled, and others have only submerged remnants present.

The Remarkable Coral Reef of South Moloka‘i

The configuration of Moloka‘i and neighboring islands has played a large role in the development of the extensive coral reef bordering the south coast. The island’s elongate east-west orientation perfectly blocks the large north Pacific swell. To the south, Lāna‘i, Maui, and Kaho‘olawe provide an effective shield against destructive storm waves and south Pacific swell. This protection, along with the low gradients of the submerged shelf and the presence of narrow coastal plains and alluvial fans that capture sediment shed from the hillsides, provided an optimum setting for coral growth.

The south Moloka‘i reef is not the result of coral growth in the past century or even the past millennium; nor is it the result of continuous growth. Accumulating evidence on its age and structure indicate that much of the

Bruce Richmond, USGS

Figure 12. Oblique aerial photographs (taken in 1998) of fishponds along the south shore of Moloka‘i. *A*, The large Kānoa (foreground) and Ali‘i fishponds jut out onto the reef flat along the central coast just west of Kawela. Note the accretion of the coast on the updrift side (east, or closest to viewer) of the ponds and erosion on the downdrift side (west, or far side). *B*, Submerged remnants of a fishpond on the reef flat off Wave Crest Condominiums, near Kalaeloa. The size and extent of fishponds on the reef flat, such as shown here, makes them a factor in sediment transport on the south shore and reef flat.

reef originated during earlier periods of reef growth, and it is quite likely that the reef was built during a number of intervals when sea level was at or near its present position (Engels and others, 2004, Barnhardt and others, 2005). In some ways the reef is robust, but in many ways it is not. The material presented in ensuing chapters points out two distinguishing characteristics of the Moloka‘i coral reef—it is remarkable and it is fragile. It is remarkable in its size, continuity, and high degree of coral cover. It is fragile in that it is a thin living coral surface built upon an old eroded coral surface. The entire reef is susceptible to changes induced by coastal development, runoff, fishing, and many other activities.

Forces Acting on the South Moloka‘i Reef

Waves, Tides, and Currents

More than any other single physical process, waves control not only the reef shape and the types of coral that grow on the reef, but even whether or not a reef can form. Waves on the ocean’s surface are mechanical energy traveling through water. The water particles in a wave move in a circular motion; these wave orbital motions decrease in size with depth and become more elliptical (“flatter”) where the wave orbits interact with the sea floor in shallow water. Every waveform has certain properties used to describe it, as shown schematically in figure 13.

The wave regime off Moloka‘i can be characterized by four end-members, as shown in figure 14—North Pacific swell, Northeast trade-wind waves, Southern swell, and Kona storm waves (Moberly and Chamberlain, 1964). The North Pacific swell is generated by strong winter (October–May) storms as they track from west to east across the North Pacific and has wave heights on the order of 3–8 m (10–26 ft) and wave periods of 10–20 seconds. The Northeast trade-wind waves occur throughout the year but are largest from April through November, when the trade winds blow the strongest. These waves have wave heights on the order of 1–4 m (3–13 ft), but they have very short periods of 5–8 seconds. Southern swell, generated by storms in the Southern and Indian Oceans from April through October, typically has small waves (heights ~1–2 m; ~3–6 ft), but they have very long periods (~14–25 seconds). Kona storm waves occur infrequently when local fronts or extratropical lows pass through the region. Kona storm waves typically have wave heights on the order of 3–4 m (10–13 ft) and wave periods of 8–12 seconds.

Tides are the rhythmic rise and fall of sea level driven by the interaction between gravitational and inertial forces of the Earth, Moon, and Sun. Although the Moon’s mass is 27 million times less than that of the Sun, because of its much greater proximity to the Earth (400 times closer), the Moon imparts twice the gravitational force on the Earth and the oceans. The Moon’s gravity pulls at the ocean’s water, dragging it towards the Moon in a bulge on the side of the Earth closest to the Moon. On the opposite side of the Earth (away from the Moon, where the Moon’s gravitational influence is less), the ocean’s inertial forces exceed the gravitational forces, causing the water to move away from the Earth and also form a bulge. Over the rest of the Earth’s surface, the two forces are relatively balanced. The two bulges in the ocean stay essentially aligned with the Moon as the Earth rotates, and as a coastal area passes under each bulge, it experiences a tidal high when it passes through the bulge and a tidal low when the shore is outside of the bulge.

The Earth completes a full revolution relative to the Moon every 24 hours and 50 minutes (the diurnal tidal cycle), and thus the two daily high tides occur 12 hours and 25 minutes (the semidiurnal tidal cycle) apart. Different points on the Earth’s surface experience different tidal patterns because the Earth’s axis of rotation is inclined relative to the position of the Moon. The shape of the ocean basins also plays a role. Most areas have two

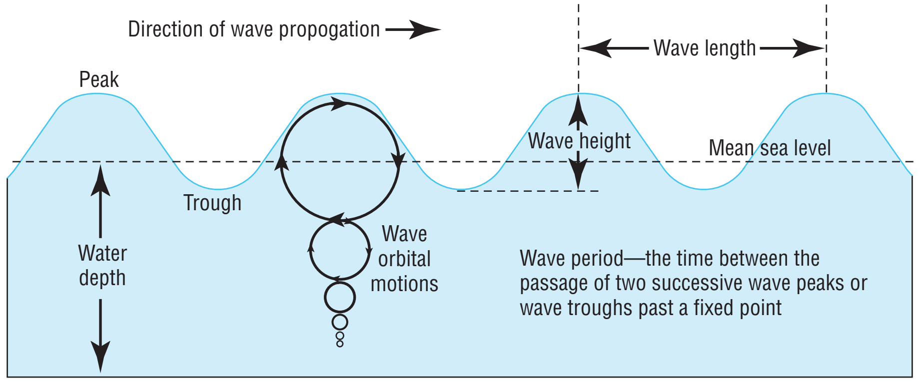


Figure 13. Diagram showing the parameters used to describe ocean surface waves

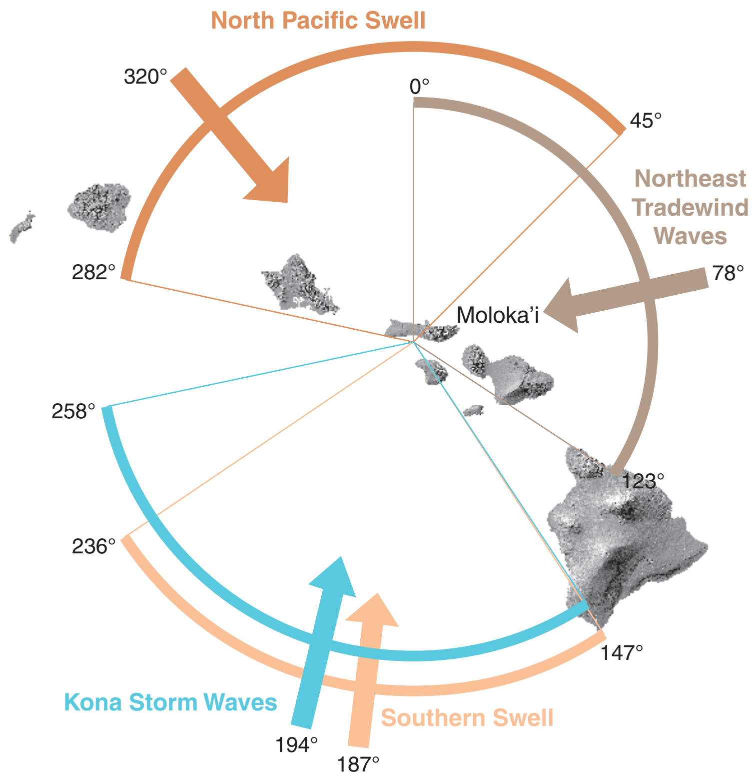


Figure 14. Wave regime for the island of Moloka‘i, modified from Moberly and Chamberlain (1964). The arrows and arcs denote mean directions and range of direction, respectively, for a given wave type. Numbers on arrows are azimuths of the direction waves come from. North Pacific swell occurs throughout the year and generates some of the largest waves in the Hawaiian region, especially during the months from October through May. Northeast trade-wind waves occur throughout the year (50 percent of the time in the winter months, 90 percent of the time in the summer months), but are largest from April through November when the trade winds are strong and consistent. Southern swell, which also occurs throughout the year, generates waves that are typically largest and most frequent from April through October, when they occur up to 50 percent of the time. Kona storm waves, which are neither frequent nor consistent, occur less than 10 percent of the time during the winter months. Note that the region off south-central Moloka‘i, where the coral reef is largest, is shadowed from most of these waves by the surrounding islands and by the island of Moloka‘i itself.

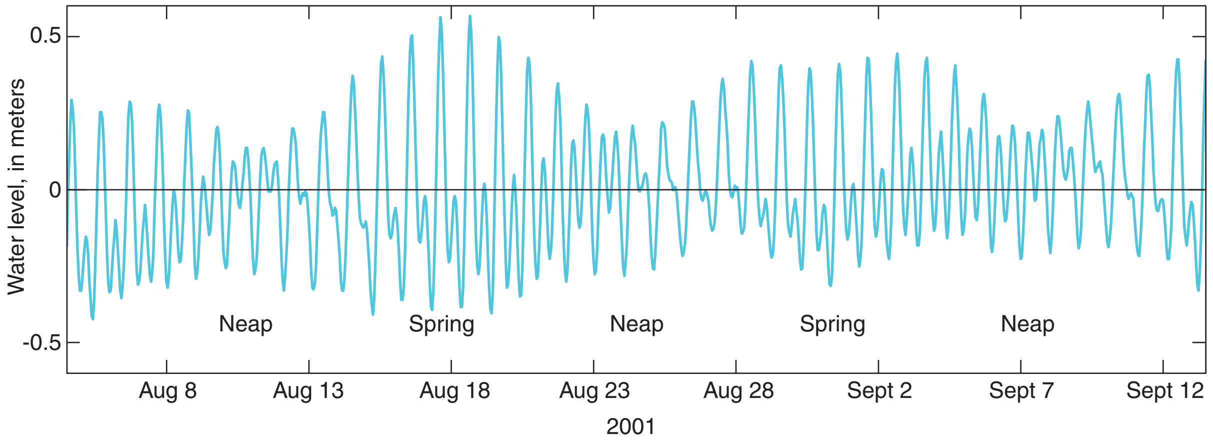


Figure 15. Forty days of tide data collected off Kamiloloa in 2001, displaying south Moloka‘i’s mixed semidiurnal tidal regime. The data set encompasses more than two complete spring-neap tidal cycles, with the peak spring tides on August 18 and September 2 and the minimum neap tides on August 11 and August 25. Moloka‘i’s mean tidal range is 0.43 m (1.4 ft), while the spring and neap tidal ranges are 0.91 m (3.0 ft) and 0.32 m (1.1 ft), respectively. Because the rough topography of south Moloka‘i’s broad fringing reef restricts flow, especially over the shallow reef crest, there is generally a time lag between the tidal elevations on the fore reef and those on the reef flat, with the maximum heights on the reef flat occurring after those on the fore reef (Storlazzi and others, 2004).

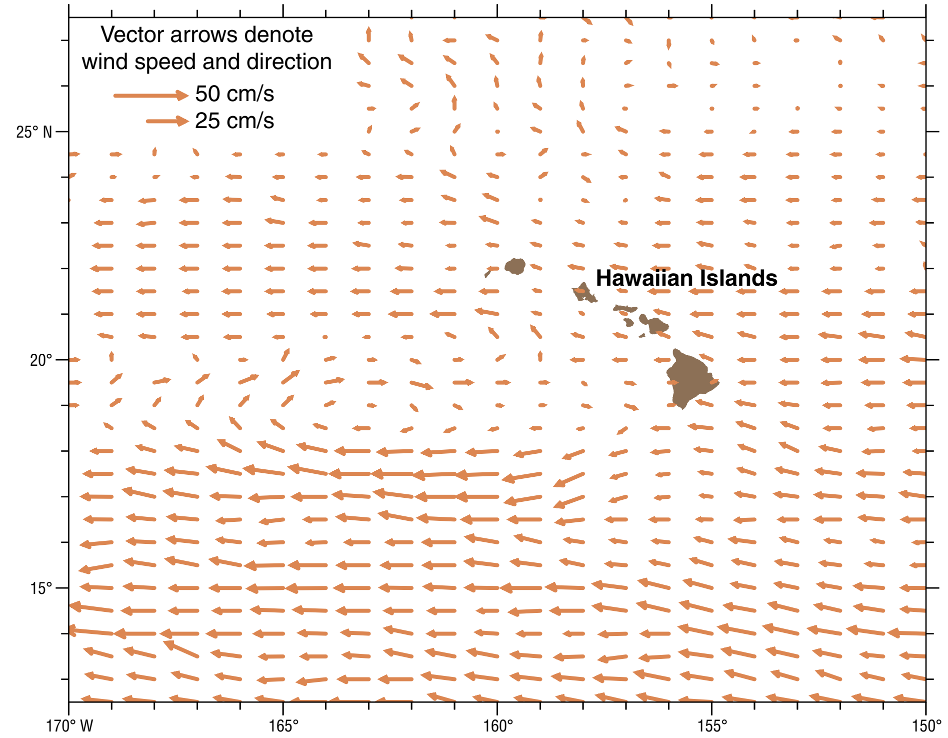


Figure 16. Diagrammatic map of average surface currents in the central Pacific Ocean, based on 40,000 observations of ship drift, 85,000 observations of satellite-tracked drifting buoys, and 8,000 modern current measurements (modified from Flament, 1996). The major current direction is westward through the main Hawaiian Islands, and a large gyre forms in the lee of the Big Island centered near 19° N, 163° W. This large-scale feature is caused by the islands standing in the path of the broad and steady trade winds, causing an ocean-atmosphere interaction that results in an island wake, similar to a river’s flow around a bridge piling (Xie and others, 2001). Circulation in the lee of the islands and close to shore is characterized by vigorous smaller scale eddies or swirls (not visible at the scale of the figure), which cause significant local variability in surface current speed and direction.

high tides and two low tides each day, a pattern that is termed a semidiurnal tide. In Hawai‘i, as in many places, the amplitudes of the two high tides and two low tides experienced each day are unequal, creating what is termed a mixed semidiurnal tide (fig. 15).

When the Sun and the Moon are aligned relative to the Earth, the combined gravitational forces of the Moon and Sun cause a very strong tide called a “spring” tide; spring tides happen approximately every 14 days at the times of new and full Moons. When the Moon and Sun are at a right angle with the Earth (first and last quarter lunar phases), their gravitational forces act separately from one another, causing a relatively weak “neap” tide approximately every 14 days. Both spring and neap tides are highlighted in figure 15. The tidal range, which is defined as the maximum water height at high tide minus the minimum height at low tide, is greatest during spring tides and least during neap tides. Although the full tidal range in Hawai‘i is relatively small compared to other coastal areas on Earth, tides are important to the reef in terms of transporting nutrients and larvae and flushing sediment and other pollutants.

The currents in the northwest Pacific Ocean form a large basin-scale clockwise circulation, called a gyre, centered at about 28° N latitude. At the latitude of Hawai‘i, the flow is roughly from east to west and increases in intensity southward (fig. 16). At the ocean’s surface, however, these large-scale ocean currents are strongly influenced by surface winds. This causes complicated circulation patterns, especially in the vicinity of the Hawaiian Islands, where topographic steering of the surface winds occurs. Circulation in the sheltered lees of islands is characterized by vigorous and changing eddies or swirls, causing significant temporal variability in surface current speed and direction (Flament, 1996).

Infrequent Events: Tsunamis

A tsunami is a very long period wave generated by a large, rapid displacement of water in the ocean. The name derives from the Japanese term for “great wave in harbor.” Landslides, earthquake faulting, submarine volcanic eruptions, and even meteorites have caused tsunamis throughout Earth’s history. Over the course of human history, earthquakes have been the most common tsunami-generating source (estimated 95 percent), followed by violent volcanic eruptions, such as those of the Indonesian volcanoes Tambora in 1815 and Krakatau in 1883 (Soloviev, 1982).

Tsunamis are often hundreds of kilometers in length (the wavelength), but in deep water they may be only a few centimeters to a meter or so in height. Tsunamis travel at several hundred kilometers per hour in the deep ocean basins and thus can propagate across the entire Pacific Ocean in less than a day’s time (fig. 17), potentially devastating coastal areas very far from where they originated. Hawai‘i, located in the center of the seismically active Pacific Basin, is susceptible to tsunamis generated from around the basin’s rim. In the 20th century alone, deadly earthquake-generated tsunamis struck the Hawaiian Islands in 1946, 1952, 1957 (fig. 18), 1960, and 1975. Overall, 26 tsunamis have been recorded in the Hawaiian Islands since 1812, or one every 7 years on average, although many of them have been inconsequential (Lander and Lockridge, 1989).

Because of their long wavelengths, tsunamis act like shallow-water waves even in the deep ocean basins. Although their heights in deep water are very small, they become much taller when they enter into shallow water because increasing drag on the sea floor slows them down. However, when tsunamis strike islands with narrow, steep shelves, they tend to have

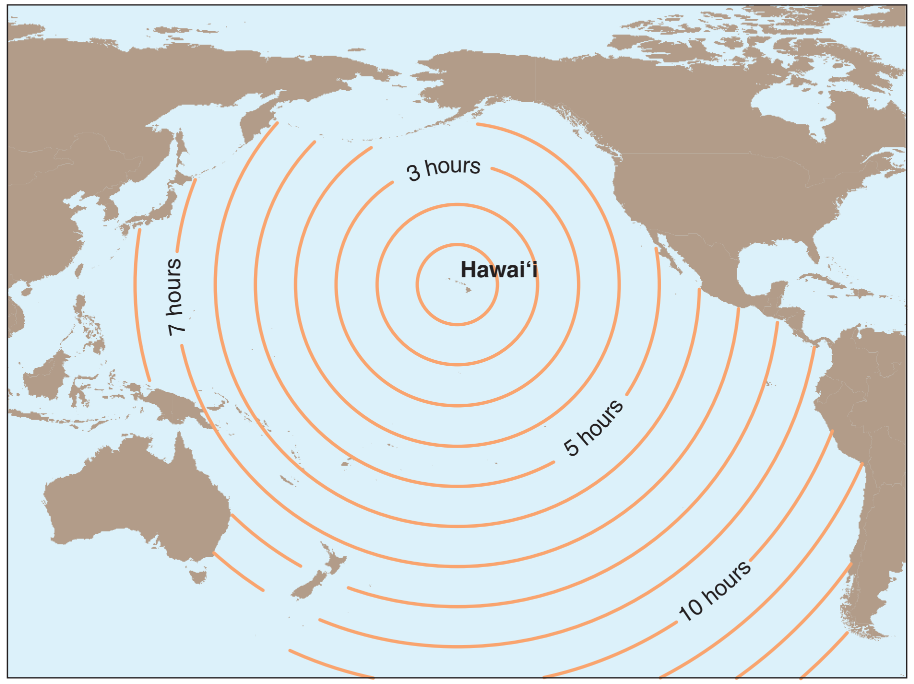


Figure 17. Map displaying approximate travel times required for tsunami waves generated anywhere on the rim of the Pacific basin to reach Hawai‘i (U.S. Geological Survey, 1997). The travel times are estimated assuming a tsunami speed of 1,000 km/h (600 mi/h). Therefore, the contours on the map are spaced at 1,000 km, or one hour of travel time.

Henry Helbush

larger run-up heights than when they strike coastal areas with broad, gently sloping shelves where more of the tsunami’s energy can be dissipated. Like shallow-water waves, tsunamis are also susceptible to energy loss by refraction around and dispersion between islands. Although the Hawaiian Islands are, in general, susceptible to high tsunami run-up because of their lack of broad shelves, the south shore of Moloka‘i is protected by the surrounding islands of O‘ahu, Lāna‘i, Kaho‘olawe, and Maui and has been affected less by large tsunamis than other Hawaiian locations. During the 1946 tsunami, for example, wave run-up heights on the north, east, and west sides of Moloka‘i averaged 10 m (35 ft), while those along the south shore averaged only 2 m (7 ft). Fletcher and others (2002) rank the tsunami hazard along the south Moloka‘i fringing reef moderately high at both the eastern (Kamalō to Kūmimi) and western (Hale O Lono to Pālā‘au) ends of the island and moderately low along the central portion (Pālā‘au to Kamalō) of the reef, where it is sheltered by Lāna‘i and Kaho‘olawe.

No studies have actively investigated the impact of any of these tsunamis on coral reefs in Hawai‘i. Observations from the December 26, 2004, Indonesian tsunami suggest that most of the damage to reefs throughout the Indian Ocean occurred in embayments, where the force of the tsunami waves was concentrated. Much of that damage was caused by debris dragged over the reefs by receding waters, rather than by the waves themselves (Fernando and others, 2005).

Figure 18. This series of three historical photographs (*A-C,* in chronological sequence) shows the arrival of a tsunami at Laie Pt. on the island of O‘ahu in March 1957. This tsunami was generated by a magnitude 8.6 earthquake located about 3,700 km (2,300 mi) away in the Aleutian Islands of Alaska.

Results from Recent Research on the Moloka‘i Reef

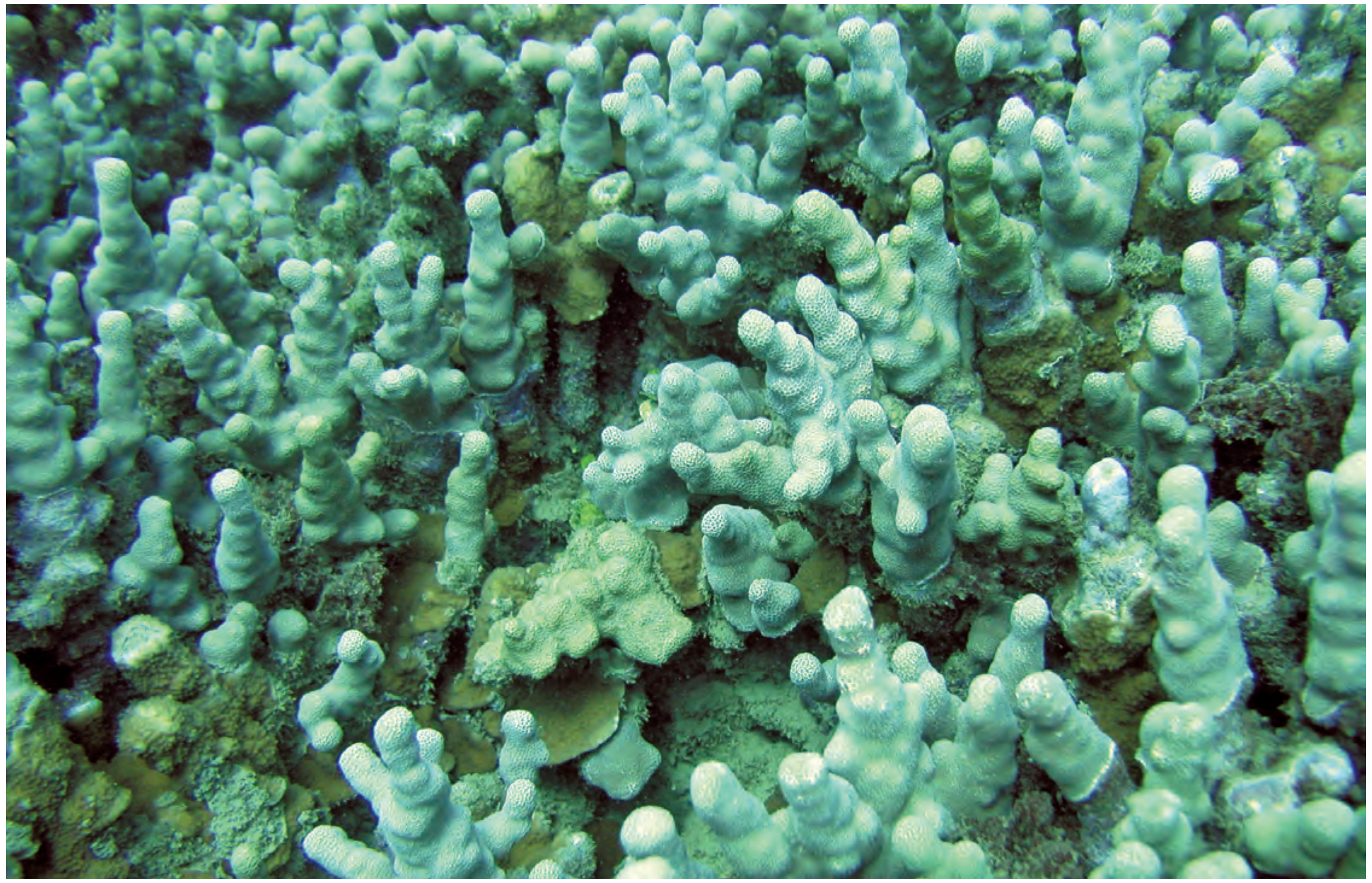
The foregoing summary of the processes that shape the Hawaiian Islands is a prelude to the main focus of this volume—the coral reef off south Moloka‘i. The chapters of this publication present our current scientific understanding of the reef itself, including its overall character and the processes that influence its long-term health. Chapters 1 through 9 summarize the origin of the reef and the character and distribution of its inhabitants, particularly corals, fish, and algae. Following those discussions, chapters 10 through 14 document key natural processes—waves, currents, runoff, and ground water—and how they affect the reef. Finally, chapters 15 through 21 address the topics of sediment runoff and toxic pollutants—why and how they are delivered to the reef, and the behavior and ultimate fate of island-derived material on the reef.

Moloka‘i is but one volcanic island in the tropics among very many worldwide. Its fringing coral reef is likewise only one among very many. It is therefore likely that many other reefs are influenced by a similar suite of physical processes and that many of those reefs also face threats from island runoff, similar to those reported here for Moloka‘i. With an eye towards those other reefs, as well as to Moloka‘i, the closing discussion following the chapters reviews the issues facing the Moloka‘i reef and the pathways that might be undertaken to ensure the long-term survival of one of the most spectacular reefs in the Hawaiian chain.

Evolution of the South Moloka‘i Fringing Reef

The fringing reef off south Moloka‘i, like the island itself, is the product of many cycles of growth and destruction. The reef we see today is a unique combination of modern growth over a volcanic surface shaped by ancestral patterns of sea-level change and reef accretion.

Aerial view of Moloka‘i reef.



Coral on the Moloka‘i fore reef.

CHAPTER 1

Antecedent Substrate Underlying the South Moloka‘i Fringing Reef and Implications for Reef Development

Walter A. Barnhardt[1], Eric E. Grossman[2], and Bruce M. Richmond[2]

The development and physical characteristics of coral reefs are closely related to the geological evolution of the islands where they form. According to the theory proposed by Charles Darwin (1842), the shape and structure of reefs evolve over geologic time, reflecting the gradual subsidence of tropical oceanic islands balanced by the upward growth of corals. Over shorter time scales, reef evolution is controlled by cycles of falling and rising sea level (Daly, 1915) that are, in turn, driven by the expansion and decay of large polar ice sheets. Erosion during lowstands of sea level, when the reef is subaerially exposed, and renewed coral growth during highstands of sea level modulate reef development.

The fringing reef along the southern shore of Moloka‘i (fig. 1) is a massive geological structure that has developed over thousands of years by the accumulation of corals and other organisms with calcium carbonate skeletons. Corals are colonial animals that inhabit shallow waters along tropical shorelines and require a stable substrate for attachment. Reef-building corals commonly become established on preexisting, hard surfaces, such as old volcanic lava flows or sedimentary rock, which can include ancient reefs.

Geologists consider the antecedent substrate to be an important factor that determines the shape of modern reefs (Purdy, 1974; Grigg and others, 2002). In their view, patterns of coral growth are largely controlled by the configuration of the foundation that lies beneath the reef. Corals need sunlight and so preferentially grow on bathymetrically higher parts of the sea floor. In addition, these bathymetric highs allow corals to grow undisturbed by sediment resuspended from the bottom, which can suffocate, abrade, and kill the reef-building organisms. New reef growth serves to amplify irregularities of elevation and slope that already exist on shallow parts of the sea floor. These irregularities commonly represent features that formed when sea level was lower, such as old stream valleys with raised banks that serve as preferred attachment points for corals. Off the south-central coast of Moloka‘i, for example, corals have encrusted the margins of a former stream channel (Pālā‘au), which meandered across the coastal plain before sea level rose and submerged it (see Storlazzi and others, this vol., chap. 3).

At a broad regional scale, however, subsurface mapping of the Moloka‘i fringing reef shows evidence for a different style of reef evolution that does not preserve or amplify preexisting topographic irregularities. The high-relief pinnacles, mounds, and spur-and-groove features of the modern reef system have developed over a broad, flat-lying platform that exhibits only limited local relief. In this chapter, a conceptual model is presented to explain the possible origin of the antecedent substrate that is buried beneath the Moloka‘i reef.

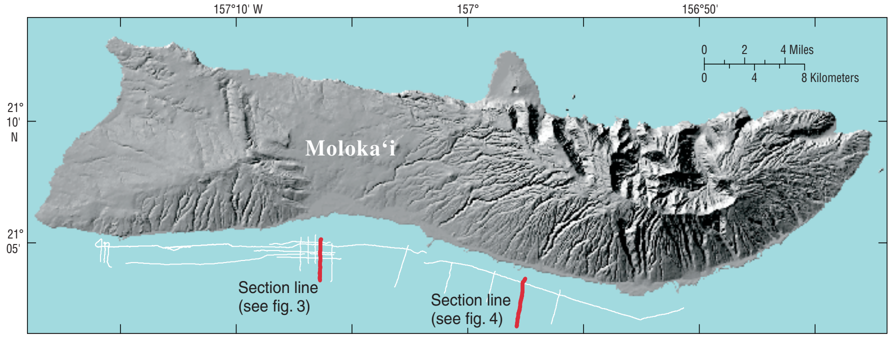


Figure 1. Map of Moloka‘i showing the locations of seismic-reflection profiles discussed in subsequent figures.

Seismic-Reflection Profiling and Reef Evolution

The U.S. Geological Survey used an acoustic technique known as “seismic-reflection profiling” to investigate the long-term development of the Moloka‘i reef. Seismic-reflection profiling relies on sound waves to image the geologic framework of the reef and adjacent areas of the sea floor. The seismic-reflection system consists of (1) a sound source that generates an outgoing pulse of sound and (2) a receiver that records the time required for each pulse to complete a two-way trip through the water column, the materials the reef, and back to the boat (fig. 2). A computer analyzes and plots the returning sound waves on paper as a series of dark and light bands that depict the thickness and geometry of materials making up the ocean floor (figs 3 and 4). These new data have important implications for understanding regional sea-level history and patterns of coastal change (Barnhardt and others, 2005). To ensure that marine mammals were not affected by the sound, we tested the equipment with a calibrated hydrophone and employed independent observers as required under a permit from the U.S. National Marine Fisheries Service.

Antecedent Substrate

The most prominent feature observed in the seismic-reflection profiles is a flat-lying, highly reflective surface that lies beneath the fore reef and marginal shelf. The strong reflection, indicated by the red line in figures 3 and 4, was generated by a sharp contrast in physical properties between the material above and below this surface. It might represent, for example, a layer of reef rock overlying volcanic rock or two stacked layers of reef rock that have different porosity or degree of cementation, perhaps due to differences in age and degree of weathering. The low-relief surface dips gently seaward at

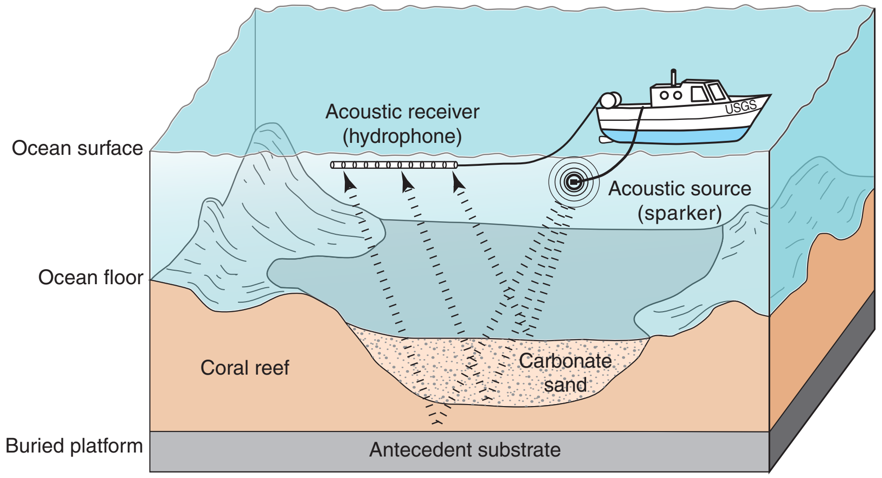


Figure 2. Block diagram showing the basic operation of a seismic-reflection profiling system. Pulses of sound are generated by the system and travel different paths (dashed lines) through water, sediment, and reef rocks. Some of the energy is reflected by the ocean floor back to the hydrophone, which records the timing and strength of each pulse. Some energy also penetrates the ocean floor and is reflected from interfaces between materials of different properties, such as a layer of loose carbonate sand overlying well-cemented reef rocks. Longer ray paths require longer travel times, so reflections from the buried surface that underlies the reef arrive later than reflections that are generated closer to the ocean floor.

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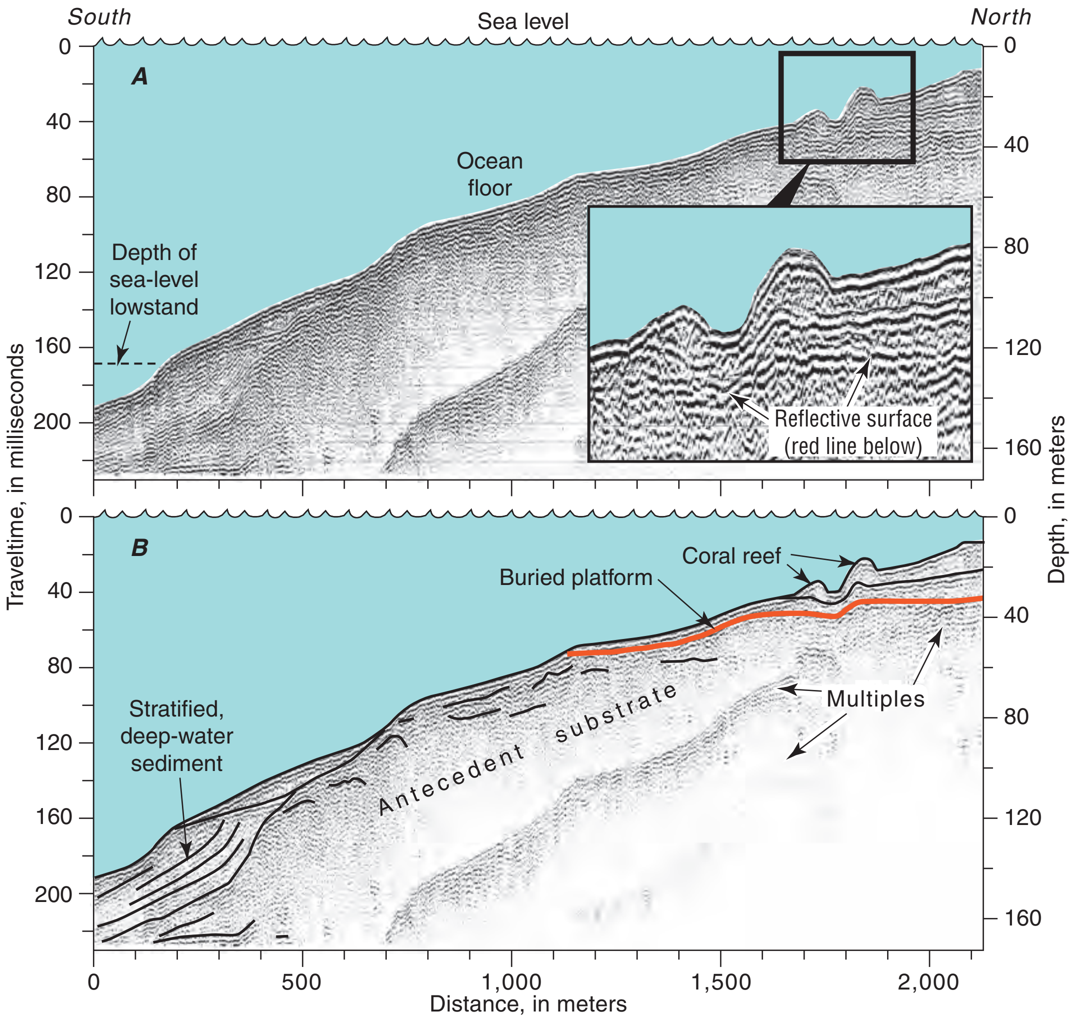
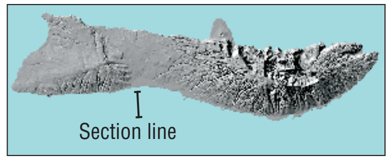


Figure 3. Cross section across the narrow, steeply dipping shelf south of Moloka‘i. *A*, Seismic reflection profile, with inset showing modern reef front. The dashed line at lower left indicates the lowstand position of sea level at about –130 m (427 ft) during the last ice age. *B*, Line-drawing interpretation of profile. The red line represents a buried platform, which is etched into the antecedent substrate and extends approximately 1 km (0.6 mi) seaward of the reef crest. The dark lines labeled “multiples” are created by sound pulses that have been reflected more than once; they do not represent geologic structures.



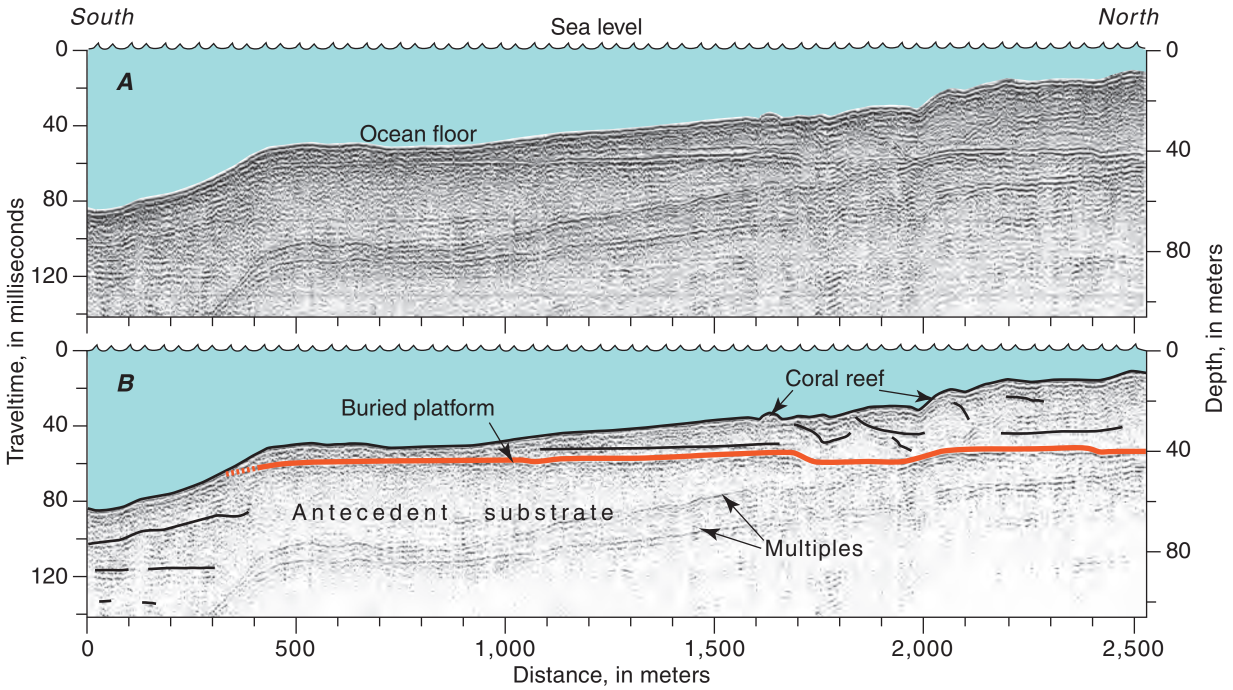


Figure 4. Cross section oriented perpendicular to the coast about midway between Kaunakakai and Kamalō. *A*, Seismic reflection profile. *B*, Line-drawing interpretation of profile. Compared to the profile in figure 3, the buried platform in this area is flatter and extends farther seaward (approximately 2 km or 1.2 mi) of the reef crest.

slopes of 1°–2° and locally crops out on the sea floor in locations offshore of the fore reef. It was traced in the subsurface for about 60 km (37 mi), nearly the entire length of the island.

Judging from its morphology and setting, the buried platform probably represents an ancient reef flat that formed at a previous highstand of sea level or, more likely, a wave-cut terrace that was eroded into the flank of Moloka‘i during the last ice age (fig. 5). We believe that erosion by coastal and terrestrial processes produced the wide, flat platform during the long period of subaerial exposure when sea level was lower. During that time, streams flowed across the exposed areas of former sea floor and locally incised deep channels. The platform was later recolonized by corals as glaciers melted and the ocean again rose to its present level. In the course of the sea-level rise, the stream channels were filled with sediment and preserved beneath the modern reef. Note that the uniformly low relief of the buried platform contrasts with the irregular shape of the overlying modern reef, which exhibits rugged pinnacles and mounds.

Deep-Water Sediment

If erosion created the buried platform when sea level was lower than today, we need to account for the large volumes of material that have been removed. Where did all the eroded sediment go? Erosion by waves, currents, and streams probably carried sediment off the reef and deposited it offshore in deep water. Indeed, large deposits of stratified or layered sediment, locally more than 40 m (131 ft) thick, occur in deep water seaward of the modern reef front (fig. 3). The wedge-shaped deposits exhibit a relatively flat top, a sharp break in slope at a depth of about 130 m (427 ft), and a smooth, steep slope that dips farther offshore. Internal reflections dip seaward and are slightly S-shaped. The morphology and depth of the sediment wedge suggests that the deposit was graded to the lowstand of sea level that occurred during the last ice age approximately 21,000 years before present.

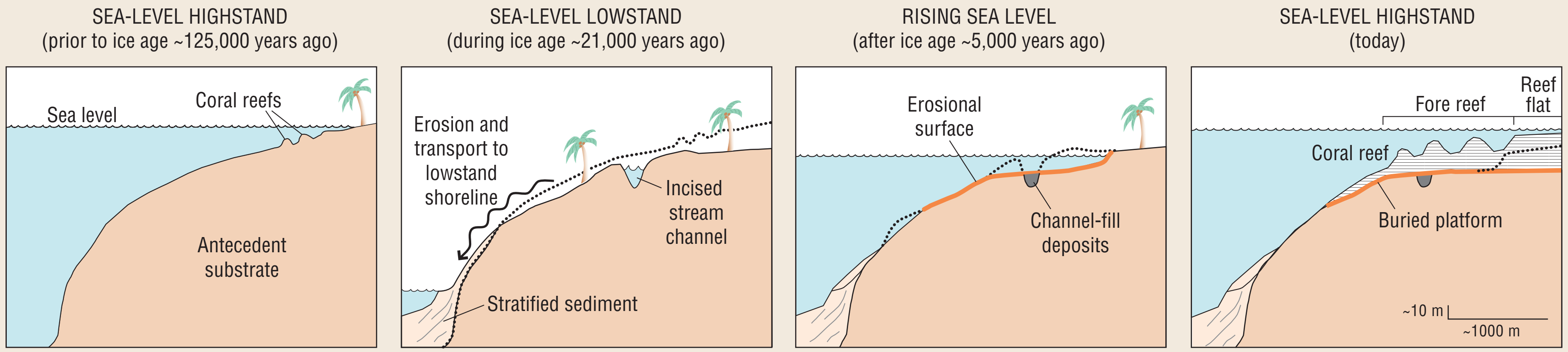
Summary

The geologic development of coral reefs is closely linked to sea-level change. Fluctuations in sea level are well documented in the Hawaiian Islands and, without doubt, have considerably influenced the development of coral reefs (see Grossman and others, this vol., chap. 10). The internal structure of the Moloka‘i reef records a complex history of reef building that was modulated by changes in global sea level and erosion by oceanic and terrestrial processes. As submarine volcanoes grew out of the sea to form the island, corals and other carbonate-secreting organisms colonized the shallow nearshore environment. High-resolution seismic-reflection data have enabled us to accurately map the morphology of the antecedent substrate on which the reef complex formed. The buried platform underlying the modern reef probably represents a wave-cut terrace that developed at some past time; a full understanding of its origin and age will require direct sampling with cores.

The rugged surface of the modern fore reef bears no resemblance to the planar morphology of the buried platform beneath. The pinnacles and spur-and-groove features (see Storlazzi and others, this vol., chap. 3) have high local relief, but the underlying platform is smooth and gently sloping. In more seaward locations, the shelf steepens and dips down at a high angle, restricting the potential area for reef growth during sea-level highstands to a narrow band that is, on average, about 1.5 km (0.9 mi) wide.

Deeper parts of the sea floor off Moloka‘i have received carbonate sand and rubble from reworking of coral reefs and terrigenous sediment from erosion of the island’s volcanoes. Although the relative contributions are poorly understood, a significant volume of sediment has accumulated in a thick, wedge-shaped deposit. This stratified sediment was probably transported across the steep shelf and sequestered offshore, mostly during the last ice age as sea level fell and remained lower than the present shoreline for thousands of years.

Figure 5. Diagrams showing a conceptual model of four steps in the development of the Moloka‘i reef in response to sea-level changes. Thin dashed lines represent island profiles in the preceding panel.



SEA-LEVEL HIGHSTAND
(prior to ice age ~125,000 years ago)

STEP 1
Previous interglacial period approximately 125,000 years ago, before the last ice age began. Sea level is at or near the present highstand elevation. Coral reefs grow in shallow waters along the margins of the island, similar to the modern setting. These reefs and/or underlying volcanic rocks form the antecedent substrate that was mapped with seismic-reflection profiles.

SEA-LEVEL LOWSTAND
(during ice age ~21,000 years ago)

STEP 2
Last glacial maximum approximately 21,000 years ago (late Pleistocene). Global sea level drops to depths of about 130 m (427 ft), exposing older reefs and marginal shelf areas. The shoreline migrates in a seaward direction. Coastal and terrestrial processes erode and rework the antecedent substrate. Pālā‘au and other streams incise their channels deeply into the emergent landscape. Stratified sediment is deposited at the lowstand shoreline and in deeper water offshore.

RISING SEA LEVEL
(after ice age ~5,000 years ago)

STEP 3
Postglacial period approximately 5,000 years ago. Ice sheets are melting and sea level is rising. Shoreline migrates landward across formerly exposed areas of the island. Waves and currents further erode the antecedent substrate, creating a relatively broad, flat platform (red line). Incised stream channels fill with sediment.

SEA-LEVEL HIGHSTAND
(today)

STEP 4
Present conditions. The rate of sea-level rise has decreased, allowing coral reefs to develop in shallow water near the coast. Reef deposits bury the wave-cut platform (red line), which is observed in seismic-reflection profiles beneath most of the Moloka‘i reef complex.

Molokaʻi reef west of Kaunakakai Harbor.

CHAPTER 2

Views of the South Moloka‘i Watershed-to-Reef System

Michael E. Field[1], Joshua B. Logan[1], Pat S. Chavez Jr.[2], Curt D. Storlazzi[1], and Susan A. Cochran[1]

The fringing coral reef along the south coast of the island of Moloka‘i is one of the most extensive fringing coral reefs in the Hawaiian chain. For a distance of about 40 km, from Hale O Lono on the west to Kamalō on the east, live coral coverage is estimated to be 60 to 90 percent (see Jokiel and others, this vol., chap. 5), higher than on all but the most protected reefs in Hawai‘i. The reef is actively accreting in depths between about 6 and 27 m (20 and 90 ft), creating, as these views presented here show, spurs, grooves, knobs, pits, and pinnacles that are home to thousands of marine organisms. Winter waves from the north restrict active reef accretion beyond the sheltered portion of the coast, but the old reef surface in those areas is still populated by numerous individual coral colonies, invertebrates, and fish. For more information about the distribution of coral see Jokiel and others (this vol., chap. 5), and for more information about the distribution of waves along the reef see Storlazzi and others (this vol., chap. 11).

The images of the south Moloka‘i coast in this chapter were created using a combination of aerial photography and high-resolution bathymetric data. The aerial photography was collected in 1993 by the National Oceanic and Atmospheric Administration (NOAA). The aerial photographs were scanned at 800 dots per inch (dpi), yielding an approximate pixel resolution of 1 m, then georectified, color-balanced, and mosaicked by the U.S. Geological Survey to produce a seamless image map covering most of the coastal area on the south coast of Moloka‘i. The aerial image maps were then digitally combined with high-resolution bathymetric data to produce the image maps shown in this chapter.

The high-resolution bathymetry was collected in 1999 and 2000 using an airborne laser-imaging system called SHOALS (Scanning Hydrographic Operational Airborne Lidar Survey) operated by a private company for the U.S. Army Corps of Engineers. The SHOALS system employs lidar (light detection and ranging) technology, with laser pulses in two wavelengths, to very accurately determine water depth at points roughly every 4 m along the bottom. For the Moloka‘i surveys, lidar data were collected at a 2-m spacing, and more than 12 million depth measurements were collected. The system is mounted in an aircraft, which allows it to quickly cover large areas. The vertical accuracy of the measurements is within 15 cm of the actual water depth. Because it is an optical technology, the maximum depth lidar can measure is dependent on water clarity; a general rule of thumb for the SHOALS system is that it penetrates approximately 2.5 times the depth that a person can discriminate objects visually. During the Moloka‘i surveys the approximate maximum depth range recorded by the lidar system was 35 to 45 m (115 to 150 ft).

Each of these two different data sets is extremely useful on its own. The aerial photography provides valuable insight into the types of reef habitat that are found in the shallow areas off the south side of Moloka‘i. To the trained eye, different reef environments can be distinguished from one another in the photography, and this information can be used to create maps depicting bottom type and habitat type (see Cochran, this vol., chap. 9). In addition to shallow water environments, the aerial photography also shows areas of land adjacent to the reef. This, in combination with elevation models, can provide important information about the natural and human-caused processes that may affect the reef, such as wave erosion or land clearing.

The usefulness of aerial photography, however, is limited to the shallow water environments that can be seen with the human eye. Even in the relatively clear water found in some areas of the Moloka‘i reef, the aerial photography begins to show low contrast in water deeper than about 10 m. At these depths the information provided by the lidar data help to fill in the picture of the reef. The dense network of lidar depth measurements can be used to create a three-dimensional computer image of the reef. This image allows us to gain information about the shape of the reef in areas that would otherwise be too deep to "see" with conventional aerial photography. By overlaying an artificially colored and shaded image on the aerial photography, we can develop a more complete picture of the ridge-to-reef environment, from the land all the way to depths greater than 40 m. This combination of high-resolution bathymetric data and high-quality photographs is a powerful and unprecedented tool for interpreting the geologic processes that contribute to the reef's development.

In the following pages, views of the south Moloka‘i reef and the adjacent land are shown using combined aerial photography and lidar. Recent advances in computer-aided mapping technology allow us to display these data sets in both two-dimensional map view and in vertically exaggerated three-dimensional perspective views. Using these two types of images and our observations from field studies, we point out features and patterns on each map sheet that are significant for understanding the processes that have affected, and continue to affect, the evolution of the reef environment. Linkages between the shape of the reef and the processes that shape it are further explored in the following chapter (Storlazzi and others, this vol., chap. 3).

"Blue holes" and channels off Kamalō.

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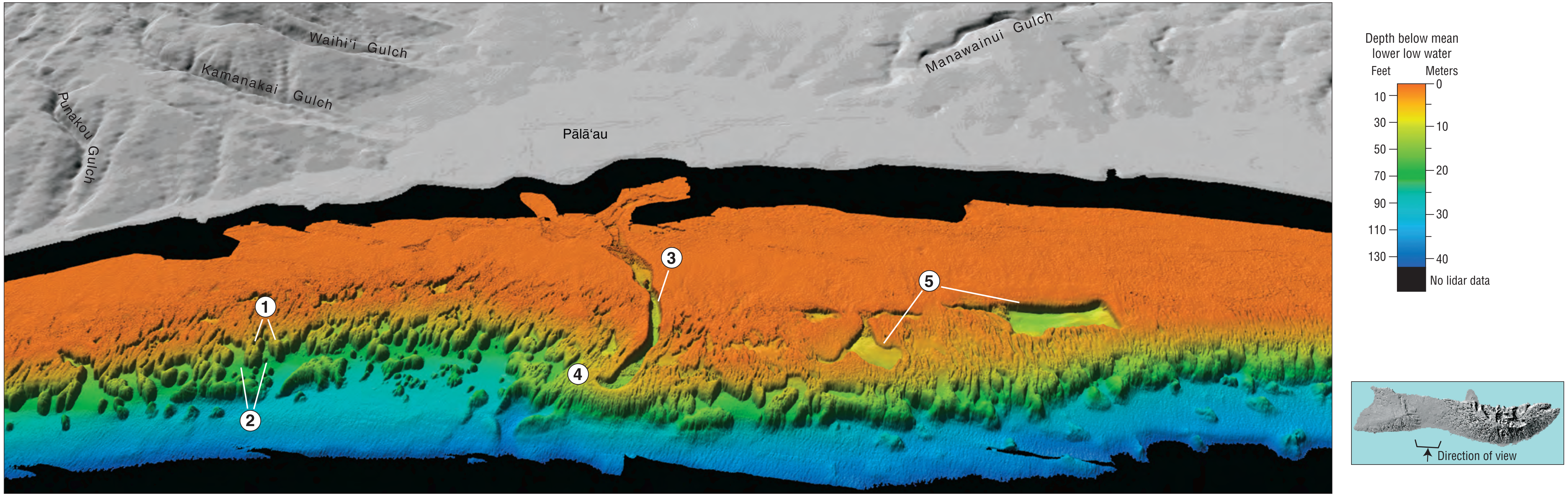
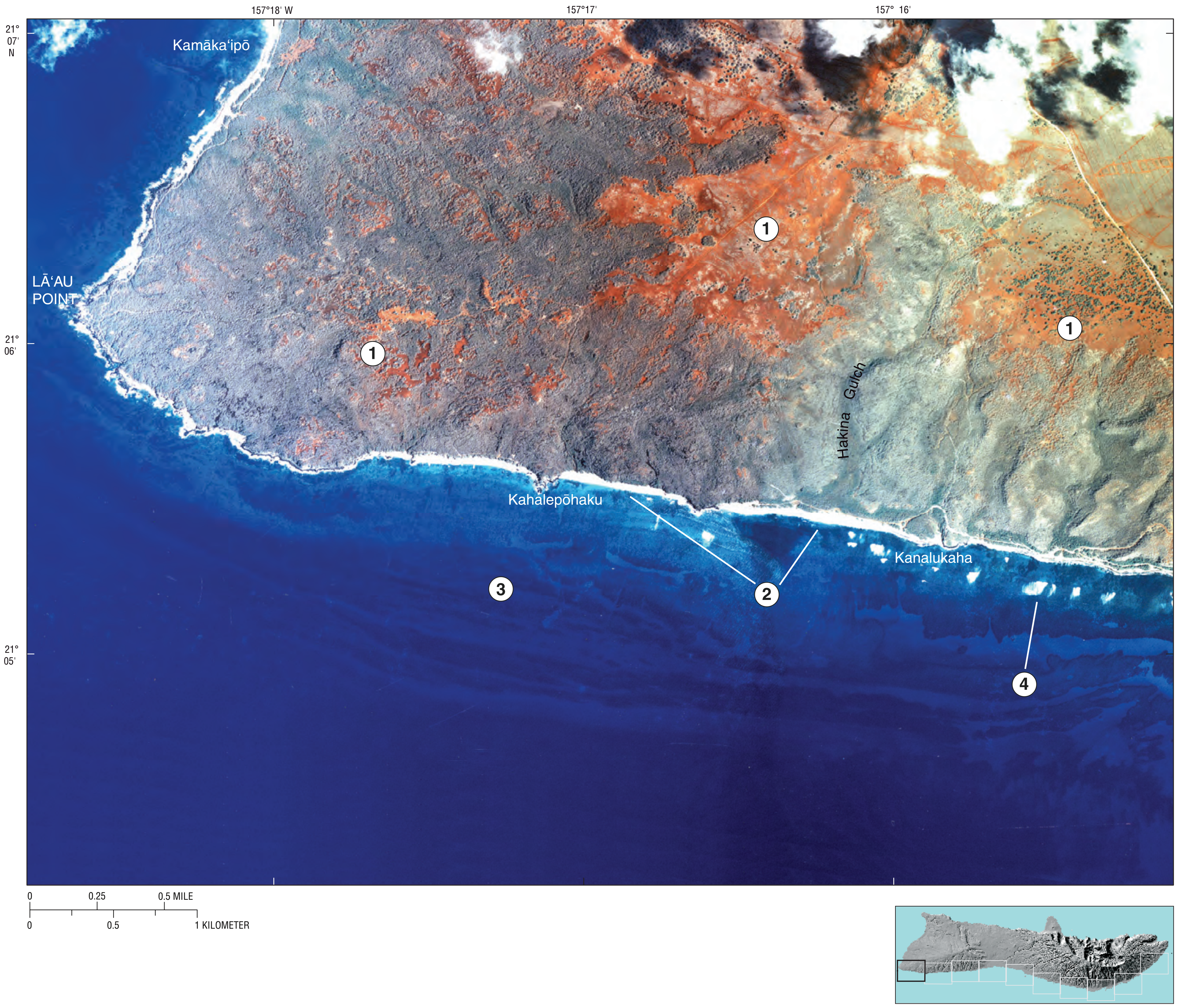


Central Moloka‘i Reef

This image is an expanded perspective view of the central portion of the coral reef off south Moloka‘i. Distinctive features include its pervasive rhythmic spur-and-groove formations (1, 2), like those that characterize many other reefs around the world, and the reef channel (3) at Pālā‘au, remnant from a stream valley that was eroded when sea level was lower than present. Note that the channel is surrounded by solid reef at its terminus (4). Also note the large solution pits (5), partially filled with sediment, east of the channel. These pits, also commonly referred to as “blue holes,” result from dissolution of the reef by flowing water, either as surface streams during times of lower sea level or as flow of submarine ground water under present conditions, followed by collapse of the overlying surface. Approximate distance across the bottom of the image is 7.5 km (4.7 mi).



Lāʻau Point

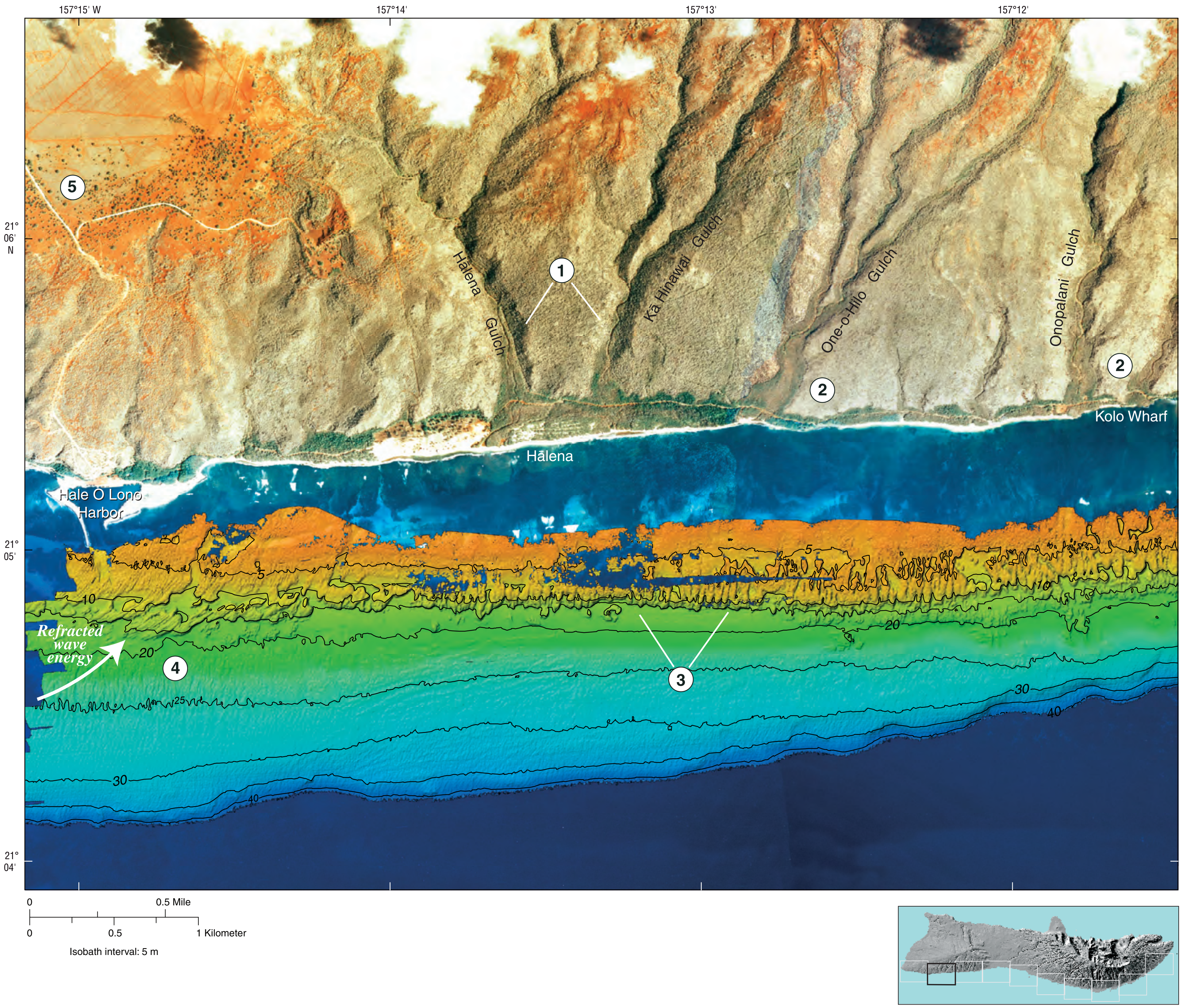
The western end of Molokaʻi is an arid, eroded surface characterized by large exposures of reddish-brown soil densely to sparsely covered by scrub vegetation and grasses (1). The exposures result from low annual rainfall coupled with heavy livestock grazing throughout much of the 20th century. The exposed soil is a source of sediment that is carried to coastal waters during infrequent flood events.

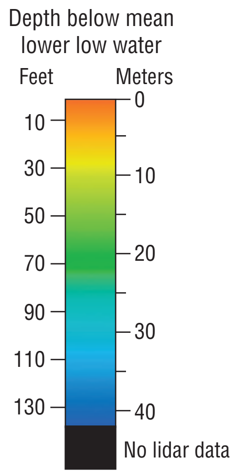
The western beaches (2) of south Molokaʻi are generally wider, more continuous, and composed of coarser sand than the central and eastern beaches. Two factors contribute to this: wave energy and sediment sources. First, the western end of the south Molokaʻi coast receives higher wave energy than farther east, where waves are blocked by the island of Lānaʻi. The southwest coast also receives refracted wave energy from north Pacific swell, and the high wave energy sorts the beach deposits and removes the smaller, lighter particles of fine sand and silt. The second factor has to do with the local availability of beach material. Much of the western shoreline of south Molokaʻi is underlain by older beach sands and beach rock that provide a ready source of material for the modern beach. The adjacent reef also provides a source of coarse material for the beaches.

The modern reef (3) on the westernmost part of south Molokaʻi is not well developed. The inner shelf consists of a dipping surface composed of shore-parallel bands of sand and old reef limestone; individual coral colonies and algae mantle the limestone. This end of the island does not have a well-defined reef crest, allowing waves to break closer to the shore (4) than they do farther east. The barely discernible dark underwater bands in the photograph are exposures of older reef limestone with scattered colonies of coral. Studies of the limestone deposits in this area show that active reef growth ceased about 5,000 years ago (see Engels and Fletcher, this vol., chap. 4). No lidar data was collected in this area, so only aerial photography is shown.

Hale O Lono

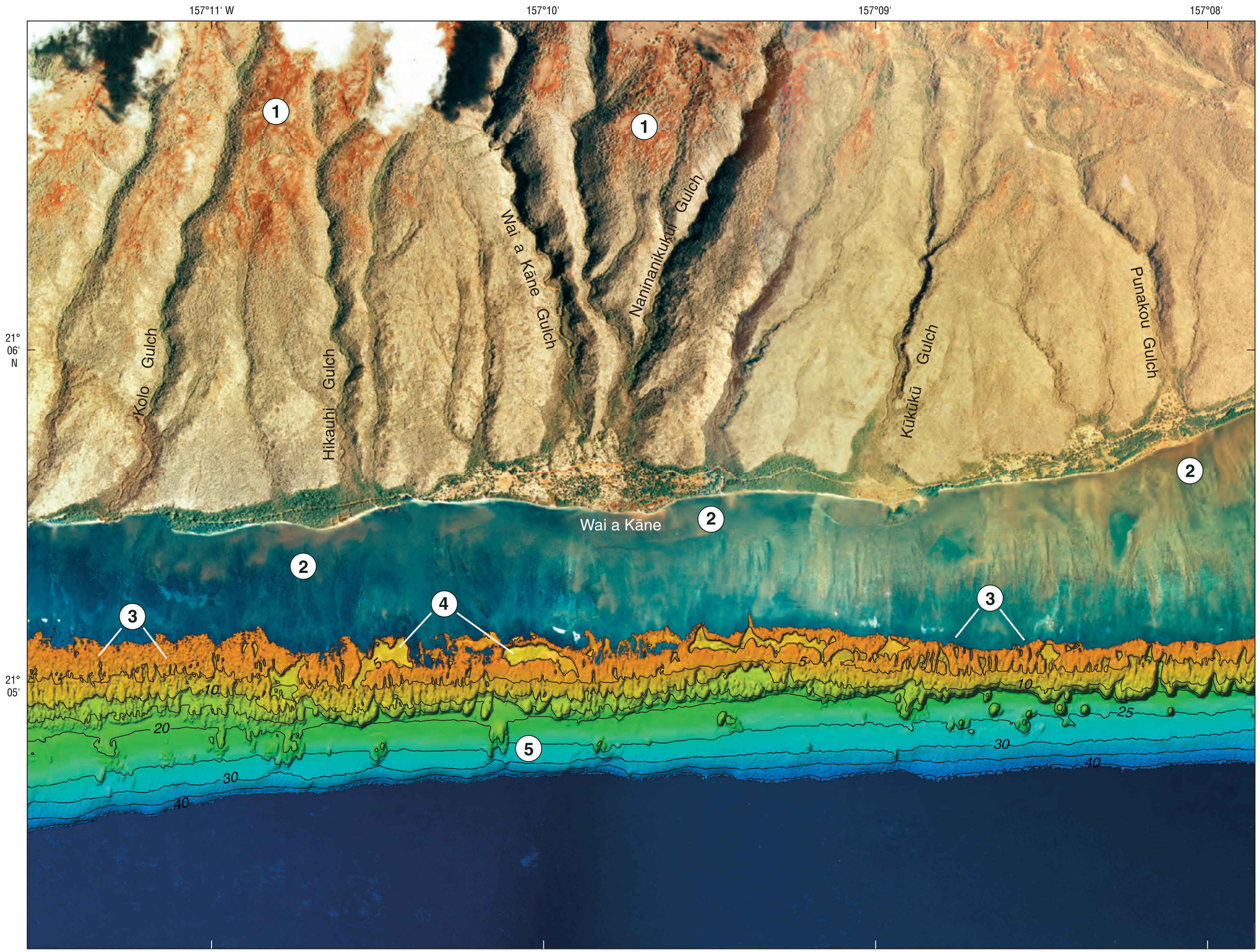
The southern slopes of Moloka‘i are heavily dissected by deep gullies (1), many of which discharge onto the coastal plain, whereas others (2) extend almost completely to the shoreline. Those gullies that meet the shoreline directly are capable of delivering sediment onto the reef during heavy rains and flooding. East of Hale O Lono Harbor, the reef shows the first indication of rhythmic spur-and-groove patterns (3), a common shape of coral reefs that is derived by coral growth along ridges oriented perpendicular to the dominant swell direction. Note that off Hale O Lono, the spur-and-groove morphology curves to the southwest (4), probably because large North Pacific swell wraps around the island and approaches the reef from the southwest, inducing growth along that trend. The road to the town of Mauna Loa can be seen in the upper left of the image (5).

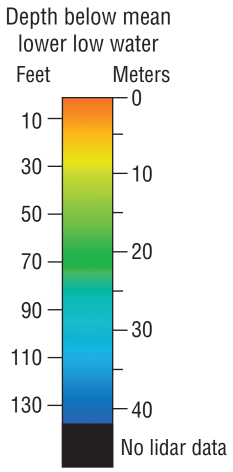


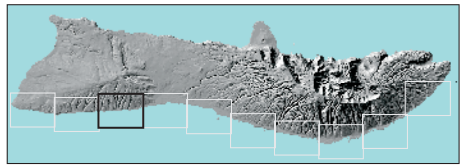


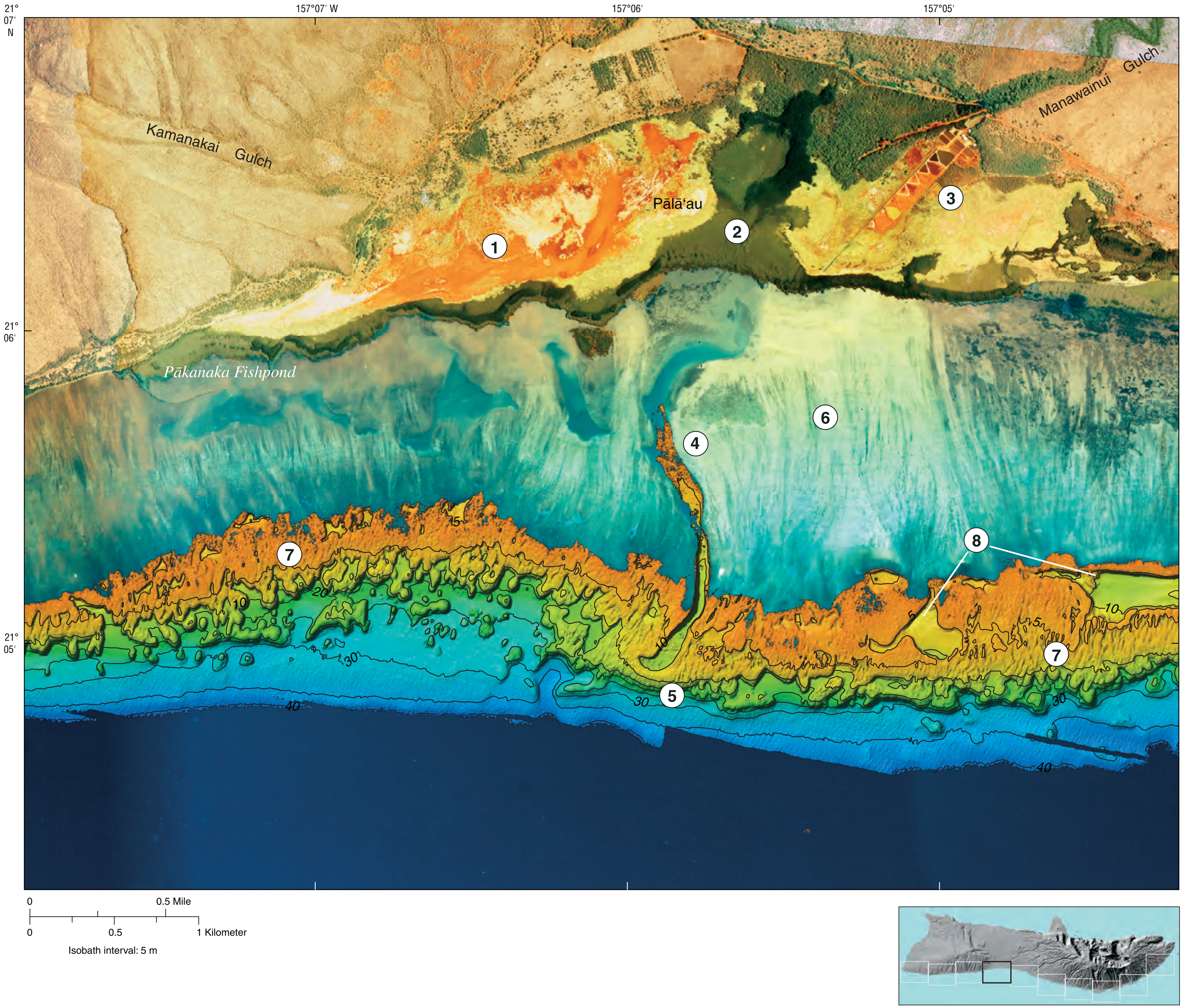
Wai a Kāne Gulch

Red-brown soils (1) are exposed on the hill slopes along the western part of south Molokaʻi as a result of low rainfall and heavy cattle grazing (Roberts, 2001). This 1993 photo captured images of plumes of turbid water on the inner reef flat (2). The fore reef here is composed of well-organized, evenly spaced spur-and-groove morphology (3) with some large shallow solution pits (4) and a few spurs in deeper water (5). The deeper spurs, although colonized on their surface, are probably remnants from earlier periods of more active reef growth, as documented by Engels and others (2004).



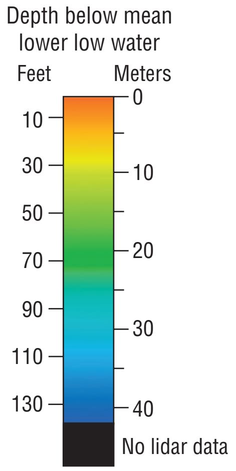


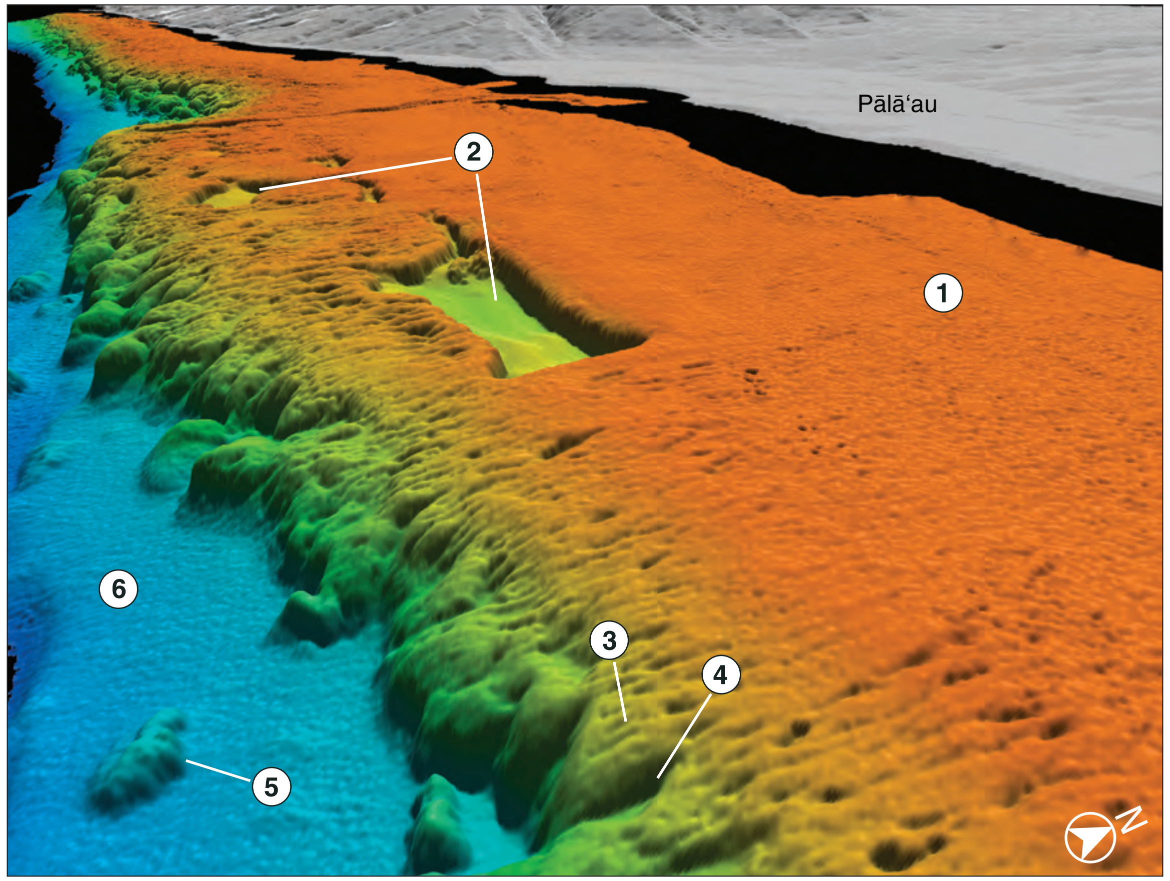


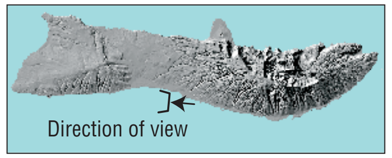


Pālā‘au

The coastal area at Pālā‘au is characterized by an extensive mud and salt flat (1) that formed from heavy flooding and runoff in the early 1900s and an extensive mangrove forest (2) that was established in 1903 to curb the heavy sediment runoff (D’Iorio, 2003). The elongated structure trending northeast-southwest (3) east of the mangroves is a shrimp farm. The reef at Pālā‘au is dissected by a meandering channel (4) that resulted from stream erosion during a period of lower sea level (>12,000 years ago). Note that the reef is not breached at the end of the channel (5), possibly from coral growth since that time, or because the water flowed through the porous reef rather than over it. East of the channel the reef flat is a broad, barren surface (6) covered by thin deposits of stained carbonate sand, giving way to an algae-covered rock surface to the east. Near Pālā‘au, the reef undergoes a subtle change in orientation, reflecting the overall change in island morphology. The trends of the fore reef on each side of the channel (7) mimic the change in orientation of the shoreline: to the west, the shoreline and reef trend west-southwest; to the east they trend east-southeast. East of the channel, the middle part of the reef is characterized by large pits (8), which likely result from extensive, long-term dissolution by fresh water flowing through the reef, followed by roof collapse.

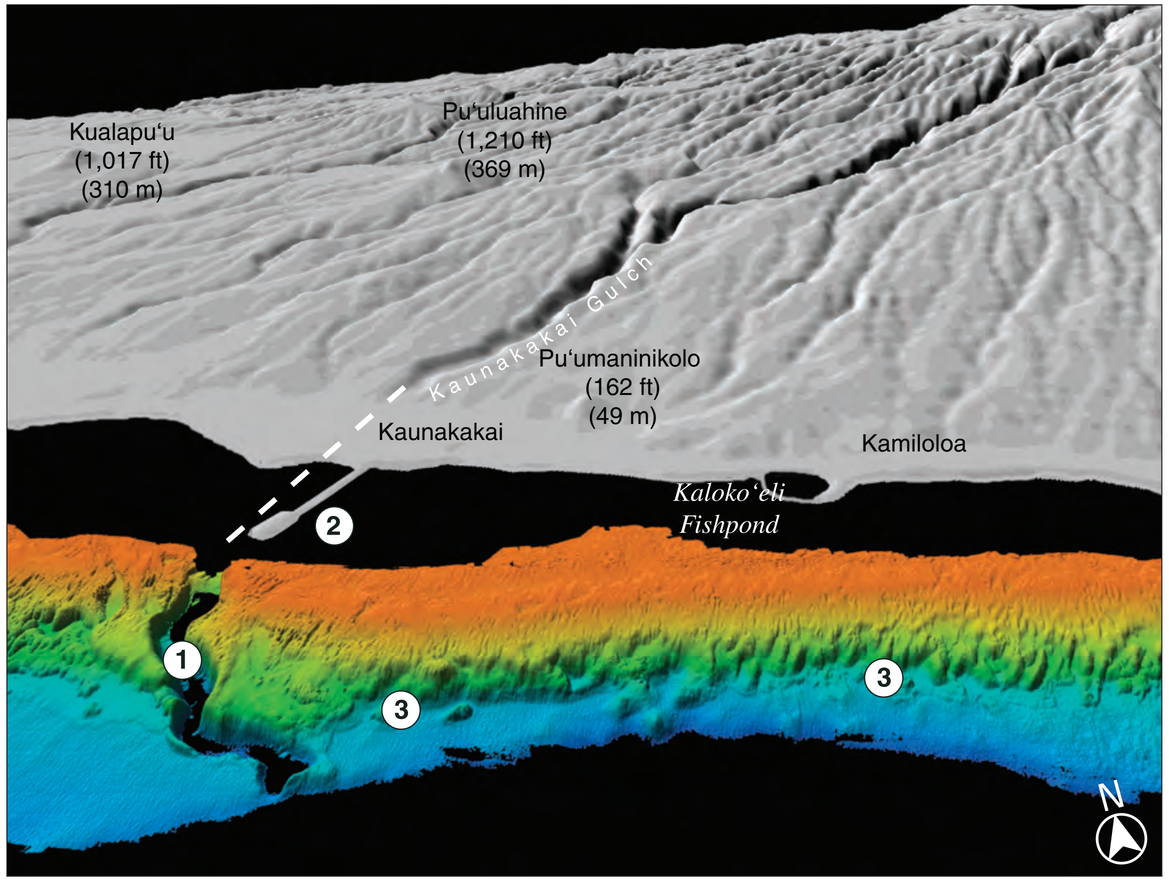


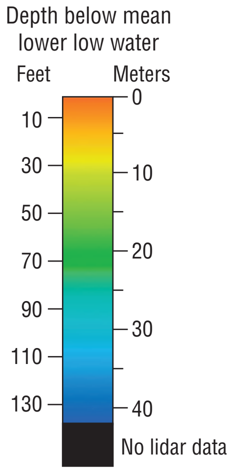


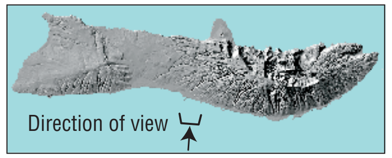


Blue Holes near ‘Umipa‘a

This perspective view of the central Moloka‘i reef near ‘Umipa‘a shows that the inner reef is characterized by a wide reef flat (1) and large, sediment-infilled pits (blue holes) (2). The east-west alignment of the inner walls on the pits (see also image of Pālā‘au area) possibly indicates a regional control related to shoreline history or reef structure. The outer reef has a pronounced spur-and-groove structure (3, 4), which gives way to isolated reef pinnacles (5) and a sediment-covered terrace (6) seaward of the reef. Approximate distance across the bottom of the image is 850 m (0.5 miles).

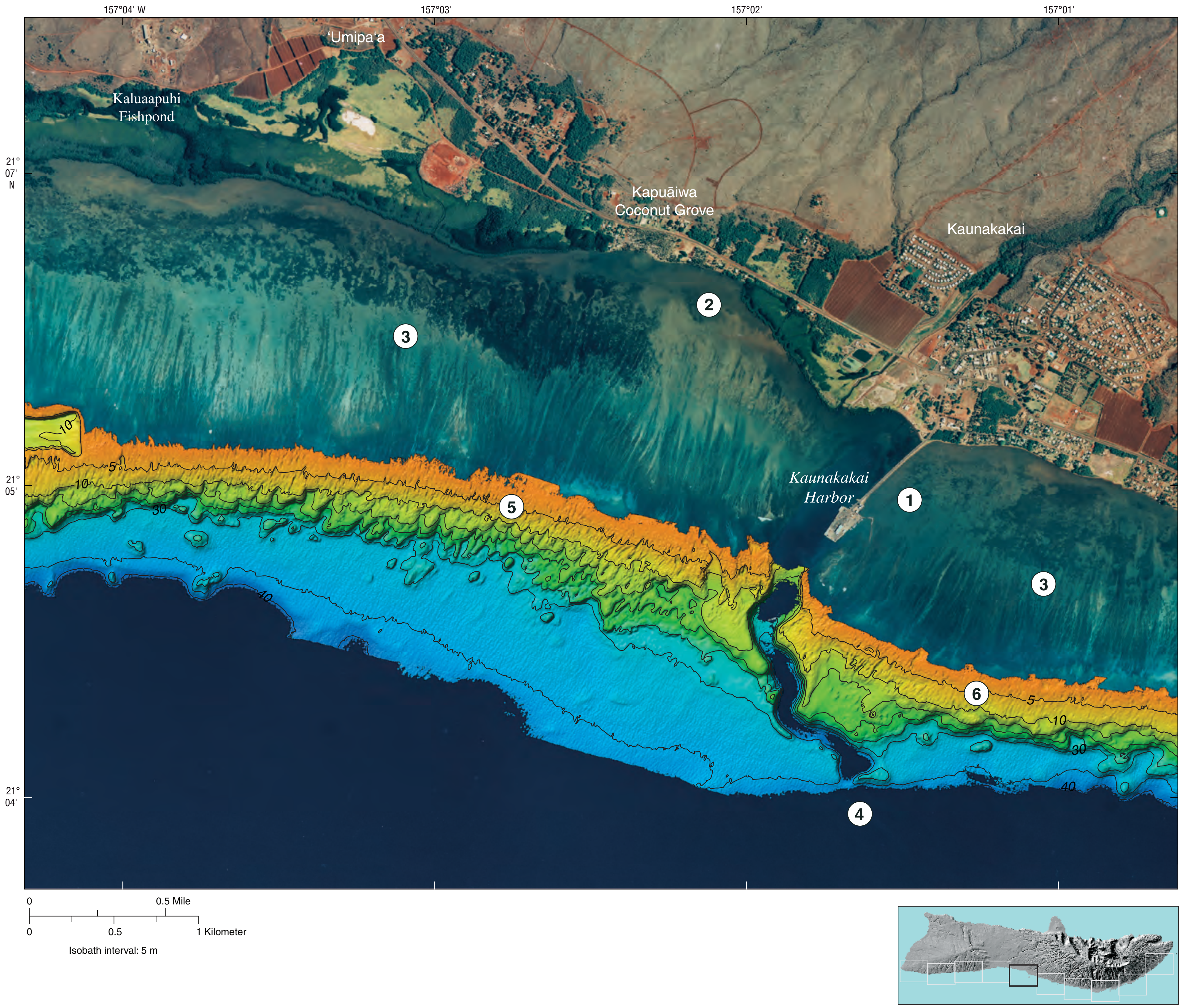






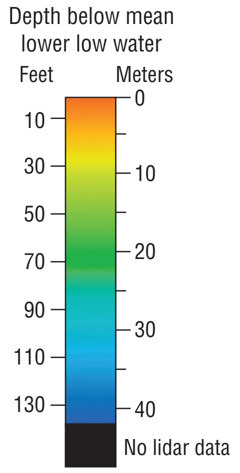
Kaunakakai to Kamiloloa

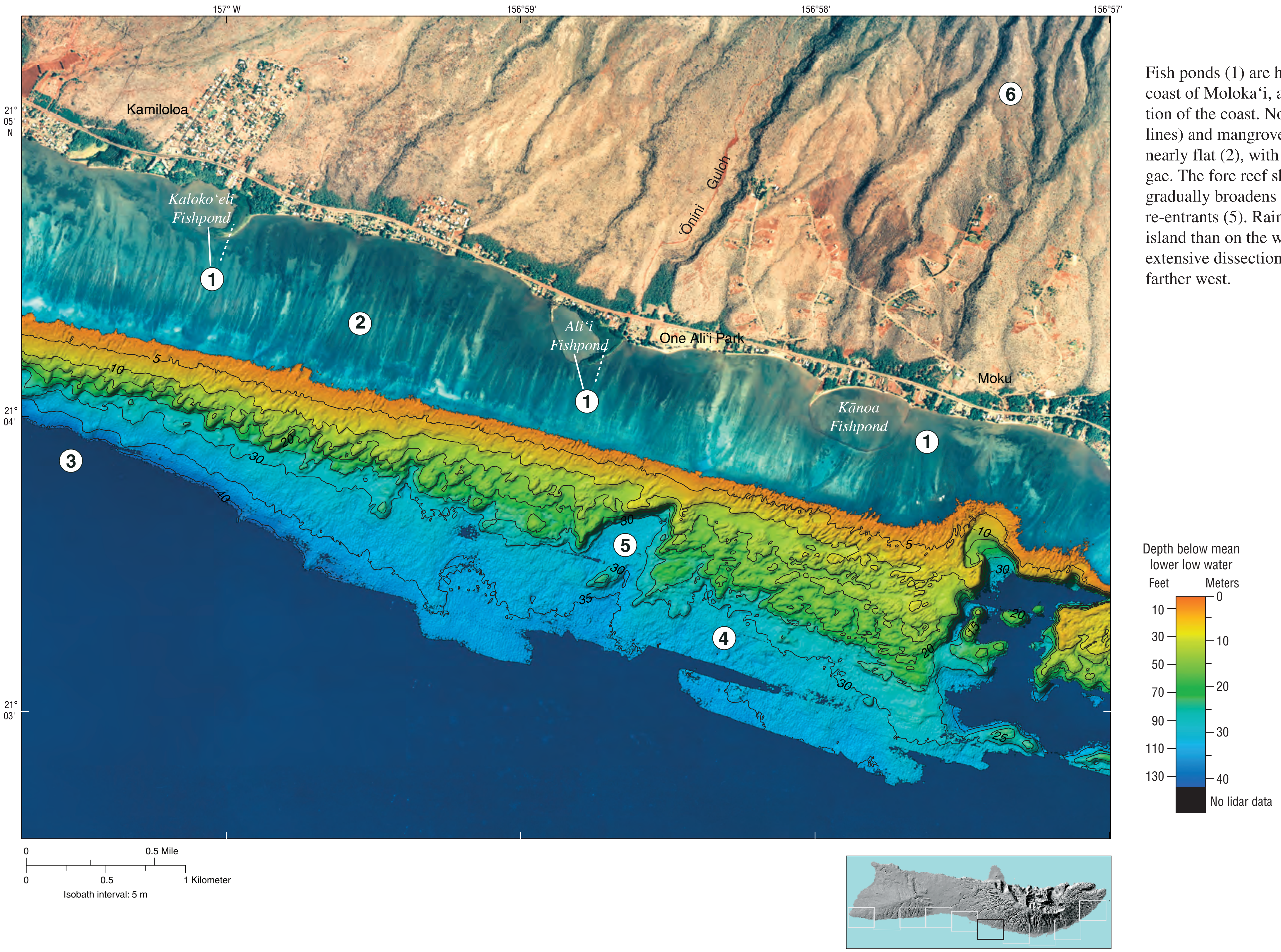
This perspective view of central Moloka‘i shows the alignment of Kaunakakai Gulch with the reef channel (1) west and offshore of the wharf (2). The channel is interpreted to have formed by stream water flowing out of the gulch when the ocean was at a lower level and the shoreline was farther south (offshore of the present shoreline). The base of the actively growing reef (3) lies at a water depth of about 28 meters (~90 feet). Approximate distance across the bottom of the image is 4.5 km (2.8 miles).



Kaunakakai

The town of Kaunakakai is the largest town on Moloka‘i and sits adjacent to the largest and most important harbor on the island. In 1934 the Kaunakakai Wharf (1) was rebuilt to its present size and configuration. It is nearly 1 km long and solid, and thus it is influential in blocking the westward flow of water and sediment along the reef flat. For more information about sediment movement along the reef, see Ogston and others (this vol., chap. 20). To the west of the wharf (2), the shoreline is eroding at Kapuāiwa Coconut Grove (D’Iorio, 2003), perhaps in response to sediment trapping by the wharf. The reef flat on both sides of the wharf (3) is very broad and mantled by thin layers of muddy sediment and macroalgae. The reef is dissected by the Kaunakakai channel (4), a former stream channel remnant from a period of lower sea level (similar to Pālā‘au channel). Note that west of the Kaunakakai channel the fore reef exhibits very well defined rhythmic spur-and-groove morphology (5), but east of the channel the morphology is subdued and flattened (6). This pattern reflects the active, healthy growth of coral west of the harbor and the limited, stunted growth that extends to the east for several kilometers.



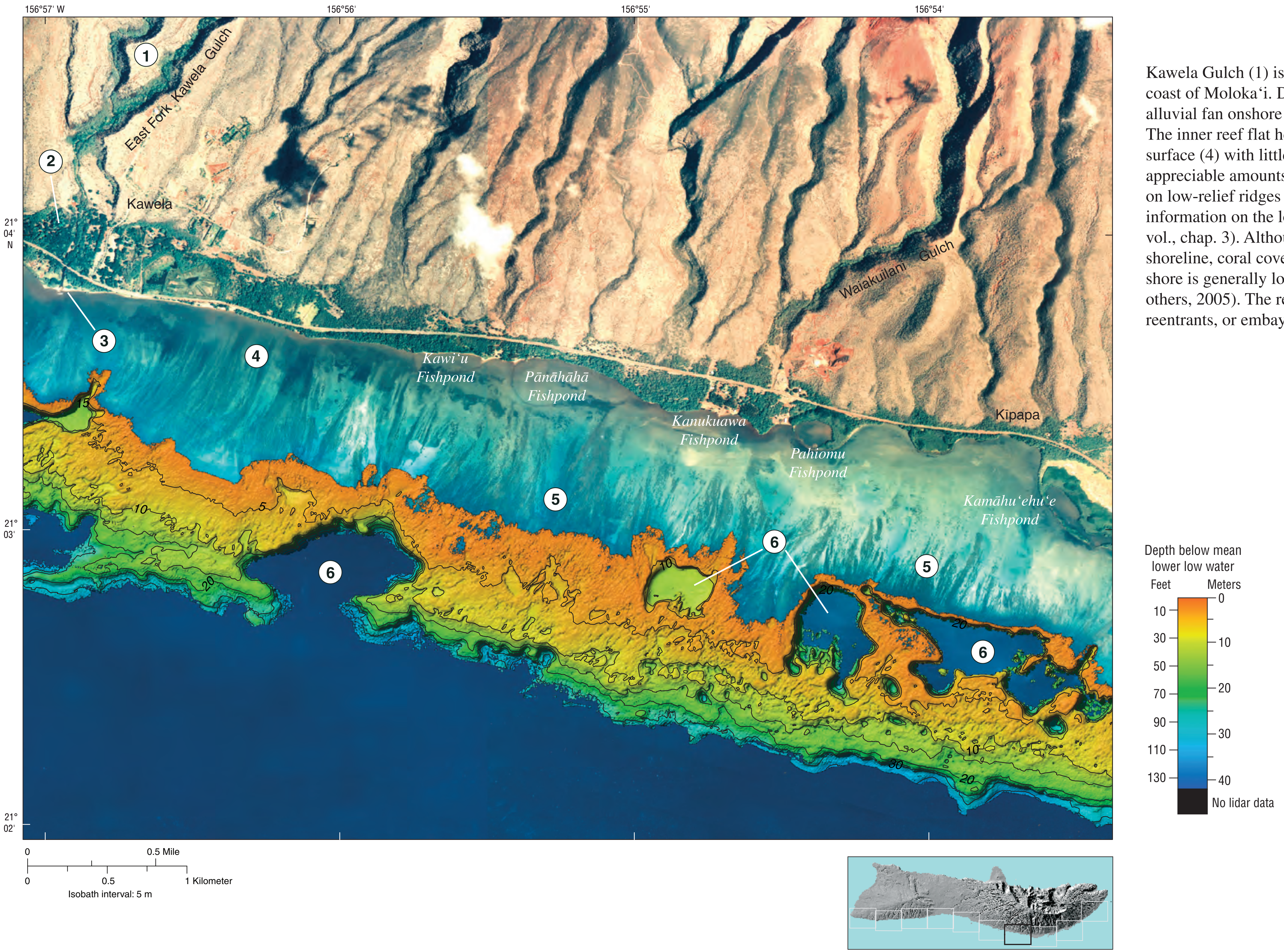


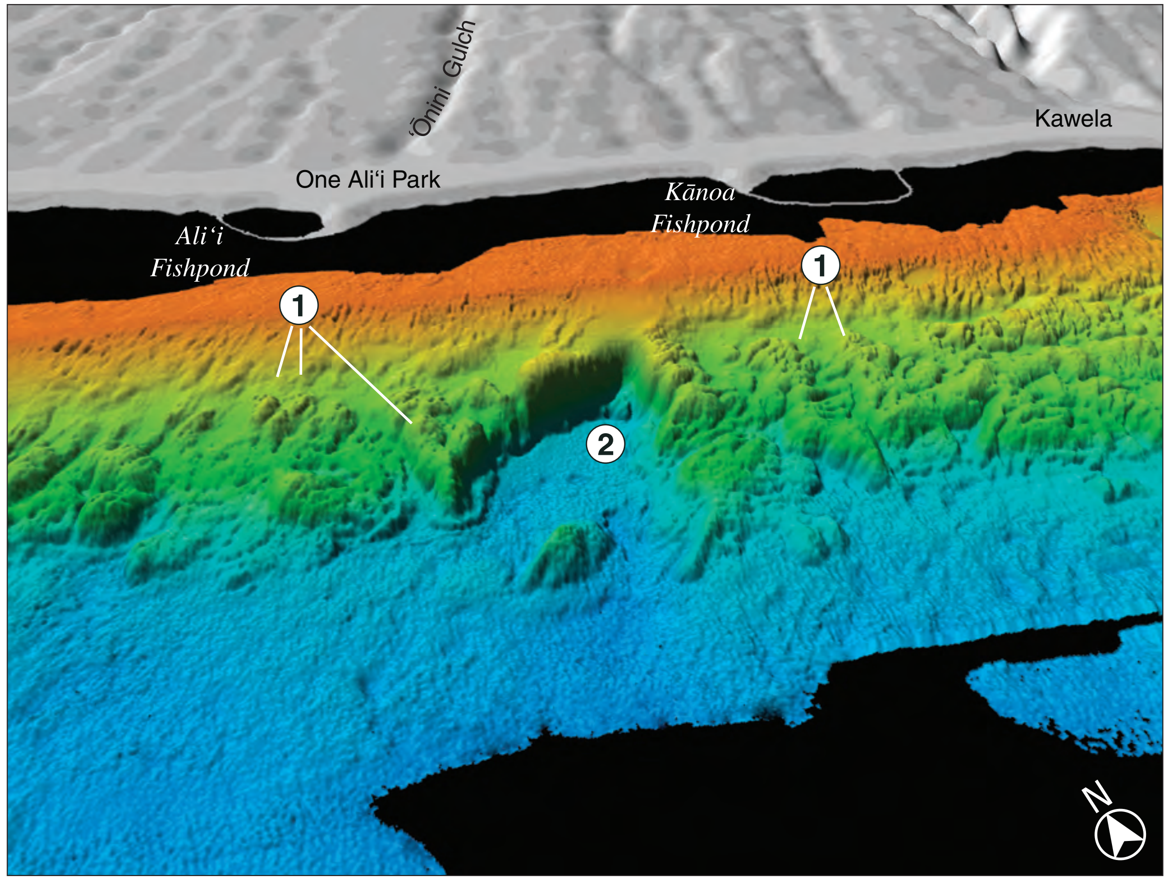
Kamiloloa

Fish ponds (1) are historical manmade features along the entire south coast of Moloka‘i, and they are particularly prominent along this section of the coast. Note the infilling of the fishponds with sediment (solid lines) and mangrove trees (dashed lines). The reef flat here is broad and nearly flat (2), with a thin covering of muddy sediment and macroalgae. The fore reef shows signs of erosion or non-growth to the west (3), gradually broadens toward the east (4), and becomes segmented by major re-entrants (5). Rainfall and slope gradients are higher on this part of the island than on the western part of south Moloka‘i, contributing to more extensive dissection and erosion on island slopes here (6) compared to farther west.

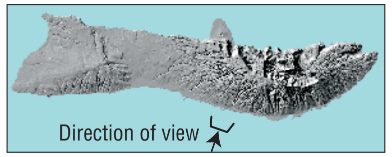
Kawela Gulch

Kawela Gulch (1) is a major pathway of water and sediment to the south coast of Moloka‘i. Deposition of sediment has created a pronounced alluvial fan onshore (2) and a pronounced lobate delta at the coast (3). The inner reef flat here, as farther to the west, is a flat, sediment-covered surface (4) with little coral growth. In contrast, the outer reef flat has appreciable amounts of live coral (Rodgers and others, 2005) growing on low-relief ridges (5) oriented perpendicular to the coast. For more information on the low-relief coral ridges, see Storlazzi and others (this vol., chap. 3). Although several coral species appear within 400 m of the shoreline, coral coverage across the entire reef flat out to 700 m from shore is generally low (<10 percent) with few exceptions (Rodgers and others, 2005). The reef crest and fore reef are characterized by large reentrants, or embayments, and pits (blue holes) (6).

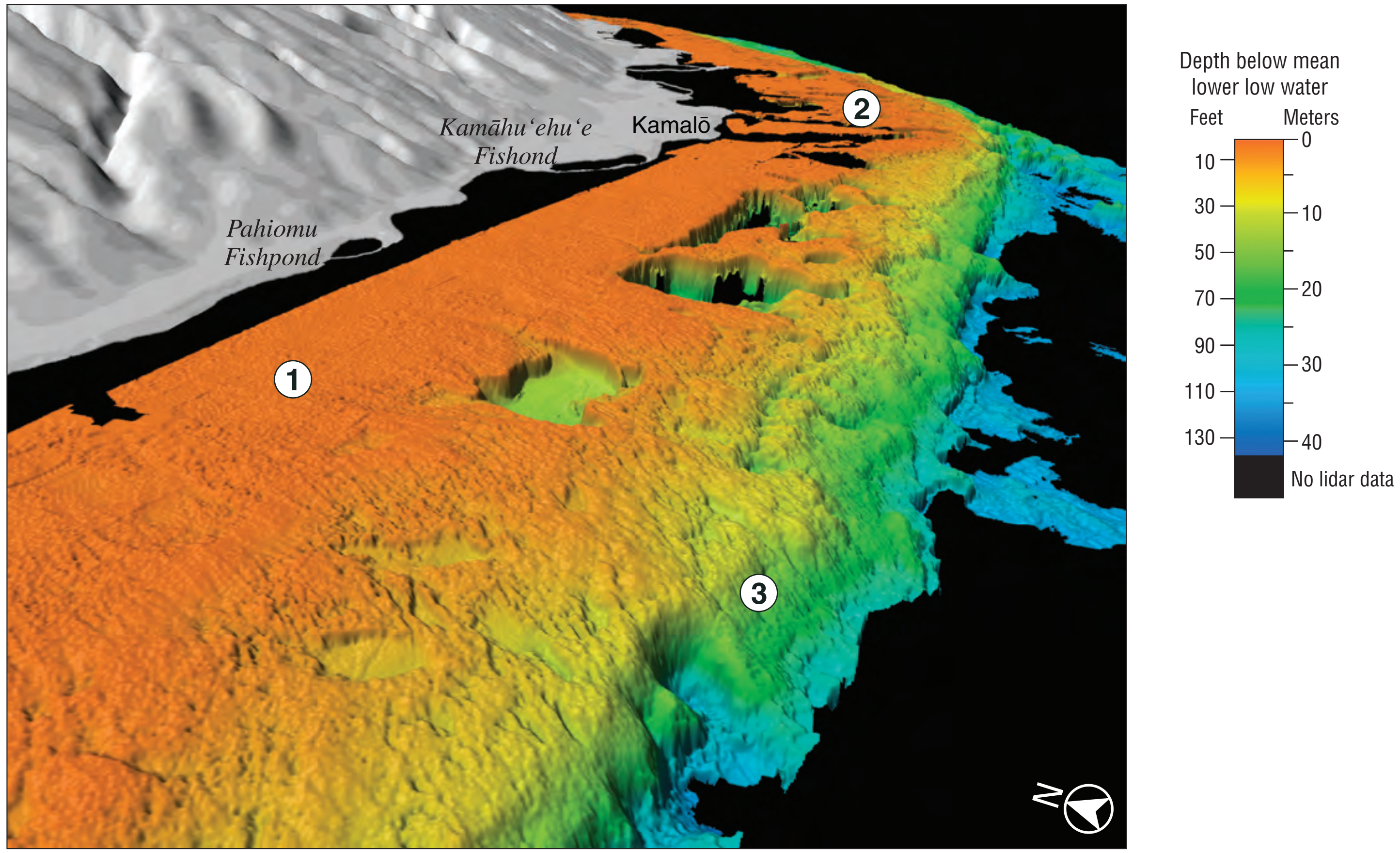




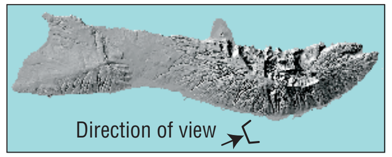
‘Onini Gulch to Kawela Gulch



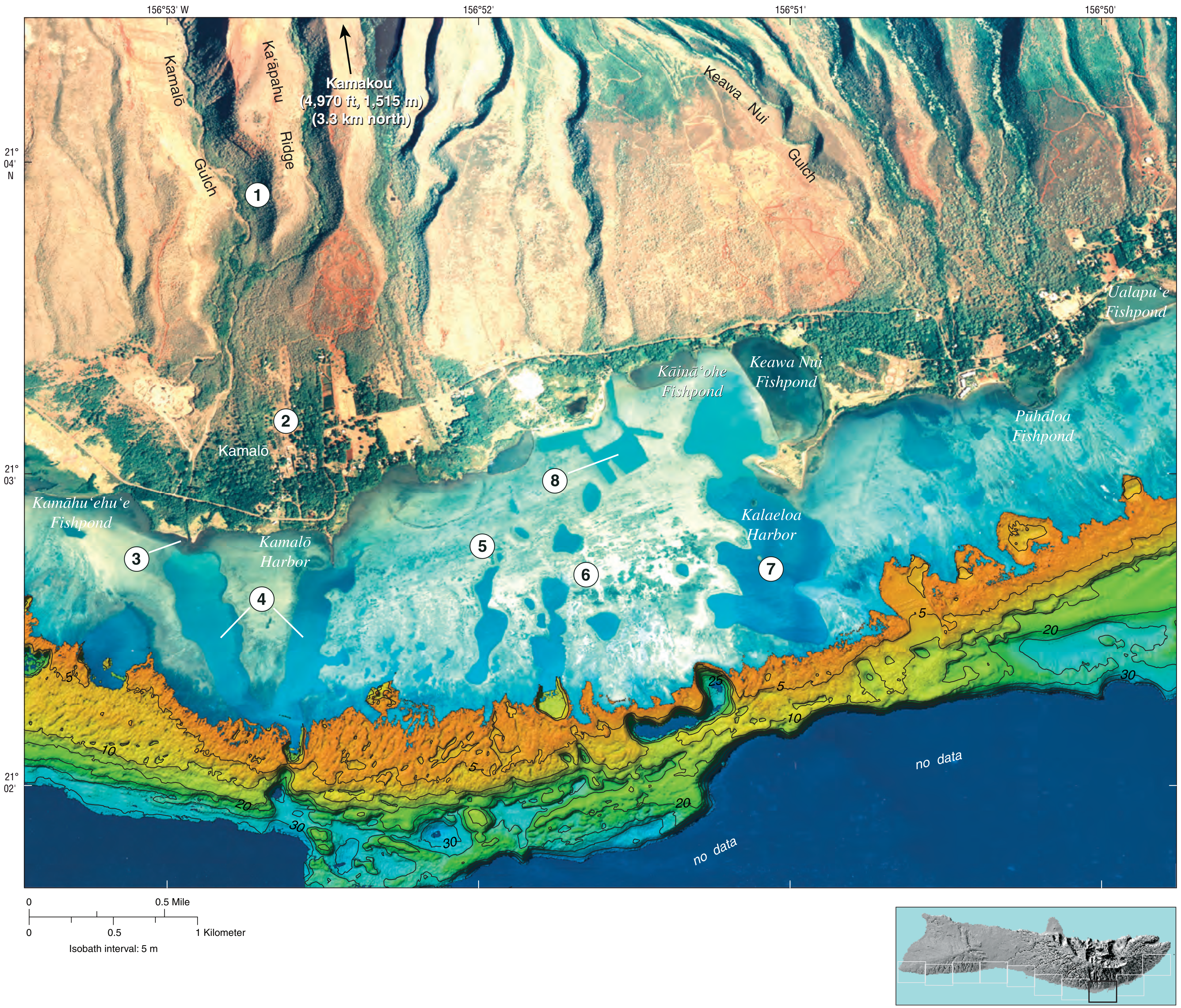
This perspective view of the reef off One Ali‘i Park in east-central Moloka‘i shows the changing shape of the reef. The spur-and-groove structure, dominant farther west (see, for example, the image of Kaunakakai) is not well defined in this area; individual spurs (1) are discontinuous and of various orientations, indicating that coral growth has not been uniform in this area. The large reentrant (2) in the reef may have been the site of stream outflow during a period of lower sea level. Approximate distance across the bottom of the image is 2 km (1.25 miles).



East toward Kamalō

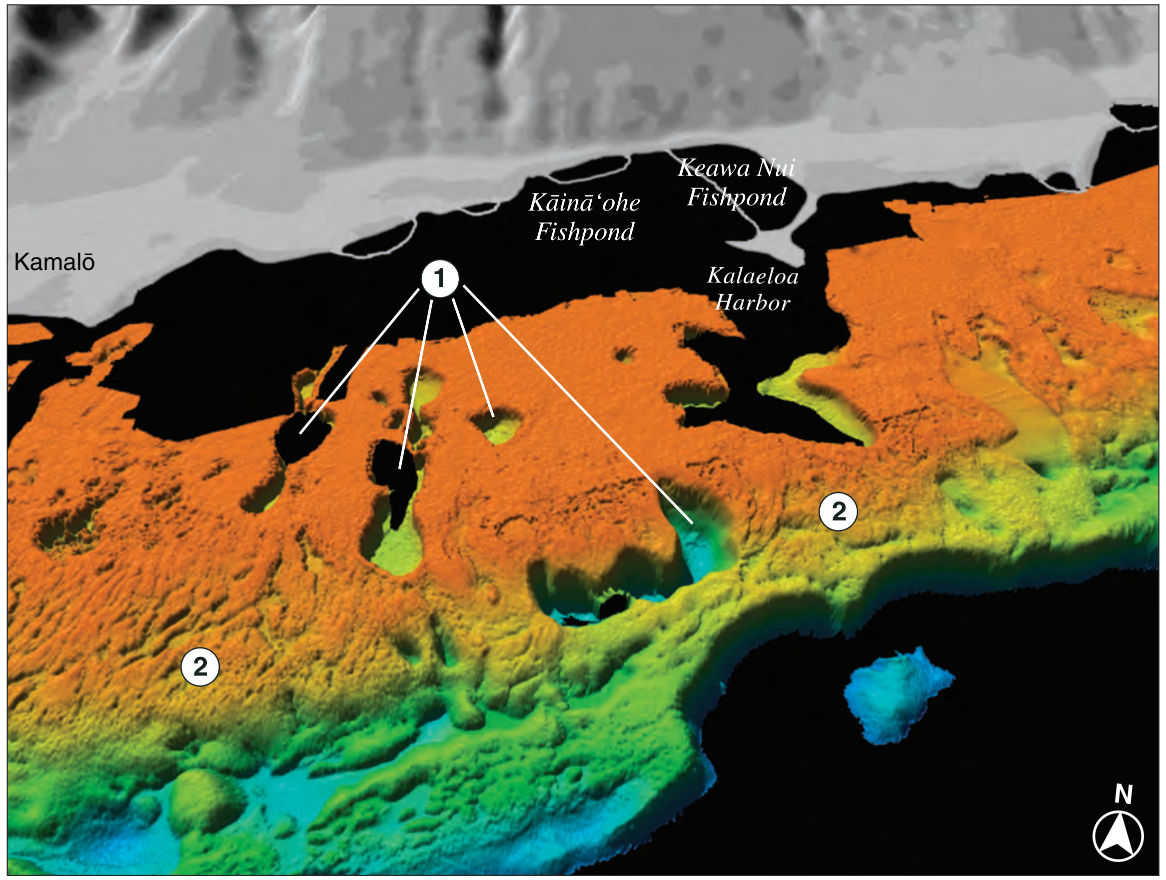


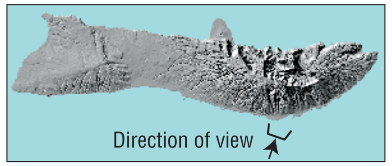
This perspective view shows the change in coastal orientation that occurs at Kamalō. It is this change that leads to higher wave energy east of Kamalō, where the coast is more exposed to winter swell. The near part of the view (1) shows the reef flat that is sheltered from the high wave energy that reaches the reef east of Kamalō. Wave energy plays a major role in the development of the reef. East of Kamalō (2), reef growth is limited. In contrast, the fore reef west of Kamalō (3) is well developed and densely covered with live coral to depths of 28 meters (~90 feet), and small isolated coral colonies may be found deeper. Note the prominent blue holes, which are deeper and more abundant on the eastern end of the reef, perhaps because of the higher levels of precipitation and water flow. Approximate distance across the bottom of the image is 1.3 km (0.8 miles).



Kamalō

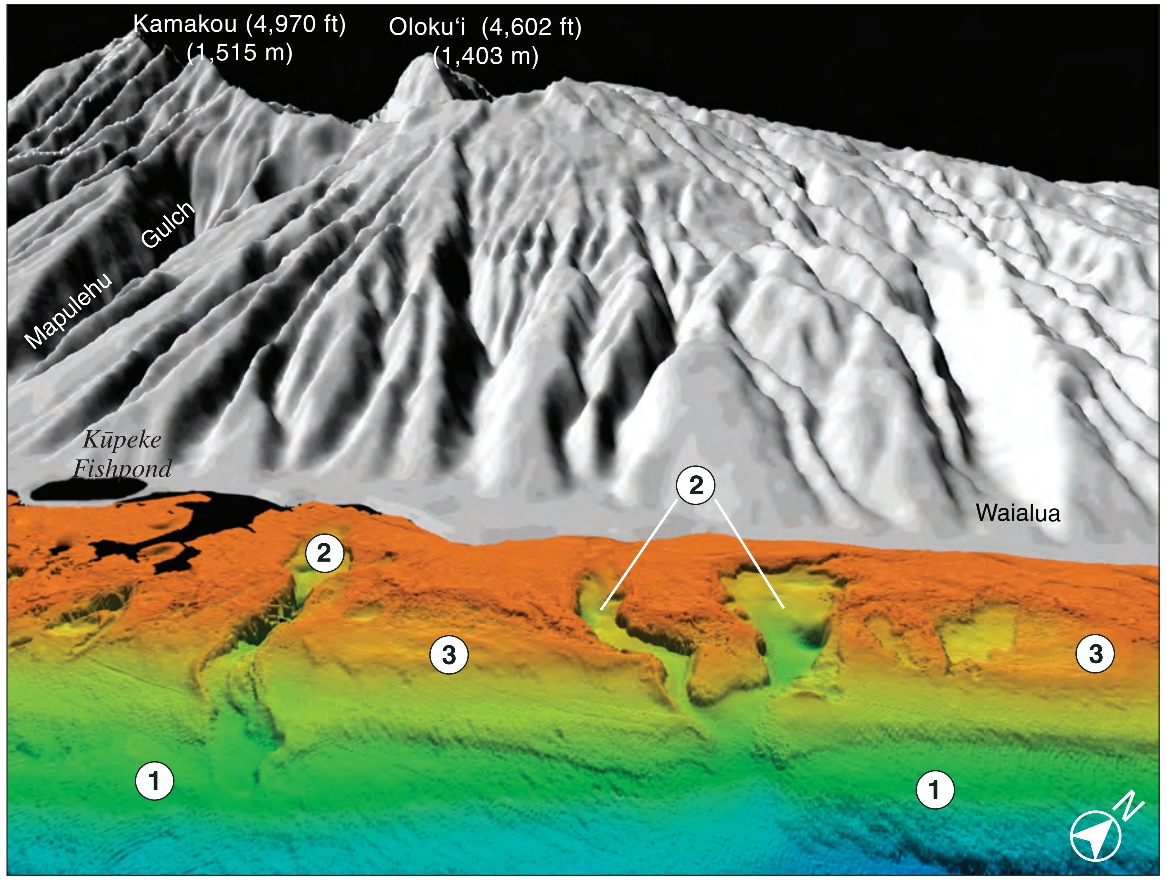
Kamalō is the point where the south Moloka‘i coast changes orientation and consequently becomes more exposed to wave energy eastward; the area also essentially marks the east end of the accreting reef of south Moloka‘i. Whereas the reef to the west of Kamalō appears to be actively accreting, the reef surface to the east consists largely of ancestral reef deposits intermittently colonized by live coral. Kamalō Gulch (1) and its adjacent gulches are the most prominent gulches along the south shore. Running steeply down from the island’s highest peak (Kamakou, 1,515 m or 4,970 ft), the gulches are wide and deeply entrenched. The large amounts of sediment that have been delivered through this system over time have built a large alluvial fan and coastal plain complex (2). The present mouth of Kamalō Gulch (3) discharges runoff directly into deep water through one of two paleochannels (4) incised by stream flow across the reef when sea level was lower than it is today. It is likely that the fine-grained sediment plumes formed during flood discharge from the gulches are driven west along the shoreline by prevailing winds. To the east of the paleochannels lie three pronounced lineations (5, 6, and 7) of deep holes in the reef flat; all three likely mark the location of freshwater flow (surface as well as ground-water discharge) across and through the reef, dissolving older reef limestone in the process. At the landward end of the string of elongated blue holes (6) is an artificially created pit (8) formed by dredging in the 1970s to create a harbor.

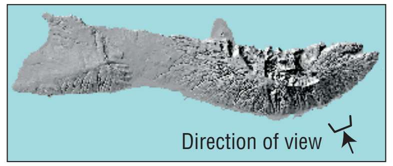




Kalaeloa

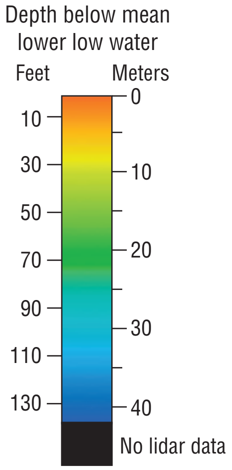
This perspective view of the Kamalō region and farther east shows that the reef is relatively smooth with numerous large blue holes (1). The blue holes are typically 6 to 24 meters (20 to 80 feet) deep and, as already pointed out, likely formed through dissolution of the preexisting reef limestone. The irregular reef surface (2) marks the transition between the actively accreting reef to the west and the sparsely covered limestone surface to the east. Approximate distance across the bottom of the image is 2.7 km (1.7 miles).

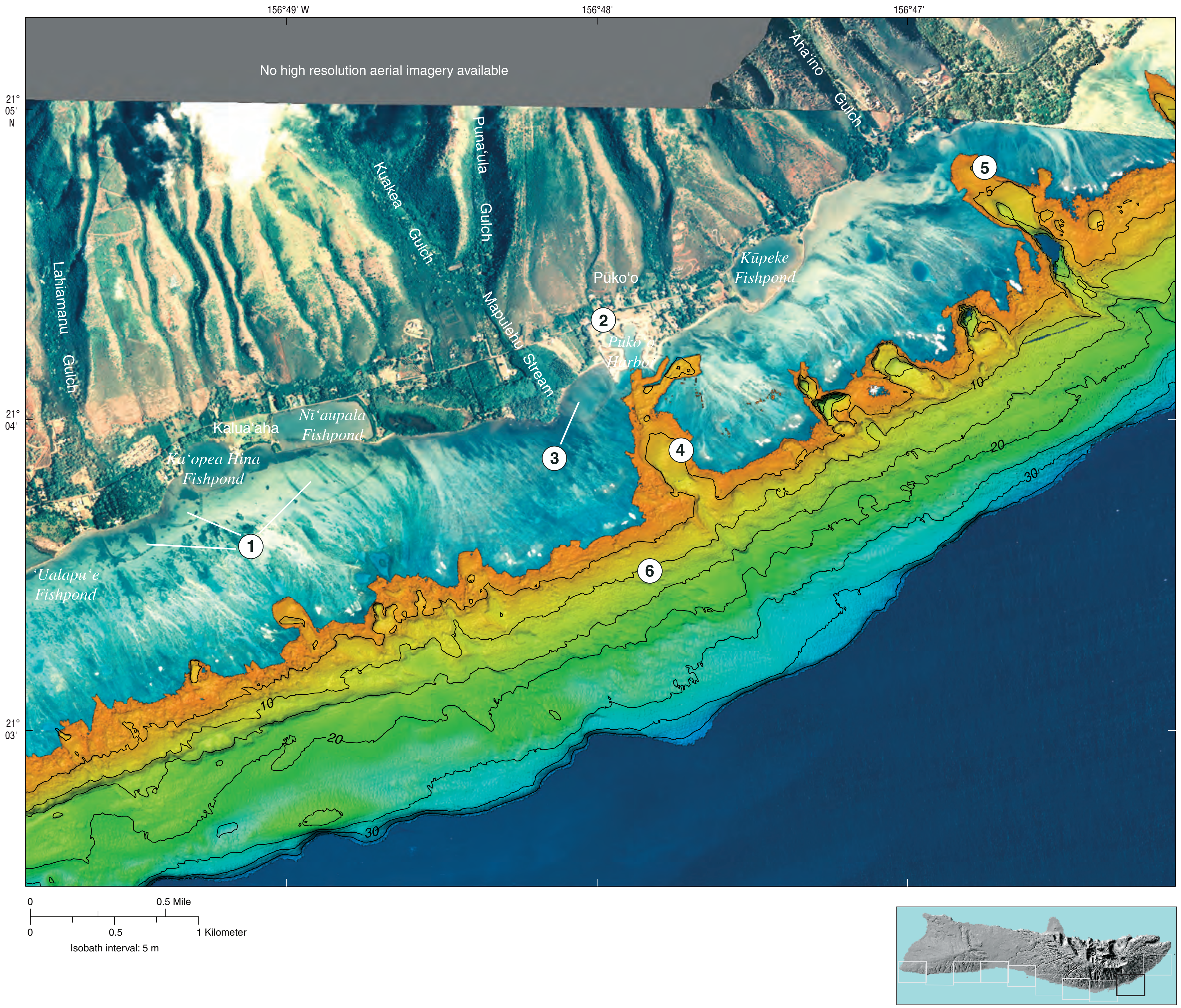




Honomuni

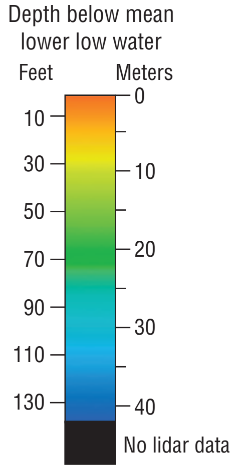
This perspective view shows that the eastern reef of south Molokaʻi is characterized by a smooth surface (1) with numerous channels and blue holes. Many of the large gullies dissecting the steep land surface align with channels incised into the reef (2). There is a complete absence of spur-and-groove formation by coral accretion in this area because of the high wave stresses. Live coral colonies are relatively sparse on the limestone surface (3). Approximate distance across the bottom of the image is 2.8 km (1.7 miles).

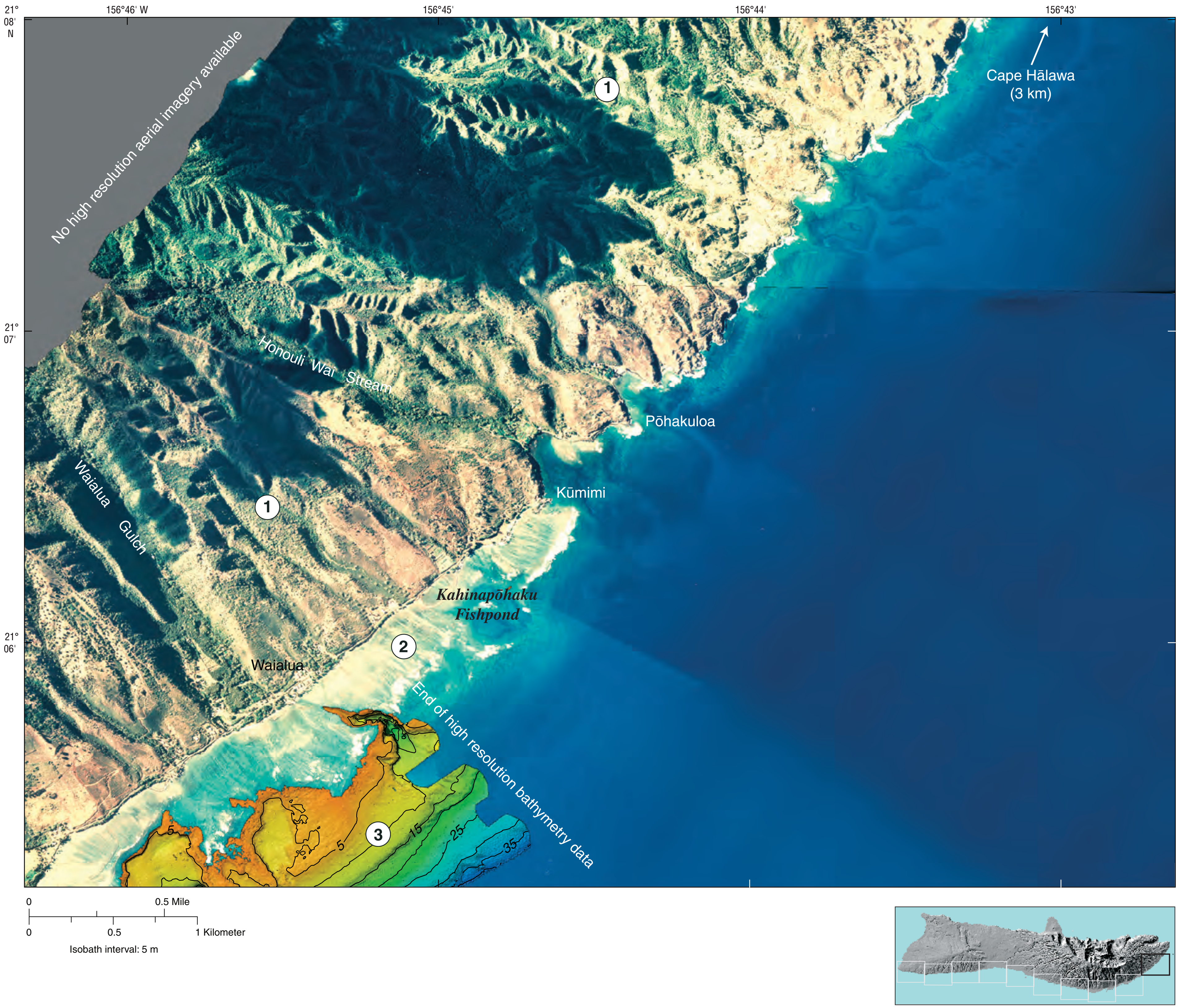




Pūko‘o Harbor

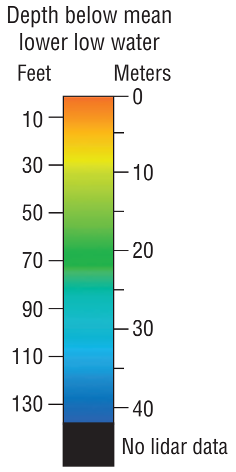
The western shoreline of the Pūko‘o Harbor image displays good examples of remnant fishponds on the inner reef flat; the stone walls have been knocked down, but the submerged boulders outlining the ponds are still evident in the aerial images (1). Pūko‘o Harbor itself (2) is the remains of a fishpond that has been altered by dredging and emplacement of fill material. The original rectangular shape of the fishpond was altered in the early 1970s in an attempt to develop a marina. However, after completion of the dredging and accompanying reshaping of the coast in this area, the project was abandoned. The existing fishpond (3) on the reef flat and its upslope gulch are aligned with a channel through the reef (4), another example of freshwater dissolution and erosion of older reef limestone, as is the channel at (5). The fore reef along this part of the island is smooth (6) and lacks the distinctive spur-and-groove pattern that characterizes the reef west of Kamalō (as seen, for example, on the fore reef on the Kaunakakai image).





Kūmimi Point

This map includes the east end of the south Moloka‘i fringing reef. The island slope is carved by numerous gullies (1), but there is little net accretion of sediment in the form of deltas or coastal-plain deposits along the shoreline. This reflects both the soil stability provided by lush vegetation as well as high-energy conditions along the shoreline that quickly move any sediment transported to the coast by stream runoff. The reef flat, nearly 2 km wide in the center of the island (see the image of Pālā‘au), is barely 0.5 km wide on this image (2) and disappears altogether at Kūmimi (also known as 20-Mile Beach). This section of the coast is subject to repeated high wave energy (Storlazzi and others, 2005), which inhibits growth of the common reef-building coral species. The surface of the fore reef here (3) is colonized by scattered coral colonies, dominantly *Pocillopora meandrina* (rose coral), which is commonly found in high wave settings in Hawai‘i. Active reef accretion is not occurring here; the fore reef in this area is simply the remnant of a former reef-building period.



View from Kawela ridgetop across the Kalohi Channel.

CHAPTER 3

Shape of the South Moloka‘i Fringing Reef: Trends and Variation

Curt D. Storlazzi[1], Joshua B. Logan[1], and Michael E. Field[1]

Ever since sailors started mapping the approaches to natural harbors at low latitudes, the complex morphology of coral reefs has been evident. Whereas the shallowest portions of the reef was the most important feature for sailors to map because of its obvious hazard to navigation, it was clear on fringing reefs that the majority of the reef lay seaward, extending into water depths of more than 40 m (132 ft). Although most sandy coasts are relatively straight and gently sloping, carbonate reefs display a wide variety of shapes, including extremely sharp boundaries and nearly vertical faces. The goal of this chapter is to document the morphology of the reef off south Moloka‘i, Hawaii, and from this infer what processes may have led to its present form.

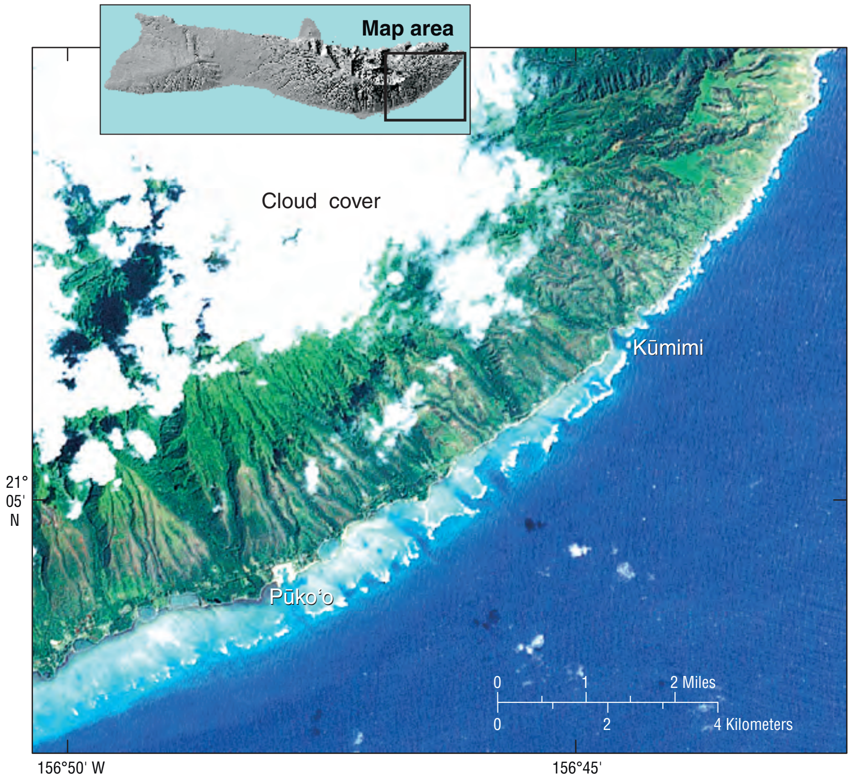


Figure 1. LANDSAT visual satellite image of the east end of the south Moloka‘i reef, showing the tapering of the reef to a narrow band at Kūmimi.

General Reef Morphology

The fringing coral reef lying off the south shore of Moloka‘i extends more than 40 km (24 mi) alongshore. The reef pinches out westward roughly 7 km (4 mi) from the west end of the island and eastward about 20 km (12 mi) from the east end of the island (fig. 1). From the shoreline out to deeper water, the reef can be generalized into three main zones: the reef flat, the reef crest, and the fore reef.

The reef flat is a low-relief, roughly horizontal surface with relatively sparse coral cover (see Cochran, this vol., chap. 9, for all benthic habitat types and coverage percentages) that extends from the shoreline to the reef crest (fig. 2). The reef flat is on average approximately 1 km (0.6 mi) wide and reaches a maximum width of more than 1.5 km (0.9 mi) offshore from the saddle between the two basaltic shield volcanoes that make up the island. The relatively flat inner half of the reef flat transitions into alternating shore-perpendicular low ridges of coral and sand-filled troughs on the outer half of the reef flat. The ridges are on the order of 0.1–1.0 m (0.3–3.3 ft) high and are covered by a variable percentage of live coral, with greater percentages of live coral farther offshore. The intervening depressed channels are mostly filled with sand and some coral gravel; these features have been termed “ridge-and-runnel” structures by Blanchon and Jones (1997).

The water over the reef flat is generally shallow, typically less than 2 m (7 ft) deep. In certain locations, however, there are “blue holes” on the reef flat that have nearly vertical walls and extend to depths of 25 m (83 ft) or greater (fig. 3). Many elongated, shore-normal blue holes correlate to onshore drainages (fig. 4) and are probably related to discharge from the adjacent streams or to submarine ground-water discharge through the reef (see Grossman and others, this vol., chap. 13). Blue holes may have been formed by stream incision or by freshwater-induced dissolution during periods of lower sea level and have subsequently partially filled in by new growth during the recent sea-level highstand. It is not clear, however, which process or processes are responsible for the shapes we see today.

The reef crest, where most deep-water waves break, is well defined along most of the reef off southern Moloka‘i. Lying at a water depth of 1–2 m (3–7 ft), it is characterized by irregular morphology, scattered corals, rubble deposits, and numerous patches of sand. The reef crest is dominated by encrusting coralline algae and robust lobate and encrusting corals.

Offshore of the reef crest, from depths of 5 to 30 m (17–99 ft), lies the fore reef, the zone of highest coral cover. It is generally characterized by

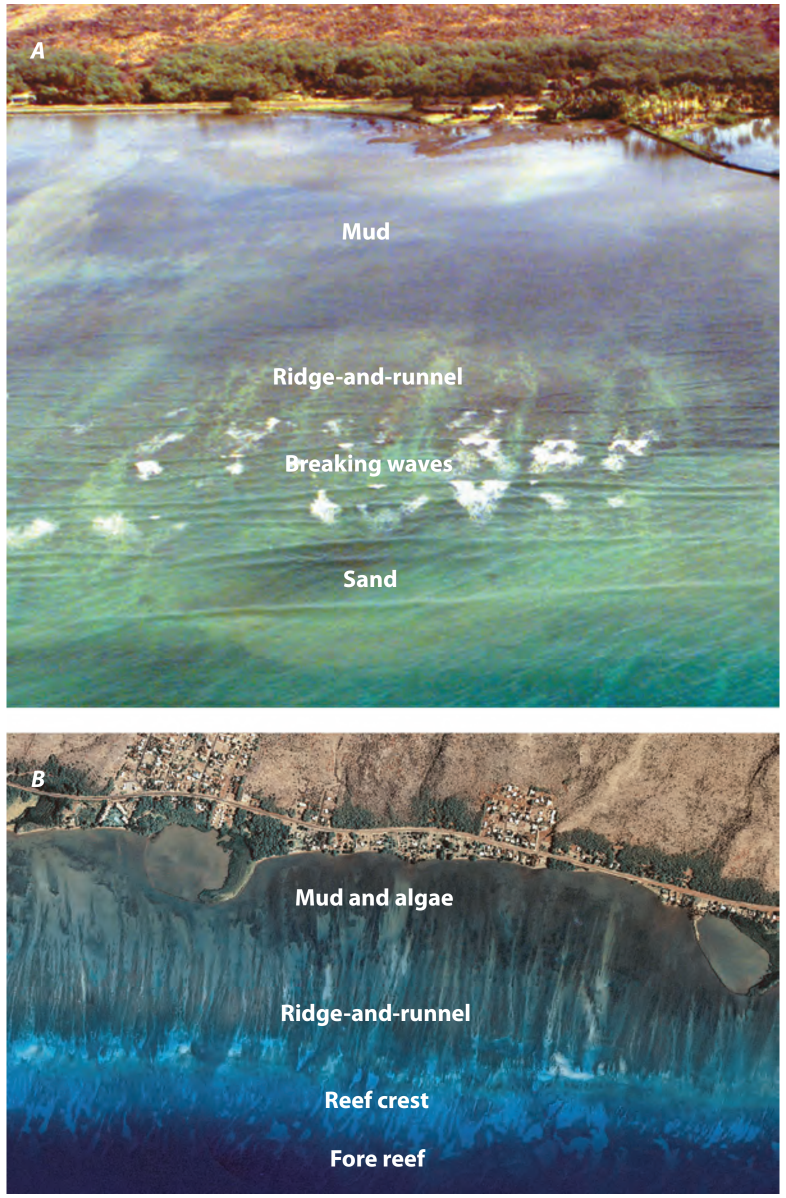


Figure 2. Aerial photographs of the inner reef flat (characterized by mud) and the outer reef flat (characterized by ridge-and-runnel topography) off south-central Moloka‘i. Note the houses for scale in both images. *A*, Oblique photograph of the reef flat just east of One Ali‘i Park. *B*, Vertical aerial photograph of the reef flat off Kamiloloa.

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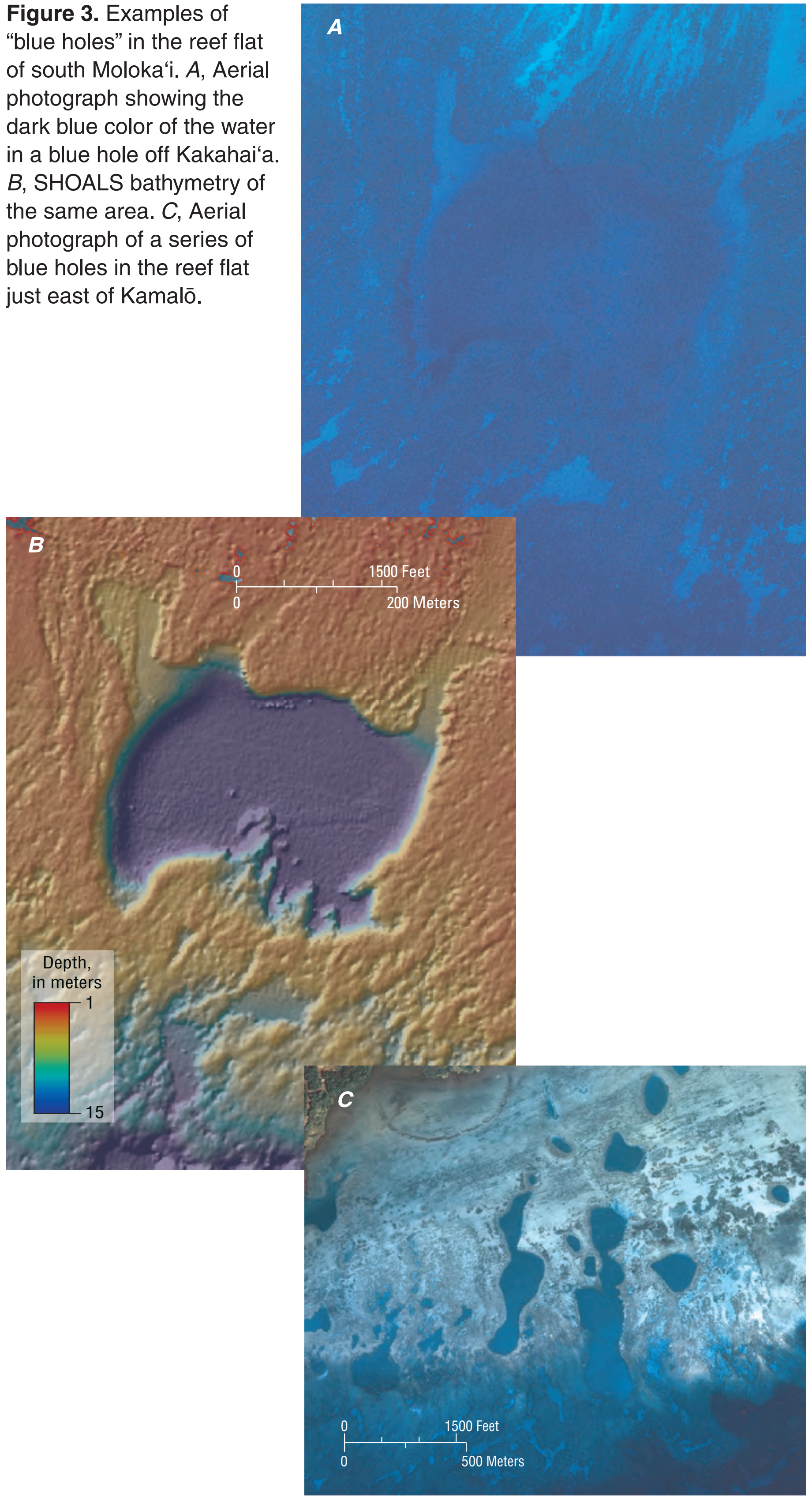


Figure 3. Examples of “blue holes” in the reef flat of south Moloka‘i. *A*, Aerial photograph showing the dark blue color of the water in a blue hole off Kakahai‘a. *B*, SHOALS bathymetry of the same area. *C*, Aerial photograph of a series of blue holes in the reef flat just east of Kamalō.

shore-perpendicular ridges of coral (coral “spurs”) that are separated by shore-perpendicular patches of sand (sand “grooves”). These features are common along wave-exposed reefs and have been termed “spur-and-groove” (SAG) structures (fig. 5). Coral cover on the fore reef is typically between 70 and 90 percent (see Jokiel and others, this vol., chap. 5, for descriptions of all corals). The reef typically ends at a depth of about 27 m (89 ft), with hard corals giving way to sand flats dominated by patches of calcareous *Halimeda* algae, similar to what was observed by Dollar (1982) on other reefs in Hawai‘i.

Large-Scale Morphology (1–10 km)

In order to understand the large-scale shape of the reef, 36 shore-perpendicular depth transects were made extending from the shoreline out to the base of the present reef. The transects were spaced at roughly 1.5-km intervals and were constructed from SHOALS bathymetric data (see Logan and others, this vol., chap. 2, for a further discussion of SHOALS). The locations of the profiles and selected depth profiles of the reef along these transects are shown in figure 6. For reference, the projected slope of the land surface beneath the reef is extended through the reef profiles to provide some insight to the likely cross-sectional area of the reef complex. No shallow reef flat is present at the ends of the island, as shown in profiles 2 and 36; field observations show a very thin veneer of live coral overlying volcanic substrate. Along the central portion of the fringing reef between Pālā‘au and Kamalō (profiles 13 through 27), a well-defined reef flat extends more than 1,200 m (3,960 ft) offshore. The reef along this stretch of coast has a steeper slope from just above 20 m (66 ft) to the 30 m (99 ft) isobath, which corresponds to the toe of the present-day living reef observed during scuba transects, similar to that observed by Dollar (1982). Intermediate between these areas of no clearly defined reef crest and well-defined reef flat are transitional regions, as shown by profiles 6 and 33. These transitional sections display a reef flat on average 500 m (1,650 ft) wide and a less steeply sloping fore reef that lacks the abrupt increase in slope between the 20 m and 30 m isobaths seen in profiles 13 through 27.

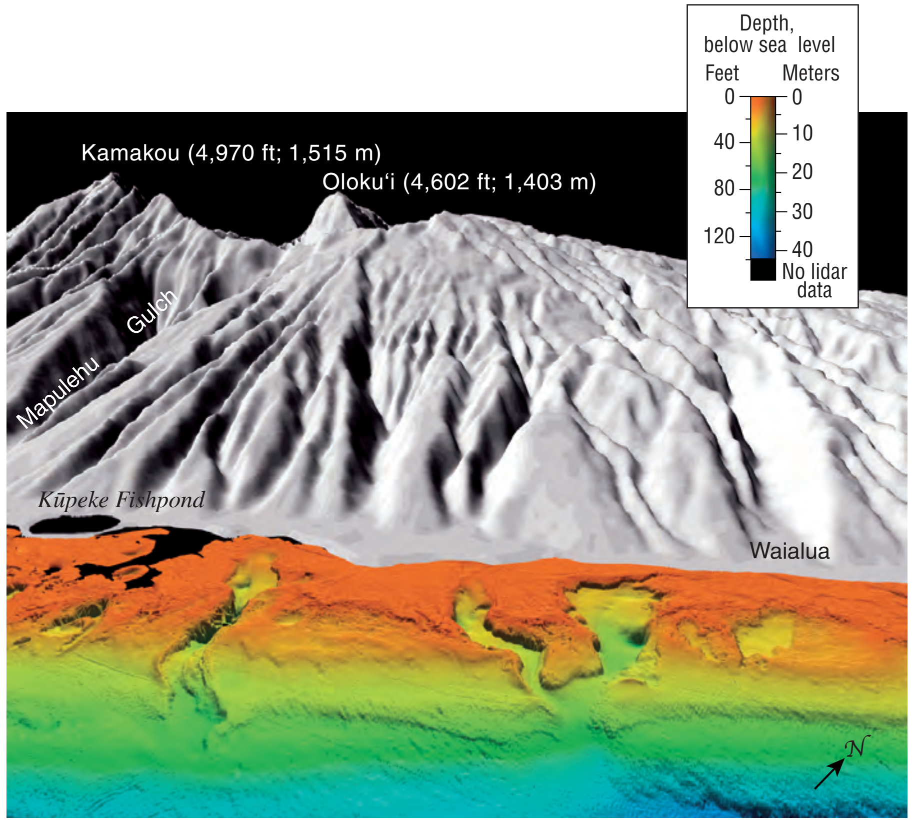
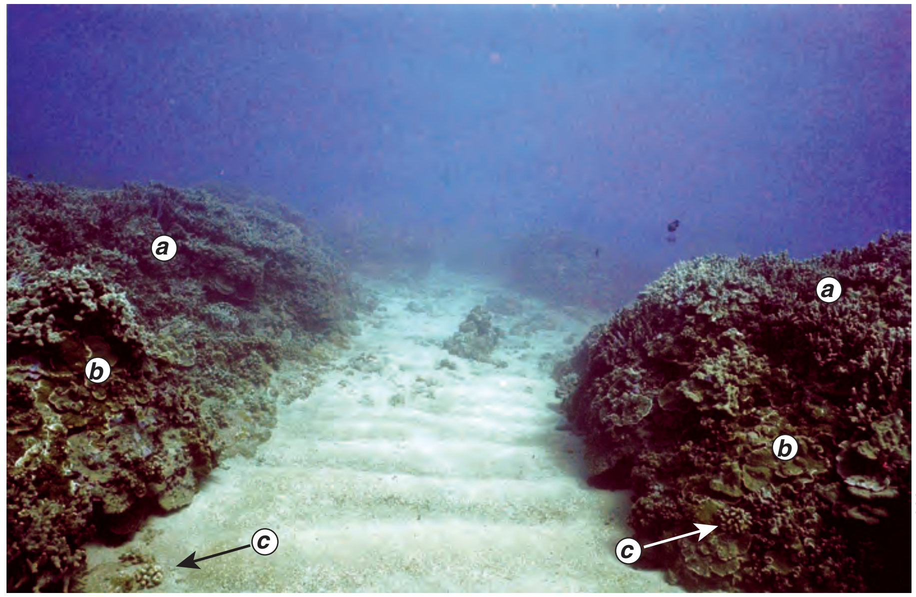


Figure 4. Perspective image of the land (grey scale) and reef (color-coded bathymetry) near Waialua, showing the correlation between terrestrial stream drainages and paleostream channels incised in the fringing reef off south Moloka‘i. Depths from SHOALS data. Approximate distance across the bottom of the image is 2.8 km (1.75 mi).

Figure 5. Underwater photograph of a spur-and-groove (SAG) structure off ‘Umipa‘a. The height between the sand-floored groove and the top of the coral spurs in the photograph is about 1.5 m (4.9 ft); the width of the groove is about 2 m (6.6 ft). Three of the main reef-building corals can be identified in the photograph: (*a*) *Porites compressa* (vertical fingers); (*b*) *Montipora capitata* (horizontal plates); and (*c*) *Pocillopora meandrina* (cauliflower). Wave-generated symmetrical ripples cover the sand bed. View is seaward.



Tom Reiss, USGS

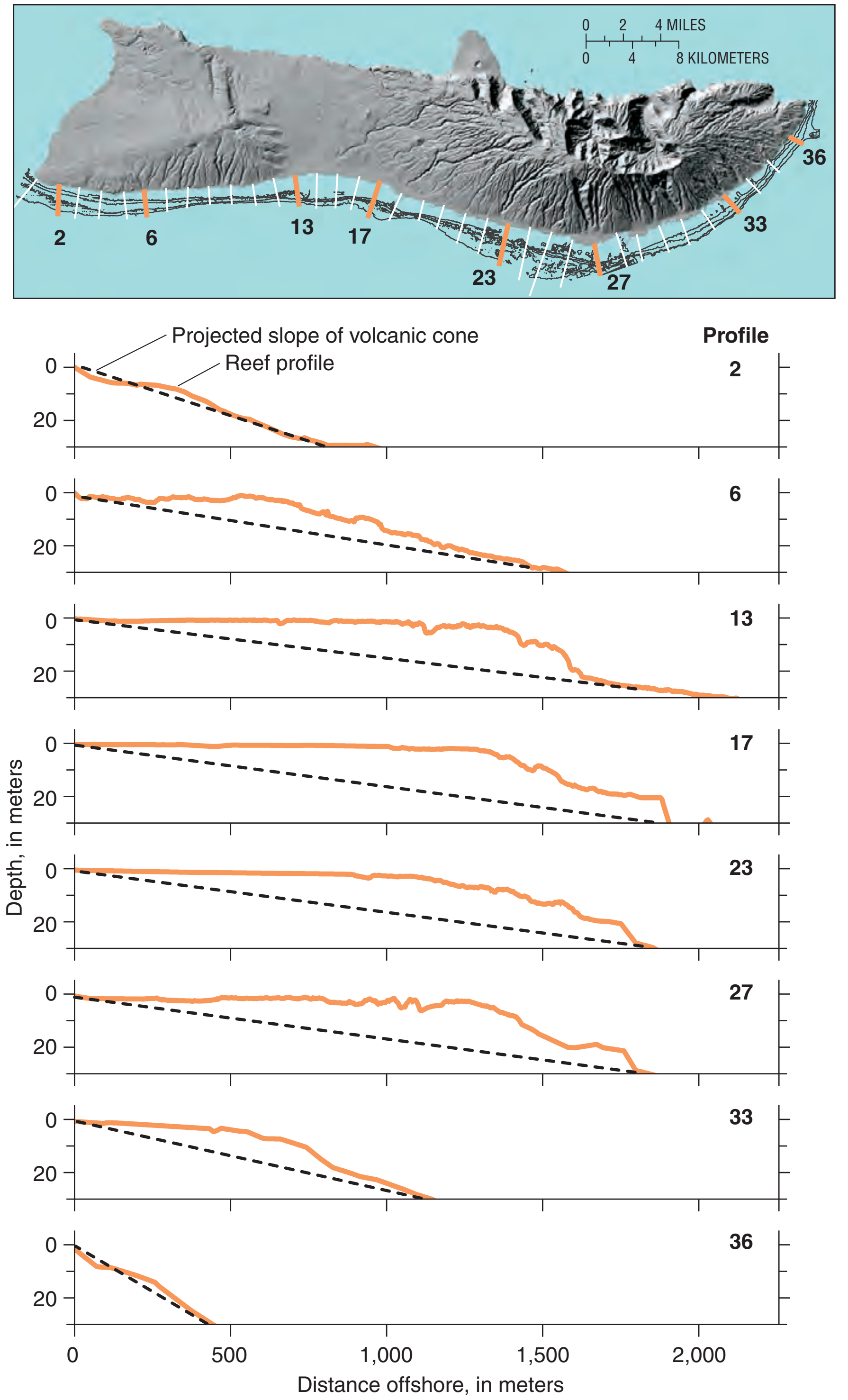


Figure 6. Depth profiles of the reef off south Molokaʻi, showing the variation in development of the reef complex alongshore. The dashed lines are projections of the slope of the volcanic cone through the reef profiles to provide some insight to the likely cross-sectional area of the reef complex. Note that the reef is almost nonexistent at the ends of the island (profiles 2 and 36) and extends more than 1,500 m (4,950 ft) offshore of the central portion of the island (profiles 13 though 27).

Small-Scale Morphology (10–100 m)

As part of an experiment to better understand small-scale reef morphology, almost 4,800 spur-and-groove (SAG) structures were mapped from the SHOALS bathymetric data along the 5-m (17 ft), 10-m (33 ft), 15-m (50 ft) and 20-m (66 ft) isobaths, with roughly 1,000 SAG structures measured per isobath. See Storlazzi and others (2003) for more information on how the calculations were made. Along the 5-m isobath (fig. 7), mean SAG heights were typically less than 1 m, with the lowest heights occurring off the middle of the island. Spurs at the 5-m isobath typically have much lower total coral cover than those along deeper portions of the reef. At this depth, the coral species that are most commonly observed are *Pocillopora meandrina* and the more robust *Porites lobata*. The alongshore trend at the 10-m isobath shows the lowest mean SAG heights at the east end of the island and a general increase in height from east to west. The trends in mean SAG height along the 15-m and 20-m isobaths displayed the greatest heights (>3 m) at the middle of the island. The spurs observed between the 10-m and 20-m isobaths typically have much higher percentages of live coral than those at 5 m. The deeper spurs tend to have slightly lower coral coverage at both the east and west ends of the island, where exposure to large waves is greater and they are covered by more robust species of coral (*P. lobata* and *P. meandrina*), than along the sheltered central portion of the reef where *Porites compressa* is dominant at similar depths.

Two trends were observed in the calculated mean values of SAG width. Mean width along both the 5-m and 10-m isobaths increases towards the east end of the island, with the widths being slightly greater on average along the 10-m isobath than along the 5-m isobath (fig. 8). Mean SAG widths along the 15-m and 20-m isobaths exhibit a different trend from that observed along the two shallower isobaths, with the largest width values generally at the center of the island.

On average, the shallowest (0.7 m) and least variable mean SAG heights are along the 5-m isobath, whereas the largest (1.6 m) and most variable mean heights are along the 15-m isobath (fig. 8*A*). Similarly, the widest (104 m) and most variable mean SAG widths are observed along the 15-m isobath, whereas the 5-m isobath displays on average both the narrowest (71 m) and least variable widths (fig. 8*B*). The variation in the ratio of spur height to width with depth displays a pattern similar to spur height and width, increasing from the 5-m isobath to the 15-m isobath, then decreasing slightly from there to the 20-m isobath (fig. 8*C*). This trend suggests that spurs tend to become more peaked (greater height to width ratio) with increasing water depth. Overall, field observations showed that the grooves tend to be wider relative to the spur width in shallow water depths (especially in more exposed areas) than in deeper water, where the grooves tend to be narrower.

Numerous short, narrow SAG structures occur at shallow water depths (fig. 9), whereas in mid water depths fewer, wider, and taller spurs dominate, followed by a reversal back to more numerous, short and narrow spurs lower on the fore reef along the 20-m isobath. The numerous short, narrow SAG structures either truncate or merge together to form the fewer, taller SAG structures along the 15-m isobath. The tall, broad SAG structures deeper on the fore reef typically terminate and are replaced by numerous, low mounds or new spurs, often separated by areas of fine sand from the shallower, continuous SAG structures. This variation in SAG morphology causes a change in slope, with a relatively low slope between the 5-m and 15-m isobaths giving way to a steeper slope between the 15-m and 20-m isobaths, forming a morphology similar to the shelf-edge “buttresses” observed by Blanchon and Jones (1997) on the Caribbean Island of Grand Cayman.

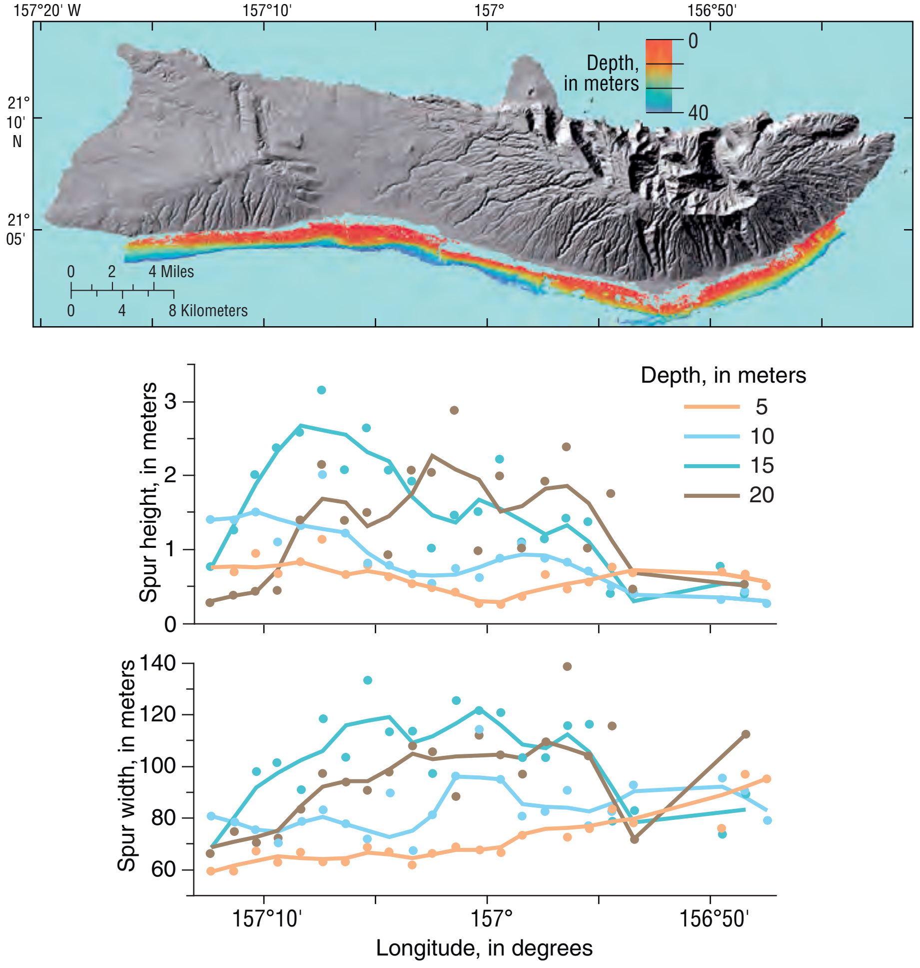


Figure 7. Plots showing the variation in spur-and-groove (SAG) morphology along the reef off south Molokaʻi. Each of the data points represents the mean spur height or width calculated over a 500-m (1,650 ft) segment of the line. Note that along the 5-m (16 ft) isobath mean spur height is higher near the ends of the island, while at greater depths (15–20 m, 50–66 ft) the heights are greater near the middle of the island. Along the 5-m isobath, and to a lesser extent along the 10-m (33 ft) isobath, mean spur width increases to the east end of the island. At greater water depths (15–20 m), spur width tends to be greatest near the middle of the island. The curves are running averages to display how spur height and width tend to vary alongshore.

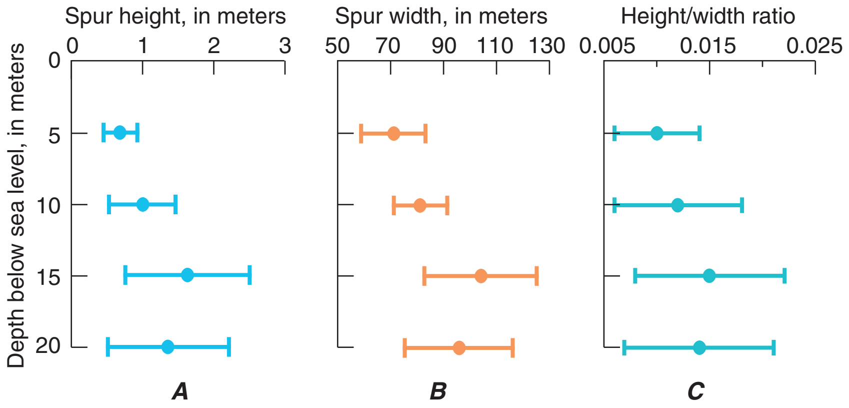


Figure 8. Variation in mean spur-and-groove (SAG) morphology with water depth. *A*, Mean ±1 standard deviation of spur height. *B*, Mean ±1 standard deviation of spur width. *C*, Mean ±1 standard deviation of the ratio of mean spur height to mean spur width. Note how all three parameters' means and their variability are smallest at the 5-m isobath, largest at the 15-m isobath, and then slightly less at the 20-m isobath than at the 15-m isobath. These variations are likely a tradeoff between light available for photosynthesis and wave energy.

Implications Of Observations To Understanding Recent Reef Development

The shape of the reef is a direct result of coral growth rates and patterns, and thus the shape of the reef conveys important information about the external factors that affect reef development. The primary physical constraints on rocky corals along a single exposed reef are food, light availability (Stoddart, 1969; Dustan, 1979), and the forces imposed by ocean waves. Light has been shown to decrease rapidly (logarithmically) with increasing water depth. Light is critical to coral growth because the symbiotic algae (zooxanthellae) housed in the corals require light for photosynthesis. Water motion induced by surface waves dominate the near-bed flow field on the inner portion (<35 m depth) of the south Moloka‘i shelf, where significant reef has developed. Wave-induced motions, and therefore wave-induced forces on corals and the sea floor, decrease rapidly (exponentially) with increasing depth. These wave-induced motions can, when very high, physically break corals, and at slightly lower levels they may inhibit settlement by juvenile coral polyps.

The width of the reef and the relative heights and widths of SAG structures provide an indication of where reef development may be greatest through the combination of high light availability for photosynthesis but relatively low wave-induced forces for the species that compose the reef community off south Moloka‘i. Maximum calculated mean spur height and width, and thus of SAG development, were measured along the 15-m isobath. In shallower depths (5–10 m), the high light availability appears to be offset by the high wave-induced forces, keeping SAG structures small, whereas along the 20-m isobath and deeper, decreased light availability inhibits high relative growth despite the low wave-induced forces (Dollar, 1982).

The reef flat is widest along the central portion of the south Moloka‘i shore and narrowest at the east and west ends of the island, even though light penetration at these shallow depths is relatively uniform. This further suggests that wave-induced forces, which vary spatially (see Storlazzi and others, this vol., chap. 11), might be a primary control on large-scale reef morphology along south Moloka‘i.

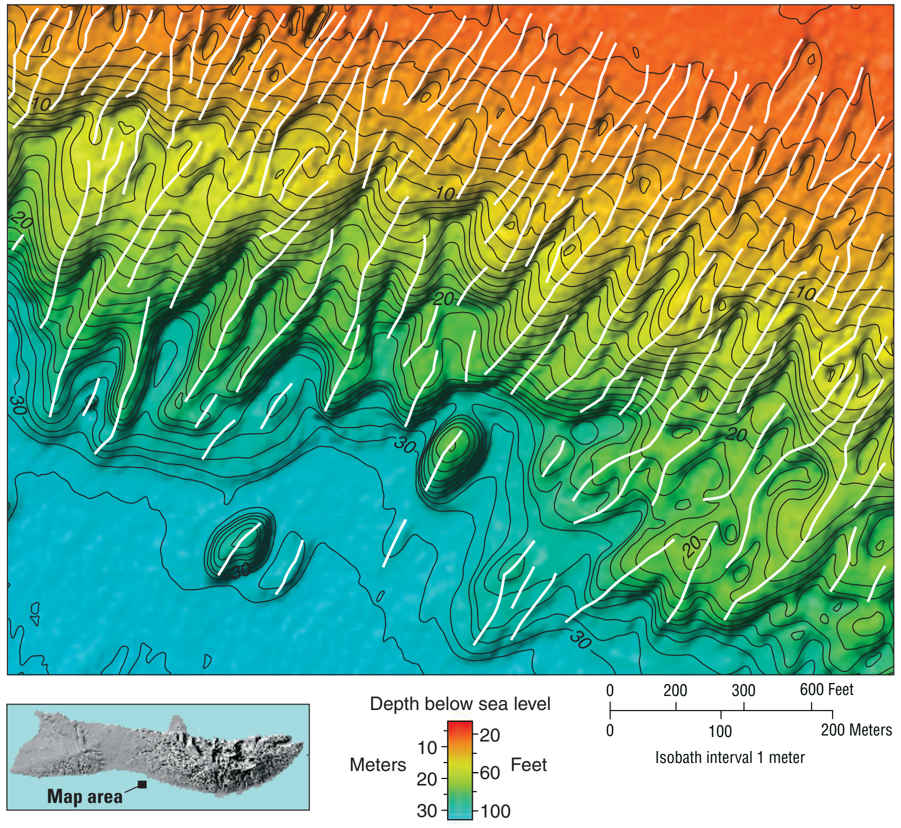


Figure 9. Color-coded image of the SHOALS bathymetry offshore of Kaunakakai overlaid with 1-m (3 ft) contours to highlight spur-and-groove (SAG) morphology. The white lines denote interpreted spur traces. Note that most of the short, narrow spurs at shallow water depths merge to form taller, broader spurs around the 15-m (50 ft) isobath. Most of the spurs at the 15-m isobath bifurcate with depth or simply truncate and are replaced by smaller, more closely spaced SAG structures. Some of the structures around the 30-m (99 ft) isobath are coral-covered mounds isolated by sand from the SAG structures at shallower depths. Also note the transition from the broad reef flat at the top of the image at a depth of 2–3 m (7–10 ft) to the steeper sloping fore reef between 10 m (33 ft) and 30 m (99 ft), below which is the more gently sloping insular shelf.

CHAPTER 4

Moloka‘i—Two Different Types of Reef Growth in the Past 8,000 Years

Mary S. Engels[1] and Charles H. Fletcher[2]

Reef growth in the main Hawaiian Islands during the current warm period (known as the “Holocene Epoch,” the past 10,000 years of Earth history) has been described in detail by only a few scientists, mostly conducting studies on the island of O‘ahu. These studies provide information that has been used to formulate a model of reef growth around the island of O‘ahu (Grossman and Fletcher, 2004, Fletcher and others, 2001). The model proposes three major components of the O‘ahu reef system, including (1) fossil reefs dating from the Pleistocene, a geologic epoch covering the period 1.8 million to 10,000 years ago, (2) reefs formed during the Holocene, and (3) a thin veneer of modern coral and coralline algae capping older reef structures or growing directly on volcanic rock.

According to the model developed for O‘ahu, Holocene reef growth was restricted to the narrow zone between the intersection of the sea floor with the wave base (the deep limit of water motion caused by waves) and the outer edge of the Pleistocene reef shelf ringing the island. Heavy wave action tends to limit reef development because of high shear stress on the sea floor, direct concussion, and sediment abrasion. At places around O‘ahu where reef growth has not been limited by waves (for instance, deeper portions of the reef in Kailua Bay and in protected Hanauma Bay), a sea-level rise of 1 to 2 m between about 4,000 and 2,000 years ago provided new environments for reef growth and sediment production (Fletcher and Jones, 1996; Grossman and Fletcher, 1998). Fletcher and others (2001) suggested that when sea level fell to its present position over the past few thousand years, reef development in shallow waters diminished and the centers of reef growth shifted from reef flat, reef crest, and upper fore reef to the lower fore reef and deeper waters seaward of the shallow island shelf. Their model assumes that the majority of Holocene growth on O‘ahu is limited to protected areas of low wave energy or to depths below wave base but still within the zone of sufficient sunlight to permit coral growth. One example of such a location is where ancestral stream channels cut through a fringing reef during periods of lower sea level.

The locations and histories of Holocene-age reefs around the other Hawaiian Islands are largely unknown, although the reports of Rooney and others (2004) and Engels and others (2004) shed light on reef growth on Moloka‘i and Kaua‘i. Rooney and others (2004) used cores of Holocene reef from Kaua‘i, O‘ahu, and Moloka‘i in support of a hypothesis that reef accretion during middle and late Holocene time was suppressed, and in places ended, by the onset of heavy North Pacific swell resulting from amplification of El Niño events about 5,000 years ago. Engels and others (2004) provided a model of reef accretion on the south shore of Moloka‘i that compared reef in the area of Hale O Lono wharf to reef at Wai a Kāne Gulch. That study is important for comparison to the O‘ahu system and thereby improves the overall understanding of how reefs developed in Hawai‘i during the Holocene.

Site Overview

The two reef sites chosen for this study are located at Hale O Lono wharf and Wai a Kāne Gulch, both on the southwest shore of Moloka‘i (fig. 1). These sites were selected for their close proximity but contrasting physical characteristics. At Hale O Lono, 5 km east of Lā‘au Point, sparse fields of live coral (mostly *Pocillopora meandrina*, *Porites lobata*, and species of the genus *Montipora*) grow on a much older (early Holocene) fossil limestone reef. The site does not have a typical reef structure (see Cochran, this vol., chap. 9). Rather, the sea floor is a fossil reef slope, interspersed with sand fields, that dips gradually away from shore. The amount of fine-grained terrestrial sediment in the water at Hale O Lono is typically small because of the arid nature of the adjacent uplands. But large amounts of runoff associated with episodic (seasonal) rainfall events may cause temporary turbidity lasting several days. Additionally, resuspension of carbonate sand can be significant during large swell events (see Bothner and others, this vol., chap. 19).

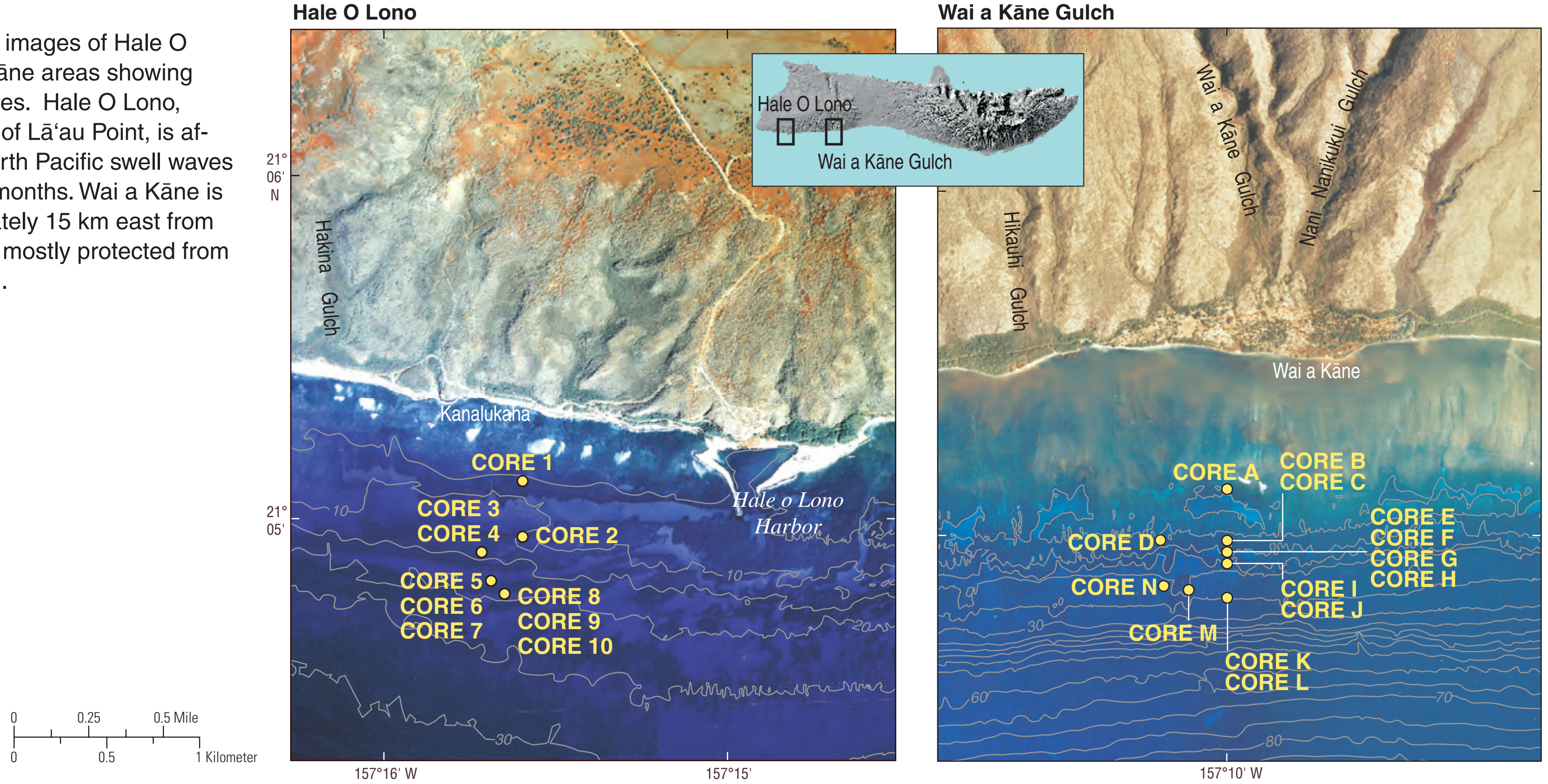


Figure 1. Satellite images of Hale O Lono and Wai a Kāne areas showing location of drill cores. Hale O Lono, located 5 km east of Lā‘au Point, is affected by large North Pacific swell waves during the winter months. Wai a Kāne is located approximately 15 km east from Lā‘au Point and is mostly protected from North Pacific swell.

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By contrast, Wai a Kāne, 10 km to the east of Hale O Lono, has a typical fringing reef structure with a reef flat, reef crest, and fore reef. The reef flat is buried under 2 cm to more than 1 m of fine terrestrial mud that comes from upland runoff (see Field and others, this vol., chap. 17). Live coral cover is low near the reef crest, perhaps suppressed by the high sediment content of runoff. Coral cover increases with depth across the fore reef, which is dominated by spur and groove features (see Field and others, this vol., chap. 2, and Storlazzi and others, this vol., chap. 3). The dominant sediment on the fore reef is carbonate sand.

Because of their close proximity (approximately 10 km), these sites experience a similar wave climate, with one notable exception—the reef at Wai a Kāne is protected from damaging North Pacific swell. During the summer, both sites are affected by Southern Ocean swell, Kona storm waves, and trade wind waves (see Storlazzi and others, this vol., chap. 11). During the winter months, trade wind waves diminish and North Pacific swell refracts around Lā‘au Point, affecting Hale O Lono more than Wai a Kāne. The Hale O Lono site also commonly experiences strong tidal currents, being adjacent to the Kaiwi Channel that separates O‘ahu and Moloka‘i.

Methodology

For this study we surveyed the modern reef environment of western Moloka‘i to develop an understanding of the community of corals and coralline algae under varying water depths and wave stresses. We use this understanding to interpret fossilized communities in drill-core samples at the two sites and reconstruct past wave stresses and water depths earlier in the Holocene. Details of the study are available in Engels and others (2004). The results of our survey are specific to the reef system on the western portion of the Moloka‘i south shore. Our survey summary relates dominant members of the coral community, their growth forms and percentage cover, and percent coralline algae cover to water depth and wave stress (the force on the reef system due to wave action; see Storlazzi and others, this vol., chap. 11). By comparing fossil coral samples in drill cores to the present-day coral and algae distribution, we were able to determine coral communities, growth forms, and percentage coral cover of the fringing reef during past periods of the Holocene Epoch. These relations provide a method for inferring probable past water-depth and wave-stress environments that governed past reef development. From this we determined a likely geologic history for the reef at the two sites.

We surveyed the reef surface at each site using a technique called the line intercept technique. This technique consisted of placing a 10-m line on the reef surface and recording every change in the composition and character of the sea floor under the tape (fig. 2). Twenty-seven transects at Hale O Lono and 19 transects from Wai a Kāne were collected in a range of depths. More than 50 different kinds of information were collected, including depth, bottom type, coral types, algal types, growth morphologies, invertebrates, and others.

Figure 2. Information on the modern coral community structure is collected using a line intercept technique. In this technique a 10-m line is placed along the bottom, as shown in this image, and every change in bottom type is recorded along the length of the transect. The length of line viewed in this image is approximately 2.5 m.

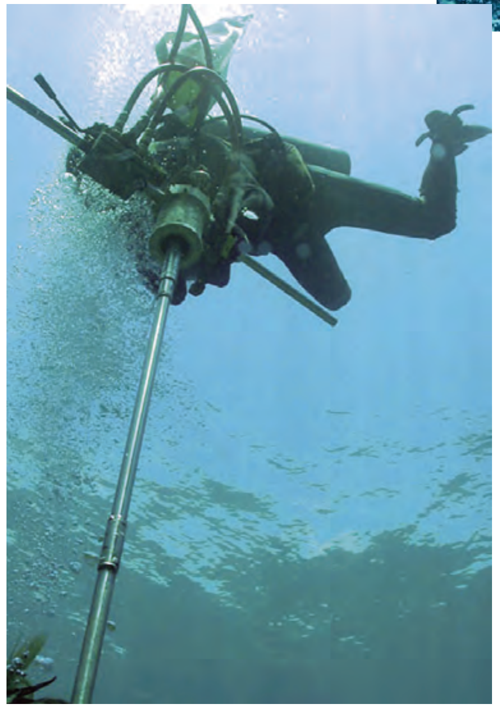


Figure 3. Divers working to reinsert the hydraulic drilling apparatus into a bore hole on the reef surface. For every section of core drilled, the full bit must be removed and then replaced with a new extension rod attached to an empty core barrel.

In order to collect reef cores, we employed a diver-operated hydraulic drill system (fig. 3). We collected 10 cores from Hale O Lono and 14 cores from Wai a Kāne. The cores averaged 2–5 m in length. All cores were split for archiving, then subsampled for ^{14}C radiometric dating (a method of determining age in years by measuring the concentration of the radioactive isotope carbon-14), X-ray diffraction analysis (a method of determining mineralogy and factors that might influence the measurement of sample age), and thin-section analysis (a rock preparation in which a sample is ground to ~0.03-mm thickness and mounted on a microscope slide to determine its structure and cementation history).

Results and Discussion

Results from the reef surface surveys were combined with modeled wave-induced near-bed shear stresses (see Storlazzi and others, this vol., chap. 11) to understand the relations to the modern, depth-related coral/algal assemblage (fig. 4). In general, coral cover increases with depth and with decreasing near-bed shear stress, while coralline algae cover increases with increasing near-bed shear stress. By comparing core samples (figs. 5, 6) to the modern coral/algal community, we were able to assess differences in reef accretion at Hale O Lono and Wai a Kāne.

The reef at Hale O Lono is early to middle Holocene in age, ranging from at least ~8,100 years old to ~4,800 years old, whereas the reef at Wai a Kāne is less than 1,000 years old. During early Holocene time, reef growth at Hale O Lono appears to have occurred in discrete events, with the centers of growth shifting landward under rising sea level. The rising sea level was responsible for opening new habitat for colonization, but it appears to have risen at variable rates throughout early to middle Holocene time. Indeed, there is a major change in the type of coral seen in some of the cores at Hale O Lono at an age between ~8,100 and ~7,900 years. One hypothesis explaining this change is that a rapid acceleration of sea-level rise led to sudden deepening of the sea floor, forcing the coral/algal community to shift from a shallow-water type to a deep-water type.

By about 4,800 years ago the reef stopped growing altogether at Hale O Lono, leaving the present fossil sea floor. Although there are live coral

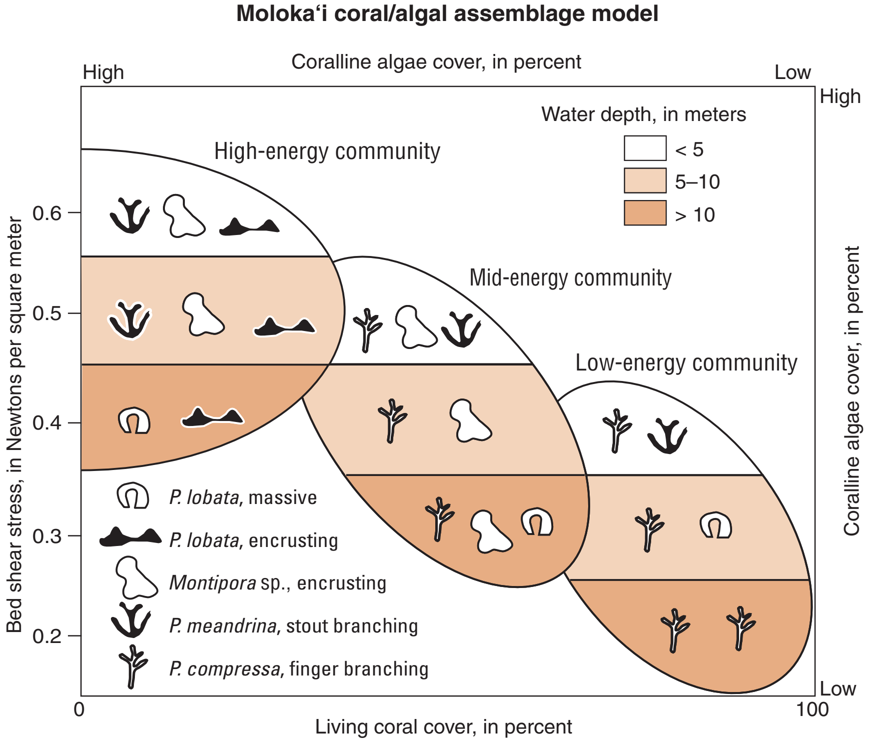


Figure 4. Model of the modern coral/algal assemblages on the south Moloka‘i reef. This model (from Engels and others, 2004) relates wave-induced near-bed shear stress with percent living coral cover, dominant coral species, and coral morphologies. How these elements interact allow us to predict where different types of bottom cover (such as coral, coralline algae, sand, and rock) might be found on the reef.

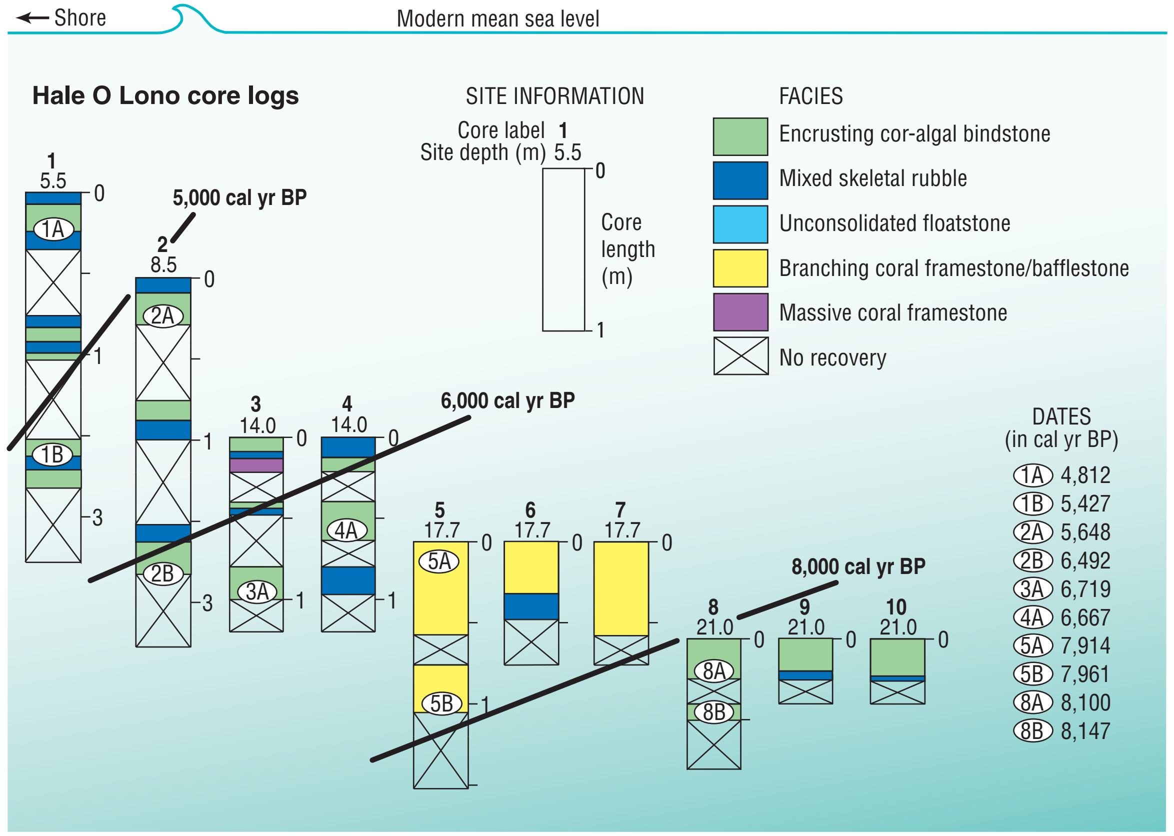


Figure 5. Drill core logs and radiometric dates from Hale O Lono. Limestones were classified according to the Embry and Klovan (1971) modification of the Dunham (1962) scheme. The age of the reef at the sea floor increases with distance offshore. No modern ages are associated with this site, suggesting little or no reef growth over the past ~4,800 yr. Contours indicate regions of similar age and highlight the shoreward stepping nature of reef growth in this area. The dominant rock type associated with cores 5–7 is branching coral framestone, a type of rock composed of a coral framework filled with carbonate sediments and then solidified. According to the modern coral/algal assemblage model, branching corals grow in low-energy, deep-water (>10 m) settings. Thus, their fossilized remains indicate a similar environment at the time of coral deposition ~7,900 yr ago. All the remaining cores at this site have coral types that are more closely associated with high-energy, shallow-water depositional environments. This distinct change in depositional environments suggests a possible rapid increase in the rate of sea-level rise ~7,900 yr ago, followed by a slowing of sea-level rise and a return to high-energy, shallow-water depositional environments.

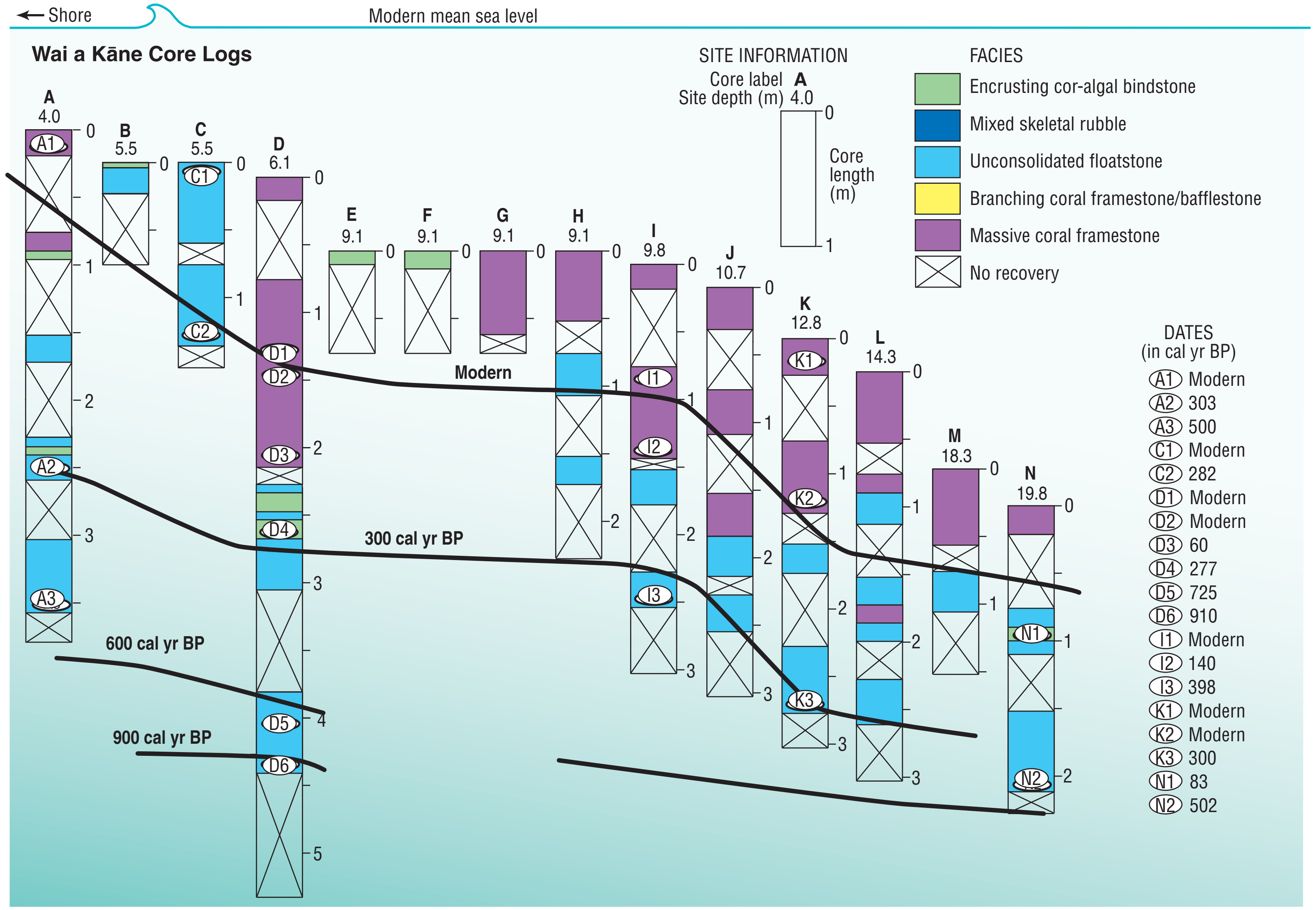


Figure 6. Drill core logs and radiometric ages from Wai a Kāne. Limestones were classified according to the Embry and Klovan (1971) modification of the Dunham (1962) scheme. This site is a young (< 1,000 yr) reef structure, extending seaward and upward from the deeper environment of the fore reef. Contours indicate regions of similar age and highlight the seaward stepping or prograding nature of this reef. The dominant rock type in these cores is unconsolidated floatstone (a type of rock in which chunks of coral rubble are surrounded by, or "float," in a sediment matrix). The unconsolidated floatstones represent accumulated reef debris that has not yet had time to solidify into a reefal limestone.

colonies growing on this old surface today, the reef as a whole does not appear to be experiencing net accretion. The fact that there has been little net reef growth since ~4,800 years ago is likely a result of a combination of two things, (1) lack of new habitat, related to falling sea level following the "Kapapa" sea-level highstand in the late mid-Holocene (Grossman and Fletcher, 1998), further compounded by island uplift due to lithospheric flexure (Watts and ten Brink, 1989) and (2) an increase in El Niño Southern Oscillation (ENSO) intensity and accompanying increase in extreme levels of North Pacific winter swell, as suggested by Rodbell and others (1999), Moy and others (2002) and Rooney and others (2004). Corals may survive the typical north swell occurring during Hawaiian winter, but immense waves, often arriving during particularly intense El Niño years, may clear the sea floor of all accumulated growth since the last huge event and reset the sea-floor clock back to its 4,800-year age.

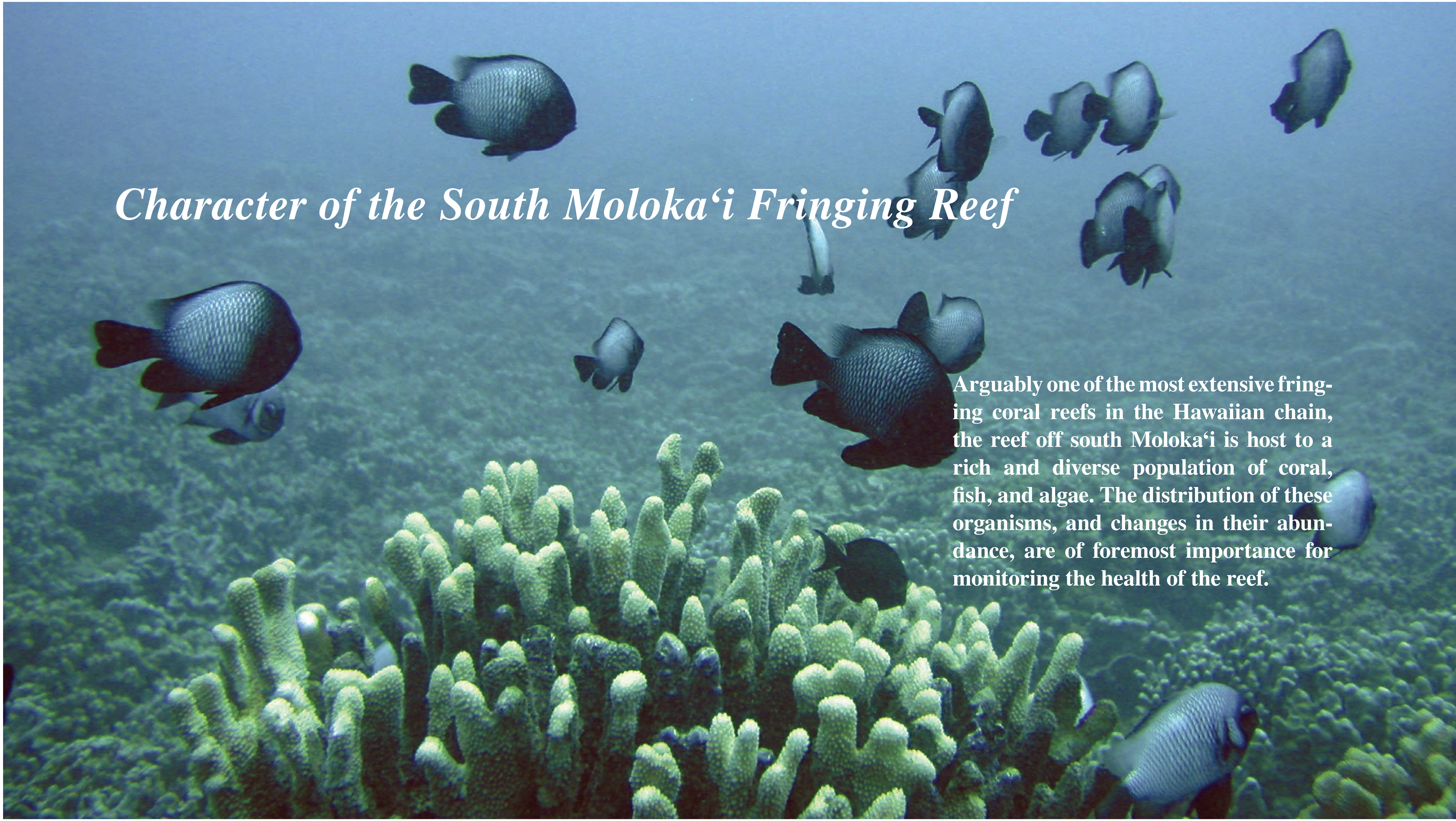
The young reef at Wai a Kāne, by contrast, has experienced significant accretion over the past 1,000 yr. The reef-flat area is limited by shallow water, sediment accumulation, and poor water quality related to the adjacent watershed. The reef crest is characterized by crusts of coralline algae and some encrusting coral growth. Seaward of the reef crest in less than 5-m water depth, reef development is limited by low accommodation space in the water column because of falling sea levels over the late Holocene and slow present rise of sea level. In deeper waters, greater than 5-m depth, thick stands of *Porites compressa* and other types of corals grow vertically. The reef is extending vertically and laterally (seaward) in this region because it is not limited by high wave energy and related shear stresses. Without rapidly rising sea level, the focus of reef growth has shifted to the deeper environments along the seaward margins of the reef, where there is room to grow outward and upward. At depths exceeding 15 to 20 m, reef growth is limited by substrate (sandy vs. hard bottom) suitable for colonization.

Age discrepancies between Hale O Lono and Wai a Kāne make direct comparison of growth histories impossible, but analysis of the sites together yields a picture of shrinking habitat suitable for reef accretion because of increased wave energy since the middle Holocene and lack of accommodation space because of falling or stable sea levels in the late Holocene. These combined conditions have caused the shift of net reef accretion from the area of the reef flat to the deeper waters of the lower fore-reef slope at Wai a Kāne, whereas at Hale O Lono high wave stress continues to suppress all reef growth. The Pleistocene foundation of older reef so prevalent on O‘ahu is not found on Moloka‘i, although additional drilling is necessary before this possibility can be confidently eliminated.

Consistent with the O‘ahu model, the major control on reef growth, at least on the western south shore of Moloka‘i, is wave-induced shear stresses from large interannual North Pacific winter swell, probably originating with amplification of the El Niño process in the middle Holocene. This factor would be accentuated and brought to greater influence by the falling sea level of the late Holocene and the relatively stable (slowly rising) sea level of the modern era. The setting of our studied reefs along a uniquely straight coastline provides the ability to examine the influence of high wave stress along a clearly definable gradient, where wave stress increases with proximity to Lā‘au Point. The fact that such different accretion histories were observed within a space of only 6 km proximity suggests how dynamic and amazing reef growth strategies can be within a relatively small area of generally similar environmental setting but differing wave influences.

Character of the South Moloka‘i Fringing Reef

Arguably one of the most extensive fringing coral reefs in the Hawaiian chain, the reef off south Moloka‘i is host to a rich and diverse population of coral, fish, and algae. The distribution of these organisms, and changes in their abundance, are of foremost importance for monitoring the health of the reef.


Fish and coral of the Moloka‘i reef.

Sunset from Moloka'i Shores condominium complex.

CHAPTER 5

Reef Corals and the Coral Reefs of South Moloka‘i

Paul L. Jokiel[1], Eric K. Brown[2], Ku‘ulei S. Rodgers[1], and William R. Smith[1]

Rich and diverse marine benthic habitats exist along much of the south Moloka‘i coral reef, as demonstrated by maps of the area (see Cochran, this vol., chap. 9 for a complete discussion of benthic habitats). Habitats that support corals generally contain a characteristic assemblage of coral species that can be referred to as a “coral community.” Composition of each coral community is controlled by numerous environmental factors that influence recruitment, growth, and mortality of each component species. Different species show different adaptations to various environmental conditions, which enable some species to thrive in certain habitats but not others.

Corals that develop framework reefs in tropical waters are long-lived sedentary organisms that have a very narrow range of tolerance to temperature, salinity, water clarity, sedimentation, and nutrients. Therefore, corals can serve as excellent indicator species. Data on coral abundance and species composition allow evaluation of prevailing environmental conditions and changes over time. Corals are the keystone species that form the reef framework through secretion of limestone skeletons. The abundance and diversity of reef fish are directly related to coral community development (see Friedlander and Rodgers, this vol., chap. 7 for a complete discussion of reef fish on Moloka‘i). The ecological importance, economic value, and environmental sensitivity of corals make them ideal subjects for monitoring and assessment efforts. Brown and others (this vol., chap. 6) discuss results from several years of monitoring of coral growth off south Moloka‘i.

The Corals of South Moloka‘i

Distinguishing among the hundreds of species of reef corals in the world is based largely on microscopic features of the coral skeleton as well as on skeletal growth form. However, the number of coral species in Hawai‘i is small, and they are relatively easy to distinguish from each other in the field (Maragos, 1977; Fenner, 2005). There are five dominant species of reef-forming corals on the reefs of south Moloka‘i. They are the “rice corals” *Montipora capitata* (previously known as *Montipora verrucosa*), and *Montipora patula*; the “finger coral” *Porites compressa*; the massive “lobe coral” *Porites lobata*; and the “cauliflower coral” *Pocillopora meandrina*. South Moloka‘i reefs are also inhabited by a number of other species of reef-forming and soft corals that range in abundance from rare to common. These species increase biodiversity, have great aesthetic value, and are of basic scientific interest, but they account for only a small percentage of the total living coral cover.

Abundant Species of Hard Corals

Montipora capitata (figs. 1, 2, 4) is clearly the most widespread species off south Moloka‘i. It is highly variable in growth form and occurs in all coral habitats, including isolated rocks on the muddy inner reef flat. Its range extends to a depth of more than 30 m (100 ft) on the deepest portions of the offshore fore reef, where it takes on a frail and highly branched growth form reminiscent of a finely branched *Anacropora*. Vaughan (1907)

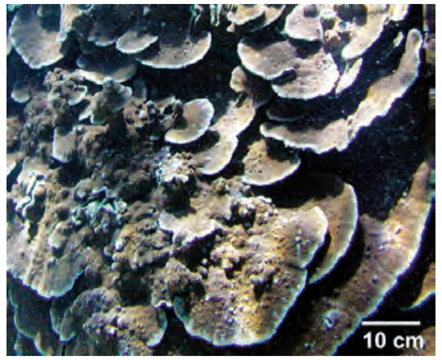


Figure 1. Encrusting and platelike growth forms of *Montipora capitata* dominate vertical faces and overhangs on the fore reef. Photograph taken at depth of 5 m (15 ft) at Pālā‘au, Moloka‘i.

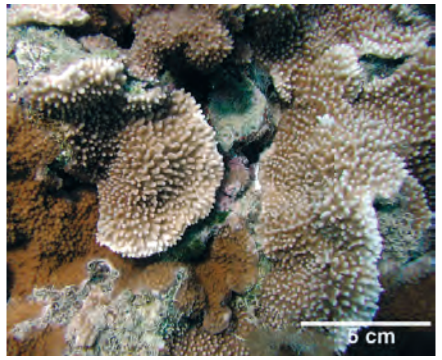


Figure 2. Platelike and encrusting growth forms of *Montipora capitata* (on the right) and encrusting *Montipora patula* (darker colony on the left) at a depth of 3 m (10 ft) on the shallow fore reef at Pālā‘au, Moloka‘i.

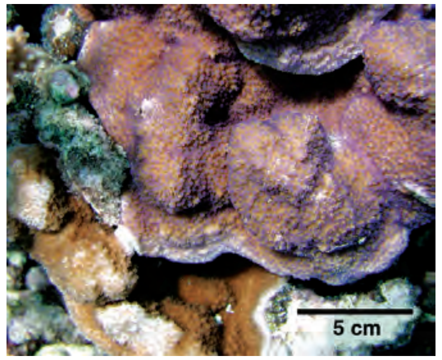


Figure 3. Purple-polyp form of *Montipora patula* (top of photograph) compared to brown variety at a depth of 3 m (10 ft) on the fore reef at Pālā‘au, Moloka‘i. The purple-polyp form of *M. patula* should not be confused with *Montipora flabellata*, which has a deep blue coloration throughout the colony.

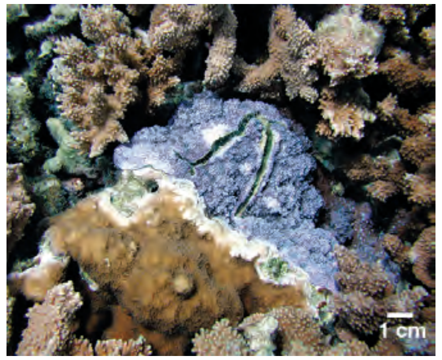


Figure 4. The three dominant species of *Montipora* compete for space on shallow reef off Kamalō, Moloka‘i. The blue species *Montipora flabellata* (upper center) struggles to overgrow the brown encrusting species *Montipora patula* (lower center). The branching growth form of *Montipora capitata* surrounds the two encrusting species in this photograph.

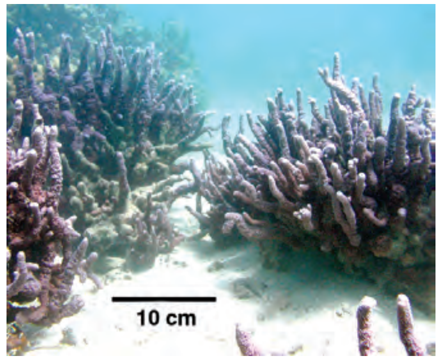


Figure 5. *Montipora flabellata* assumes a very unusual branched form on the reef flat of south Moloka‘i though symbiosis with a small shrimp known as *Gammaropsis* sp. (see text).

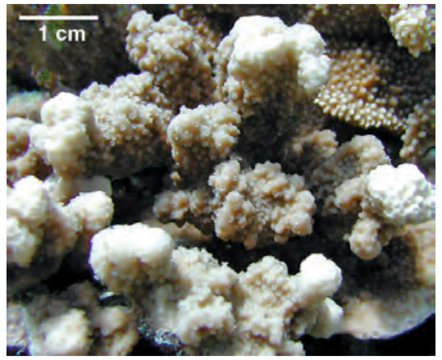


Figure 6. *Montipora studeri* (= *Montipora incrassata*) at depth of 3 m (10 ft) at Kamalō, Moloka‘i, with a small plate of *Montipora capitata* showing in the upper right.

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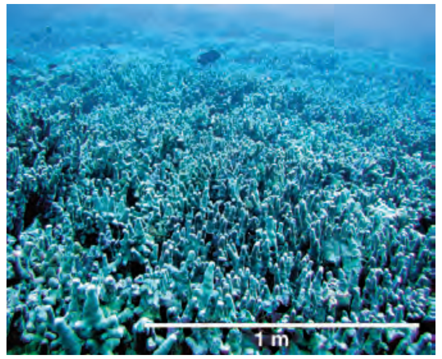


Figure 7. The deep fore reef is dominated by the “finger coral” *Porites compressa* along much of the south Moloka‘i coastline that is not affected by large waves. Photograph at 10-m (30-ft) depth off Pālā‘au, Moloka‘i.

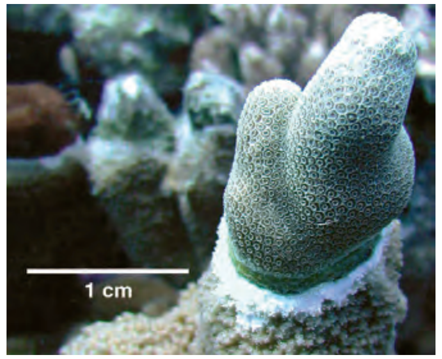


Figure 8. The “finger coral” *Porites compressa* (top) must grow vertically at a rate faster than the encrusting competitor *Montipora capitata* in order to survive. Photograph taken at depth of 10 m (30 ft) at Kamalō, Moloka‘i.

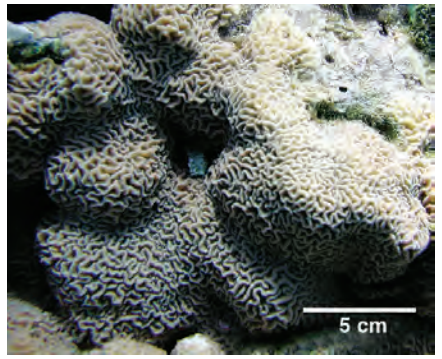


Figure 9. *Pavona varians* is an encrusting coral often found in shaded environments.

reported that *M. capitata* (which he called *Montipora verrucosa*) had the most variable growth form of any coral species. In shaded environments *M. capitata* forms large platelike structures; in calm-water environments it assumes a branched morphology; and in areas of high wave action it takes on an encrusting growth form.

Montipora patula (figs. 2, 3, 4) is an encrusting and plate-forming species that does not have a branching growth form. *M. patula* is somewhat more restricted in range than *M. capitata*, being more common in environments of higher wave energy and less abundant in environments subject to high sedimentation rates.

Montipora flabellata (figs. 4, 5) is a blue encrusting species commonly found in shallow, high-wave-energy environments (Jokiel and others, 2004). This species does not normally have a branching growth form and, by itself, cannot compete with branched species. However, unique branched colonies of *M. flabellata* occur on the outer reef flat at south Moloka‘i that have not been reported from other locations in Hawai‘i. The unusual branched morphology is the result of a mutualistic symbiosis between the coral and a small shrimp. The shrimp is an unidentified species of gammarid amphipod in the genus *Gammaropsis*. The shrimp forms a tube, and as the tube grows outward, the coral skeleton grows and encrusts the tube. Each branch of the coral thus has a hollow tube running up the center and an opening at the tip that provides a home for this small crustacean. In this way the coral is able to form a branched colony while the amphipod is given the protection of the coral skeleton (fig. 5). To the casual observer the opening at the end of the branch resembles a terminal polyp, and this growth form could easily be mistaken for a member of the genus *Acropora*.

Montipora studeri (fig. 6) is uncommon and generally found in wave-disturbed habitats, but isolated colonies have been observed as deep as 10 m (30 ft) along the south Moloka‘i coastline. Fenner (2005) recently revised this species name to *Montipora incrassata* Dana, 1846.

Porites compressa is a conspicuous coral and occurs in abundance at depths of 10–30 m (30–90 ft) on the fore reef (fig. 7) and can be found in most environments at lower abundance. The species is also successful in many shallow calm-water environments, such as along the rim of “blue holes” and in the shallows off Kamalō Pier. *P. compressa* is endemic to the Hawaiian Archipelago (Veron, 2000) and is an important framework coral. Its highly branched growth form provides cryptic habitats and cover for many species.

Porites compressa is most abundant in deeper areas on platforms and on the tops of ridges where wave energy is low (Dollar, 1982). This species can outgrow most other corals for space through rapid vertical growth of branches. Several encrusting species of coral are associated with this community, but they are generally forced to live in the spaces between the *P. compressa* branches because of the ability of this branched species to outgrow the encrusting forms. Occasionally some encrusting species can gain the upper hand. For example, *Montipora patula* can be seen overgrowing a branch of *P. compressa* (fig. 8) in some environments. Other encrusting species, such as *Pavona varians* (fig. 9), can be found deeper within the branches of *P. compressa* as well as in cryptic habitats, such as under ledges or in crevices. *Pavona maldivensis* (fig. 10) also follows this pattern, but is rare off south Moloka‘i.

The species in the genus *Porites* with more massive growth habits are ultimately classified by microscopic structures of the skeleton, but they can be distinguished from each other in the field off south Moloka‘i by certain diagnostic features. *Porites lobata* is the most common species of *Porites*. This species is generally yellow in color and forms massive to encrusting colonies. *P. lobata* is a long-lived species able to withstand periodic storm waves that remove the fast-growing and more delicate branching species that would otherwise overgrow the colonies (Grigg, 1983). Some shallow environments are dominated by colonies of *P. lobata* measuring 5 to 10 m in diameter (fig. 11). The polyps of this species are located in deep

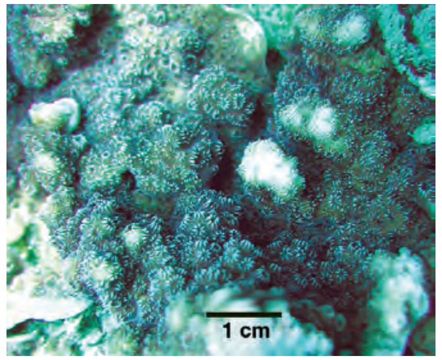


Figure 10. The encrusting coral *Pavona maldivensis* grows in crevices and under ledges.

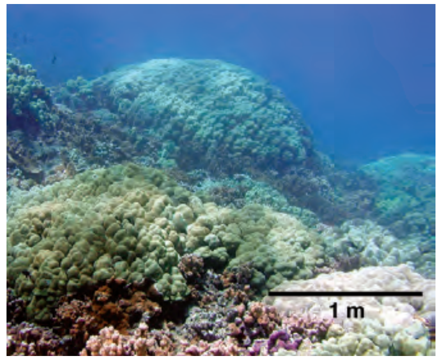


Figure 11. The shallow fore reef is commonly dominated by large yellow colonies of *Porites lobata*. Photograph taken at depth of 2 m (6 ft) at Kamalō, Moloka‘i.

Figure 12. *Porites evermanni* at a depth of 2 m (6 ft) at Kamalō, Moloka‘i.

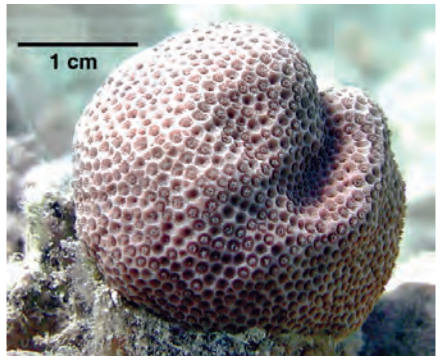


Figure 13. *Porites brighami* on the shallow reef flat near Pālā‘au, Moloka‘i. Note the deep calices in comparison to *Porites evermanni* (fig. 12).

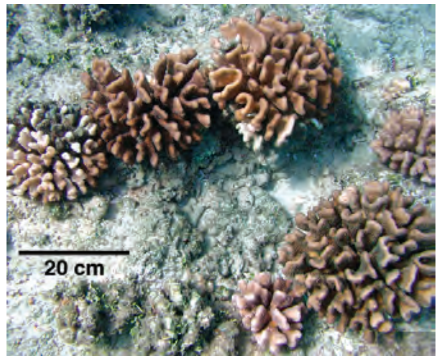


Figure 14. The shallow fore reef and reef crest are commonly dominated by the rose or cauliflower coral *Pocillopora meandrina*. Photograph taken at depth of 2 m (6 ft) off Kamiloloa, Moloka‘i.

Figure 15. *Pocillopora eydouxi* growing at a depth of 10 m (30 ft) off Pālā‘au, Moloka‘i.

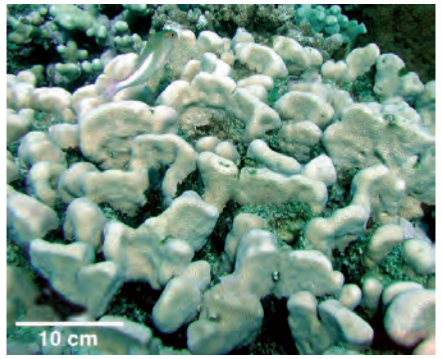


Figure 16. *Pavona duerdeni* colony growing in shallow fore reef area at Pālāʻau, Molokaʻi.

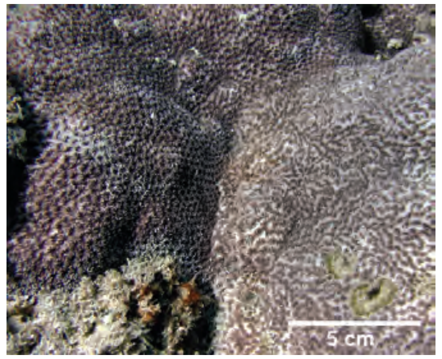


Figure 17. The encrusting reef coral *Leptastrea purpurea* at Pālāʻau, Molokaʻi.

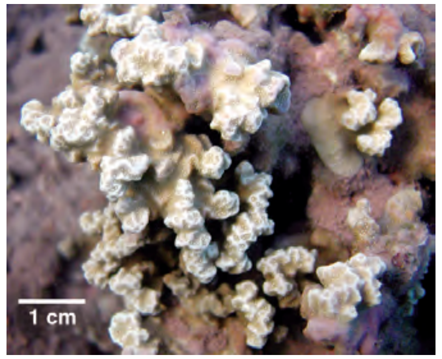


Figure 18. *Porites rus* on the reef crest at Kamiloloa, Molokaʻi.

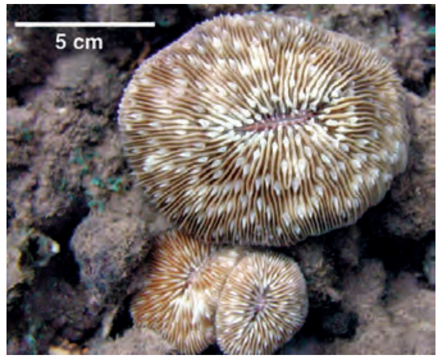


Figure 19. "Mushroom coral" *Fungia scutaria* on outer reef flat at Kamiloloa, Molokaʻi.

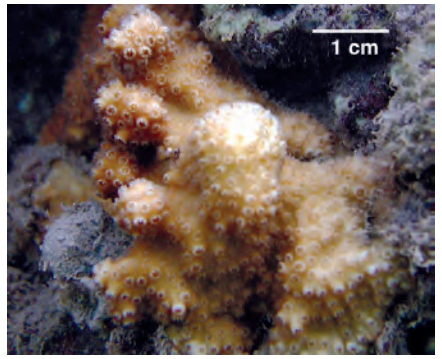


Figure 20. *Cyphastrea ocellina* on outer reef flat at Kamiloloa, Molokaʻi.

Figure 21. *Porites lichen* (= *Porites* cf. *bernardi*) on outer reef flat off Kamiloloa, Molokaʻi.

calices (Veron, 2000). By comparison, the closely related species *Porites evermanni* has very shallow calices (fig. 12). At Molokaʻi, *P. evermanni* is uncommon and is light blue-grey in color. It can form large massive colonies but is generally restricted to water depths of less than 1–2 m (3–6 ft) off south Molokaʻi. This coral has been classified as *Porites lutea* by Fenner (2005) because the two cannot be distinguished from each other, and *P. lutea* is the older name. A third species, *Porites brighami*, has very deep calices (fig. 13) and forms very small colonies that seldom exceed 5 cm (2 in) in diameter. *P. brighami* is relatively rare off south Molokaʻi and only occurs in shallow, high-wave environments, such as the reef crest or outer reef flat.

Pocillopora meandrina has a dense, hard skeleton that resists breakage (Rodgers and others, 2003) and thus is able to dominate shallow areas characterized by high wave energy where other species cannot persist (fig. 14). *Pocillopora ligulata* is a species closely related to *P. meandrina*, which occurs in environments of high wave energy. It has the general appearance of *P. meandrina* but with very thin and ragged branches. *Pocillopora eydouxi* is similar to *P. meandrina* but with thick large branches (fig. 15). This species occurs from the reef flat through the shallow fore reef at depths of 1–10 m (3–30 ft), generally as isolated large colonies. *P. eydouxi* is very vulnerable to extreme storm surge because of its large size.

Less Common Species of Hard Corals

Pavona duerdeni (fig. 16) has a very dense skeleton that can form very massive colonies with ridgelike structures. In the Hawaiian Islands this species is more common on south-facing shores. This species is typically found on the upper fore reef, reef crest, and seaward edge of the reef flat.

The encrusting coral *Lepastrea purpurea* (fig. 17), which has a hard, dense skeleton that resists abrasion, is commonly found on the reef crest and outer reef flat.

Porites rus is uncommon on most Hawaiian reefs. Scattered colonies occur on the reef crest on south Molokaʻi in the Kaunakakai region (fig. 18). An unusual situation occurs on the outer shallow reef flat and shallow fore reef on the west side of the Kaunakakai channel. This area is dominated by an extremely large population of *P. rus* colonies that covers an acre or more.

The solitary, free-living coral *Fungia scutaria* (fig. 19) is an easily recognized hard coral. This species is typically found tucked into crevices in the reef. Although not common in Hawaiʻi, *F. scutaria* can be locally abundant.

Cyphastrea ocellina (fig. 20) can be found on reef flats, the reef crest, and the shallow fore reef. *Porites lichen* is another species with a similar distribution (fig. 21) with small greenish cryptic colonies less than 1 in (2.5 cm) in diameter. The calices of this species are often aligned to form rows. *P. lichen* reported from Hawaiʻi is not the same species as *P. lichen* found in other areas of the Pacific, where they commonly grow to a much larger size. Therefore, this Hawaiian species has recently been reclassified as *Porites* cf. *bernardi* Vaughan, 1907 by Fenner (2005).

Pocillopora damicornis is a finely branched species typically found in shallow, calm-water environments. Off south Molokaʻi, *P. damicornis* is found on the reef flat, despite muddy sediment and competition from macroalgae (fig. 22). *Psammocora stellata* (fig. 23) occupies the same reef-flat habitats as *Pocillopora damicornis*, but it is less abundant. This species occurs primarily on the shallow reef flat and is often found growing on rocks and rubble very close to shore.

Soft Corals and Octocorals

Several "soft corals" and an octocoral are found on the reefs of south Molokaʻi. These do not contribute to the formation of the reef, because they do not form a calcium carbonate (limestone) skeleton. Although these species are uncommon off south Molokaʻi, they are interesting organisms that contribute much to the biodiversity and beauty of the reefs. The soft coral *Sinularia molokensis* is extremely rare (fig. 24). Only a few colonies are known to exist in the world, and all of these are recorded

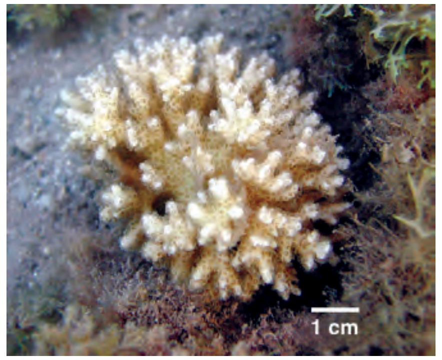


Figure 22. *Pocillopora damicornis* on inner reef flat off Kamiloloa, Molokaʻi.

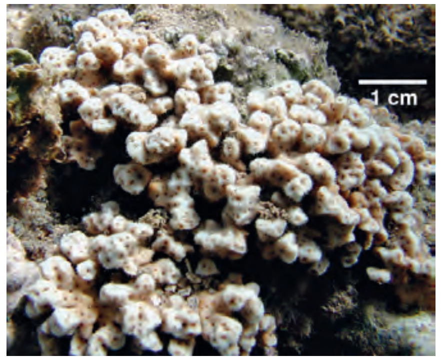


Figure 23. *Psammocora stellata* on shallow inner reef flat at Kamiloloa, Molokaʻi.

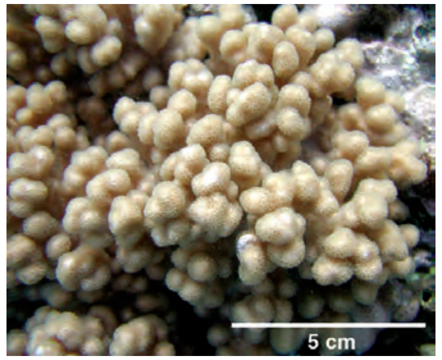


Figure 24. *Sinularia molokensis* is a very rare soft coral and known only from a few colonies that occur on Molokaʻi.

from Molokaʻi. *S. molokensis* occurs on the fore reef at depths of 1–6 m (3–20 ft). *Palythoa tuberculosa* is found in shallow, high-wave-energy environments on the reef crests (fig. 25), but this species rarely occurs on the deeper reefs. *Zoanthus pacificus* is uncommon on the reefs of south Molokaʻi, but it has been observed in shallow water at the east end of the island and in water as deep as 10 m (30 ft) off Pālāʻau (fig. 26). *Anthelia edmondsoni* is a small endemic octocoral that is common in shallow, high-wave environments off many of the Hawaiian Islands but rare off south Molokaʻi. Note the presence of eight tentacles (fig. 27). Colonies of this species are generally velvetlike and of purple color in shallow water and more brownish in deep water.

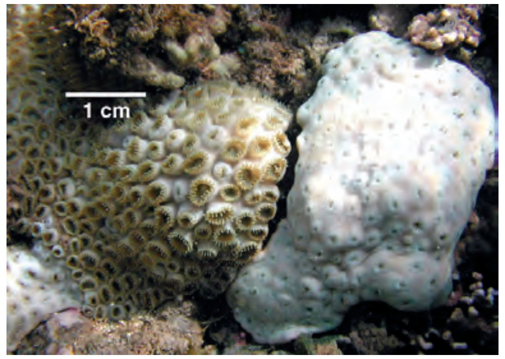


Figure 25. *Palythoa tuberculosa* with polyps expanded (far left) and contracted (near right) on the reef crest at Kamiloloa, Molokaʻi.

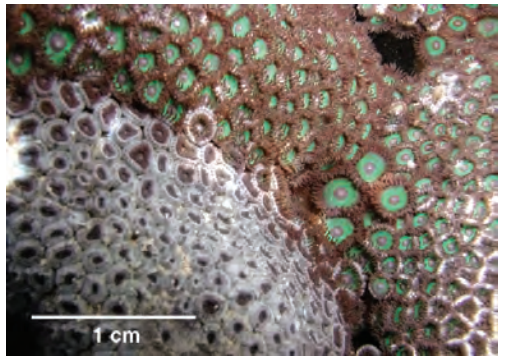


Figure 26. *Zoanthus pacificus* is uncommon off south Molokaʻi but is found on shallow areas near the east end of Molokaʻi and more rarely in deeper water along the rest of the coastline.

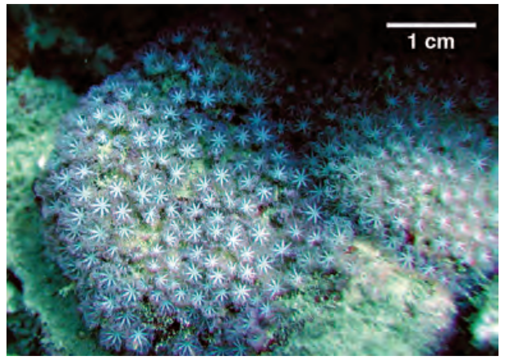


Figure 27. This small colony of *Anthelia edmondsoni* was photographed at a depth of 10 m (30 ft) off Pālāʻau, Molokaʻi.

Major Environmental Factors Affecting Coral Community Structure off South Molokaʻi

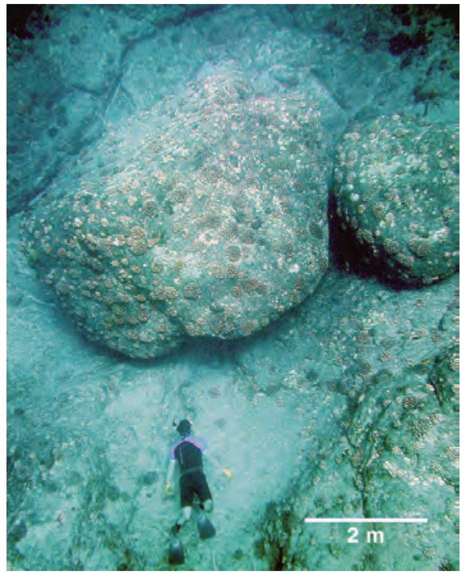
Physical Factors

Currents and Waves

Wave energy is an important factor controlling development of coral reef communities (Storlazzi and others, this vol., chap. 11; Grigg, 1983). Anomalous and extreme wave events such as hurricanes can pulverize corals, but such catastrophic events are very infrequent, so the prevailing wave regime is of greater importance over the long run. Many fast-growing species do not recruit, grow, or survive in high-wave-energy regimes. Corals adapted to strong water motion cannot compete effectively in environments of weak water motion. Each major reef-building species modifies its morphology to fit environmental conditions; thus the prevailing wave regime shapes the structure of the coral community. For example, the growth form of the coral *Montipora capitata* is delicate and branching in calm water, but becomes encrusting in areas with strong water motion.

In extreme situations, wave impact retards or prevents establishment of reef coral communities. The large North Pacific swell that strikes the north coast of Molokaʻi during the winter can move boulders the size of trucks (fig. 28). Such waves can fragment and abrade all except the most wave-resistant coral species, which persist on isolated outcrops and in protected, recessed areas where wave force and abrasion are minimized. The elongate east-to-west orientation of Molokaʻi shields much of the reef along the south coast from the North Pacific swell. North Pacific swell wraps around the extreme east and west ends of the island, influencing reef development in these areas (see Storlazzi and others, this vol., chap. 11 for more information on waves). The southeast coast from Kamalō to Hālawa is severely affected by the large northeast trade wind swell passing through the Pailolo Channel. The south coast of Molokaʻi falls into the “wave shadow” of surrounding islands, but it is potentially vulnerable to the infrequent storm waves associated with hurricanes or “Kona” storms from the south. Hurricane Iwa caused extensive damage to the Kaunakakai wharf during late November 1982 and presumably damaged the surrounding fragile reefs (Capt. Joe Reich, oral commun., 2001). A paradox is that such extreme events can also remove years of accumulated sediment and thereby rejuvenate coral growth on a reef.

Figure 28. The force of large storm waves from the North Pacific prevents development of a reef framework off the north coast of Molokaʻi. Note diver in the lower portion of the figure. Photograph taken at Kalaupapa on the north coast of Molokaʻi.



Light

Light is absolutely necessary for reef growth. Corals are plant-animal symbioses that require sunlight as a primary source of energy. Therefore, their lower depth distribution is set by light penetration. Waters above the ocean reefs off south Molokaʻi are of sufficient clarity to permit development of rich *Porites compressa* communities to depths of 30 m (100 ft). At greater depths, the substrate is unsuitable for corals, and the reef gives way to a sand terrace dominated by the alga *Halimeda* (see Smith and others, this vol., chap. 8 for more discussion of alga distribution). High turbidity inshore because of fine sediment from land runoff dramatically reduces light penetration on the shallow reef flats. The impact and processes that influence sediment runoff and turbidity are discussed in more detail in chapters 17 through 21.

Temperature

Temperature is a primary physical factor governing reef coral distribution (Wells, 1957). The optimum growth temperature for Hawaiian reef corals is 27°C (81°F), although they can tolerate prolonged temperature of from 20°C to 29°C (68–84°F) and short exposure to temperatures of 18°C to 31°C (64–88°F). Under calm sunny periods during the summer months, temperature on the inner reef flat can approach the upper lethal temperature for these reef corals.

Salinity

Reef corals have been described as having very narrow salinity tolerance (Wells, 1957), but corals and coral reefs are known to occur under natural conditions at salinities ranging from 25 parts per thousand (ppt) to 42 ppt (Coles and Jokiel, 1992). Reef kills caused by low salinity associated with flood events have been reported throughout the world, as well as from Hawaiʻi (Jokiel and others, 1993). Salinity on the reefs of south Molokaʻi is generally close to that of the open ocean, which is on the order of 34–35 ppt (Ogston and others, this vol., chap. 20). Hawaiian corals can tolerate salinity of 15 ppt for several days without dying. This represents a 50-percent dilution of seawater with freshwater. During extreme floods, such low salinity can occur near stream mouths on the reef flat, but the freshwater is rapidly mixed with seawater that is pushed over the reef crest by wave action. Freshwater is much less dense than seawater, so it often forms a surface layer that does not reach corals in deeper water. Rising and falling tides further flush the reef flat. Thus, live coral can be found scattered across the shallow reef flat even close to shore. Floods definitely represent a major but episodic stress for corals on the Moloka‘i reef flats, but corals continue to persist in this environment.

Substrate Type

Reef corals generally require a hard substratum. A substratum of sand and mud is unsuitable for coral settlement and growth. Corals can, however, develop in these areas through initial settlement on isolated outcrops of hard rock. Accretion of skeletal material over many generations of coral will produce larger coral mounds or ridges surrounded by mud or sand. The solitary coral *Fungia scutaria* (see fig. 19) can persist on unstable rubble substrate because of unique hydrodynamic properties (Jokiel and Cowdin, 1976).

Figure 29. Movement of sediment across the bottom can smother and later uncover large coral colonies, as well as new coral settlements. Photographs of live *Pocillopora meandrina* (top) a buried colony (middle) and an uncovered dead colony (bottom) were taken at a depth of 3 m (10 ft) off Kamiloloa, Moloka‘i.

Figure 30. The coral *Pocillopora meandrina* (center of picture) is being overgrown by the fast-growing purple *Montipora flabellata* (bottom of picture) and by the branching growth form of *Montipora capitata* (top of picture). Photograph taken at depth of 3 m (10 ft).

Sand and mud are transported onto and off the reef in response to currents and waves (see Bothner and others, this vol., chap. 19 and Ogston and others, this vol., chap. 20). Passage of sediment through coral communities can smother new coral settlements and encrusting corals and can even bury large coral colonies (fig. 29), which are killed and sometimes uncovered later by subsequent erosion.

Depth

Depth of water is an important factor for corals, mainly because light and water motion diminish with depth. Deeper corals are subjected to less risk from wave energy under normal conditions. However, these corals are limited by lower light intensity, which causes a reduction in growth.

Land Impact

Terrigenous runoff carries freshwater, fine sediment, and nutrients onto the reef (Field and others, this vol., chap. 21; and Roberts and Field, this vol., chap. 15). The shallow inshore reefs of Moloka‘i have been profoundly affected by increased runoff and sediment from two centuries of improper land-management practices. A major impact to the inshore is the extreme sedimentation of fine mud.

Biological Factors

Competition

The limited amount of space available on a coral reef results in competition. Corals compete with each other as well as with other organisms for this resource. In optimal environments (for example, high light and moderate water motion), the fast-growing encrusting or branching species have the advantage. They have lightly constructed skeletons that allow them to rapidly overgrow other species (fig. 30). This eventually leads to total dominance by the single most successful competitor (see example in fig. 7). Such weak skeletons, however, cannot persist in high-wave environments, where the slower growing corals with dense skeletons have the advantage.

Predators and Parasites

Numerous organisms feed directly on coral tissue. Various butterfly fish feed exclusively on coral polyps, and large parrotfish will occasionally scrape tissue and underlying skeletal material from live corals (Brock, 1979). The nudibranch mollusk *Phestella sibogae* feeds on *Porites* coral. The snail *Drupella*, and the “cushion starfish” *Culcita* feed directly on a variety of corals. The flatworm *Prosthiostomium montiporae* feeds on the coral *Montipora*. Generally, coral predators and parasites do not inflict severe damage on coral colonies. A notable exception is the “crown of thorns starfish” (*Acanthaster planci*), which will eat the tissue off of entire coral colonies (fig. 31).

During 1969–70, a large aggregation estimated to consist of 20,000 *Acanthaster planci* was observed off south Moloka‘i (Branham and others, 1971). They were feeding selectively on *Montipora capitata*. The infestation occurred on the rich coral reefs between Kawela and Kamalō. At that time the coral cover in the area was estimated visually and was reported to consist of approximately 90 percent *Porites compressa* and about 5 percent *Montipora capitata*. The area of uniform coral cover was reported to be approximately 1 km wide and extended to depths of 30 m (100 ft), where the bottom becomes a sandy slope. This description generally fits conditions that exist today, suggesting that major changes have not occurred in the reefs over the 1971–2004 time period. The State of Hawai‘i Department of Fish and Game undertook extensive surveys and eradication efforts after discovery of the infestation (Onizuka, 1979). Divers killed a total of approximately 26,000 starfish between 1970 and 1975 by injecting them with ammonium hydroxide. Additional surveys were conducted throughout the State of Hawai‘i, but no other infestations were detected at that time.

Disease

All organisms are subject to disease, and corals are no exception. However, little is known about the diseases of corals. Recently, interest in this area has grown tremendously because of serious outbreaks of coral disease in many parts of the world (Richardson, 1998). Off south Moloka‘i, very few diseased corals have been observed on the fore reef, where conditions

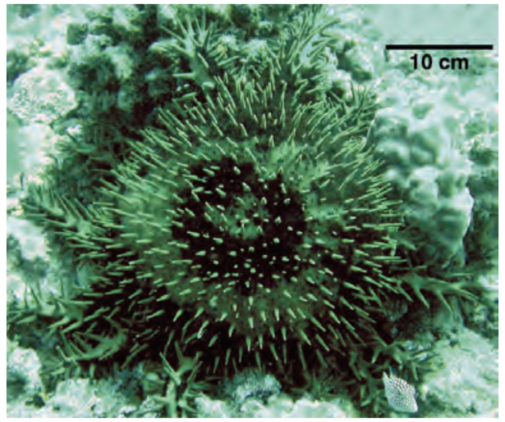


Figure 31. Adult *Acanthaster planci* or “crown of thorns starfish” off Kamiloloa, Moloka‘i, feeding on the coral *Montipora capitata*. The starfish is approximately 25 cm (10 in) in diameter.

are very favorable to coral growth (fig. 32). Dead and dying corals are more common on the highly stressful reef flat and the damaged fore reef off Kamiloloa. Corals that are weakened by adverse environmental conditions, such as high sediment loading, high organic input, and reduced light availability, are under stress. Increased environmental stress makes corals more prone to disease, as is the case with other organisms.

Bioerosion

Along with the physical forces of wave action, organisms play a significant role in abrading the reef framework. The rasping action of grazing fish (fig. 33) and urchins wears away carbonate rock (Brock, 1979). Boring sponges and boring mollusks degrade and weaken coral skeletons (Hutchings and Peyrot-Clausade, 2002).

Herbivorous Fish

Herbivorous fish crop competitive algae, to the advantage of reef corals (Karlson, 1999). Overfishing can reduce the number of herbivores on a reef and thereby tip the balance in favor of the algae (Hughes, 1994). A healthy population of these fish off south Moloka‘i (Friedlander and Rodgers, this vol., chap. 7) will keep competitive algae under control.

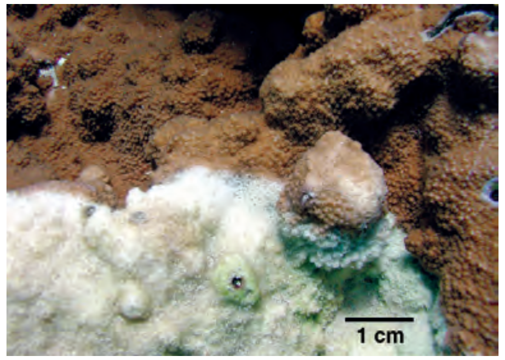


Figure 32. Coral *Montipora patula* at Kamalō, Moloka‘i, showing rapid death of diseased tissue exposing a white coral skeleton.

Figure 33. Parrotfish rasp away encrusting organisms along with carbonate substratum on the reef crest at Pālā‘au. Grazing by fish and urchins is a major erosive force on the reefs of south Moloka‘i, producing carbonate sand and fine carbonate mud in the process.

Distribution of Corals on South Moloka‘i Reefs

Coral Zonation from Deep Ocean to Shore

Deep Fore Reef

The deep fore reef (fig. 34) extends from a depth of approximately 10 m (30 ft) out to the sand shelf at 30–40 m (90–120 ft). This zone consists of coral platforms bisected by sand channels. In areas of high coral coverage, the tops of the platforms are dominated by a *Porites compressa* community, whereas the vertical sides are dominated by a *Montipora* spp. community.

Shallow Fore Reef

The shallow fore reef extends from a depth of approximately 2 m (6 ft) to a depth of approximately 10 m (30 ft). This zone is characterized by spur-and-groove morphology consisting of sand channels, ridges, and buttresses (Cochran, this vol., chap. 9). In many places there is a shallow shelf extending seaward that receives the brunt of the wave action.

Reef Crest

Diverse wave-resistant coral species and encrusting coralline algae characterize the reef crest. This area receives extremely heavy wave impact, resulting in low coral cover. Diversity of coral species, however, can be relatively high. Dominant species, such as *Porites compressa*, *Montipora flabellata*, small *Pocillopora meandrina*, *Pocillopora ligulata*, and *Montipora studeri* are often found in this zone, as well as in the shallow fore reef and the seaward edge of the reef flat. *Leptastrea purpurea* is an encrusting species with a hard skeleton that is found on the reef crest, shallow fore reef and outer reef flat, but with a somewhat scattered distribution. *Pavona duerdeni* occurs on the reef crest and extends deeper into the shallow fore reef. This species has a hard dense skeleton and is resistant to waves and sediment abrasion.

Reef Flat

Shoreward of the reef crest there is a strong environmental gradient on the shallow reef flats of south Moloka‘i. The seaward edge of the reef flat is subjected to waves breaking over the reef crest and to strong currents. Small carbonate rock outcrops surrounded by coral rubble characterize the seaward reef flat. Depth diminishes shoreward of the reef crest. Wave energy is dissipated as the water decreases in depth moving toward the shoreline (Denny, 1988). Toward shore the substrate becomes sandy with scattered rocks. Near the shoreline the sand grades into mud.

The coral community on the outer reef flat is characterized by high coral diversity and low coral cover. Wave disturbance prevents the dominance of substratum by the more rapidly growing species, so many other species

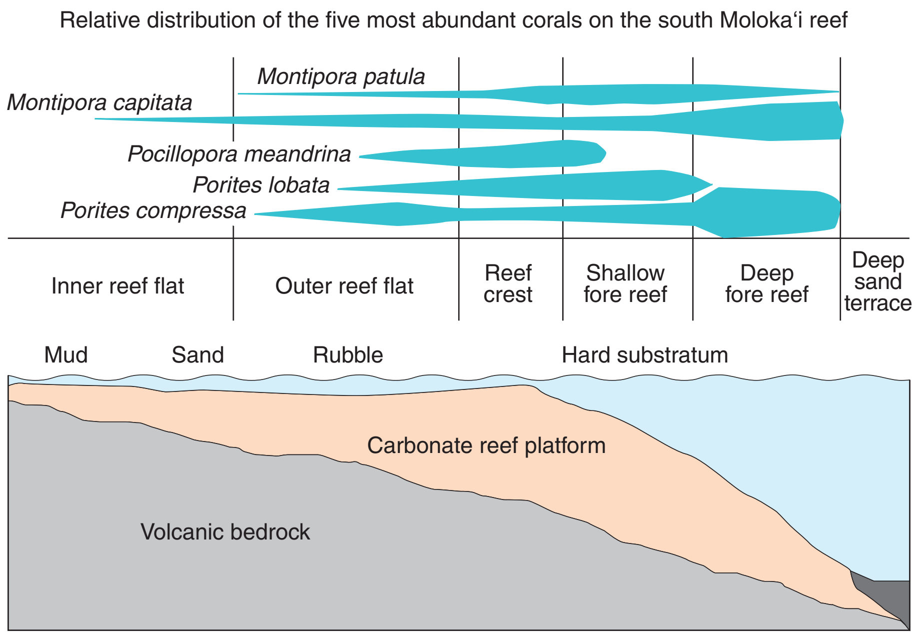


Figure 34. This generalized profile shows the distribution of the five most abundant species of corals along a typical section of reef between Kamalō and Kawela, Moloka‘i. Relative abundance of each species at each point along the cross section is represented by the thickness of the color bar.

Figure 35. This aerial image shows the portion of the south Moloka‘i coast from Kawela (left) to Kamalō (center) and U‘alapu‘e (right). The areas of darker blue on the image on the reef flat are channels and “blue holes.” The straight-edged hole in the reef flat (right center, near shore) is from a dredging operation in the late 1960s. Distance across the image is approximately 7 km.

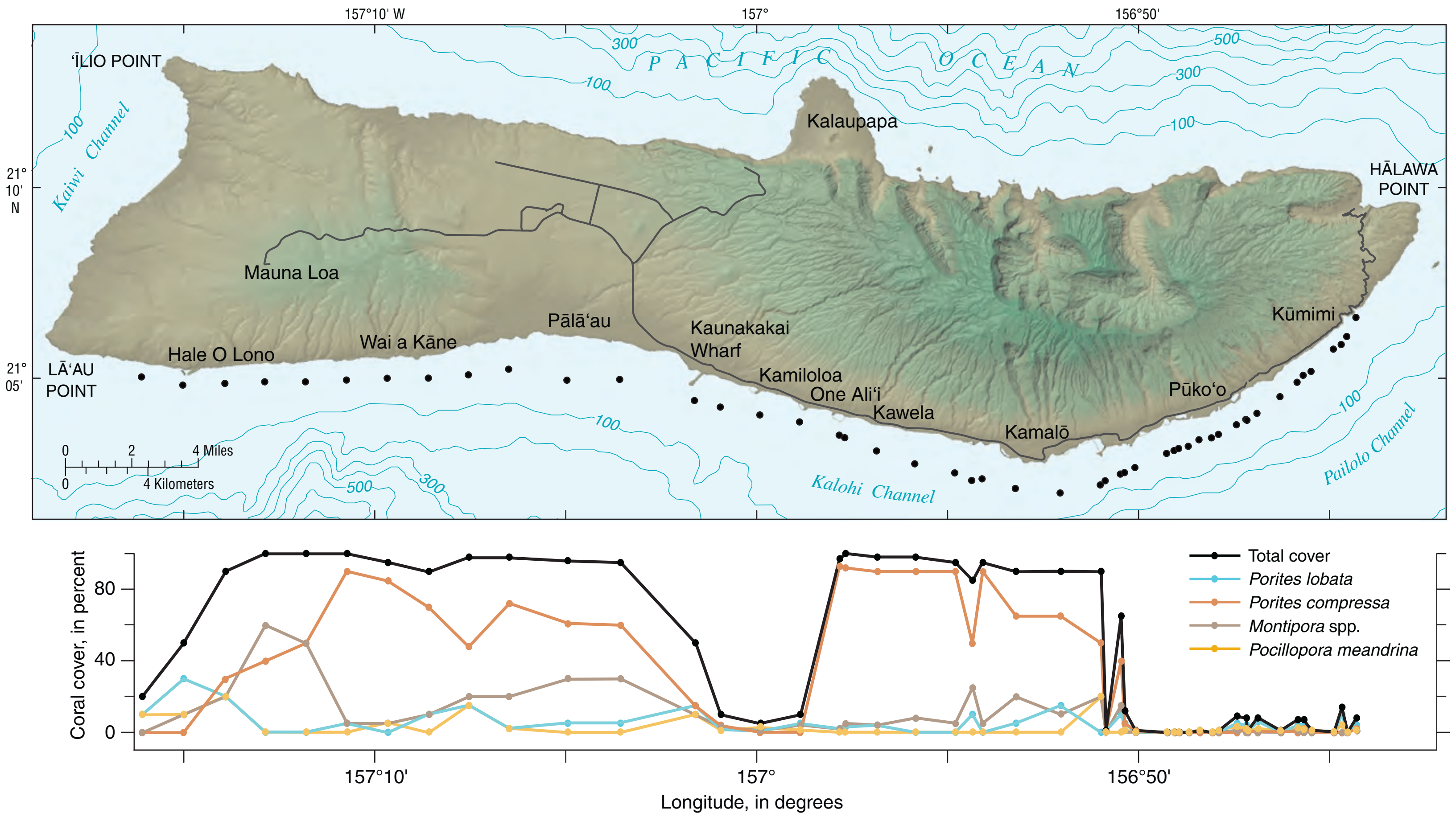


Figure 36. Distribution of reef corals along the fore reef of south Moloka‘i at a depth of 10 m (30 ft). Map shows sampling sites (black circles); depth contours in meters.

rarely found in deeper water occur on the outer reef flat. All of the common species are found here, mixed with several species not common in deeper water. The mushroom coral *Fungia scutaria* is a solitary free-living coral that is not attached to the reef. This coral can live on the unstable rubble and fore reef. *Porites* cf. *bernardi* (previously known in Hawai‘i as *Porites lichen*) is a small encrusting species that is characteristically apple green in color with calices arranged in rows. Colonies are generally less than 2 cm (1 in) in diameter and are found hidden in crevices and under overhangs on the carbonate outcrops. *Cyphastrea ocellina* is another common encrusting species that occurs here in similar habitats.

One of the unique features of the south Moloka‘i reef is the system of deep “blue holes” that lie to the east of Kamalō (fig. 35). This portion of the reef is cut by areas of deeper water. The holes are partly in alignment and may be remnants of submerged stream valleys that have been cut off and partly filled in by reef growth. Perhaps the remaining holes are areas where reef development was retarded by freshwater and sediment discharged from Kamalō Gulch. Another hypothesis is that the blue holes are karst features caused by ground-water dissolution with consequent undermining of the carbonate reef structure (Grossman and others, this vol., chap. 13). The coral community growing along the edges of the blue holes is similar in composition to the coral communities found in Kāne‘ohe Bay, O‘ahu. The dominant coral is *Porites compressa*, with small amounts of *Pocillopora damicornis*, *Cyphastrea ocellina*, and *Montipora* spp.

Distribution of Corals Along the South Moloka‘i Fore Reef

Estimated coral cover, by dominant species, along the 10-m (30-ft) depth contour is shown in figure 36. These data were obtained by visual estimates from the surface rather than by detailed transects. Data recorded by the type of visual survey used in this chapter can show a slightly higher total coverage, biased in favor of the branched species, when compared to the digital methodology used for the monitoring stations (Brown and others, this vol., chap. 6). Estimation of coral over a wide area by the visual method has a resolution of from 20 to 40 cm, whereas the digital methodology has a resolution of a few millimeters. Furthermore, there is a parallax effect when viewing a large area by the visual method from the surface, which results in seeing the sides of the branching finger corals and not the intervening spaces between branches. The visual method does not account for the small dead areas between the branches, nor will it record coverage by the small cryptic encrusting species. Nevertheless, a recent comparison study by Jokiel and others (2005) has demonstrated that the various coral survey methods commonly used in Hawai‘i yield very similar estimates for coral cover.

It is apparent that the coral distribution along the 10-m (30-ft) depth contour is bimodal, with two areas having high coral cover and three areas having very low coral cover. On the western end of the south Moloka‘i reef, the extremely high wave energy from the North Pacific swell wraps around Lā‘au Point and suppresses coral development (Storlazzi and others, 2002, 2003). Coral coverage increases rapidly to the east of Hale O Lono and remains high along the coastline to Kaunakakai, where a sharp decrease is observed. Coral cover from Kaunakakai to Kawela is quite low. Coverage increases sharply between Kawela and Kamalō, where the coastline turns northeast and another sharp decrease is noted. Low coral coverage along the southeast coast from Kamalō to Hālawa on the east can be attributed to the destructive wave impact of the northeast trade wind swell (Storlazzi and others, this vol., chap. 11). The existence of low coral cover between Kaunakakai and Kawela is not easily explained.

Damage Along the Kaunakakai-Kawela Sector

A detailed visual survey was conducted by teams of scuba divers from Kaunakakai to Kawela along a series of transects run perpendicular to shore from depths of 30 m (100 ft) to 10 m (30 ft) (fig. 37). West of Kaunakakai and east of Kawela the coral cover is very high at all depths. Between Kaunakakai and Kawela, however, is an area of damaged reef with low to nonexistent coral cover. Two important features of the coral distribution were noted. First, damage increases westward with depth from Kawela to Kaunakakai. Second, the distribution is essentially bimodal, with either low coverage (0–20 percent) or high coral coverage (80–100 percent), separated by a very sharp intervening boundary.

Damage Along the Coast from Kamalō to the East End of Moloka‘i

The drop in coral cover between Kamalō and the east end of the island can easily be explained by high wave stress due to northeast trade wind swell (Storlazzi and others 2003; Storlazzi and others, this vol., chap. 11). The break in both coral cover and wave stress is remarkably sharp.

Anthropogenic Change: Man and Corals of the South Moloka‘i Reef

Over the past two centuries, improper land-use practices have led to accelerated erosion of the watersheds, with increased sediment and nutrient input onto the coral reefs (Roberts and Field, this vol., chap. 15). Initially the problem was overgrazing by cattle and sheep, but overgrazing continues to

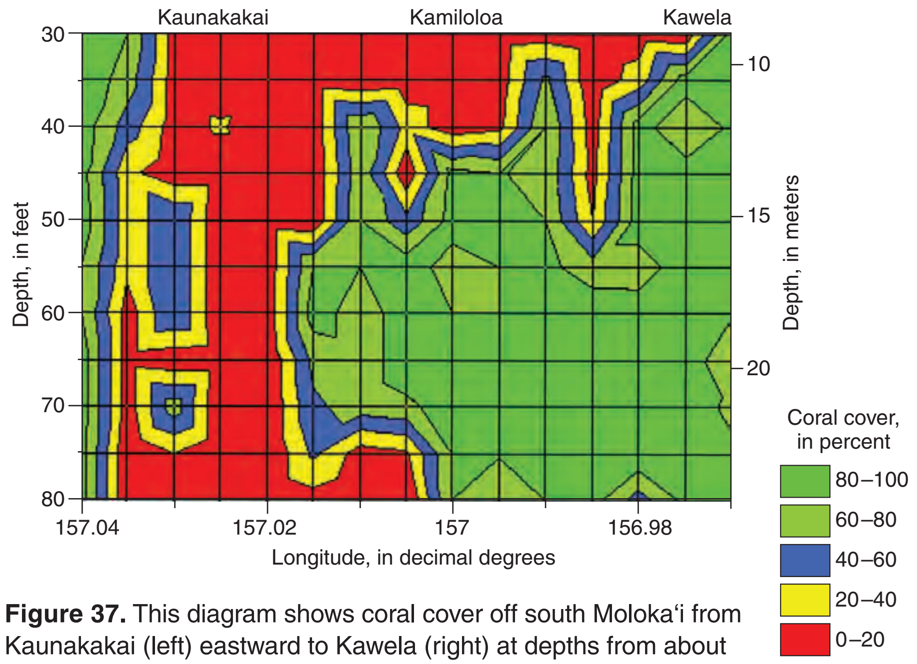


Figure 37. This diagram shows coral cover off south Moloka‘i from Kaunakakai (left) eastward to Kawela (right) at depths from about 10 m (30 ft) to about 25 m (80 ft). The figure represents coral cover on the reef face as viewed from seaward.

this day as a result of uncontrolled feral ungulates (deer, pigs, and goats) that are rapidly increasing in number on the watersheds. Initial cattle- and sheep-ranching operations were followed by extensive development of plantation agriculture (sugar cane and pineapple), which further contributed to the sediment and runoff problem (Roberts and Field, this vol., chap. 15). More recently, there are reports of introduced algae, which could negatively affect the shallow inshore reef communities (Smith and Field, this vol., chap. 8).

Fishing is an important activity on the reefs of south Moloka‘i, but the low human population has less impact on the reefs than what is observed on the more populated Hawaiian Islands (Friedlander and Rodgers, this vol., chap. 7). Effects of future climate change on the coral reefs of south Moloka‘i could be disastrous if current warming trends continue (Hughes and others, 2003). Hawaiian reefs have already begun to experience the impact of mass bleaching events (Jokiel and Brown, 2004).

Some of the impacts of coastal construction were discussed previously in this chapter. Damage due to dredging has also occurred on the reefs of south Moloka‘i. Kamalō was a prime fishing area with extensive coral cover before a series of aborted dredging operations in the area that began in the late 1960s. The dredging occurred on the inner reef flat east of Kamalō near Kalaeloa Harbor. The prevailing westward currents carried silt from the dredge operation down the coast and well past Kamalō (fig. 38). The fine silt covered reefs downcurrent, killing the coral. The area took on the appearance of a wasteland—everything was covered with fine silt, and the fish left the area (Capt. Joe Reich, oral commun., 2001). Even after the company went bankrupt and abandoned the dredging operation, the fine sediment continued to remobilize whenever the wind speed and wave heights increased. Chronic turbidity and sedimentation prevented any recovery of the reefs for many years. As fine sediment was winnowed out and transported offshore, the area slowly began to improve. These reefs showed signs of recovery by mid 1970s. Recovery was well underway by the early 1980s, with full recovery by 1990. The reefs off Kamalō presently appear to be “pristine,” but much of the area actually represents a regenerated reef that was heavily damaged by siltation.

Conclusion

The coral reefs off south Moloka‘i represent a great living treasure that has been damaged by increased sedimentation resulting from improper land-use practices and from coastal construction. Nevertheless, a large portion of the fore reef to the east of Kaunakakai and to the west of One Ali‘i remains relatively pristine. Diverse habitats in this area support rich coral reef communities. The reefs of south Moloka‘i represent a significant source of sustenance, recreation, and inspiration to all and must be managed carefully to prevent further decline.

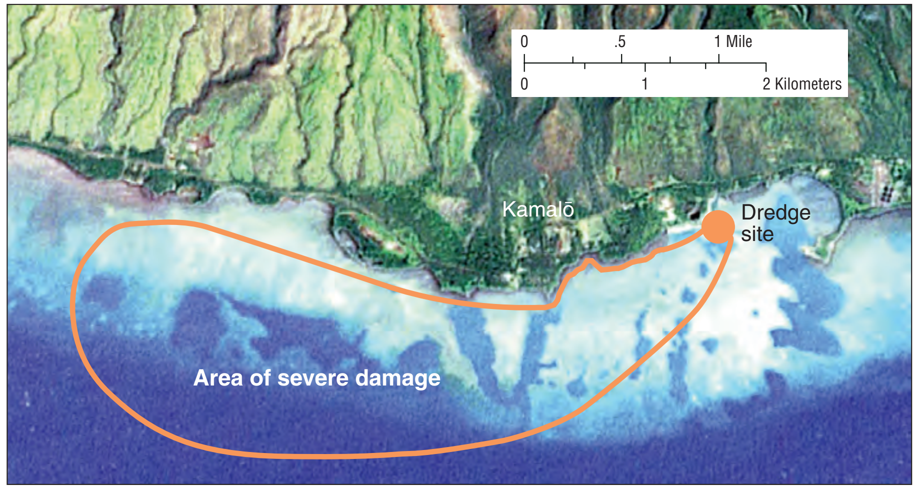


Figure 38. This map shows the area of damage near Kamalō resulting from a dredging project in the late 1960s.

CHAPTER 6

The Status of the Reefs Along South Moloka‘i: Five Years of Monitoring

Eric K. Brown[1], Paul L. Jokiel[2], Ku‘ulei S. Rodgers[2], William R. Smith[2], and Lucile M. Roberts[2]

In Hawai‘i, coral reefs are subjected to a variety of natural and anthropogenic stresses at several spatial and temporal scales (Grigg and Dollar, 1990). The intensity and duration of these factors can both directly and indirectly alter the physical and biological structure of the reef (Connell and others, 1997). Natural factors, such as acute wave disturbances (Dollar and Tribble, 1993), freshwater inputs (Jokiel and others, 1993), and predator outbreaks (Done, 1992) can affect the shallow-water reef communities at small spatial (10–100 m) and temporal (0–1 yr) scales. Chronic disturbances, such as non-point source pollution, are more difficult to detect because changes to the community landscape are subtle and occur over longer time periods (Pastorok and Bilyard, 1985). How different types of disturbance influence coral community structure is only beginning to be understood and quantified (Edmunds, 2000).

Disturbances can lead to a deteriorating or “unhealthy” coral population if recovery of the community does not occur or if the community is replaced by another perceived to be less desirable. DeVantier and others (1998) defined a “high quality” or “healthy” reef as one with high diversity of corals and associated biota and a strong reef-building capacity. The reef-building capacity is usually represented by high species richness and high absolute percent cover of hard corals (DeVantier and others, 1998). Szmant (1996) has incorporated temporal changes in her definition of reef health by stating that shifts from reefs dominated by corals to areas dominated by macroalgae signal the decline of a reef from a healthy state to an unhealthy one. These definitions, however, tend to depict reefs as static, steady-state systems without incorporating cyclical variation in substrate cover, coral growth, or recruitment. Categorizing reefs as “healthy” based primarily on high coral cover does not take into account geographic areas such as Hawai‘i that naturally have low to moderate coral cover. Many of these areas are in good condition compared to other regions of the world (Wilkinson, 2000). Long-term monitoring programs can clarify natural cycles present in the system over time and provide an overview of population trends in the reef community. In addition, long-term monitoring is necessary to understand the role of natural and anthropogenic processes in changes in reef ecosystems (Hughes and Connell, 1999).

Long-term monitoring involves repeated surveys of organisms and/or environmental parameters at selected sites over time (Rogers and others, 1994). Documenting changes in the community structure at various spatial and temporal scales using a well-designed monitoring program can assess the condition (such as deteriorating, improving, or undergoing a phase shift) of various reefs and focus research on causal links among the various factors (Hughes, 1993; Done and Reichelt, 1998). In Hawai‘i, long-term coral reef monitoring projects have been conducted to detect change in coral cover at a small spatial scale at Kahe Point (Coles, 1998), Hanauma Bay (C. L. Hunter, written commun., 2000), Honolua Bay, Kahekili Park, Puamana, and Olowalu on Maui (Brown, 1999), and Molokini (B. N. Tissot, written commun., 2000).

The fringing reef along the south shore of Moloka‘i is considered to be one of the best-developed reef tracts in the Hawaiian archipelago (Storlazzi and others, 2003). This reef tract, however, has been subjected to a variety of natural (Branham and others, 1971) and anthropogenic (Roberts, 2001; J. Reich, oral commun., 2001) stresses during the course of human habitation. Consequently, recent research efforts have focused on the response of the reef system to these stresses and the possible causal mechanisms.

The purpose of this chapter is to provide baseline spatial and temporal data for reefs along the south shore of Moloka‘i. Percent coral cover and population dynamics (for example, recruitment) of the abundant coral species at three sites are described using two approaches. First, visual quadrats and digital video transects were used to analyze historical development of each reef over the past 5 years. Second, a more detailed but smaller scale approach used fixed photoquadrats to track individual colonies over the same time period to document life-history patterns (for example, growth, recruitment, and mortality) of various species at each reef. These patterns helped characterize the present condition of these reefs and identified areas undergoing changes that could be explored with future research studies.

Methods

Study Sites

Three long-term monitoring sites were established along the south coastline of Moloka‘i to examine changes in coral cover over time (Pālā‘au, Kamiloloa, and Kamalō) (fig. 1). At each site two stations were sampled, at 3-m (10-ft) and 10-m (33-ft) depths. Sites were haphazardly selected along a perceived gradient of sediment stress and wave exposure. Historical erosion at Pālā‘au suggested that this site would show evidence of severe sediment deposition (Roberts, 2001). Eastward towards Kamiloloa, higher coral cover was predicted because of lower sedimentation levels and a more wave-sheltered environment. Finally, at the easternmost site of Kamalō, coral cover was expected to be highest and protected from all but the most severe storm events. These study sites were incorporated into the Hawai‘i Coral Reef Assessment and Monitoring Program (CRAMP) monitoring sites in 2000 as

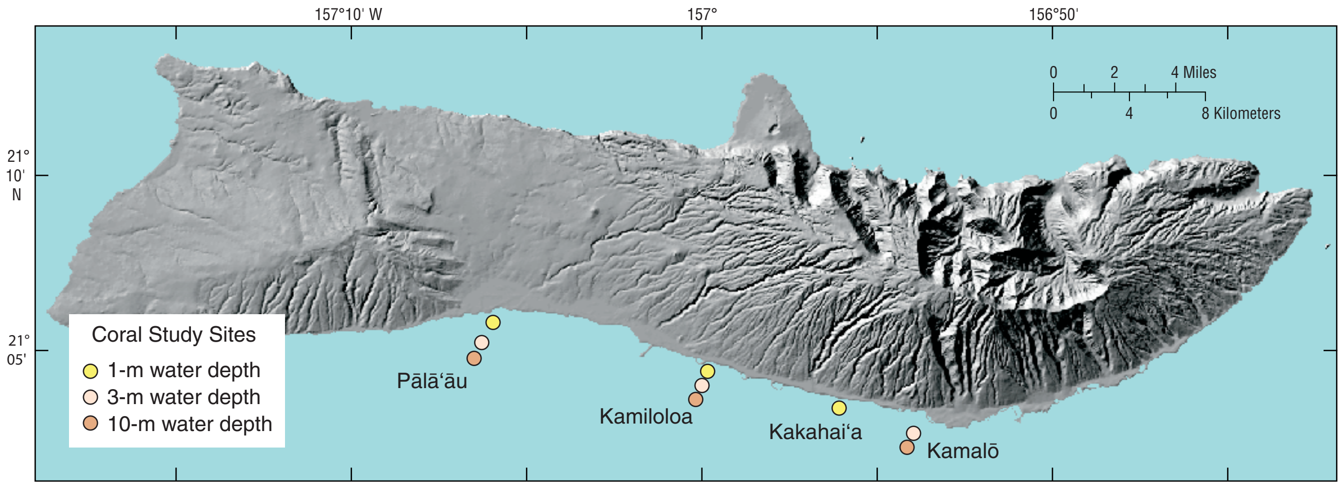


Figure 1. Study sites at Pālā‘au, Kamiloloa, and Kamalō along the south shore of Moloka‘i, Hawai‘i. At each site there are 3 stations, at depths of 1 m, 3 m, and 10 m (3.3 ft, 10 ft, and 33 ft). The 1-m station at Kakahai‘a served as the inshore station for Kamalō because of inaccessibility to suitable habitat near the Kamalō 3-m and 10-m stations.

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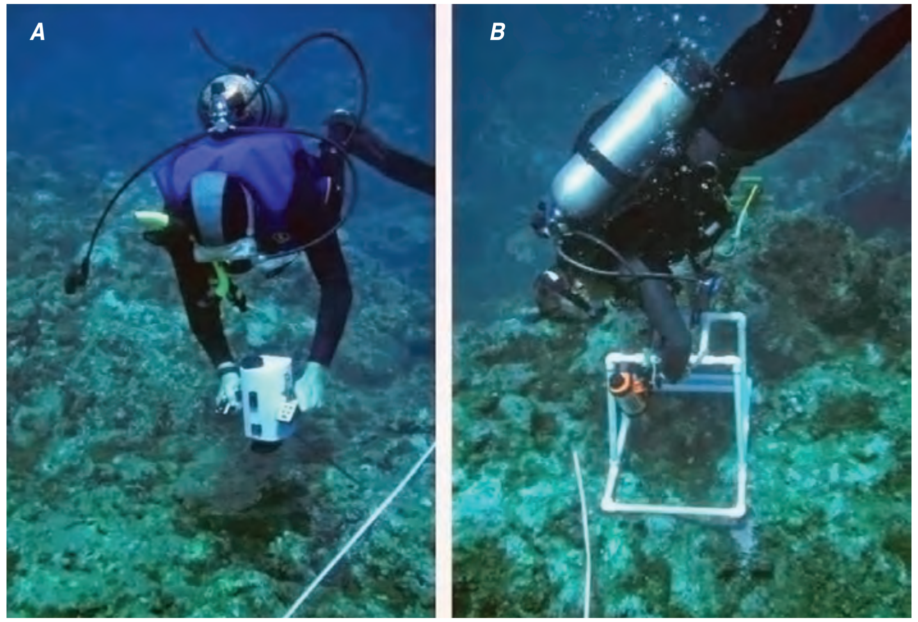


Figure 2. Digital video-transect (*A*) and photoquadrat (*B*) methods used to survey the benthic community. Ten permanent (fixed) 10-m (33 ft) transects were initially selected at random within a grid 2 m ×100 m (6.6 ft × 330 ft) along either the 3-m (10 ft) or 10-m isobath and videotaped annually from a height of 0.5 m (1.6 ft) above the substrate. Five photoquadrats at each station were randomly established in 2000 within the same grid and sampled at least once a year. At the shallow (1-m; 3.3-ft) station, sample size was increased to 10 photoquadrats to accommodate the more dynamic environment.

part of the larger statewide effort to document changes in coral cover (Jokiel and others, 2004).

Three additional stations were set up at 1-m depth (3.3-ft, on the reef flat) to document life-history patterns in highly turbid water (Pālāʻau, Kamiloloa, and Kakahaiʻa). The shallow stations on the reef flat at Pālāʻau and Kamiloloa were inshore of the deeper 3-m and 10-m stations (fore reef). Kakahaiʻa served as the inshore station for Kamalō because of inaccessibility to suitable habitat near the Kamalō 3-m and 10-m stations. These shallow stations were established at transitional locations on the reef flat where coral cover first became prevalent (approximately 5 percent) as one moved from shore out to the reef crest. Theoretically, these areas represented the landward edge of live coral and would most likely be influenced by anthropogenic processes nearshore.

Trends in Coral Cover

Sites were monitored annually from 2000 to 2004 using the CRAMP protocol (Brown and others, 2004; Jokiel and others, 2004) with digital video transects (fig. 2*A*). Percent cover was tabulated for coral (by species), macroinvertebrates (for example, urchins, sea stars), and other benthic substrate types (coralline algae, turf algae, macroalgae, and sand). Total mean percent coral cover, mean percent coral cover by species, species richness (number of species per transect) and diversity were calculated for each site.

Life-History Patterns

A set of five fixed photoquadrats at each 3-m and 10-m station was used to examine growth, recruitment, and mortality of individual corals (for example, Hughes, 1985; Porter and Meier, 1992) (fig. 2*B*). At the shallow 1-m stations, sample size was increased to 10 photoquadrats to compensate for the more dynamic environment. Scanned slides from the photoquadrat sampling were analyzed using image-processing software to determine horizontal areal coverage of each coral colony by species. The fate (dead, exposed, fusion, areal growth, re-emerged, recruit, and shrinkage) was tracked over the time period of the study. More detailed methods for photoquadrats are described in Brown (2004) and Brown and others (2004); examples of image analysis (fig. 3) and life-history processes (fig. 4) are included here. Only the recruitment data are presented because of the complexities of life-history dynamics that are beyond the scope of this chapter. Recruits were defined as new colonies with a minimum detectable size of 0.5 cm in diameter (area 0.2 cm^2) and no previous record of settlement in a particular location within the plot. Typically this size represents colonies of approximately 1 to 2 years of age and is defined as "visible recruitment" in contrast to "invisible recruitment" (<0.5 cm in diameter) (Fitzhardinge, 1993).

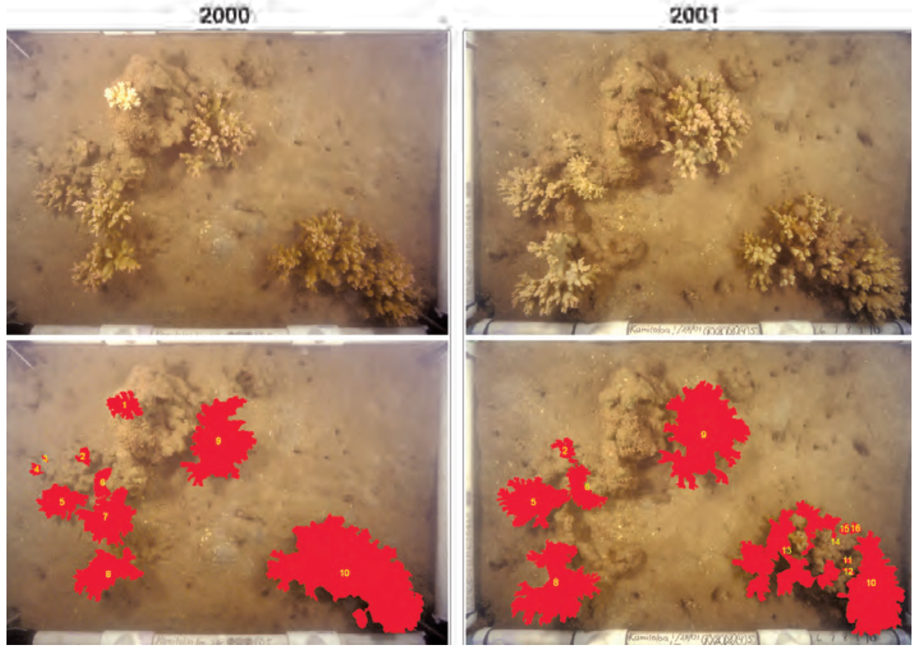


Figure 3. Examples of how coral colonies were tracked within a photoquadrat using computer image analysis. The top photographs depict the raw images in 2000 (left) and 2001 at the Kamiloloa 1-m (3.3 ft) station. The bottom row shows the labeled colonies after analysis. Each unique colony was labeled and measured for total two-dimensional area by digitally tracing the colony boundary using SigmaScan®.

Data Analysis

The long-term coral cover data were analyzed using a General Linear Model (GLM) repeated measures ANOVA design. Planned comparisons or contrasts were used to examine changes in total coral cover within each station from the initial survey to the last survey. The recruitment data were also analyzed using a General Linear Model (GLM) repeated measures ANOVA design. Planned comparisons or contrasts were then used to examine temporal trends in recruitment levels within each station and between stations across depths. For the purposes of this chapter, statistical patterns were reported without the accompanying probability values. A more detailed description of data analysis techniques can be found in Brown (2004).

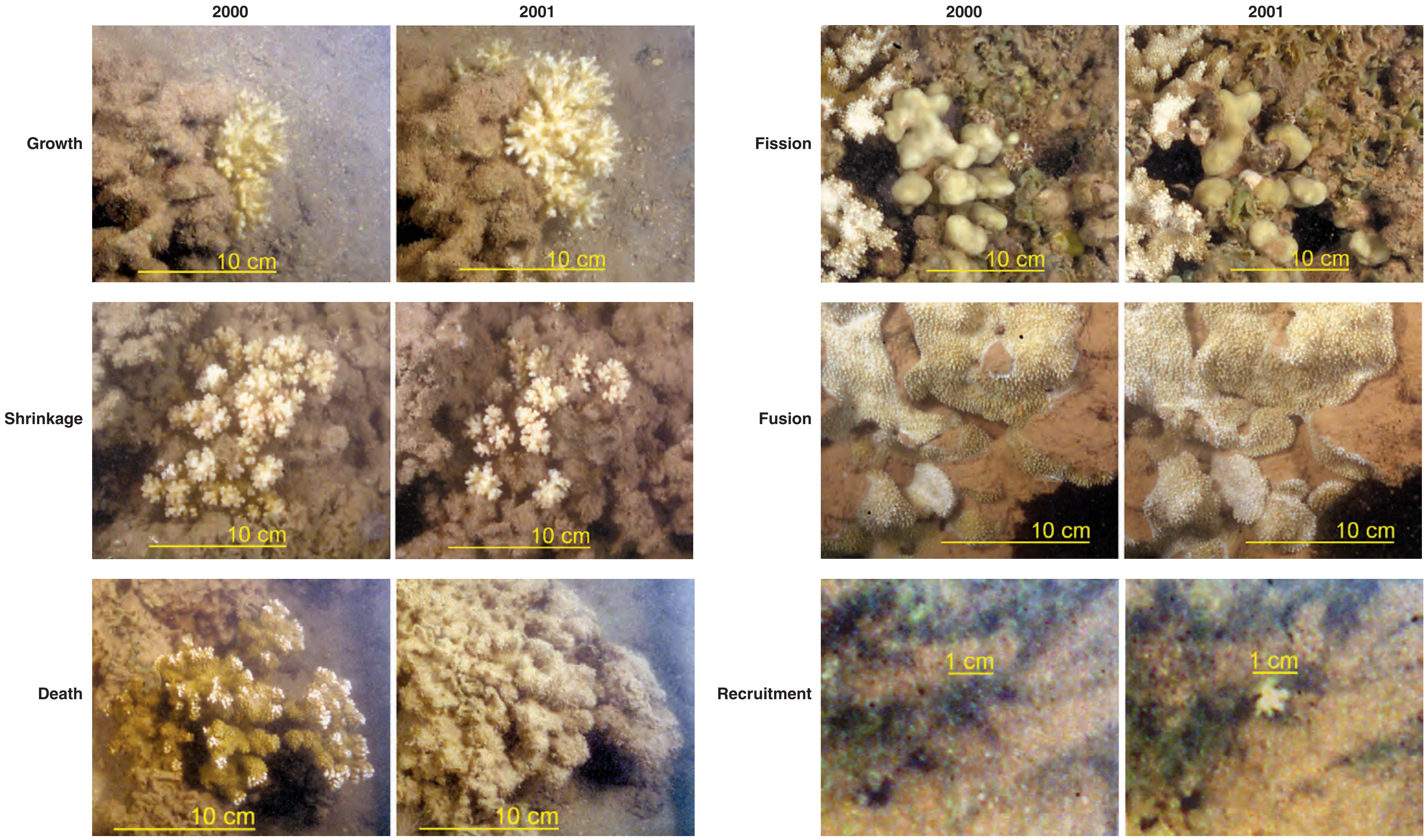
Results

Trends in Coral Cover

A total of 13 coral species were documented across all of the six stations in the initial baseline survey in 2000 (table 1). Overall, the top 5 species with the highest coverage were *Montipora capitata* (21 percent), *Porites compressa* (9 percent), *Montipora patula* (8 percent), *Porites lobata* (3 percent), and *Pocillopora meandrina* (1 percent) (fig. 5). Coral cover was highest initially at the Kamalō 10-m and 3-m stations (75 percent at both stations) and lowest at the Kamiloloa 10-m station (<1 percent). At the Kamalō stations, *Montipora capitata* (25 percent at 10 m; 59 percent at 3 m) and *M. patula* (24 percent at 10 m; 9 percent at 3 m) had the highest percent cover, followed by *Porites compressa* (25 percent at 10 m; 1 percent at 3 m), *P. lobata* (<1 percent at 10 m; 3 percent at 3 m), and *Pocillopora meandrina* (<1 percent at 10 m; <1 percent at 3 m). The community assemblage at the Pālāʻau 10-m station was also dominated by *Montipora* species (*M. capitata* 33 percent; *M. patula* 13 percent), but there was a large component of *Porites* species (*P. compressa* 25 percent; *P. lobata* 1 percent). The Pālāʻau 3-m station actually had a higher percentage of *Porites* species (*P. compressa* 5 percent; *P. lobata* 13 percent) than *Montipora* species (*M. capitata* 7 percent; *P. lobata* 3 percent) and a small percentage of *Pocillopora meandrina* (2 percent). As noted previously, the Kamiloloa 10-m station had the lowest coral cover (<1 percent), which was distributed over 7 species. The Kamiloloa 3-m station had slightly higher coral cover (4 percent) but only 6 species were observed. *P. meandrina* was the most abundant coral at this shallow station (table 1).

The long-term trends in coral cover showed stations declining, recovering (increasing), and remaining stable (fig. 6). Since 2000, coral cover at the two stations at Pālāʻau has remained relatively stable (fig. 6). The one exception was the 10-m station, which experienced a significant drop in absolute cover of 12 percent (17 percent relative) in 2004. The decline in cover was primarily attributed to *Porites compressa* (10 percent absolute, 40 percent relative). In contrast, the 3-m station at Pālāʻau experienced a decrease of <2 percent (5 percent relative decrease) in total coral cover from 2000 to

Figure 4. Examples of different life-history processes documented from 2000 to 2001 in photoquadrats. In the first year of this project, all colonies were given a unique number, even though it is highly probable that many of the colonies were the result of prior fission events. After the initial labeling, colonies (including fragments from documented fission events) were followed each year to calculate growth, shrinkage, and record total mortality. Colonies in the fission category represented any daughter colony separated from the parent colony. Fission also included fragmented colonies that fell into the plot and were still loose. Colonies that had undergone fusion were consolidated into one larger initial colony without any evidence of prior boundaries. Recruits were defined as new colonies with a minimum detectable size of 0.5 cm (0.2 in) in diameter (area 0.2 cm^2; 0.03 in^2) and no previous record of settlement in a particular location within the plot. Typically this size represents colonies around 1 to 2 years of age and is defined as "visible recruitment" in comparison to "invisible recruitment" (diameter <0.5 cm; 0.2 in).



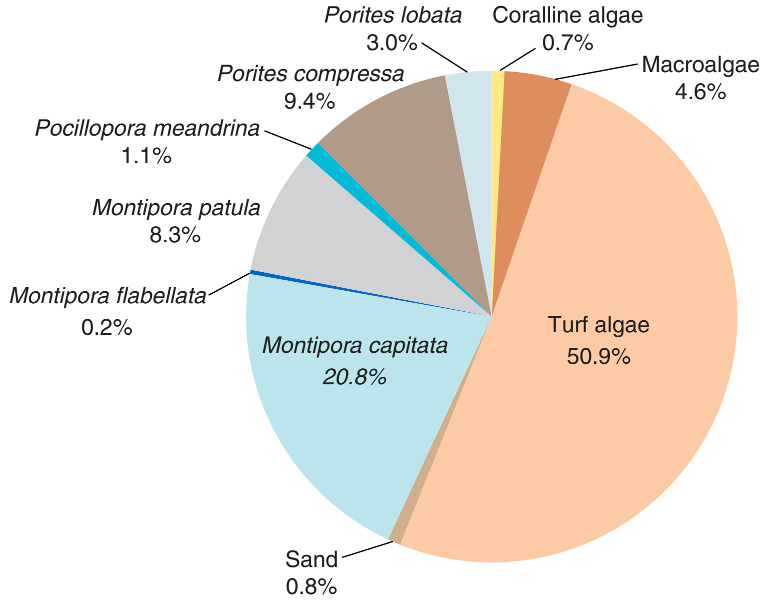


Figure 5. Chart showing mean percent substrate cover among all six of the 3-m (10-ft) and 10-m (33-ft) sites off south Moloka'i in 2000. See table 1 for data and list of common names. Substrate types and coral species with 0.1 mean percent cover or less are not included on chart.

2004. This small decrease was not statistically significant and could easily be attributed to measurement error. Consequently, the reef at the 3-m station was considered to be stable.

Coral cover at the Kamiloloa 10-m station showed a statistically significant increase of 5 percent in absolute coral cover (646 percent relative increase) since 2000 (fig. 6). The two principal species accounting for the recovery were *Montipora capitata* (4 percent absolute increase, 1,550 percent relative) and *M. patula* (1 percent absolute increase, 1,300 percent relative). *Pocillopora meandrina* and *Porites lobata* were minor components of the assemblage. In contrast, coral cover at the Kamiloloa 3-m station has remained relatively stable over the past 5 years (fig. 6) even though there has been a 1 percent decrease (30 percent relative) in coral cover. This change was statistically significant but probably not ecologically important, because coral cover was initially very low. *P. meandrina*, which was the most abundant coral in terms of coverage, has declined by 2 percent (49 percent relative) during this time period. Other species (for example, *M. capitata* and *M. patula*) that were not recorded in the initial surveys have begun to appear in the benthos, suggesting that a community shift is occurring in the assemblage.

The Kamalō 10-m station experienced a statistically significant decline in coral cover of 16 percent (21 percent relative decline) from 2000 to 2002, but it has since stabilized around 62 percent. This is still significantly lower than in the initial survey (fig. 6). The decrease in cover was primarily because of loss of *Porites compressa*, which declined steadily from 25 percent to 6 percent (76 percent relative decline) over the past 5 years. In comparison, percent cover of *Montipora capitata* has remained constant around

Table 1. Baseline percent cover by substrate type at the six south Moloka‘i CRAMP stations in 2000. Dashes (–) indicate none observed.

Substrate Type	Taxon	Common Name[1]	Pālā‘au 3 m	Pālā‘au 10 m	Kamiloloa 3 m	Kamiloloa 10 m	Kamalō 3 m	Kamalō 10 m	Mean
Coralline algae			<0.1	0.6	<0.1	0.3	0.1	3.1	0.7
Macroalgae			0.2	2.6	4.3	19.6	0.4	0.1	4.5
Turf algae			69.3	22.9	87.4	78.7	24.4	21.1	50.6
Sand			0.1	–	4.5	0.2	–	–	0.8
Coral	*Leptastrea purpurea*	Crust coral	<0.1	–	<0.1	–	–	–	<0.1
	Montipora capitata	Rice coral	6.5	32.7	–	0.2	59.5	25.2	20.7
	Montipora flabellata	Blue rice coral	–	<0.1	–	–	0.8	0.1	0.2
	Montipora patula	Sandpaper rice coral	3.0	12.9	–	0.1	9.2	24.3	8.2
	Pavona maldivensis	Maldive coral	–	<0.1	–	–	–	–	<0.1
	Pavona varians	Corrugated coral	–	–	–	–	<0.1	<0.1	<0.1
	Pocillopora damicornis	Lace coral	<0.1	–	0.1	–	0.1	–	<0.1
	Pocillopora eydouxi	Antler coral	0.2	0.1	–	0.1	0.2	–	0.1
	Pocillopora meandrina	Cauliflower coral	1.5	0.6	3.5	0.1	0.6	0.2	1.1
	Porites brighami	Brigham’s coral	–	–	<0.1	0.1	0.1	<0.1	<0.1
	Porites compressa	Finger coral	5.3	24.7	–	–	1.0	25.2	9.4
	Porites lobata	Lobe coral	13.0	1.5	0.1	0.3	3.0	0.2	3.0
	Unknown coral		0.1	0.1	<0.1	<0.1	0.2	–	0.1
	Total percent coral cover		29.6	72.4	3.7	0.9	74.6	75.2	42.7
	Species richness[2]		9	9	6	7	11	8	8

[1] Common names are from Fenner (2005).

[2] Species richness is the total number of coral species documented at a site.

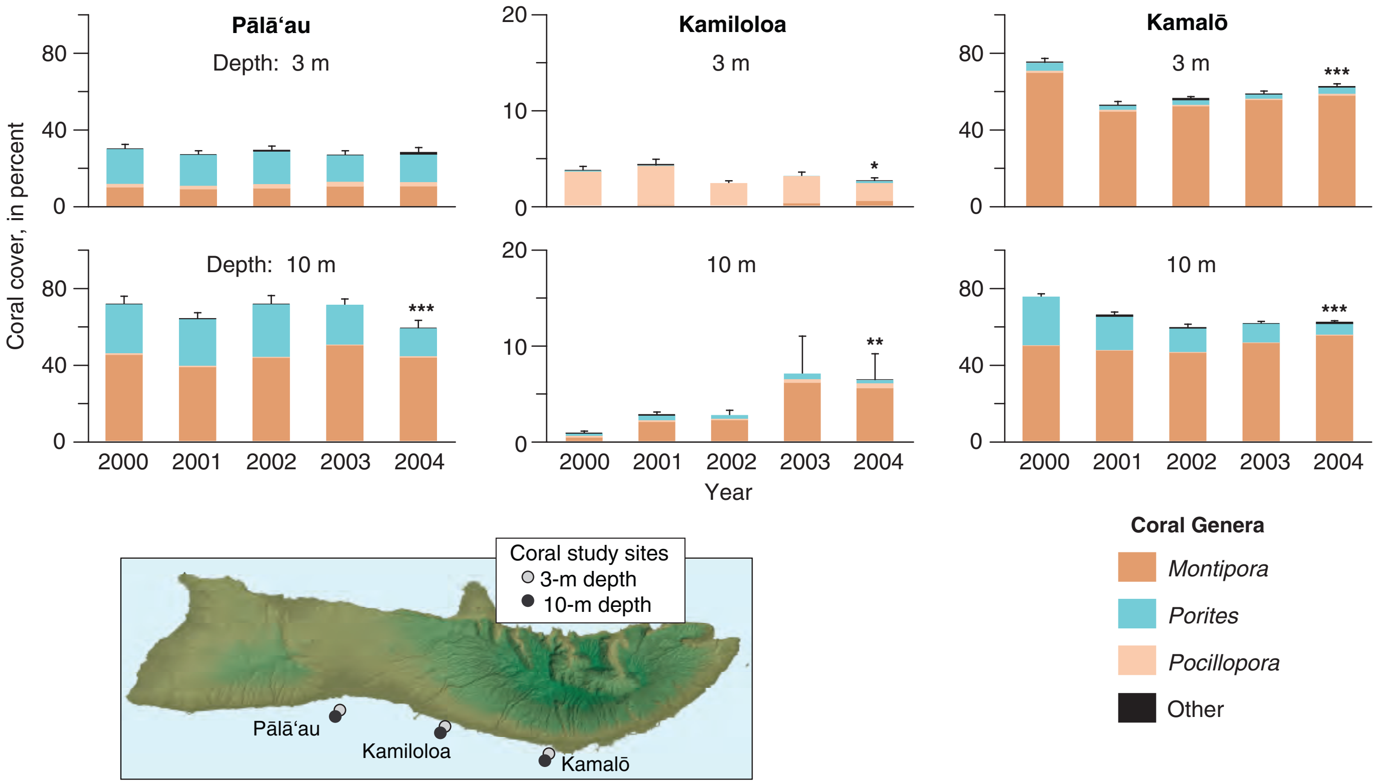


Figure 6. Trends in coral cover for the abundant genera at the deeper Moloka‘i stations (3-m and 10-m; 10-ft and 33-ft) from 2000 to 2004. Mean ± 1 standard error with a sample size of 10 transects at each station. Significant changes in coral cover from the initial survey in 2000 to the last survey in 2004 are denoted on the figures (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$). Note the different Y-axes for the Kamiloloa 3-m and 10-m stations.

25 percent while *M. patula* has actually increased 5 percent (22 percent relative). Coral cover at the 3-m station at Kamalō also suffered an initial decline of 22 percent (30 percent relative) from 2000 to 2001 (fig. 6). The coral community, however, seems to be recovering, as indicated by increases in coral cover for both *M. capitata* (6 percent absolute, 16 percent relative) and *M. patula* (6 percent absolute, 61 percent relative). The recent increase in cover, however, has not compensated for the initial loss, and consequently, cover at this station remains significantly depressed (fig. 6).

In summary, temporal trends across sites indicate that four of the six stations (Pālā‘au 10 m, Kamiloloa 3 m, and Kamalō 3 m and 10 m) experienced a statistically significant drop in coral cover after the initial survey (fig. 6). In contrast, the Pālā‘au 3-m station appeared to be holding steady, while coral cover at the centrally located Kamiloloa 10-m station increased significantly. Some of the changes in coral cover may not be ecologically important because of the confounding effects of possible measurement error with the low absolute values. In the case of the Kamalō 3-m station, recovery appears to be taking place after an initial decline in 2001. The trends will become clearer with continued monitoring over the next decade.

Life-History Patterns—Recruitment

A total of 221 new coral recruits were documented in the 60 photoquadrats from 2000 to 2004. The five most abundant species of recruits were *Montipora capitata* (89), *M. patula* (32), *Pocillopora damicornis* (26), *Porites compressa* (23), and *Porites lobata* (22) (fig. 7). Another five species (*Cyphastrea ocellina, Montipora flabellata, Pavona maldivensis, Pocillopora damicornis,* and *Porites lichen*) formed 13 percent of the new recruits in the photoquadrats. The majority of *Montipora* recruits were observed at the Kamiloloa 3-m and 10-m stations (fig. 8). Spatially, *Porites* recruits formed a larger component of the recruiting classes at the Pālā‘au 3-m, Kakahai‘a 1-m, and Kamalō 3-m stations than at the Kamiloloa stations. In comparison, pulses of *Pocillopora* recruitment were sporadic and appeared during various times at the Pālā‘au 1-m, Pālā‘au 10-m, Kamiloloa 1-m, Kamiloloa 3-m, and Kakahai‘a 1-m stations.

Recruitment rates varied by depth within a site. The number of new recruits at the Pālā‘au 1-m and 3-m stations declined after 2001, but this was not a statistically significant change (fig. 8). The recruitment rate in 2001 was 2.7 recruits/m^2/yr at the 1-m station and 3.0 recruits/m^2/yr at the 3-m station. These levels decreased to 0.3 and 0.6 recruits/m^2/yr, respectively, by 2004. In contrast, recruitment levels increased at the 10-m station from 0 recruits/m^2/yr in 2001 to 2.4 recruits/m^2/yr by 2004. This increase was not statistically significant because of the high variation in recruitment numbers.

At Kamiloloa, recruitment rates at the 1-m station were relatively stable across the 4 years and ranged from 0.9 to 1.8 recruits/m^2/yr (fig. 8). The recruitment rate at the 3-m station was 6.1 recruits/m^2/yr in 2001 and then jumped up to 8.5 recruits/m^2/yr in 2002. In 2003 and 2004, recruitment dropped off to 2.4 and 3.0 recruits/m^2/yr, respectively. The 10-m station at Kamiloloa followed a similar pattern, with high recruitment in 2001 (17.0 recruits/m^2/yr) followed by an increase in 2002 (23.0 recruits/m^2/yr) and then a subsequent decline in 2003 and 2004 to 3.0 recruits/m^2/yr. The declines in 2003 and 2004 from the preceding years were statistically significant.

Recruitment rates at the Kakahai‘a 1-m station showed a general decline from 5.2 recruits/m^2/yr in 2001 to 0.9 recruits/m^2/yr in 2004 (fig. 8). This decrease was not statistically significant even though it represented a fivefold drop in recruitment. The most likely explanation for the apparent decrease is that recruitment fluctuated dramatically among the photoquadrats, especially in 2001.

The 3-m and 10-m stations at Kamalō displayed an even more pronounced and steady decline in recruitment than at Kakahai‘a (fig. 8). At the 3-m station, recruitment rates dropped from 2.4 recruits/m^2/yr in 2001 to 0 recruits/m^2/yr in 2004. The 10-m station experienced a tenfold decrease in recruitment, from 6.1 recruits/m^2/yr in 2001 to 0.6 recruits/m^2/yr in 2004. Despite the dramatic reduction in recruitment rates, these declines were not statistically significant because of the high variability in recruitment rates among photoquadrats.

In summary, recruitment rates at Pālā‘au were generally lower in comparison to the other sites at each of the depths sampled (fig. 8). In comparison, Kamiloloa had the highest recruitment rates, and this was attributed to the high initial recruitment of *Montipora* spp. Over time, most of the stations experienced a drop in recruitment rates, except for the Pālā‘au 10-m station, which increased, and the Kamiloloa 1-m station, which remained at a consistently low level. Deeper stations generally had higher recruitment rates than the corresponding shallow stations at a given site. The Pālā‘au 10-m station, however, had low initial recruitment rates compared to the shallow stations, but in 2004 recruitment was more than threefold higher than the shallow stations.

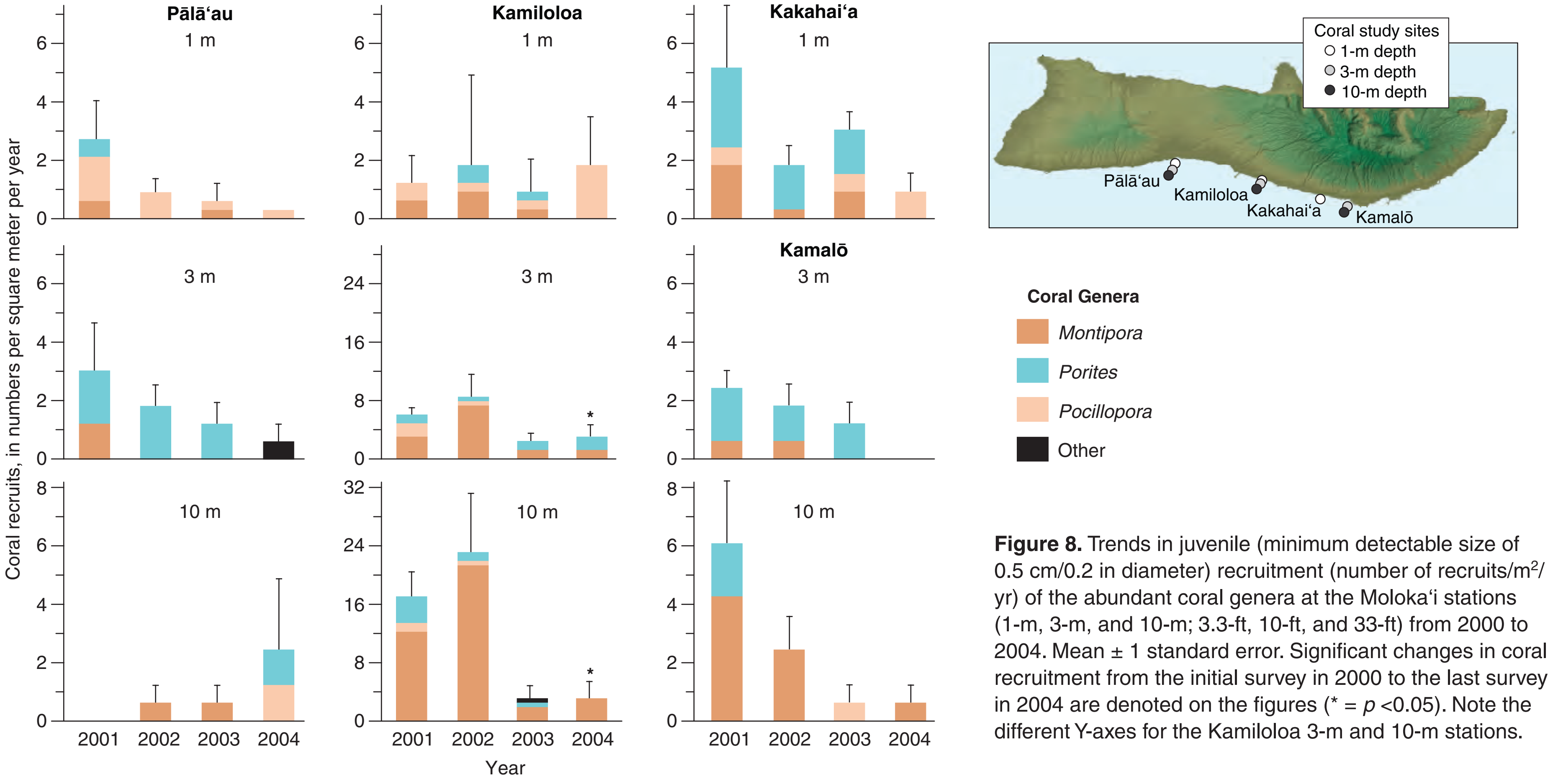


Figure 8. Trends in juvenile (minimum detectable size of 0.5 cm/0.2 in diameter) recruitment (number of recruits/m^2/yr) of the abundant coral genera at the Moloka‘i stations (1-m, 3-m, and 10-m; 3.3-ft, 10-ft, and 33-ft) from 2000 to 2004. Mean ± 1 standard error. Significant changes in coral recruitment from the initial survey in 2000 to the last survey in 2004 are denoted on the figures (* = $p < 0.05$). Note the different Y-axes for the Kamiloloa 3-m and 10-m stations.

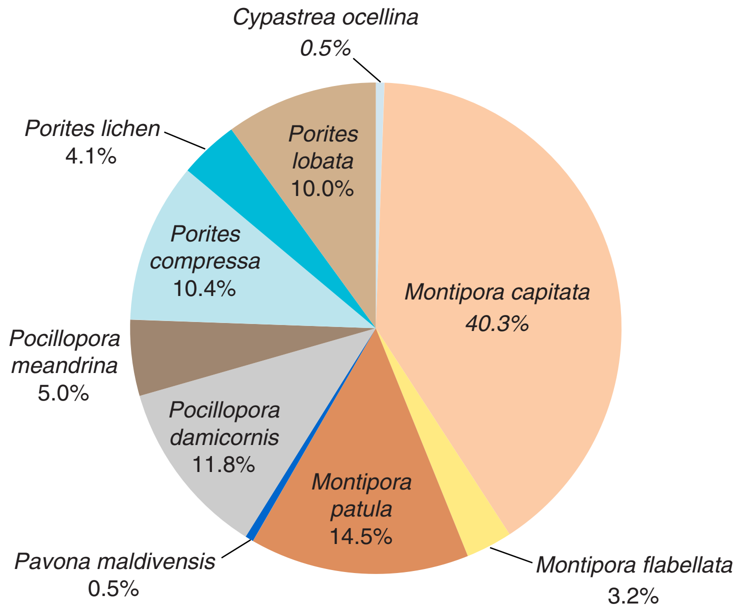


Figure 7. Chart showing percentage of new coral recruits by species among all nine of the stations off south Moloka‘i from 2000 to 2004. See table 1 for data and list of common names.

Discussion

Trends in Coral Cover

Analysis of long-term monitoring data at stations along the south shore of Moloka‘i over the past 5 years has documented patterns of reef decline, recovery, and stability. Stations spanning a distance >20 km, such as the Pālā‘au 10-m, Kamiloloa 3-m, and Kamalō 3-m and 10-m stations, all experienced declines in coral cover since 2000, although the Kamalō 3-m station appeared to be recovering (fig. 6). In contrast, coral cover at the centrally located Kamiloloa 10-m station was increasing, while less than 200 m away at the 3-m station it decreased. In addition, the Pālā‘au 3-m station, which is only 250 m from the 10-m station, appears to be holding steady compared to the declining 10-m station. What explains these differences in community trends over varying distances?

Coral community structure at each of the stations reflects the influence of natural and anthropogenic factors along the fringing reef tract. The principal natural factors on the south shore of Moloka‘i, discussed separately in other chapters in this volume and elsewhere, include wave exposure (Storlazzi and others, this vol., chap. 11), tidal cycle (Storlazzi and others, 2004), wind patterns (Storlazzi and others, this vol., chap 11), freshwater intrusion (Grossman and others, this vol., chap. 13), and natural erosion from land (Roberts and Field, this vol., chap. 15). Wave disturbance has been proposed as the primary factor shaping coral reef communities in Hawai‘i (Grigg, 1983; Jokiel and others, 2004). The long-term trends in coral cover on Moloka‘i suggest that stations within a site at a scale of several hundred meters are influenced differently by wave events. Indeed, Connell and others (1997) observed that reefs in close proximity (30-300 m) at Heron Island in the Great Barrier Reef varied in their response to natural disturbances such as cyclones over a 30-year period. Edmunds (2002) also found contrasting patterns in long-term (12 yr) cover data from two sites in the U.S. Virgin Islands separated by <1 km. He attributed this pattern to the different depths and the coastal features that protected one reef from the impact of Hurricane Hugo in 1989.

In the present study at Moloka‘i, it appears that depth may also play a role in producing differential trends in coral cover, but the trends were not the same at a given depth. Disturbances (for example, waves, flooding, coastal development) over the past 5 years may have been of sufficient magnitude to alter coral community structure between stations within a site. For example, the cooler average water temperatures at the shallow Kamalō and

Kakahai‘a stations suggests that freshwater intrusion has been higher than at deeper stations and stations further west (E. K. Brown, written commun., 2004). Spatial patterns in historical precipitation levels on Moloka‘i support this observation (Giambelluca and Schroeder, 1998). Heavy rainfall in Hawai‘i has been known to result in reef “kills” caused by freshwater intrusion at the surface on shallow reef areas (Jokiel and others, 1993). This may explain the sudden decline in coral cover from 2000 to 2001 at the Kamalō stations. Precipitation levels during this time period, however, were not abnormally high (National Climatic Data Center, v://www.ncdc.noaa.gov/oa/ncdc.html, accessed August 31, 2007), so this scenario does not appear likely. Biological factors such as predation, parasitism, disease, competition, and bioerosion can also play a role and add to the dynamic changes that occur on reefs.

The primary anthropogenic factor on Moloka‘i appears to be sedimentation from erosion (Roberts, 2001) and the subsequent resuspension of the sediment along the reef flat (Ogston and others, 2004; Storlazzi and others, 2004; Presto and others, 2006). Initial site selection for this study was based on a perceived sediment stress gradient from Pālā‘au, which was believed to be the most heavily impacted site, to the more easterly Kamalō, with relatively little sediment influx. Roberts (2001) reported that cattle ranching in western and central Moloka‘i in the mid-to-late 1800s and early 1900s resulted in a severe loss of native vegetation, producing upland erosion and subsequent deposition at Pālā‘au. Parts of the shoreline at Pālā‘au have prograded approximately 200 m since the late 1800s (see D’Iorio, this vol., chap. 16, for a further discussion of historical shoreline changes). Consequently, it was hypothesized that the sediment influx would have detrimental impacts on the adjacent reef. Clearly this was not the case at Pālā‘au, where moderate to high coral cover has been coupled with the relatively steady state in community structure. It appears that the introduction of the mangroves in 1902 (Roberts, 2001), coupled with the reduction in cattle grazing, served to retain upland sediment close to shore and reduce sediment influx onto the reef. Kamiloloa farther east was the depauperate site, with some of the lowest coral cover in the state (Jokiel and others, 2004). Surveys of coral cover at 1-km intervals along the 10-m isobath indicated that coral reefs at Kamiloloa are situated in a pocket of low (<5 percent) coral cover surrounded by regions of extremely high (>60 percent) coral cover (Storlazzi and others, 2005). Thus, it appears that most of the anthropogenic stress is now focused on the region between Kawela and Kamiloloa because of the sediment influx and resuspension (Storlazzi and others, 2004).

An important point to consider in the development of a coral reef is the coral community structure at the initial observation. The Pālā‘au 10-m and Kamalō 3-m and 10-m stations all had high coral cover >50 percent in 2000. Consequently, it is much more likely that coral cover would decline rather than increase (Hughes, 1993). In comparison, the Kamiloloa stations had <5 percent coral cover, so the probability of coral cover increasing is much greater. Therefore, long-term trends must be interpreted with caution.

Recruitment Patterns

Biological processes such as recruitment could explain coral-cover temporal patterns at stations in close proximity. Recent evidence suggests that many marine populations of corals, fish, molluscs, and crustaceans once considered open to larval input at a large spatial scale are in fact relying more on self-recruitment than on outside sources (Kingsford and others, 2002; Sponaugle and others, 2002; Swearer and others, 2002; Warner and Cowen, 2002). Perhaps the coral populations in this study are self-seeding and therefore heavily influenced by the local adult community. Harriott (1992) hypothesized this relationship at an isolated subtropical reef (Lord Howe Island), but in that case the coral recruits came from brooding corals rather than the broadcast spawners documented in this study. Brooding corals have exhibited a shorter time to competency (Harriott, 1992) and a larger dispersal potential than broadcast spawners (Richmond, 1988), which would facilitate self-seeding. Consequently, it is not directly apparent in this study that self-seeding is occurring, but genetic analysis of the coral recruits and surrounding adult population may help resolve this question. Supply-side considerations indicate that a decline in living tissue would subsequently reduce reproduction and ultimately recruitment (see, for example, Hughes and others, 2000). The lag time, however, between the decline in coral cover and the subsequent reduction in local recruitment may not be evident in the short time frame of this study.

Spatial patterns in recruitment rates at the Moloka‘i stations generally corresponded to trends in coral cover. For example, the Kamiloloa 10-m station had the highest annual recruitment rate among the 9 stations (fig. 8), and this was the only station that experienced an increase in coral cover. This increase was attributed to the high initial recruitment of *Montipora* spp. in 2001 and 2002, which also most likely resulted in the abundance of this genus in the community structure (fig. 6). Other examples included the low recruitment rate at the Pālā‘au 10-m station coupled with the declining coral cover at this same station. Some recruitment patterns, however, did not match the trend in coral cover. An example is the high annual recruitment at the Kamiloloa 3-m station (fig. 8) and the low coral cover that was actually decreasing (fig. 6). This pattern suggests that high water motion and the resulting sediment stress (Storlazzi and others, 2004) are limiting recruitment success at this station. Other possibilities exist to explain the poor relationship between recruitment and coral cover trends at certain stations. Perhaps the source of recruitment is from nearby reefs outside the sampling area, or maybe differential mortality is occurring at the stations for all age classes.

Temporal patterns in recruitment are more difficult to interpret because of the highly variable nature of recruitment (Hughes and others, 1999a; Brown, 2004) and the short time frame of this study. For example, the higher initial recruitment at each of the stations may simply be an episodic recruitment pulse rather than a high, sustained level of recruitment along the Moloka‘i coastline followed by a subsequent decline. Therefore, understanding temporal patterns in recruitment probably requires monitoring over time scales commensurate with coral reproductive patterns (that is, decades).

In general, recruitment rates for similar species and genera were lower in this study compared to other studies around the globe (table 2). Higher rates were documented by Smith (1992) for *Porites astreoides* (12.1 recruits/m^2/yr) in Bermuda and by McClanahan (2000) for *Porites* spp. (3.3 recruits/m^2/yr) in the Maldives (table 2). Connell (1973) and Connell and others (1997) reported recruitment rates averaging 5 recruits/m^2/yr for all coral taxa on recovering reefs subjected to periodic cyclones in the Great Barrier Reef. In their study, the highest recruitment rates (mean 8 to 13 recruits/m^2/yr) occurred at reefs that experienced the greatest absolute declines in percent coral cover (Connell and others, 1997). Smith (1992), however, observed similar recruitment rates at both damaged (12 recruits/m^2/yr) and control (13 recruits/m^2/yr) reefs in Bermuda. In addition, Loch and others (2002) documented recruitment rates of 12 recruits/m^2/yr at reefs in the Maldives that had experienced severe bleaching during the 1998 El Niño event. Consequently, high recruitment rates associated with various disturbance events imply either that larval sources are not necessarily local or that adult fecundity was unaffected by the storms, at least within the spatial scale (100 m) of the sampled adult community.

Perhaps the coral communities on Moloka‘i, with low coral recruitment in comparison to other areas, have not experienced disturbances of sufficient magnitude to open up suitable substrate for new recruits. Indeed, the highest recruitment rates were observed at stations (Kamiloloa 3-m and 10-m) with the lowest coral cover. If these Kamiloloa stations had experienced a recent disturbance, then substrate could have become available for settlement from adjacent coral communities with high cover. Larger scale qualitative surveys have documented coral-rich communities east and west of Kamiloloa (Storlazzi and others, 2005) that could easily have accounted for the high recruitment seen at these stations. It is important to note, however, that disturbance events are not necessarily associated with wave phenomena and do not necessarily promote recruitment. For example, sediment stress, either acute or chronic, might actually reduce the amount of available substrate for recruitment (Rogers, 1990; Fabricius, 2005). Given the high recruitment levels at the two Kamiloloa fore reef stations coupled with high sediment accumulation (Storlazzi and others, 2004) and resuspension (Ogston and others, 2004), it appears that sediment may not influence recruitment rates as much as other factors such as adult fecundity (Hughes and others, 2000). Lack of sediment data at the other stations, however, limits any spatial and temporal conclusions regarding disturbance type and recruitment.

In Hawai‘i, other studies of juvenile recruits (>0.5 cm in diameter) on natural substrates have included Polacheck (1978) on O‘ahu and Brown (2004) on Maui. Polacheck (1978) found no *Montipora* spp. or *Porites* spp. recruits and lower *Pocillopora meandrina* recruitment rates (0.18 recruits/m^2/yr) in comparison to this study (mean 0.26 recruits/m^2/yr) (table 2). His study sites off Waikīkī may not have been conducive for good recruitment because of large areas of unconsolidated sediment (Coyne and others, 2003), which can inhibit survival of new recruits (Fabricius, 2005). Polacheck’s study was also 1 year in duration and may not have detected episodic recruitment events. In contrast, Brown (2004) documented high recruitment rates for all species at his west Maui sites (table 2). The difference in recruitment rates between these studies can possibly also be explained by the lower coral cover, and thus more available substrate, at the west Maui stations (Brown, 2004). It should be noted, however, that areas existed on both islands with plenty of available space but low recruitment. Thus, other factors (for example, sedimentation stress, larval availability) must also be contributing to the low recruitment observed in these photoquadrats.

Table 2. Average coral recruitment on natural substrates for juveniles (minimum detectable size of 0.5 cm/0.2 in diameter and no previous settlement record) of coral species and genera in the Caribbean, Pacific, and Indian Oceans.

[Recruitment rates for Moloka‘i are averaged across all nine stations for the four years 2001–2004.]

Site	Region	Genus/Species	Common Name[1]	Recruitment (number of recruits/m^2/yr)	Reference
O‘ahu, Hawai‘i	Pacific	*Montipora capitata*	Rice coral	0	Polacheck (1978)
Maui, Hawai‘i	Pacific	*Montipora capitata*	Rice coral	4.5	Brown (2004)
Moloka‘i, Hawai‘i	Pacific	*Montipora capitata*	Rice coral	1.4	Brown and others, this study
Maui, Hawai‘i	Pacific	*Montipora flabellata*	Blue rice coral	0.3	Brown (2004)
Moloka‘i, Hawai‘i	Pacific	*Montipora flabellata*	Blue rice coral	0.1	Brown and others, this study
Great Barrier Reef	Pacific	*Montipora foliosa*	*	0.3	Connell (1973)
Great Barrier Reef	Pacific	*Montipora hispida*	*	0.3	Connell (1973)
Maui, Hawai‘i	Pacific	*Montipora patula*	Sandpaper rice coral	1.0	Brown (2004)
Moloka‘i, Hawai‘i	Pacific	*Montipora patula*	Sandpaper rice coral	0.5	Brown and others, this study
Maldives	Indian	*Montipora* spp.		0.4	McClanahan (2000)
Great Barrier Reef	Pacific	*Pocillopora damicornis*	Lace coral	0.7	Connell (1973)
Moloka‘i, Hawai‘i	Pacific	*Pocillopora damicornis*	Lace coral	0.2	Brown and others, this study
O‘ahu, Hawai‘i	Pacific	*Pocillopora meandrina*	Cauliflower coral	0.2	Polacheck (1978)
Maui, Hawai‘i	Pacific	*Pocillopora meandrina*	Cauliflower coral	1.0	Brown (2004)
Moloka‘i, Hawai‘i	Pacific	*Pocillopora meandrina*	Cauliflower coral	0.2	Brown and others, this study
Maldives	Indian	*Pocillopora* spp.		0.1	McClanahan (2000)
Great Barrier Reef	Pacific	*Porites annae*	Nodule coral	0.7	Connell (1973)
Bermuda	Caribbean	*Porites astreoides*	Mustard hill coral	12.1	Smith (1992)
Florida	Caribbean	*Porites astreoides*	Mustard hill coral	1.3	Miller and others (2000)
O‘ahu, Hawai‘i	Pacific	*Porites compressa*	Finger coral	0	Polacheck (1978)
Maui, Hawai‘i	Pacific	*Porites compressa*	Finger coral	1.7	Brown (2004)
Moloka‘i, Hawai‘i	Pacific	*Porites compressa*	Finger coral	0.3	Brown and others, this study
Maui, Hawai‘i	Pacific	*Porites lobata*	Lobe coral	1.1	Brown (2004)
Moloka‘i, Hawai‘i	Pacific	*Porites lobata*	Lobe coral	0.3	Brown and others, this study
Great Barrier Reef	Pacific	*Porites lutea*	Mound coral	0.9	Connell (1973)
Florida	Caribbean	*Porites porites*	Finger coral	0.4	Miller and others (2000)
Maldives	Indian	*Porites* spp.		3.3	McClanahan (2000)

[1] Common names are from Fenner (2005) for Pacific species and Humann (1993) for Caribbean species. Species denoted with an * have no documented common name.

Statewide and Global Comparisons of Reef Condition

Spatial patterns in coral cover indicate that reefs along the south shore of Moloka‘i have both some of the highest levels and some of the lowest levels of coral cover found in Hawai‘i (Jokiel and others, 2004). Sections of the reef around Kamalō contain some of the most densely packed coral communities in the State. Temporal patterns, however, reveal that the Moloka‘i sites may not be faring as well as other sites in Hawai‘i. From 2000 to 2002, the six CRAMP stations on Moloka‘i discussed here experienced the largest decline (by island) compared to the other 54 CRAMP stations on Kaua‘i, O‘ahu, Kaho‘olawe, Maui, and Hawai‘i (Jokiel and others, 2004) (fig. 9). The decline was not statistically different from those stations on O‘ahu and Maui, but declines in coral cover on O‘ahu and Maui corresponded to high human populations. In contrast, Moloka‘i has a small population relative to land area (Juvik and Juvik, 1998), so causal mechanisms have focused on poor land-use management, attempted coastal development (Roberts, 2001), and the subsequent sediment influx and resuspension on the reef (Ogston and others, 2004). Efforts are currently underway on Moloka‘i to control feral ungulates and revegetate upland areas.

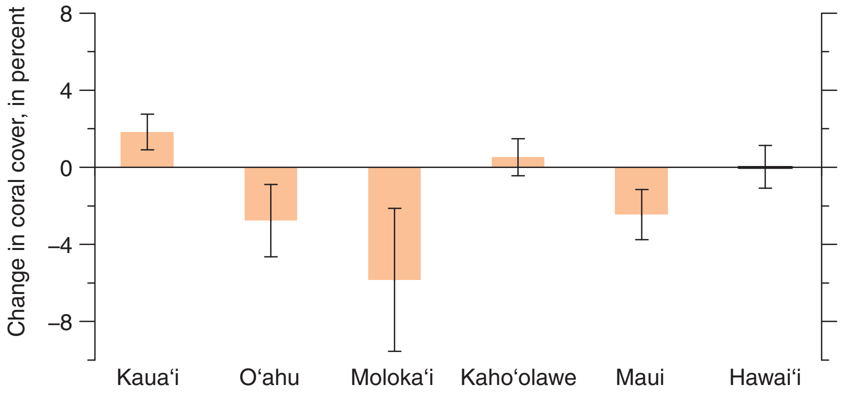


Figure 9. Mean percent change (±1 standard error) in coral cover by island at sites across the state of Hawai‘i from 1999 to 2002 (from Jokiel and others, 2004).

Reefs in the Hawaiian archipelago appear to be doing better than reefs in other parts of the world. Of the 20 regions examined in the latest biennial review, “Status of Coral Reefs of the World: 2004,” the Hawai‘i region had the highest percentage of reefs (93 percent) at low or no threat level (Wilkinson, 2004). Only 1 percent of the reef area in the region is considered destroyed (Waikīkī) compared to a high of 65 percent in the Persian Gulf (Wilkinson, 2004). The south shore of Moloka‘i, however, was included in the 5 percent of Hawai‘i’s reefs at the threatened stage. Local residents are taking steps to reverse this pattern by changing upslope land-use patterns and limiting coastal development. These proactive measures may not be enough to protect near-shore reefs, because changes in global climate are elevating water temperatures in Hawai‘i above critical thresholds for corals (Jokiel and Brown, 2004). If annual water temperatures continue to increase with extended durations of seasonal high temperature anomalies, then reefs along the south shore of Moloka‘i may not recover. In addition, long residence time and resuspension of sediment may compound the problem (Ogston and others, 2004; Presto and others, 2006). The reefs in decline may already be responding to these chronic disturbances, which could lead to the demise of the Moloka‘i reefs. Coral reef ecosystems, however, operate in a cyclical fashion over time (Karlson, 1999), and therefore the decline we are currently witnessing may simply represent the downward portion of the community cycle before the upswing. Indeed, one station (Kamalō 3-m) is already showing signs of recovery.

Conclusions

Temporal trends in coral cover indicate that four of the six CRAMP stations on Moloka‘i (Pālā‘au 10-m, Kamiloloa 3-m, and Kamalō 3-m and 10-m) experienced a statistically significant drop in coral cover from 2000 to 2004. In contrast, the Pālā‘au 3-m station appeared to be holding steady, while coral cover at the centrally located Kamiloloa 10-m station increased significantly. Temporal patterns reveal that Moloka‘i may not be faring as well as other sites in Hawai‘i, but from a global perspective the reefs along this coastline are better off than elsewhere. Spatial patterns in recruitment rates at the Moloka‘i stations generally correspond to trends in coral cover but there are exceptions (for example, the Kamiloloa 3-m station). Recruitment rates of comparable coral species and genera are generally lower along the south shore of Moloka‘i than at other sites around the State and globally.

Moloka‘i has the longest contiguous reef tract in the main Hawaiian Islands, but there are signs that the reef community along the south shore may be experiencing a difficult period in its evolution. Coral recruitment patterns and anthropogenic stressors will need to be closely monitored to see if the reef ecosystem can continue to sustain itself. Projected changes in climate and sea level will further exacerbate an already tenuous situation along this coastline and could lead to the demise of an outstanding fringing reef area.

CHAPTER 7

Coral Reef Fishes and Fisheries of South Moloka‘i

Alan M. Friedlander[1,2] and Ku‘ulei S. Rodgers[3]

Fish provide food, cultural identity, and commerce to a broad majority of the local population of Moloka‘i and are an integral component of the marine environment. Fishes transfer energy from one location to another by their movement and thereby enhance the overall productivity of the ecosystem. Herbivorous fishes help control the spread of alien and nuisance limu (seaweed), while predators help to maintain high turnover rates and increase productivity within the ecosystem. The high proportion of species that are endemic (found nowhere else on earth) makes Hawai‘i an important location for global marine biodiversity.

Importance of Coral Reef Fishes to Hawaiian Culture

Fishing has been a way of life for Hawaiian people for centuries, with fish and shellfish providing the major protein source (Kamakau, 1839; Titcomb, 1977). Native Hawaiians depended on fishing for survival, which motivated them to acquire a sophisticated understanding of the factors that caused limitations and fluctuations in their marine resources (fig. 1). Using their familiarity with specific places and through much trial and error, Hawaiian communities were able to develop ingenious social and cultural controls on fishing that fostered, in modern terminology, “sustainable use” of marine resources (Hui Malama o Mo‘omomi, 1995). The traditional system in Hawai‘i emphasized a code of conduct that was strictly enforced (Friedlander and others, 2002a; Poepoe and others, 2007). Harvest management was not based on a specific amount of fish, but on identifying the specific times and places that fishing could occur so it would not disrupt the basic processes and habitats of important food resources. Understanding when, where, and how to conduct fishing so that it was compatible with local resource dynamics required an intimate knowledge of natural rhythms and processes associated with these resources (Hui Malama o Mo‘omomi, 1995; Poepoe and others, 2007).

Figure 1. Hawaiians have traditionally harvested the sea for sustenance and cultural purposes. Photos courtesy of Hawai‘i State Archives.

Decline in Coral Reef Fishes in Hawai‘i

A shift from purely subsistence to commercial fishing occurred with the arrival of the British and American whaling fleets during the early 1800s (Schug, 2001). After contact with Westerners, a breakdown of the traditional system of laws and regulations (kapu) and the demise of the watershed (ahupua‘a) as a management unit led to the virtual elimination of traditional Hawaiian fisheries management practices (Smith and Pai, 1992; Lowe, 2004).

Over the past 100 years the coastal fisheries in Hawai‘i have undergone enormous changes (Shomura, 1987, 2004). The early 1900s saw a rapid change from subsistence to a cash economy and large increases in the commercial landing of fish and other marine resources ensued (Cobb, 1905; Schug, 2001). Following statehood, Hawai‘i saw a rapid growth in tourism, an increasingly urban resident population, and the continued development of shoreline areas for tourism and recreation. These changes resulted in another change in the character of the coastal fisheries—they became dominated by recreational anglers and a greater number of part-time commercial fishers, who curtailed their fishing to take advantage of more lucrative economic activities (Friedlander, 2004).

Commercial landings for a number of important species have shown dramatic declines since the 1900s (fig. 2). These declines in fish abundance and size, particularly around the more populated areas of the state, are likely the cumulative result of years of chronic overfishing (Shomura, 1987; Friedlander and DeMartini, 2002). Other factors contributing to the decline of inshore fisheries include a growing human population, destruction or disturbance to habitat, introduction of new fishing techniques (for examples, inexpensive monofilament gill nets, scuba, spear guns, power boats, sonar fish finders, GPS), and loss of traditional conservation practices (Brock and others, 1985; Lowe, 1996; Friedlander and others, 2003).

Importance to Biodiversity Conservation

In addition to food and recreation, the wide variety of fishes observed in Hawaiian waters are also important to the overall health of the coral reefs and ultimately of the islands. Herbivorous parrotfishes and surgeonfishes feed on limu (seaweed) and help to prevent the overgrowth of limu on corals. Other fishes, such as weke (goatfishes), feed on shrimp and crabs in the sand and transfer that energy back onto the coral reef, thus enhancing

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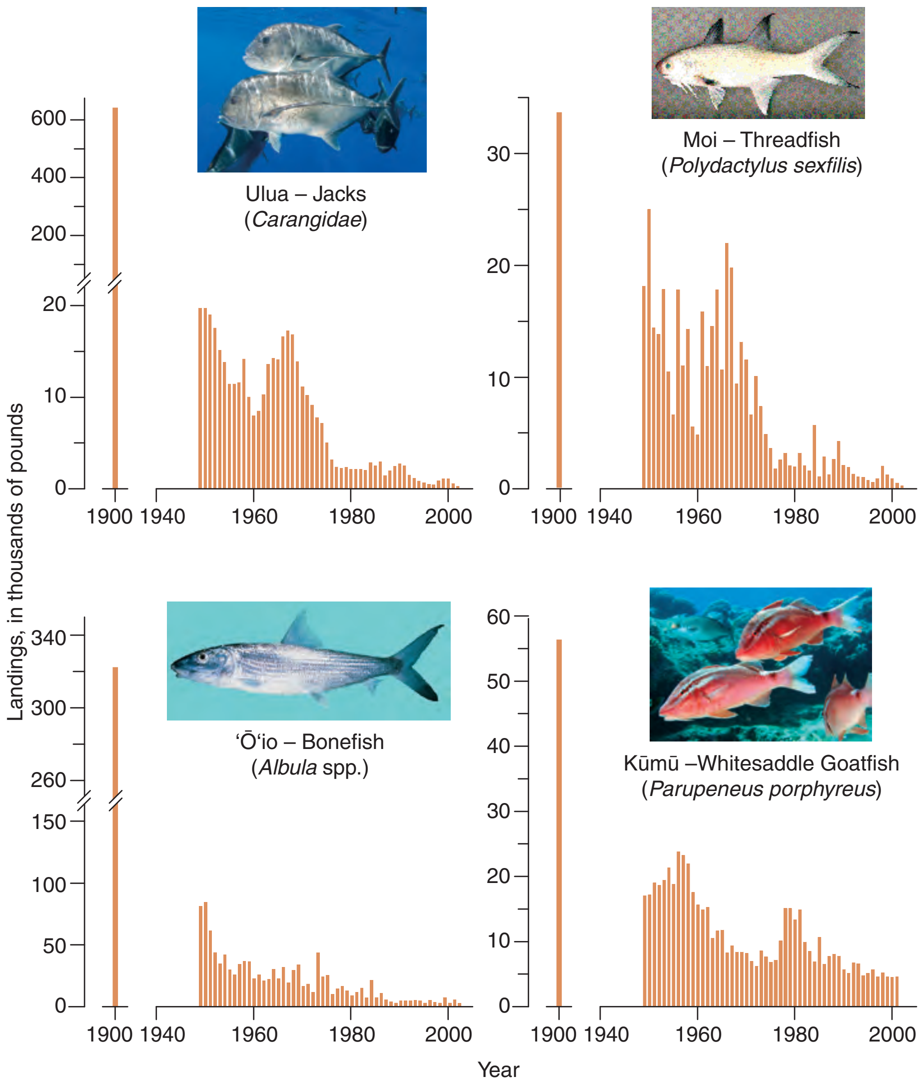


Figure 2. Statewide commercial catch data from Hawaii Department of Land and Natural Resources/Division of Aquatic Resources (DLNR/DAR) from 1948 to 2005. Data for 1990 from market surveys conducted by the United States Fish Commission. Adapted from Friedlander and others, 2005. Data sources: Cobb, 1905; DLNR/DAR, unpublished data.

the productivity of the entire ecosystem. Because fishes move energy from one part of the ecosystem to another, they are good indicators of large-scale ecosystem health.

Conserving coral reef fishes is also important to global marine biodiversity. The faunas of isolated oceanic archipelagos like the Hawaiian Islands represent species conservation hotspots that have become increasingly important because of continual losses of biodiversity on coral reefs worldwide (DeMartini and Friedlander, 2004). Owing to its geographic isolation, the proportion of endemic fishes (found nowhere else on earth) in Hawai‘i is the highest of any known tropical marine ecosystem (Randall 1996, DeMartini; and Friedlander, 2004). Many of the endemic fish species in Hawai‘i (fig. 3) are some of the most common, like hīnālea lauwili (saddle wrasse, *Thalassoma duperrey*) and kole (goldring surgeonfish, *Ctenochaetus strigosus*). Other endemics are valued food fishes like uhu uliuli (spectacled parrotfish, *Chlorurus perspicillatus*) and kūmū (whitesaddle goatfish, *Parupeneus porphyreus*). The loss of endemic species not only affects Hawai‘i but also represents a loss of global genetic diversity.

The purpose of this chapter is to describe the fish and fishery resources of the south Moloka‘i reef tract on the basis of information obtained from scientific surveys, as well as fisheries catch data and local knowledge.

Methods

Description of Survey Methods

Sampling Stations

Three permanent monitoring sites (Pālā‘au, Kamiloloa, Kamalō) have been established on the south Moloka‘i reef tract to measure coral growth and benthic cover (see Brown, this vol., chap. 6). At each site, one fish sampling station was located at 3-m depth and another at 10-m depth. Surveys along four transects, separated by 5-m gaps, were conducted at each station. Additional samples were collected using a stratified random sampling approach, where samples were stratified by major habitat type using NOAA's benthic habitat maps (Coyne and others, 2003) (fig. 4). These additional stations were classified as either shallow (≤5 m) or deep (10–20 m).

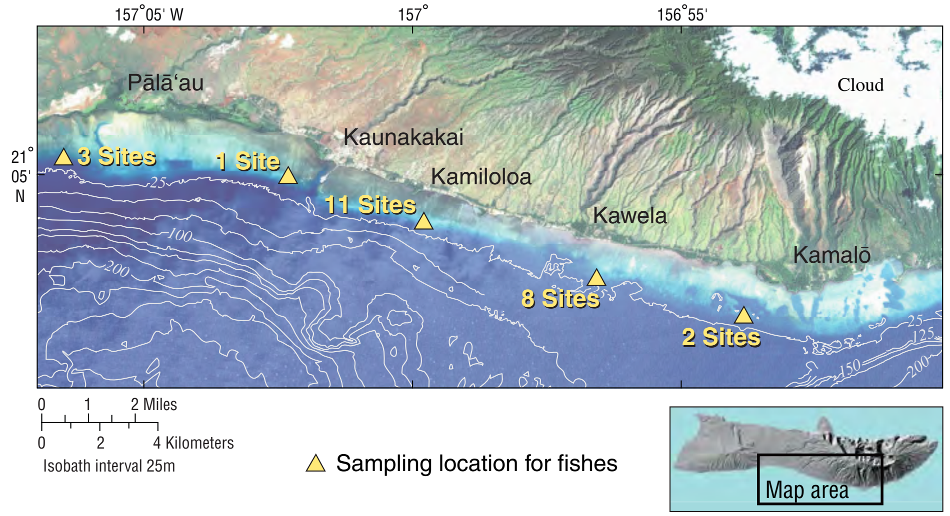


Figure 4. Satellite image showing sampling locations for fishes along the south shore of Moloka‘i.

Fish Surveys

At each station, data were collected on fish, habitat complexity (rugosity), and benthic cover. Fish assemblages were assessed using standard underwater visual belt-transect survey methods (fig. 5; V.E. Brock, 1954; R.E. Brock, 1982). A scuba diver swam each 25-m by 5-m transect at a constant speed and identified, to the lowest possible taxon, all fishes visible within 2.5 m to either side of the centerline (125 m^2 transect area).

Total length (TL) of fish was estimated to the nearest centimeter and converted to weight using a standard length-weight conversion. Total length was converted to standard length (SL) using the methodology presented by FishBase (http://www.fishbase.org, last accessed April 29, 2008). An index of relative dominance (percent frequency of occurrence times percent total numbers or percent total biomass) was calculated for comparison among taxa. Fish taxa were categorized into four trophic categories according to various published sources and FishBase. Species diversity was calculated from the Shannon-Weaver Diversity Index (Ludwig and Reynolds, 1988): H'=S (p_i ln p_i), where p_i is the proportion of all individuals counted that were of species i.

Figure 3. Endemic species (found nowhere else on earth) represent some of the most common and economically important fishes found in Hawai‘i.

Figure 5. Underwater fish survey method. The left image shows a diver recording information on fishes along a belt-transect. In the right image, a diver is calibrating length estimates using model fishes.

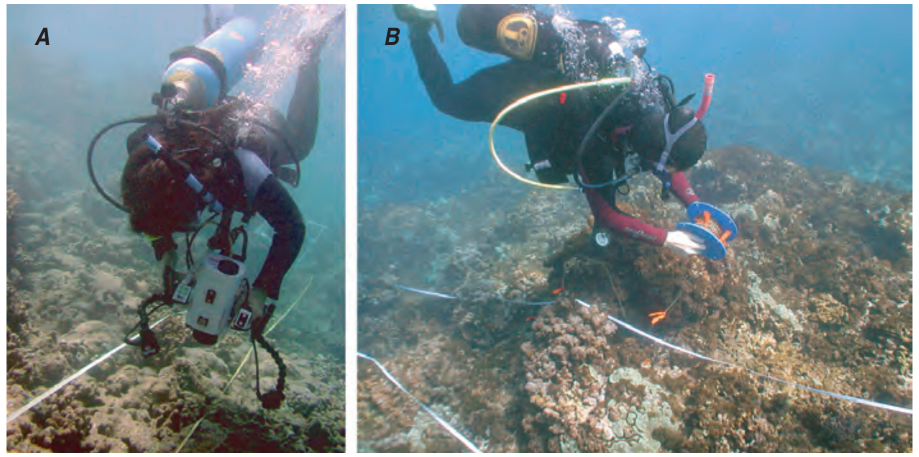


Figure 6. Underwater habitat assessment method on the south Moloka‘i reef. *A*, A diver using an underwater video camera to record benthic cover. *B*, A diver is measuring habitat complexity using a rugosity chain marked with orange flags.

Trophic Categories (primary food items and representative taxa)

- Herbivores: plant eaters; primarily parrotfishes and surgeonfishes
- Invertebrate feeders: feed on crustaceans, mollusks, and other invertebrates; representatives of this group includes goatfishes and trigger fishes
- Piscivores: primarily fish eaters; jacks including kāhala (amberjack, *Seriola dumerili*) and uku (green jobfish, *Aprion virscens*)
- Planktivores: plankton feeders; damselfishes and some unicornfishes

Benthic Habitat Assessments

To assess the characteristics of benthic populations (percent cover, species richness and diversity of corals, algal functional groups, and substrate cover), high-resolution digital images were taken along transects using a digital camera in an underwater housing (fig. 6*A*). To measure reef-surface complexity, a small-link chain (1.3 cm per link) was draped along the full length of the centerline of each transect (fig. 6*B*). Care was taken to ensure that the chain followed the contour of all natural fixed surfaces directly below the transect centerline. The ratio of distance along the reef-surface profile to linear horizontal distance gave an index of spatial relief or rugosity.

Results

Description of Fish Assemblage

Dominant Species

A total of 99 taxa of fishes were recorded on quantitative transects between January 2001 and February 2002. Dominance of fishes on south Moloka‘i reefs was calculated on the basis of contribution of each species to the total biomass or numerical abundance multiplied by the proportion of samples in which that species occurred (fig. 7). The introduced ta‘ape (bluestripe snapper, *Lutjanus kasmira*) accounted for 22 percent of the total fish biomass observed on transects, but this represented a single school of approximately 500 individuals observed on only one transect at Kakahai‘a. The dominant species by weight was the bullethead uhu (Bullethead Parrotfish, *Chlorurus sordidus*) accounting for 10 percent of total fish biomass and occurring on 70 percent of all transects. Mā‘i‘i‘i (brown surgeonfish, *Acanthurus nigrofuscus*) was the most important species by number and second most important by weight. It occurred in 74 percent of the transects and accounted for 13 percent of the numerical abundance and 5 percent of the total biomass observed. The endemic kole (goldring surgeonfish, *Ctenochaetus strugosus*) was also abundant and occurred on 62 percent of the transects and made up 11 percent of the numerical abundance and 6 percent of the total weight. Hīnālea lauwili (saddle wrasse, *Thalassoma duperrey*), also an endemic species, was the most ubiquitous species, appearing on 94 percent of all transects.

Dominant Families

The top five families listed below, plus jacks, accounted for nearly 90 percent of the total biomass observed on transects along the south Moloka‘i reef tract (fig. 8). Surgeonfishes, primarily mā‘i‘i‘i and kole, were the dominant family by both numbers and weight. Several schools of manini (convict tang, *Acanthurus triostegus*) were encountered, ranging in size from 43 to 88 individuals per school. The bullethead uhu was the most important parrotfish species by weight and number, followed by the palenose uhu (*Scarus psittacus*). Triggerfishes were the third most important family by weight and sixth by number. Humuhumu‘ele‘ele (black durgon, *Melichthys niger*), humuhumu hi‘u kole (pinktail durgon, *Melichthys vidua*), humuhumu nukunuku āpua‘a (reef triggerfish, *Rhinecanthus rectangulus*), and humuhumu lei (lei triggerfish, *Sufflamen bursa*) were the dominant species in the family. Hīnālea lauwili made up most of the wrasses by weight and number, while ta‘ape accounted for most of the snappers, followed by uku (green jobfish, *Aprion virscens*).

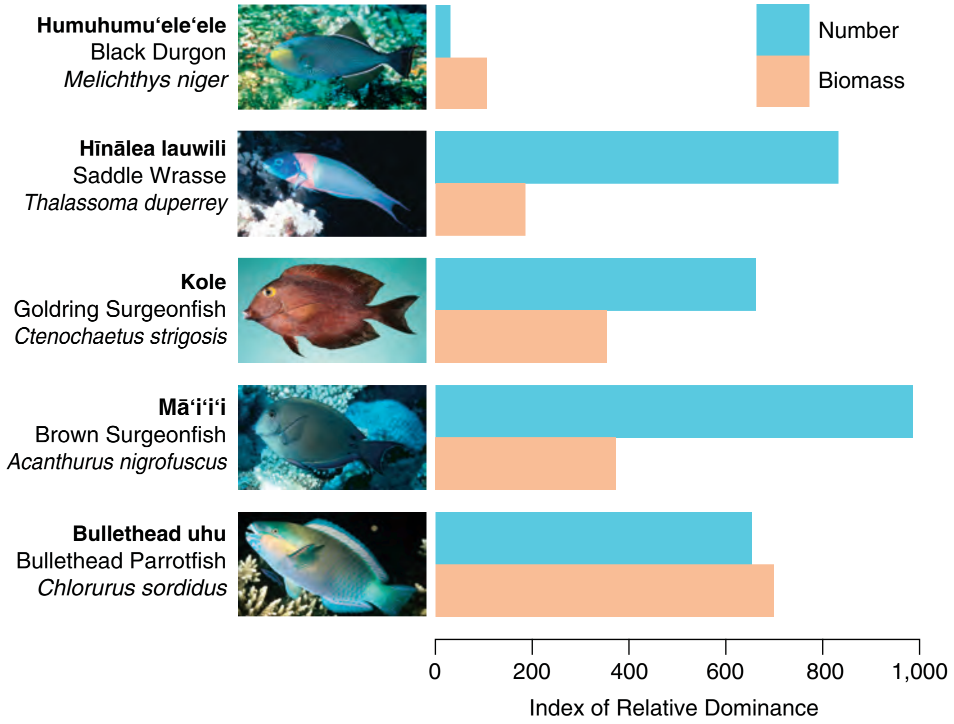


Figure 7. Index of relative dominance (percent frequency of occurrence times percent total number or percent total biomass) for the five most dominant species of fish appearing on transects along the south Moloka‘i coast.

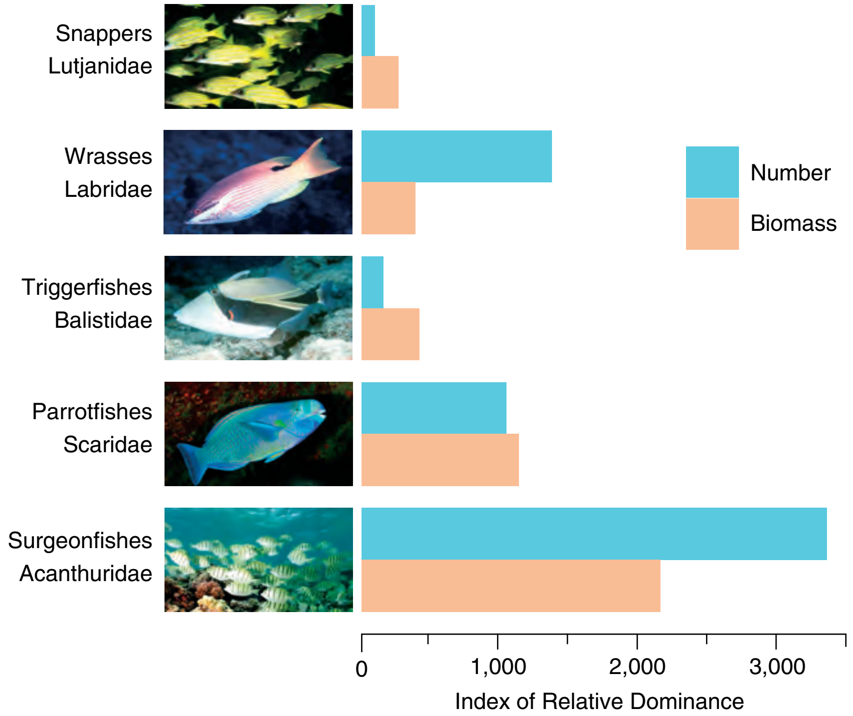


Figure 8. Index of relative dominance (percent frequency of occurrence times percent total number or percent total biomass) for the five most dominant fish families appearing on transects along the south Moloka‘i coast.

Dominant Trophic-Category Guilds

Herbivores were by far the most important feeding guild observed, with parrotfishes and surgeonfishes dominating this group (fig. 9). Bullethead uhu accounted for 23 percent of the total herbivore biomass, followed by kole (13 percent) and mā‘i‘i‘i (12 percent). Invertebrate feeders were the next most abundant feeding guild by both numbers and weight, with nearly 70 percent of the biomass consisting of ta‘ape. Large piscivores were not commonly observed in the survey area, but the few large individuals contributed disproportionately to the overall biomass relative to their numbers. Kāhala (amberjack, *Seriola dumerili*) made up 69 percent of the total piscivore biomass, followed by uku (19 percent), and the introduced roi (peacock grouper, *Chephalopholis argus*, 8 percent). In contrast to piscivores, small planktivores were numerically common (9 percent of total numerical abundance), but accounted for only a small proportion (3 percent) of the total fish biomass.

Native, Endemic, and Introduced Species

A total of 612 native reef and inshore fishes (down to 200 m or ~600 ft) have been identified from the Hawaiian Islands (Randall, 2007). Endemic species (found nowhere else on earth) accounted for 37 percent of numerical abundance and 29 percent of biomass on the south Moloka‘i reef tract (fig. 10). Kole was the most abundant endemic species by both weight and number. Manini (convict tang, *Acanthurus triostegus sandvicensis*) is an endemic subspecies that was the second most important endemic species by weight and third by number. Hīnālea lauwili was numerically the second most common endemic and, despite its small size, accounted for 12 percent of total endemic biomass.

At least 13 species of introduced marine fishes have become established in Hawai‘i (Eldredge, 1994). Of these species, ta‘ape, to‘au (blacktail snapper, *Lutjanus fulvus*), and roi have established viable breeding populations in the state. Ta‘ape and roi have been particularly controversial because they have adapted well to Hawaiian waters and are often blamed for depletion of desirable species by competition or predation (Friedlander and others 2002a; Oda and Parrish, 1981; Randall, 1987). The introduced ta‘ape accounted for 22 percent of the total fish biomass observed on transects, but, as noted earlier, represented a single school of 500 individuals. Roi accounted for less than 10 percent of the weight of introduced species and was observed on about half of all transects (mean = 0.48 individuals/125m^2).

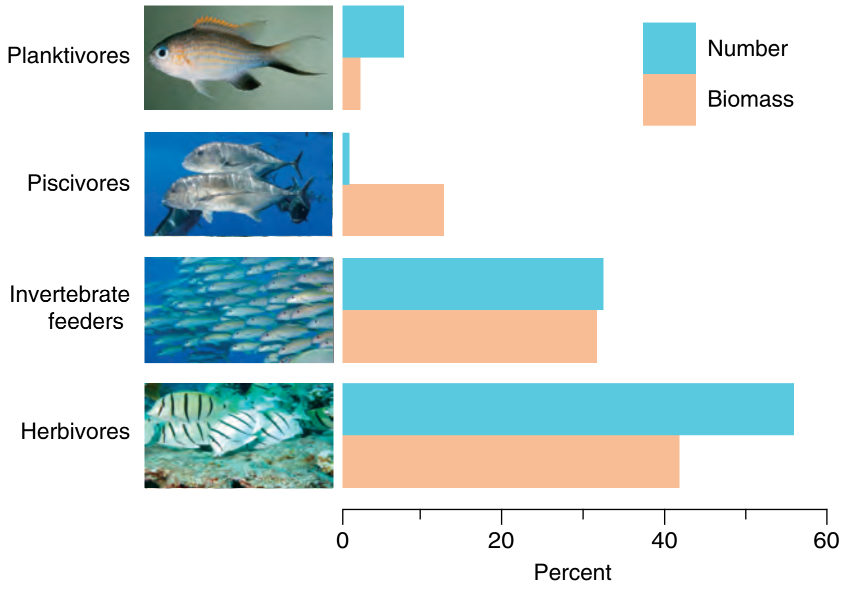


Figure 9. Percentages of total biomass and numerical abundance among major trophic fish guilds along the south Moloka‘i reef tract.

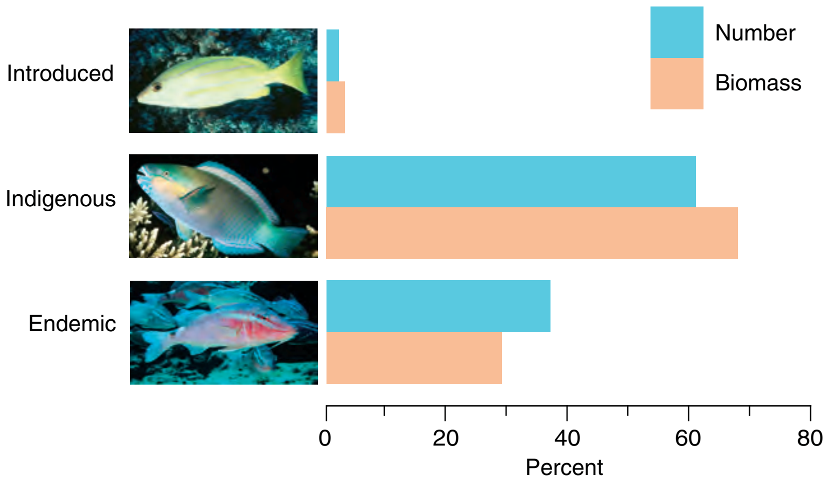


Figure 10. Mean percentages of endemic, indigenous, and introduced species along the south Moloka‘i reef tract.

Spatial Distribution of Fish Assemblage Characteristics

The number of species, biomass (weight of fishes), number of individuals, and diversity (an index that combines number of species and number of individuals) are important characteristics of the fish assemblage and are useful in describing and comparing assemblages among stations. The deep transects at Pālā‘au and Kakahai‘a had the highest values for most fish assemblage characteristics (table 1). Diversity was low at Kakahai‘a, owing to the dominance of a school of 500 ta‘ape at one deep survey site. Kamiloloa and Kamalō had the lowest values for most assemblage characteristics at both deep and shallow sites.

The number of species was comparable across depth strata, with the lowest values for both depths occurring at Kamiloloa and Kamalō (fig. 11). Biomass was highly variable among, as well as within, stations. The biomass at the deep Kakahai‘a sites (3.60 t/ha) was more than 12 times greater than at the adjacent shallow sites (fig. 12). The number of individuals observed was fairly consistent among most stations (fig. 13). The exceptions included the deep Kakahai‘a site, which was dominated by a large school of 500 ta‘ape, and the shallow Pālā‘au site, where high numbers of surgeonfishes were recorded. Diversity was high among stations, with no apparent trends observed (fig. 14).

Table 1. Ranking of fish assemblage characteristics by survey location.

[Individual variables were given a ranking score from 1 (highest value) to 9 (lowest value). See figures 11–14 for actual values. Overall rank was determined by averaging the ranking scores of the four individual parameters (1 = highest, 9 = lowest).]

Location	Depth	Species	Biomass	Number	Diversity	Overall Rank
Pālā‘au	Deep	1	6	3	1	1
Kakahai‘a	Deep	2	1	1	8	2
Pālā‘au	Shallow	4[1]	2	2	6	3
Kaunakakai	Shallow	4[1]	3	6	2	4
Kamalō	Shallow	6	5	4	4	5
Kakahai‘a	Shallow	3	8	7	3	6
Kamiloloa	Deep	7	4	5	7	7
Kamalō	Deep	9	7	8	5	8
Kamiloloa	Shallow	8	9	9	9	9

[1] Tied

Spatial Distribution of Fish Trophic Structure

Herbivores dominated at all shallow sites, with the exception of Kamiloloa (fig. 15). The high percentage of invertebrate feeders there (76 percent) was a function of overall low biomass, primarily herbivores. Low overall biomass at the shallow location at Kakahai‘a also resulted in a higher proportion of invertebrate feeders (28 percent), primarily a mixture of goatfishes, wrasses, and butterflyfishes. Planktivores were not common at any of the shallow sites.

Although herbivores dominated at the deep stations at Pālā‘au and Kamalō, they were not as abundant overall as at shallow stations. At Kakahai‘a, invertebrate feeders (almost exclusively ta‘ape) account for nearly half of the total fish biomass. Kāhala and uku were responsible for the high predator biomass (42 percent) at this location. The relatively high percentage of invertebrate feeders (19 percent), piscivores (19.5 percent), and planktivores (16 percent) at Kamiloloa was a function of overall low biomass, primarily of herbivores.

Comparison with Locations Statewide

Overall species number, biomass (kg), and species diversity along the south Moloka‘i reef tract range near the state median when compared with other locations statewide (Rodgers, 2005). Pālā‘au, Kaunakakai, and Kakahai‘a possessed values for most fish assemblage characteristics higher than the state average, but most fish assemblage characteristics at Kamiloloa

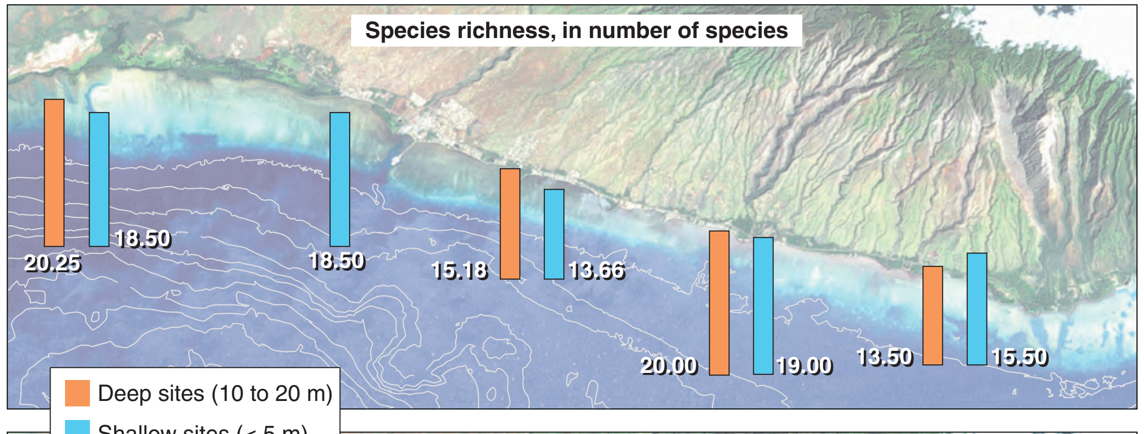


Figure 11. Mean species richness of fishes (number of species) observed on transects along south Moloka‘i reef tract. Orange = deep sites (10 to 20 m), blue = shallow sites (≤5 m).

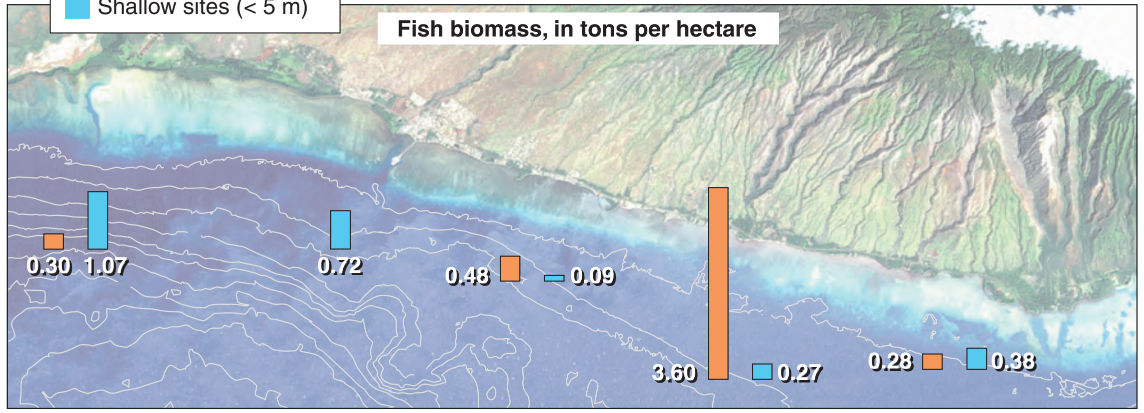


Figure 12. Mean fish biomass (in tons per hectare) observed on transects along south Moloka‘i reef tract. Orange = deep sites (10 to 20 m), blue = shallow sites (≤5 m).

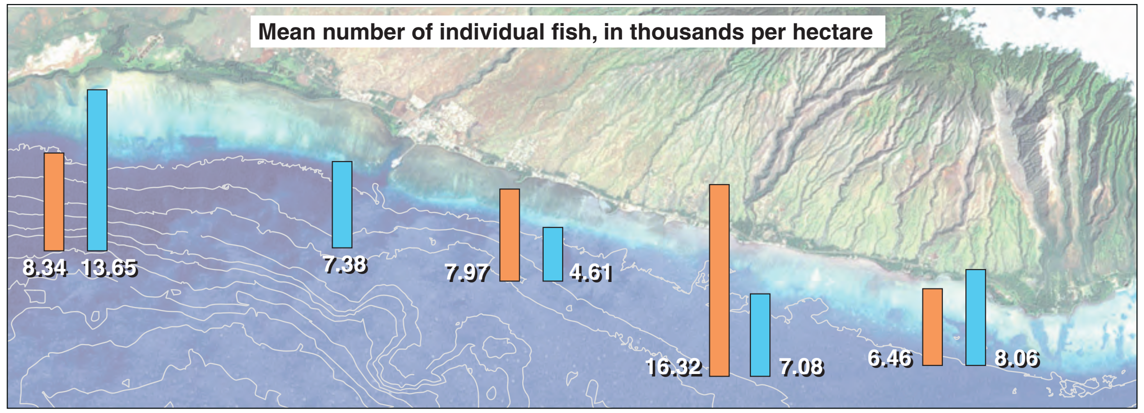


Figure 13. Mean number of individual fish (in thousands per hectare) observed on transects along south Moloka‘i reef tract. Orange = deep sites (10 to 20 m), blue = shallow sites (≤5 m).

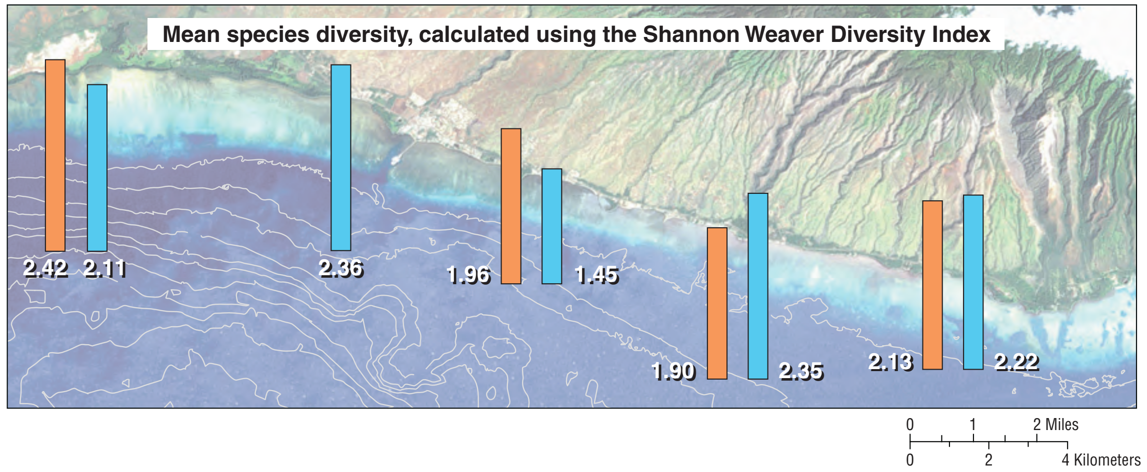


Figure 14. Mean species diversity (calculated using the Shannon Weaver Diversity Index) observed on transects along south Moloka‘i reef tract. Orange = deep sites (10 to 20 m), blue = shallow sites (≤5 m).

and Kamalō were well below the state average (fig. 16). Fish biomass at Kakahai‘a was among the highest observed biomass values in the state, while only 5 km away, Kamiloloa had some of the lowest observed biomass values statewide.

Fisheries of South Moloka‘i

The broad reef fringing the southern shore of Moloka‘i is probably the most productive reef flat for the harvest of reef fishes and invertebrates in the main Hawaiian Islands (Bartram 1992). This extensive area supports a wide variety of commercial, subsistence, and recreational fisheries (table 2). The only consistent long-term source of data on the coastal fisheries of Hawai‘i is the commercial landings database maintained by the State Division of Aquatic Resources (DAR). Commercial landing data between 1998 and 2002 were used to examine characteristics of the commercial fishery along the south coast of Moloka‘i (reporting areas 310 and 314). The average annual commercial harvest during this time period was just less than 10,000 kg (22,000 lbs) This is in sharp contrast to the early 1980’s, when approximately 68,000 kg (150,000 lbs) per year was harvested in the same location (Bartram, 1992).

Fisheries catch statistics alone are unreliable because of underreporting by commercial fishers and a large, resident recreational and subsistence fishing catch that goes unreported. The subsistence reef-fish fishery harvest may be as high as 45,000 kg (100,000 lbs) a year, or more than four times that of the commercial harvest (Bartram 1992). Information on subsistence and recreational components of the fishery was obtained from local knowledge, interviews, and written sources.

Commercial Landings by Gear Type and Species

Deep-sea handlining, primarily for ‘ula‘ula koa‘e (long-tailed red snapper, *Etelis coruscans*, known more commonly by its Japanese name,

Table 2. Major fishing methods employed along south Moloka‘i reef tract.
[Adapted from Bartram (1992).]

Gear type	Character of fishery	General areas fished
Spearing	Mostly recreation/subsistence	Middle to outer reef flat in areas with coral heads and other vertical relief
Throw netting	Subsistence	Inner reef flat, fishponds, mangrove thickets; water depths to waist-deep
Surround netting	Commercial/subsistence	Harbors, man-made basins, reef channels; water depths >20 ft; targeting akule and other schooling species
Drag netting	Subsistence	Inner reef flat, fishponds
Bullpen netting	Commercial	Outer reef flat (5–10 ft depth) in sandy and other areas of low relief
Gill netting	Commercial/subsistence	Reef flat (usually inner and middle); low-tide depths of 5–6 ft; areas of low bottom relief

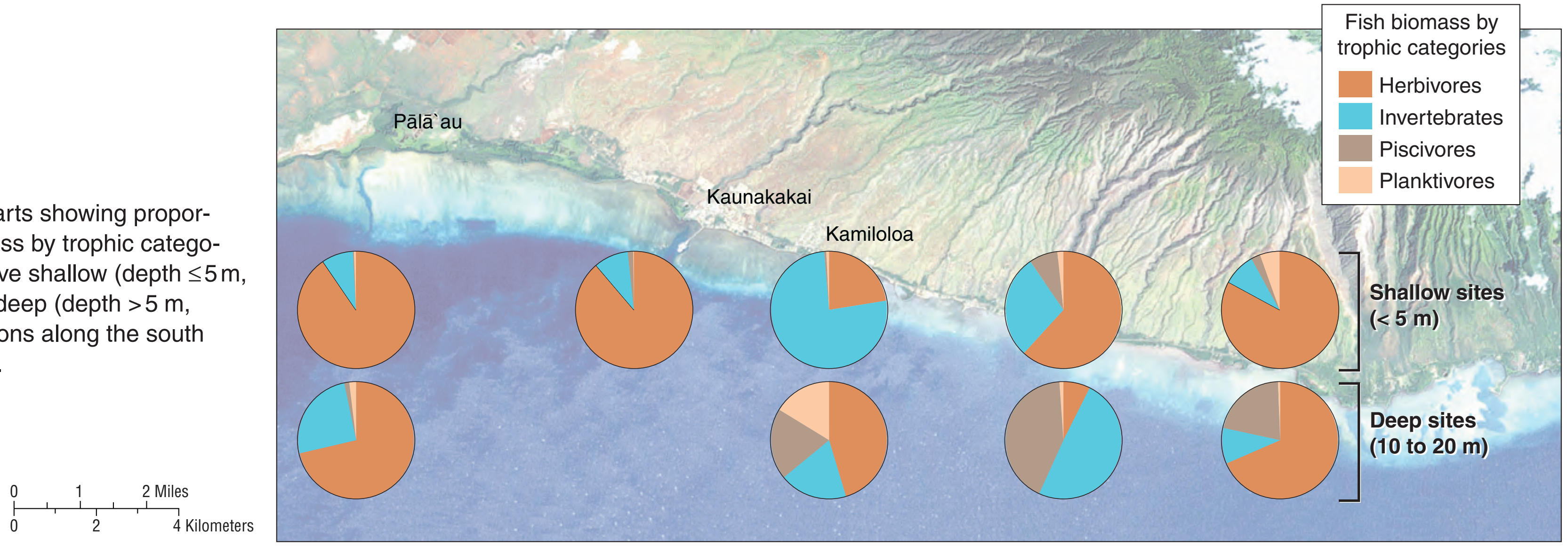


Figure 15. Pie charts showing proportions of fish biomass by trophic categories observed at five shallow (depth ≤5 m, top row) and four deep (depth >5 m, bottom row) locations along the south Molokaʻi reef tract.

onaga), ʻulaʻula (red snapper, *Etelis carbunculus*, known commonly as ehu), and ʻōpakapaka (pink snapper, *Pristipomoides filamentosus*), constituted 16 percent of the total weight landed and 36 percent of the value of catch from 1999 to 2002 (table 3). This was followed in total value (1998 to 2002) by gleaning for limu manauea, also known as ogo (seaweed, *Gracilaria* spp.) (3,837 kg/8,441 lbs., $24,102) and ʻopihi (limpets, *Cellana* spp.) (558 kg/1229 lbs., $3,543), which are the major species taken using this method.

The inshore handline catch was dominated by akule (bigeye scad, *Selar crumenophthalmus*) (80 percent by weight and 69 percent by value) with the remaining portion consisting of various reef fishes and invertebrates (fig. 17*A*). Netting caught a diverse assemblage of fishes, with weke (goatfishes, *Mulloidicthys* spp.) and ulua (jacks, *Carganidae*) making up 73 percent of the total catch (fig. 17*B*). Parrotfishes accounted for 30 percent of the catch by diving, followed by kole (23 percent), heʻe (octopuses, 20 percent), ula (spiny lobster, *Panulirus* spp., 1 percent), and ulua (8 percent) (fig. 18*A*). The trolling catch consisted of ono (wahoo, *Acanthocybium solandri*, 48 percent), mahimahi (dolphinfish, *Coryphaena hippurus*, 31 percent), ulua (9 percent), aku (skipjack tuna, *Katsuwonus pelamis*, 7 percent), and kawakawa (wavy-back tuna, *Euthynnus affinis*, 5 percent) (fig. 18*B*).

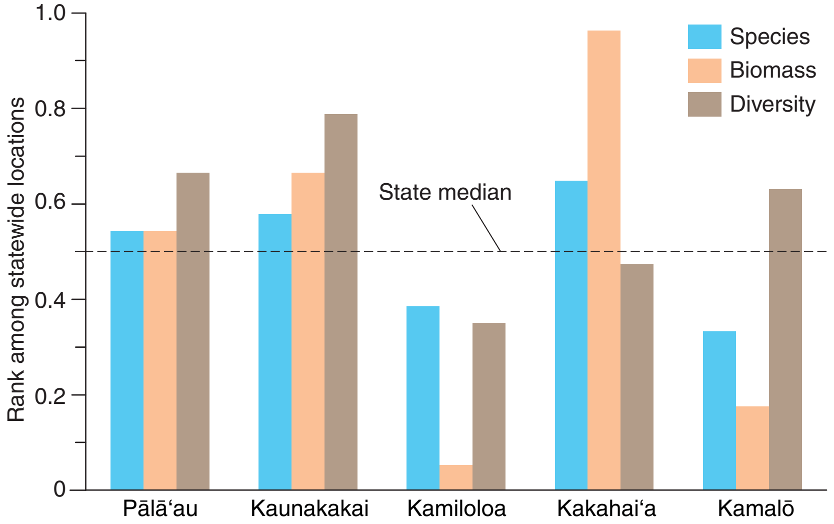


Figure 16. Rank for fish-assemblage characteristics along the south Molokaʻi reef tract (see figs. 11, 12, 14 for details) relative to locations statewide (data from Rodgers, 2005). A rank of 0.5 equals the State median.

Table 3. Commercial fisheries landings data from Hawaii Department of Land and Natural Resources, Division of Aquatic Resources for reporting areas 310 and 314 for 1998-2002 by gear type.

[Values are annual means for five-year period.]

Fishing method	No. fishers	No. trips	Kg caught	Lbs caught	Value ($)
Deep-sea handline	6.8	43.0	1,601	3,523	16,555
Gleaning	5.6	185.2	2,400	5,280	7,923
Inshore handline	10.6	64.8	1,697	3,734	7,339
Net	8.6	41.0	1,910	4,203	5,531
Dive	8.0	48.0	1,113	2,449	5,187
Troll	24.4	90.4	1,170	2,573	3,068
Grand Total	64.0	472.4	9,891	21,763	45,603

Noncommercial Fishing Activities

The noncommercial harvest of fish and invertebrates is an important food source for many Molokaʻi residents. The Governor's Molokaʻi Subsistence Task Force (1994) found that among Hawaiian families surveyed, 38 percent of all food was acquired through subsistence, and Molokaʻi residents relied on subsistence to a much greater extent than those of neighboring islands. Interviews conducted with co-op members of the Molokaʻi Ice House, Inc., in 1991 indicated average catches of reef fishes and akule to be about 90 kg (200 lbs) per person per year (Bartram, 1992). If this average is applicable to all Molokaʻi households with subsistence fishermen, then the subsistence reef fishery harvest may approach 45,000 kg (100,000 lbs) annually (Bartram, 1992).

There are a number of subsistence and recreational fishing activities that Molokaʻi residents practice along the south shore. Shore-based fishing includes throw-netting and pole and line fishing. Locals pole fish from shore for pāpio (juvenile jacks, *Caranx* spp.), weke and ʻoama (juvenile goatfishes, *Mulloidicthys* spp.), and halalū (smaller sized akule). Crabbing with lantern is still common, but less so than in the past. Throw netters mainly target moi (Pacific threadfin, *Polydactylus sexfilis*), āholehole (Hawaiian flagtail, *Kuhlia* spp.), enenue (chubs, *Kyphosus* spp.), and ʻamaʻama (mullet, *Mugil cephalus*). In addition to fishes, other marine resources are locally collected for food. Crabbing with spotlight or flashlight on rocky shores for ʻaʻama crab (*Grapsus tenuicrustatus*) is still common. Limu (seaweed) species such as limu kohu (*Asparogopsis taxiformis*) and manauea (*Gracilaria coronopofolia*) are harvested along the beach and upon inshore flats. Collecting of opihi (limpets, *Cellana* spp.) also occurs in rocky shoreline habitats toward the east end of the south shore.

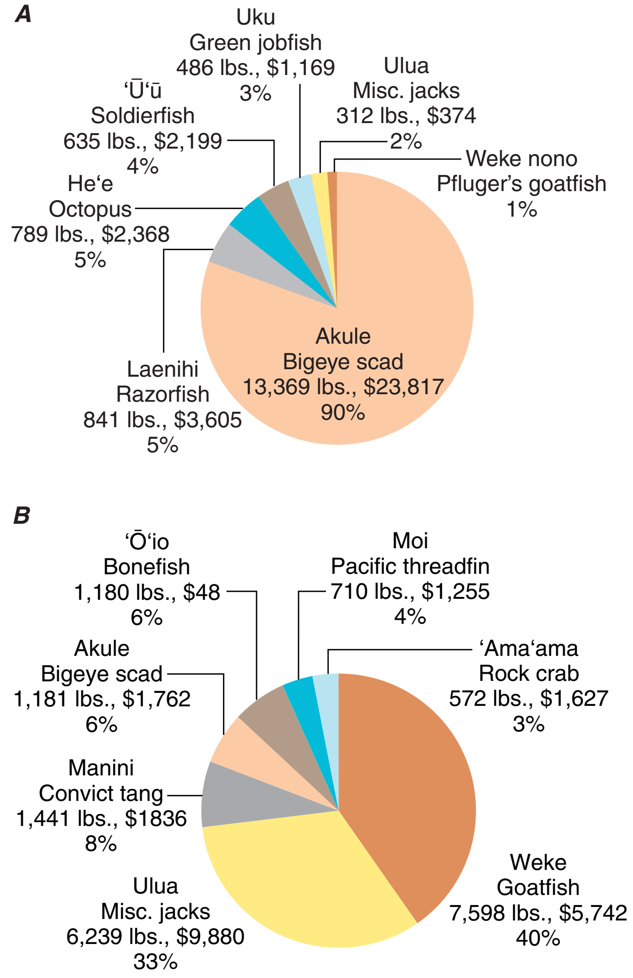


Figure 17. Catch of major species off south Molokaʻi between 1998 and 2002 by (*A*) shallow handlining and (*B*) netting. Numbers are weight, value, and percentage of total weight.

Offshore, the extensive reef flat off the south shore of Moloka‘i supports a variety of fishing activities. Diving for kole, he‘e, uhu, manini, kūmū, ‘ū‘ū (soldierfishes and squirrelfishes, Holocentridae), uma-uma lei (orangespine unicornfish, *Naso literatus*), kala (bluespine unicornfish, *Naso unicornis*), palani (eyestripe surgeonfish, *Acanthurus dussumieri*), pualu (yellowfin surgeonfish, *A. xanthopterus*), moana ukali (goatfish, *Parupeneus* spp.), ula and ula papa (slipper lobster, *Parribacus antarcticus*) occurs often. Gill netting and surround netting are common methods as well. Gill netting is most frequent along the inshore edge of the fringing reef. The most common species caught are weke, ‘ama‘ama, pāpio, ō‘io (bonefish, *Albula* spp.), kala, and enenue. Surround netting is frequently used for particular species like akule that are usually found in deeper waters such as channels, bays, and outside the fringing reef. Trolling and boat-based spinning for pāpio along the reef flat and outer reef crest is also a popular activity among residents. Other activities in this area include line fishing in sand channels for o‘io and outside the fringing reef for weke ‘ula (*Mulloidicthys vanicolensis*), pāpio, uku and laenihi or nabeta (razorfish, *Iniistius* spp.). Netting for kona crab (*Ranina ranina*) is also conducted in these sandy areas. Farthest off the south shore, trolling for pelagic species such as ono and mahi mahi and bottom-fishing for onaga, ehu, and ‘ōpakapaka, are performed by both commercial and recreational fishers.

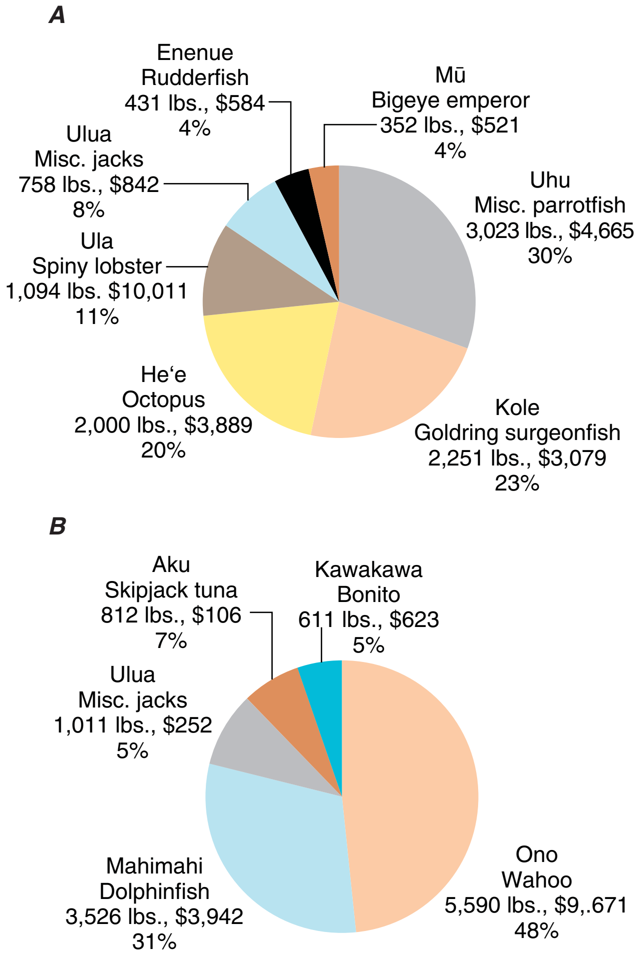


Figure 18. Catch of major species off south Moloka‘i between 1998 and 2002 by (*A*) diving and (*B*) trolling. Numbers are weight, value, and percentage of total weight.

The importance of the fishery resources to the local community is very great. The harvest of marine resources still serves as a considerable supplement to locals’ incomes and is a significant part of local culture. Lū‘au for graduations and birthdays are still events that ‘necessitate’ many customary foods, such as ‘opihi. In the absence of large supermarkets, marine resources are still very much a large part of the local Moloka‘i diet, especially in comparison to other islands such as O‘ahu.

South Moloka‘i Fishponds

Ancient Hawaiian fishponds (loko i‘a), dating back to the 13th century, are unique in the world and have been recognized as the most extensive and productive systems of early aquaculture. It has been estimated that close to 500 fishponds producing more than 900,000 kg (2,000,000 lbs) of fish each year were in use before Western contact in 1778 (Summers, 1971). This phenomenal feat of engineering is evidenced by its longevity, with many of the original ponds still in existence. As a highly efficient form of resource management, fishponds provided a sustainable protein source that could be harvested during rough oceanic conditions and by those no longer able to fish. Representing not only survival, the fishponds had an inseparable relationship to religious beliefs and political practices.

The loko kuapā shoreline pond enclosed by a rock wall, is the most familiar of the four basic types of fishponds. The multipurpose sluice gates (mākahā) evolved into a system of gates and channels that regulated the flow of water, allowed entrance to fingerlings, and facilitated harvest. Within these fish farms, constructed of basalt and coral, numerous fish species and limu (seaweed) were raised and harvested. The most common included awa (milkfish, *Chanos chanos*), ‘ama‘ama, awa‘aua (ladyfish, *Elops hawaiensis*), āholehole, and ulua and pāpio, while some species, such as the moi, kūmū and ō‘io, were reserved for the ali‘i (royality).

This extensive modification of the coastline altered both downslope and alongshore sediment transport while shifting nearshore current patterns (Roberts, 2001; Ogston and others, this vol., chap. 20). Fishpond cultivation rapidly declined with increasing urbanization and coastal development, changes in land tenure, loss of knowledge of pond management practices, and decline in the native population (Hlawati, 2002). Because these events affected Moloka‘i less than the other Hawaiian Islands, more intact fishponds remained there. By 1930, however, grazing and agricultural activities on Moloka‘i contributed to their abandonment as the majority filled with sediment. Today, remnants of more than 70 ponds remain on the south shore of the island of Moloka‘i (fig. 19). Keawanui and ‘Ualapu‘e fishponds have been federally recognized as national historical landmarks. A wetland bird sanctuary has been created with lands surrounding and including the freshwater Kakahai‘a fishpond. Some ponds have been restored and are currently being used by local residents (Wyban, 1992).

Strong advocates of preservation and restoration of the remaining fishponds have renewed community interest in complementing a subsistence lifestyle. These historic structures provide a significant archeological, spiritual, and cultural link with the past. They hold important significance as an educational resource, in preserving cultural values, and in stimulating economic opportunities within the community.


Erica Muse

Figure 19. Aerial views of south Moloka‘i fishponds. Houses give indication of scale.

Traditional Fisheries Management

There has been a renaissance of traditional community-based fisheries management throughout the Pacific, and rediscovery of these traditional techniques offers great promise for improving the management of marine fisheries. In coastal communities, fishermen (and women) combine empirical information on fish behavior, the physical environment, and fish habitats to determine when, where, and how to fish (Ruddle, 1994). This information in some communities has been passed down over many generations, and traditional knowledge can play an important role in designing effective fishery management systems (Johannes, 1997). Many of the management tools used today, such as closed areas, closed seasons, size limits, and restricted access, were used by Pacific Islanders centuries ago to manage their fisheries resources (Johannes, 1978)

A number of communities throughout Hawai‘i are currently strengthening local influence and accountability for the health and long-term sustainability of their marine resources through revitalization of local traditions and resource knowledge (Friedlander and Brown, 2004). The community in the Ho‘olehua Hawaiian Homesteads on the island of Moloka‘i exemplifies this trend (Poepoe and others, 2007). Community-sanctioned norms for fishing conduct are being reinforced through continual feedback based on local resource monitoring, education, and peer pressure (Friedlander and others, 2002b; Poepoe and others, 2007).

The most effective means to elicit proper conduct of fishing is by educating young people in the community to understand that they have responsibilities, as well as rights, for marine resource use. The continuation of traditional Hawaiian practices in and around Mo‘omomi Bay (fig. 20) helps to maintain social and cultural identity and provides reinforcement of values shared by the Ho‘olehua community (Poepoe and others, 2007). The repetition of subsistence fishing activities is one of the ways that knowledge, values, and identity are transferred to succeeding generations. Cultural survival is thus entwined with resource conservation. Each community will have to develop management strategies that are compatible with their own unique situation. Environment, history, and resources will all dictate what type of management regime is best suited for each individual community.

Summary

The fish assemblage of the south Moloka‘i reef tract provides food, recreation, commerce, and cultural identity to the local human population. In addition, it is an integral component of the south Moloka‘i marine environment, helping to maintain a healthy ecosystem. The large number of endemic species on these reefs attests to the unique composition of the ecosystem and its importance in global marine biodiversity.

The broad reef fringing the south shore of Moloka‘i is probably the most productive reef flat in the main Hawaiian Islands for the harvest of reef fishes and invertebrates. The fish assemblage represents a diverse fauna that is healthier than those in more heavily exploited urban areas around the State, but it has shown signs of decline in overall health and quality over time. The average annual commercial catch has declined from a peak of 68,000 kg (150,000 lbs) per year in the early 1980s to roughly 10,000 kg (22,000 lbs) today. In addition, the men and women of the fishing community have expressed concern about the declining size and abundance of several important resource species such as kūmū and moana kale (blue goatfish, *Parupeneus cyclostomus*). There is a great need for more localized control of these resources in order to rehabilitate existing stocks and ensure sustainable harvests in the future. The revitalization of some of the existing fish ponds could help to provide additional food resources for the community as well as revive local culture. To be effective, fisheries management must function within a specific local context. Communities and their individual members should exercise control over local inshore marine resource use and be accountable for the health and productivity of local resources (Poepoe and others, 2007). Wise use and conservation are essential in order to provide improved utilization and appreciation of these resources for future generations.

Figure 20. Local traditions and resource knowledge help to guide fishing practices in the Ho‘olehua community on the north shore of Moloka‘i

CHAPTER 8

The Seaweed and Seagrass Communities of Moloka‘i

Jennifer E. Smith[1,2], Heather L. Spalding[2], Ryan Okano[2], and Celia M. Smith[2]

The marine environment around the island of Moloka‘i has many different types of habitats and unique marine communities. The focus of this chapter is to describe the marine plant communities around the island, with a general focus on those off the south shore. Both seagrasses (true marine plants) and the seaweeds (which are not considered to be “true” plants, see below) will be discussed in detail. Seaweeds or marine algae are ocean-dwelling photosynthetic organisms that belong to several diverse evolutionary lines, the most prominent being the green algae (chlorophytes), the brown algae (phaeophytes), and the red algae (rhodophytes). There are many other groups of photosynthetic organisms in the ocean, including photosynthetic bacteria (cyanobacteria), but they are not the focus of this chapter.

The Hawaiian Islands support more than 500 species of marine algae (Abbott, 1999; Abbott and Huisman, 2004), and species new to science are still being discovered on a regular basis. To Hawaiians the word “limu” is used to describe seaweeds, many of which are important for food and/or cultural activities. The term seaweed specifically refers to photosynthetic marine organisms that are members of a disparate kingdom of organisms known as kingdom Protista. These organisms are not considered to be true plants, even though the evolutionary ancestor of land plants was a green alga. They are generally simpler in organization, lacking typical plant organs such as leaves, roots and stems, and they do not reproduce by making fruits and seeds. Because seaweeds are immersed in water, they generally do not need specialized organs to take up water and nutrients (although some seaweeds do have specialized structures). Instead, the entire algal thallus (body) can photosynthesize and absorb nutrients from the water.

There are true marine plants, known as seagrasses, which also live completely immersed in seawater and are often quite abundant in shallow back-reef environments on coral reefs. Seagrasses can form dense meadows, which can be important nursery habitats for a number of commercially important fish and invertebrate species (Mumby and others, 2004; Dorenbosch and others, 2005; Gratwicke and Speight, 2005; Valentine and Heck 2005). The following sections will focus on the benthic (bottom dwelling) communities around Moloka‘i, with an emphasis on seaweeds, seagrasses, and some cyanobacteria.

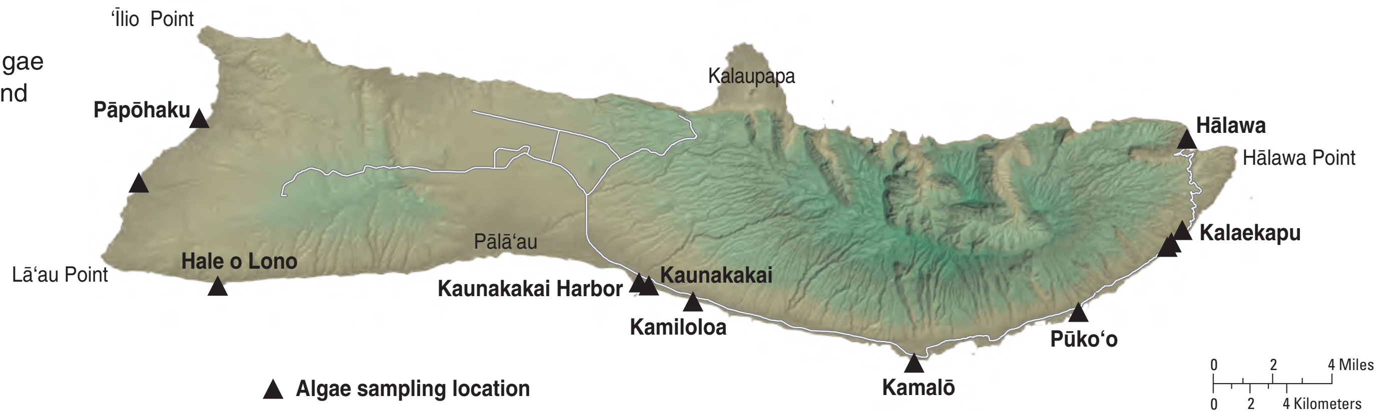
A number of physical and biological factors influence the distribution and abundance of seaweeds and seagrasses on tropical reefs (Lobban and Harrison, 1994). Physical factors include substrate type, temperature, salinity, light levels, hydrodynamics or wave exposure, nutrient availability (nitrogen and phosphorous), sedimentation, and others. Some of the most important biological factors affecting the distribution and abundance of seaweed communities on coral reefs are predation or grazing by herbivores (both fish and invertebrates that eat seaweed) and competition with other benthic organisms (other seaweeds, seagrasses, and corals) (Carpenter, 1986; Hughes and others, 1999b; McCook, 1999; Miller and others, 1999; Smith and others, 2001; Stimson and others, 2001; Thacker and others, 2001; Jompa and McCook, 2002; Diaz-Pulido and McCook, 2003; Jompa and McCook, 2003; McClanahan and others, 2003).

One of the most intriguing areas of research in coral reef ecology has been to understand how and why corals dominate the landscape in tropical marine environments while plants dominate most other ecosystems on the planet (Odum and Odum, 1955). Reef ecologists generally believe that a combination of physical and biological factors favor the dominance of corals over algae in healthy or pristine reef-slope areas. Humans, however, can have dramatic effects on coral reef communities by altering any of the above factors, often shifting the competitive edge away from the corals and in favor of faster growing algae (Hughes and others, 1999b; Hughes and Connell, 1999; Jackson and others, 2001; Aronson and others, 2003; Hughes and others, 2003; Pandolfi and others, 2003a, b; Bellwood and others, 2004; Pandolfi and others, 2005). There are, of course, always exceptions, and it is worth mentioning that in the remote Northwestern Hawaiian Islands seaweeds are often more abundant than corals (Vroom and others, 2005) in the absence of any chronic human disturbance (this is generally believed to be the result of low water temperature).

From a biological perspective, dense populations of grazers (for example, surgeonfish, parrotfish, and sea urchins) on healthy reefs help keep algae cropped to low levels (Carpenter, 1986; McCook, 1999; Miller and others, 1999; Smith and others, 2001; Thacker and others, 2001; Belliveau and Paul, 2002; McClanahan and others, 2003). Generally, on healthy or pristine reefs where fish and invertebrate are abundant, the algae that are present are either very small turfs that have fast growth rates or are either chemically and/or physically defended against grazers (Carpenter, 1986). Experimental evidence suggests that the loss of gazers from reefs through overfishing or from disease outbreaks can allow algae to begin overgrowing corals and eventually cause a phase shift in which long-lived, slow-growing corals are replaced by fleshy, fast-growing seaweeds (Hughes and others, 1987; Hughes, 1994; Hughes and others, 1999b; McCook, 1999; Jackson and others, 2001; Bellwood and others, 2004).

From a physical perspective, the availability of nutrients, primarily nitrogen and phosphorus, can also influence the growth rates and abundance of algae on reefs (Smith and others, 1981; Bell, 1991; Bell, 1992; Lapointe, 1997; Smith and others, 2001). Most reefs have developed in the clear, warm, and nutrient-deficient waters of the tropics. The coral

Figure 1. Map of Moloka‘i showing the algae sampling sites surveyed between 1999 and 2003. See text for further details.



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organisms and their symbiotic zooxanthellae (microscopic single-celled algae that live inside the coral tissue) are extremely efficient at using nutrients and are able to survive with very little external nutrient input. Reef algae and seagrasses, on the other hand, need external sources of nitrogen and phosphorus to survive. These organisms are able to absorb nutrients from the water column, sand, or sediment. On healthy reefs the low input of nutrients generally limits the growth of algae. In some cases where nutrient inputs are high (for example, from sewage outfalls, terrestrial runoff containing agricultural fertilizers, landscaping, river runoff, sedimentation), algae may be able to overgrow corals and become dominant, even occasionally forming large blooms, as can be seen on some of the shallow reefs of Maui (Smith and others, 2005).

The introduction of exotic or nonnative species has caused numerous problems in the Hawaiian Islands, both on land and in the sea. These invasive species are seen as one of the largest threats to global biodiversity, because they are often able to outcompete native species (Vitousek and others, 1997) and even cause extinction events. In Hawaiʻi, this is particularly a problem because there are so many endemic species (species which are only found in Hawaiʻi) that are highly specialized to specific habitats. Several species of marine algae have been introduced to Hawaiian reefs, primarily for experimental aquaculture (Smith and others, 2002). Unfortunately, many of these species have spread from their initial points of introduction (mainly on Oʻahu) and have become quite abundant on the shallow reef-flat environments around the Hawaiian Islands, including Molokaʻi (Smith and others, 2002; Smith and others, 2004; Conklin and Smith, 2005; Smith and others, 2005). Some of these exotic species are a particular concern because they have been shown to cause reductions in species diversity and coral cover on Oʻahu (Smith and others, 2004).

Different Algal Communities and Functional Groups

Marine algae can be classified in several different ways. The most general classification for reef algae includes three functional groups: macroalgae, turf algae, and crustose coralline algae (Littler, 1980; Littler and others, 1991). Macroalgae are generally taller than a few centimeters and include hundreds of species in the Hawaiian Islands. These species can be either fleshy or calcified (containing calcium carbonate). Calcified species usually have a whitish hue and may have a chalky texture. Turf algae represent a community of very small (less than a few centimeters tall), usually filamentous algae including hundreds of species and even juvenile stages of larger algae. Algal turfs are an important food source for many reef fish species. Finally, crustose coralline algae (CCA), or heavily calcified pink crusts, look like a nonliving pink pavement. The CCA are incredibly important for reef building, as they are known to cement corals and other reef components together. They are also extremely strong and can withstand very large wave stresses. CCA commonly form an "algal ridge" along the reef crest, which is the portion of the reef where waves break (Macintyre and others, 2001). It is the CCA and the algal ridge, along with the corals themselves, that build reef structure. CCA also play an important role in the development of reefs because they are the primary substratum upon which many coral larvae settle (Harrington and others, 2004). Essentially, the CCA not only help to build reefs but they facilitate the persistence of corals as well.

Algal Communities of Molokaʻi

The remaining sections of this chapter will discuss the benthic marine algal communities around Molokaʻi, ranging from Hālawa Bay in the east, around the south shore, and ending at Pāpōhaku Beach Park in the west (fig. 1). The north shore of the island is generally very difficult to access and has not been surveyed or assessed by the authors, so it will not be discussed here. Brief descriptions of the marine communities from each of the other coastal regions (west, south, and eastern coasts) will be accompanied by photographs of some of the dominant algal species or groups found in these respective areas. The majority of the data presented here come from two years of shallow-water surveys that were conducted by snorkel, and only a limited amount of data is available to describe the offshore reef-slope communities from Kamalō, Kamiloloa, and Pālāʻau (fig. 1). Lastly, the deep-water algal communities off the south shore will be discussed briefly, using the results of some recent (2004) submersible and ROV (remotely operated vehicle) surveys.

The Eastern Shore

The eastern shore of Molokaʻi is characterized by basalt points, bays with sandy beaches, and narrow, shallow reef flats. The shoreline is part of the windward shore and is regularly exposed to waves and wind. At Hālawa Bay, large boulders make up much of the intertidal zone, and these boulders are colonized by the brown algae *Endarachne binghamiae* (fig. 2) and *Hincksia mitchelliae* (fig. 3). The boulders also provide substrate for CCA and many invertebrates such as the shingle urchin, *Colobocentrotus atratus* or hāʻukeʻuke (fig. 4) and several species of limpets (ʻopihi) are common. The basalt benches and tidepools common along most of the eastern shore are generally dominated by several species of large brown algae, including *Turbinaria ornata* (fig. 5) and *Sargassum* (limu kala) (fig. 6), as well as CCA. In the shallow subtidal environments many spe-


Figure 2. The brown alga *Endarchne binghamiae* is commonly found growing on intertidal boulders in the Hawaiian Islands. The length of this species ranges from 5 to 20 cm (2 to 7.8 in).


Figure 3. The filamentous brown algae *Hinksia mitchelleae*, which is usually found growing in small clumps either on boulders or shallow basalt benches in the intertidal zone. *Hinksia* is unsually no bigger than 3 cm (1.2 in) in diameter.


Figure 4. A typical Hawaiian intertidal boulder field showing the purple shingle urchin grazing on algae. The pink crusts are crustose coralline algae (CCA) and the small brown turfs are the filamentous brown alga *Hinksia*.

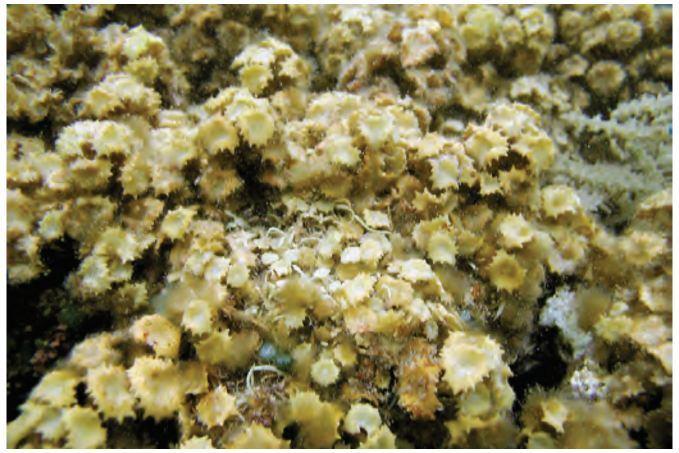


Figure 5. The brown alga *Turbinaria ornata* is commonly found growing in tidepools and in other environments of high wave energy. Individuals of *Turbinaria* can range from 1 to 30 cm (0.4 to 12 in) in length.

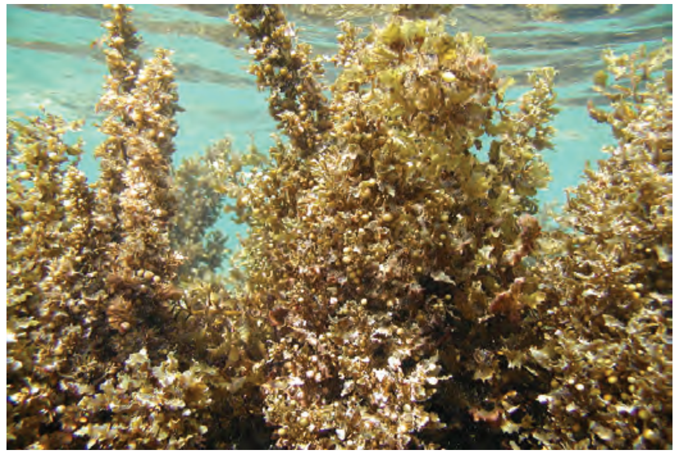


Figure 6. One of the three species of *Sargassum* (limu kala) commonly found in Hawaiian intertidal environments, especially in tidepools or on shallow reef flats. *Sargassum* species are some of the largest seaweeds in Hawaii (on average 20 cm/8 in tall) and can reach heights of nearly 1 m (3 ft).

Figure 7. The red alga *Asparagopsis taxiformis* (limu kohu) is common in shallow reef-flat environments, exposed benches, and subtidal reef environments. This alga is also known as limu kohu and is regularly eaten after being fermented to prevent poisoning from the high concentrations of ammonia contained in the alga. *Asparagopsis* is a delicate alga that is usually less than 10 cm (4 in) tall.

Figure 8. The red alga *Melanamansia glomerata* is a very common component of shallow and deeper reef communities in Hawai‘i. Many other species of algae commonly grow on top of *Melanamansia*, making it sometimes difficult to identify in the field. Individuals of *Melanamansia* are usually around 10 cm (4 in) tall.

Figure 9. *Portieria hornemannii* is a very common species of red alga found on shallow reef flats and deeper reef-slope environments in Hawai‘i. *Portieria* is a delicate alga usually less than 10 cm (4 in) tall.

Figure 10. The calcified red alga *Dichotomaria marginata* is quite common in Hawai‘i, where it is usually found growing on steep to vertical surfaces such as basalt walls or slopes. Individuals are usually less than 15 cm (5.9 in) tall.

Figure 11. *Galaxaura* species are commonly found on the exposed windward coast of Moloka‘i.

Figure 12. *Tricleocarpa* is a branching calcified red alga that is common in the shallow subtidal environments around Hawai‘i. This alga commonly grows on hard substrates in subtidal areas on both the east and west shores of Moloka‘i. *Trichleocarpa* is usually more heavily calcified than *Galaxaura* and is usually no taller than 15 cm (5.9 in).

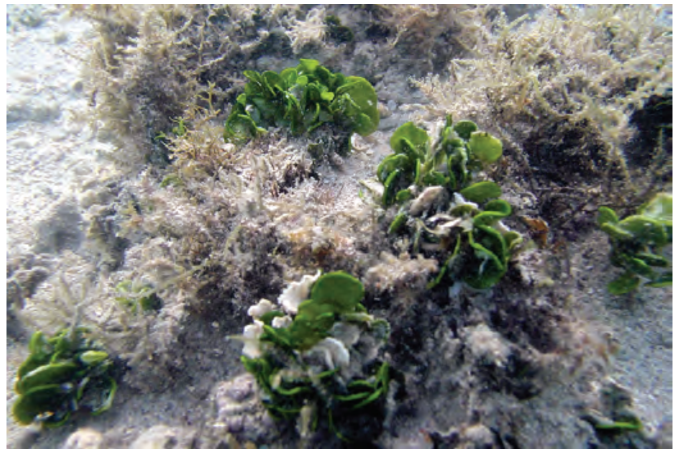


Figure 13. The calcified green alga *Halimeda discoidea* is common in the shallow reef-flat environments on the windward shore of Moloka‘i. This species can also be found on the outer portions of the extensive shallow reef flats off the south shore. *H. dicoidea* grows in small rosettes reaching heights of 5–10 cm (2–4 in).

Figure 14. The green alga *Dictyosphaeria cavernosa*, otherwise known as “bubble algae,” is common on Hawaiian reefs in both the shallow subtidal and deeper reef-slope environments. It is often seen growing between corals as shown in this picture, where it is growing under a colony of the coral *Montipora capitata*. *Dictyosphaeria* has very large cells, which are often visible to the naked eye.

Figure 15. The green alga *Codium edule* commonly grows on the bottom in shallow subtidal environments. There are numerous other species of *Codium* (limu waiwai’ole) in Hawai‘i, some of which are commonly consumed in salads.

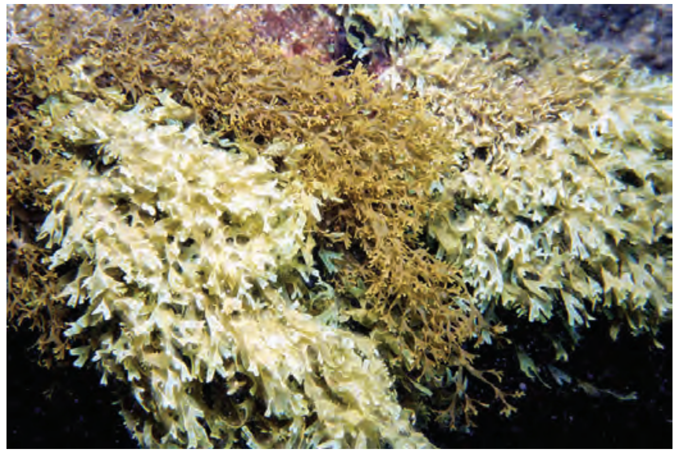


Figure 16. Several species of *Dictyota* are common in Hawai‘i, including the two pictured here. *Dictyota sandwichensis* is often an iridescent blue-green to yellow color, whereas *Dictyota acutiloba* is more of a caramel-brown color. The various species of *Dictyota* can vary in size from less than a centimeter to several centimeters in length.

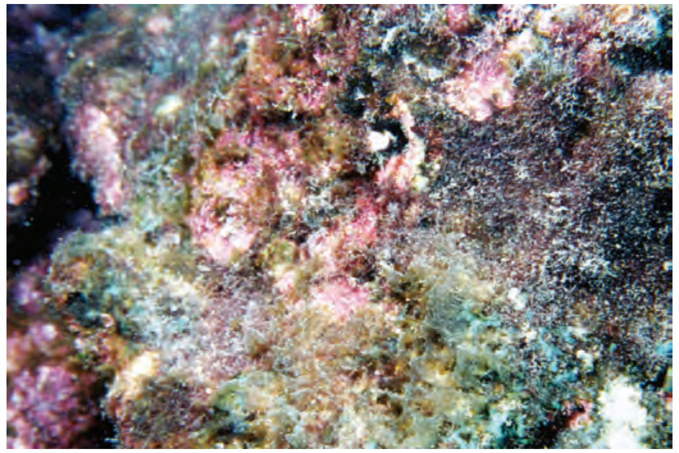


Figure 17. The mixed species communities of small filamentous algae (less than 2 cm/0.8 in tall), otherwise known as turf algae, are a very common and important component of reef ecosystems. These communities serve as the primary food source for numerous species of grazing fish and sea urchins. The turfs have extremely fast growth rates and so are considered to be an extremely efficient energy source for the reef community.

cies of red algae are common, including *Asparagopsis taxiformis* (limu kohu) (fig. 7), *Melanamansia glomerata* (fig. 8), and *Portieria hornemannii* (fig. 9), as well as some calcified red algae, including *Dichotomaria* spp. (fig. 10), *Goalaxaura* spp. (fig. 11), and *Tricleocarpa* (fig. 12). Numerous other species of algae are present, either out in the open such as *Halimeda discoidea* (fig. 13) or in the cracks and crevices, hidden away from the mouths of herbivorous fish and sea urchins. Algae present include, among many others, species of *Dictyosphaeria* (fig. 14), *Codium* (fig. 15), *Dictyota* (fig. 16), and of course turf algae (fig. 17) and CCA (fig. 18).

The South Shore

The Reef Flat

The south shore is characterized by very wide (100s of meters) shallow (0–2 m, 0–6 ft) reef flats (Storlazzi and others, this vol., chap. 3), which provide an extensive amount of habitat for marine algae. Most of these shallow reef flats are composed of a soft sandy or muddy bottom (Cochran, this vol., chap. 9) and will only support growth of algae or seagrasses that can anchor themselves into the soft substrata. Most notably, the endemic seagrass *Halophila hawaiiana* is quite abundant (fig. 19). Interestingly, *H. hawaiiana* exhibits two different growth forms on Moloka‘i. The common morphology is shown in figure 20, where the leaves of the seagrass are oval; the other growth form is shown in figure 21, where the leaves are more linear in shape. It is unclear if these two growth forms are different genetic entities (different species) or if they are just responding to differences in environmental conditions. Nonetheless, it is interesting that they are both found growing side by side on Moloka‘i. *Halophila decipiens* looks very similar to the oval morphotype of *H. hawaiiana* and may also be present on Moloka‘i. These seagrasses are particularly important on shallow reef-flat and/or lagoonal areas for a number of reasons. Primarily, they help to stabilize sediments by anchoring their roots into the soft bottom, inhibiting erosion and preventing sediment transport onto the fore reef, where it could smother the coral community and associated fauna. Seagrasses are also an important food source for many organisms, including sea turtles. Furthermore, seagrasses are known to provide habitat and shelter for numerous species of fishes and invertebrates during different stages of their life cycles.

In addition to the seagrasses, several species of macroalgae are found on these shallow reef flats growing on small pieces of reef rubble or other occasional areas of hard bottom, including some weedy nonindigenous invasive species. The invasive red alga *Acanthophora spicifera* (fig. 22) is quite common along the entire south coast and can be found growing from shore all the way out to the reef crest. This alga can be seen overgrowing or smothering many species of coral (fig. 22). Another invasive red alga, *Hypnea musciformis* (fig. 23), can also be found on the south shore but is most common near the town of Kaunakakai. *Hypnea* grows abundantly on the shallow reef flats and sometimes washes ashore (fig. 24). This alga forms massive blooms on the island of Maui, likely as the result of increased nutrient input from shore (Smith and others, 2002).

Several species of *Gracilaria* can be found on Moloka‘i’s south shore. *Gracilaria coronopifolia* (limu manauea) (fig. 25) grows in large clumps on the shallow reef flats on Moloka‘i’s south shore. This species is regularly harvested for food and can be found in the common raw fish salad known as “poke.” *Gracilaria parvispora* (long ogo) (fig. 26) can occasionally be found growing attached to small rocks close to shore on the reef flats, but this species is also harvested regularly and is uncommon in the wild. Both ogo and manauea are grown on Moloka‘i in fishponds or other areas for human consumption. The invasive species *Gracilaria salicornia* (gorilla ogo) (fig. 27) is also present on the shallow reef flats of the south shore. This species was introduced to Moloka‘i in the 1980s from O‘ahu (the O‘ahu population originated from a population found in Hilo, which was most likely accidentally introduced by ships from the Philippines before the 1900s, during the whaling era). *G. salicornia* was only found at a few locations on Moloka‘i—specifically Pūko‘o fishpond and in front of the canoe club at Kaunakakai Harbor—but it may be spreading. This species is invasive on O‘ahu, where it is one of the most dominant species in Waikīkī and in Kāne‘ohe Bay (Smith and others, 2004).

Several other species of red algae can be found on the shallow reef flats of Moloka‘i, but *Spyridia filamentosa* (fig. 28) is probably among the most common. This species is easily recognized because the numerous small hairs that cover the thallus usually trap sediment, giving it a dirty appearance. Other common species include members of the brown

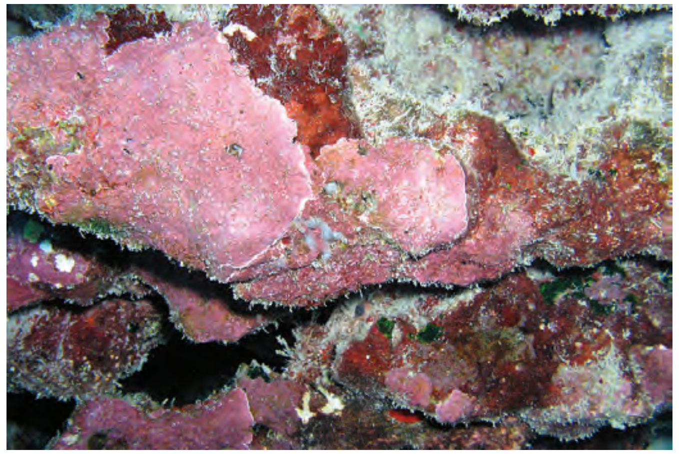
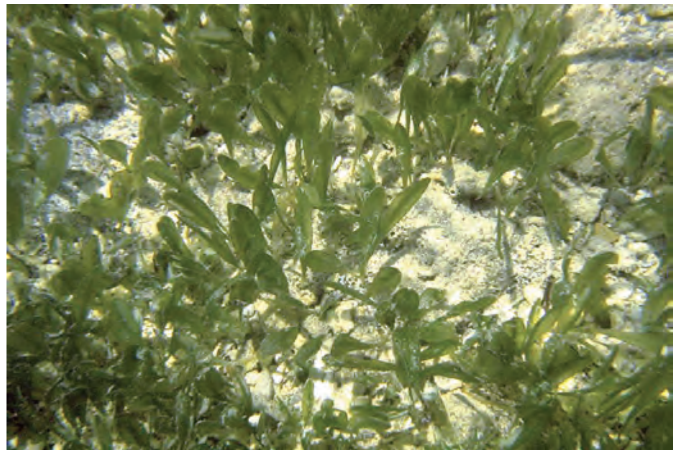


Figure 18. Crustose coralline algae (CCA) are pictured here in various shades of pink. CCA are heavily calcified red algae that help to cement and bind reefs together. These organisms are quite common in all reef zones in Hawai‘i and include around 25 species, although very little is known about their taxonomy. CCA look more similar to pink cement or rock than they do to other algae.

Figure 19. A meadow of the endemic seagrass *Halophila hawaiiana* growing along the south shore of Moloka‘i. Leaves of *Halophila* are usually less than 5 cm (2 in) in height, but meadows can cover several hundred square meters.



Ron Phillips

Figure 20. The common growth form of the endemic Hawaiian seagrass *Halophila hawaiiana* (note the oval or paddle-shaped leaves) growing on the shallow reef flats of south Moloka‘i.

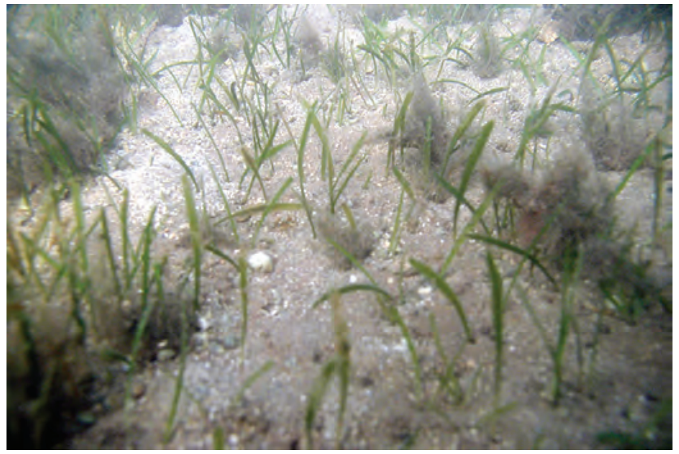


Figure 21. The more elongated and linear-shaped leaves of a different growth form of *Halophila hawaiiana* can also be found growing on the shallow reef flats of Moloka‘i.

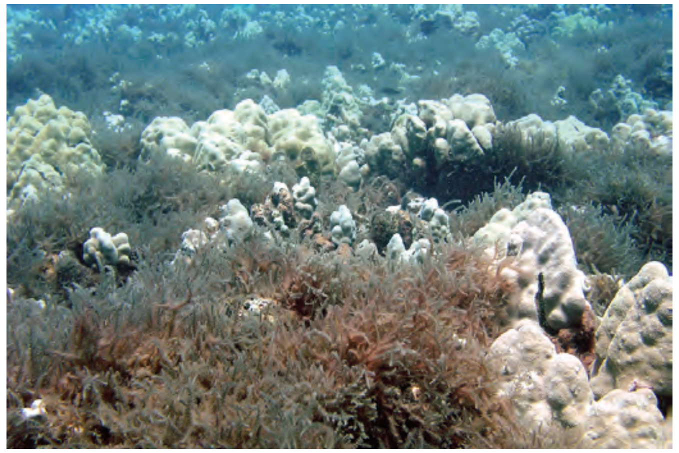


Figure 22. The invasive red alga *Acanthophora spicifera* can be seen in the foreground of this picture, where it is growing over the coral *Porites lobata*. This alga is one of the most common species of algae on the south shore of Moloka‘i and can be found from Hale O Lono Harbor in the west all the way to Kalaekapu in the east. *A. spicifera* was first introduced to O‘ahu in the 1950s by a heavily fouled barge that originated from Guam. *A. spicifera* is usually less than 15 cm (5.9 in) tall, with small spike-like side branches.

Figure 23. The invasive red alga *Hypnea musciformis* was first introduced to O‘ahu in the 1970s for experimental aquaculture and has now spread to all of the main Hawaiian Islands except the Big Island of Hawai‘i. It is quite common on the south shore of Moloka‘i, and it forms large blooms on the island of Maui.

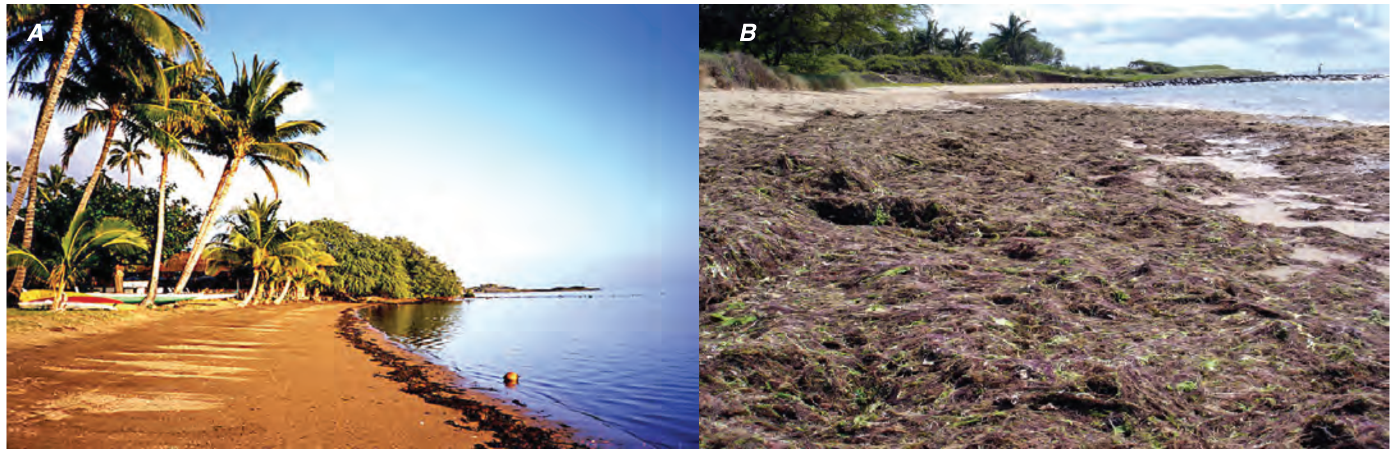


Figure 24. The red alga *Hypnea musciformis* washed up on beaches. *A*, A small band of *H. musciformis* lines the beach of Kamiloloa at low tide. *B*, Thousands of pounds of this alga wash onto the beaches every day on Maui (photo taken at north Kihei).

Figure 25. *Gracilaria coronopifolia*, or limu manauea, growing on the shallow reef flat along the south shore of Moloka‘i. This alga has thin branches (1 mm), but an individual can grow to the size of a bowling ball.

Figure 26. *Gracilaria parvispora*, or long ogo, grows on the shallow reef flat along the south shore of Moloka‘i. This species is also commercially cultivated on Moloka‘i in fishponds and other areas for food (limu poke) and is also used as garnish for meals in restaurants. This species is usually very long and wispy, with branches growing to 50 cm (19.6 in) in length.

Figure 27. The invasive red alga *Gracilaria salicornia,* or gorilla ogo, growing near Kaunankakai Harbor. This alga was introduced to Moloka‘i from O‘ahu in the 1980s for aquaculture projects that were later abandoned. This species is highly invasive on O‘ahu and has the potential to become a problem on Moloka‘i. *G. salicornia* is usually yellow, orange, or brown in color and can grow in large clumps 30 cm (12 in) or more in size.

Figure 28. The red alga *Spyridia filamentosa* is quite common on the shallow reef flat of Moloka‘i. This species is often covered with a dusting of sediment and seems to be able to tolerate growing in extremely muddy areas. *Spyridia* has soft delicate branches and can grow up to 20 cm (7.8 in) in height.

Figure 29. The lightly calcified brown alga *Padina* growing on the reef flats near Kamiloloa. This species is common in muddy areas and can grow quite large, with blade diameters up to 25 cm (10 in).

Figure 30. The green alga *Caulerpa sertulariodes* growing in the sand on the shallow reef flat of the south shore of Moloka‘i. Most species of *Caulerpa* have small root-like rhizoides, a horizontal runner, and upright blades. In this species the blades resemble a fern frond but are only 2–3 cm (0.8–1.2 in) tall.

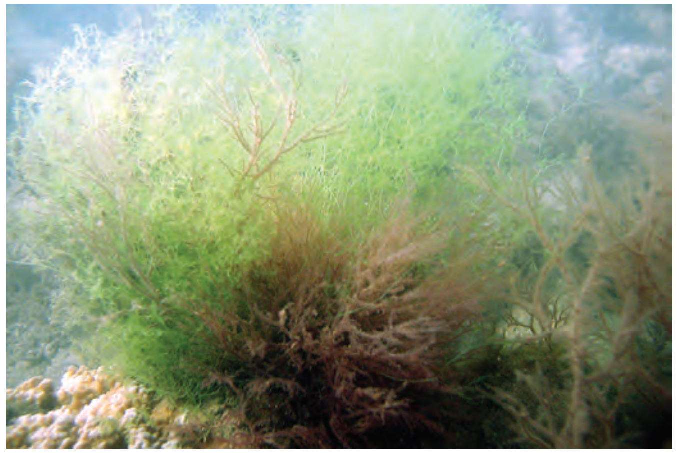


Figure 31. The filamentous green alga *Cladophora vagabunda* growing intermixed with the red alga *Spyridia filamentosa* (lower right). Most species of *Cladophora* are very fine and delicate, but they can grow quite large (~20 cm/7.8 in tall), often resembling green cotton candy.

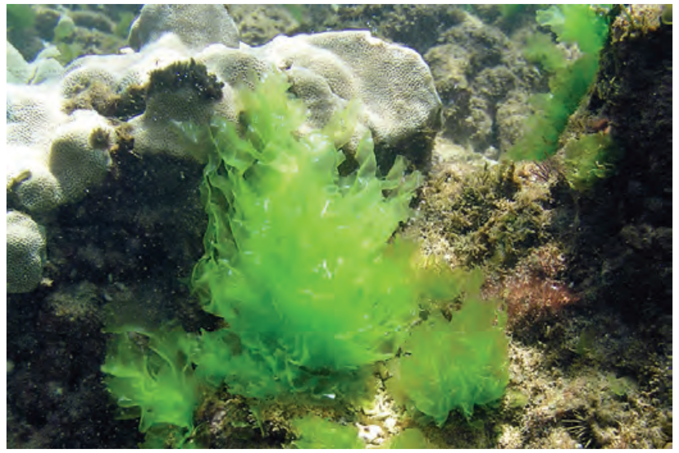


Figure 32. The green alga *Ulva fasciata*, or limu pālahalaha, is common in shallow nearshore environments, especially near nutrient or fresh sources such as springs or streams. *Ulva* is also known as sea-lettuce because its bright green blades resemble leaves of lettuce grown on land.

algal genus *Padina* (fig. 29), which are easily recognized by the rings of calcification that lightly cover the flat leaf-like thallus. Several species of *Caulerpa* can be found in Hawai‘i, and *Caulerpa sertularioides* (fig. 30) is quite common on Moloka‘i. The calcified green alga, *Halimeda discoidea* (fig. 13) is locally abundant, growing in small clumps. Other green algae such as the filamentous *Cladophora vagabunda* (fig. 31), the blade *Ulva fasciata* (limu pālahalaha) (fig. 32), and the commonly eaten *Enteromorpha* spp. (limu ‘ele‘ele) (fig. 33) are also common, especially in areas close to shore near fresh water sources such as springs or stream mouths. The cyanobacteria *Lyngbya majuscula* (otherwise known as swimmer's itch because it produces a toxin which can irritate the skin; fig. 34) grows on top of other algae on the reef flats. *Lyngbya* seems to bloom seasonally in the summer, when it can become quite abundant; by the fall it nearly completely disappears.

In summary, the shallow reef flat and back reef habitats on Moloka‘i are dominated by macroalgae, seagrass, soft sediment, and reef rubble. These areas seem to be quite productive, and because of numerous factors including extensive habitat, they support a diversity of algal species. The high amount of terrigenous sediment deposited in these areas may also contain both organic and inorganic nutrients, thus potentially fertilizing the algal communities. The three invasive nonindigenous algae found on the south shore reef flats seem to be able to outcompete native species in other areas around the Hawaiian Islands and therefore are of concern for marine resource management. The reef flats are important resources, because they support numerous fish, invertebrate, and seaweed species, of which many are harvested for subsistence consumption.

The Reef Slope

There is a limited amount of information known about the algal communities in the deeper (2–20 m, 6–60 ft) reef-slope environments around Moloka‘i. However, in a single survey in 2002, two divers collected more species of algae (as many as 85) from Pālā‘au, Kamiloloa, and Kamalō than from any other sites surveyed around the eight main Hawaiian islands that same year. These sites represent some of the highest diversity sites for algae that the authors have seen. Although most of the species were members of the turf community and were small filamentous forms, several species of red macroalgae were also quite common. Species such as the fleshy red-bladed *Kallymenia sessilis* (fig. 35) and *Halymenia* sp. (fig. 36) were present. The brilliantly iridescent red algal species, including members of the genera *Halicrysis* (fig. 37), *Dasya* (fig. 38), *Martensia* (fig. 39), and *Neomartensia* (fig. 40) and *Acanthophora pacifica* (fig. 41) were all present.

In the deeper areas off the reef slope, the green alga *Halimeda kanaloana* becomes the dominant benthic organism in soft sandy areas. This endemic species forms extensive meadows (fig. 42) in the soft bottom areas off the south shores of Moloka‘i, Lāna‘i, Kaho‘olawe, and Maui. It generally occurs in depths ranging from less than 1 m to more than 90 m (300 ft) (Verbruggen and others, 2006). All species of *Halimeda* are heavily calcified and are important sand producers. When these organisms reproduce, they relocate all of their intracellular material into their gametes, which are then released by the thousands into the water column—only an empty white skeleton of the adult plant is left. Usually within a day, the adult plant crumbles into a pile of small calcium carbonate discs that eventually break down into sand (fig. 43; Field and others, this vol., chap. 17). This process is easy to recognize in areas where *Halimeda* is abundant, because the plantlike segments are still identifiable. Although there are several other sand producers in the tropics, *Halimeda* is likely to be among the most important because of the fast turnover rates of these plants.

The reef slope communities along the southeast and southwest shores of Moloka‘i are largely dominated by hard corals, but the algal communities are also incredibly diverse and are composed of some rare species. The reef slope communities near Kaunakakai have very low coral cover (Jokiel and others, this vol., chap. 5), and are predominantly covered in fleshy algae such as *Spyridia* and thick stands of turf algae. Along most of the south shore, the green alga *Halimeda* forms extensive meadows (fig. 42) in the waters beyond the reef slope, extending out into deep water.

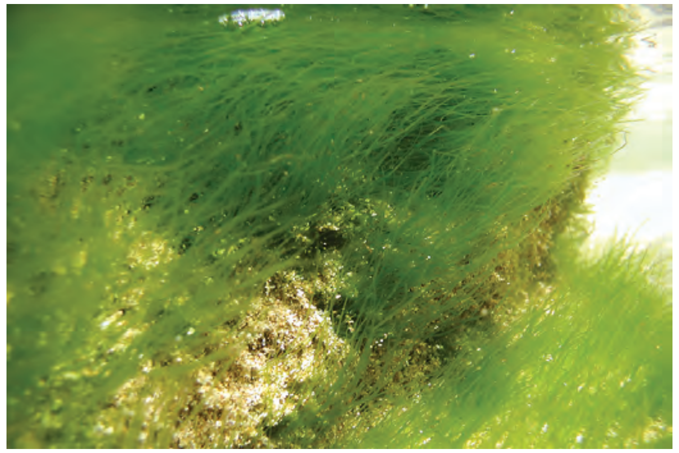


Figure 33. *Enteromorpha* (this alga is now considered to be in the genus *Ulva*, but it often grows in tubes rather than sheets), or limu ‘ele‘ele, can be seen growing at the land-sea interface and is often common in brackish water where springs or streams enter the marine environment. Individual tubes of *Enteromorpha* can reach more than 30 cm (12 in) in length.

Figure 34. The cyanobacterium *Lyngbya majuscula* is often found growing on top of other algae such as *Sargassum*. This species often forms large ephemeral blooms in the summer. It also produces a toxin that has been known to cause skin rashes in swimmers.

Figure 35. The fleshy red-bladed *Kallymenia sessilis* growing in the interstices of the coral *Monitpora capitata*. *Kallymenia* is usually 5–10 cm (2–4 in) in height.

Figure 36. The large, dissected, red-bladed *Halymenia* is common in wave-swept subtidal habitats in Hawai‘i. Blades of *Halymenia* can reach up to 40 cm (15.7 in) in height, but most individuals are 20 cm (7.8 in) or less.

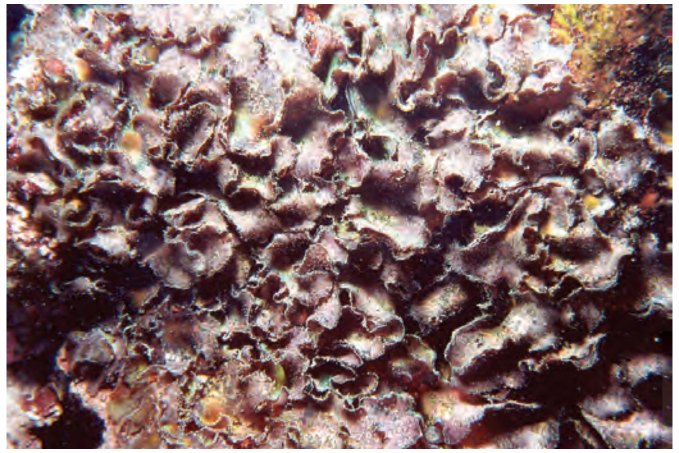


Figure 37. The golden, iridescent red alga *Halycrisis* is common at Pālāʻau. This alga grows tightly adhered to hard substrates and is no taller than 5 cm (2 in).

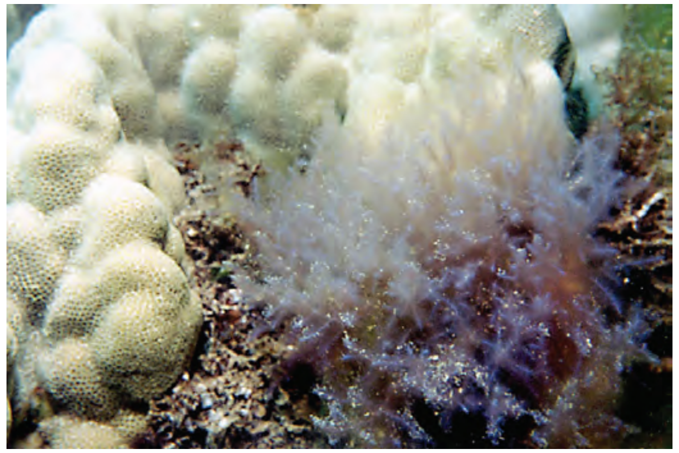


Figure 38. The delicate iridescent red alga *Dasya irridescens* is shown here growing next to the coral *Porites lobata* (lobe coral). *Dasya* grows up to about 10 cm (4 in) in height.

Figure 39. The fragile and iridescent red alga *Martensia fragilis*. This alga can vary in color from blue to purple to red and orange and is usually 5-10 cm (2-4 in) in height.

Figure 40. The delicate mesh-like iridescent red alga *Neomartensia flabelliformis* resembles gauze. This species is very fragile and is usually 5-15 cm (2-5.9 in) in height.

Figure 41. The blue to purple iridescent red alga *Acanthophora pacifica*. This species is far less common than the invasive counterpart, *Acanthophora spicifera*. *A. pacifica* is usually about 5 cm (2 in) in height.

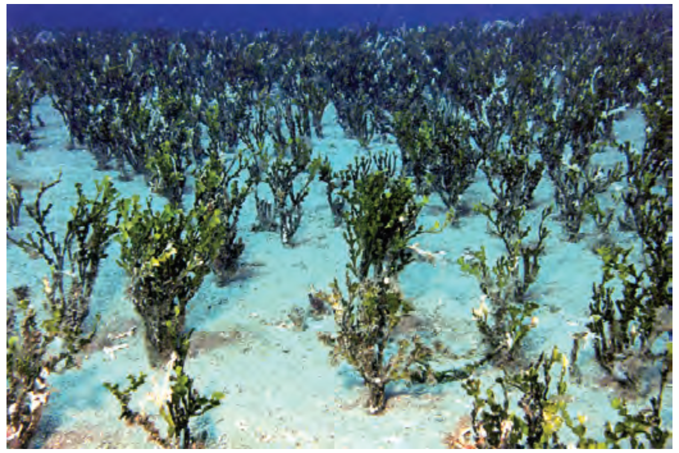


Figure 42. A meadow of the calcified green alga *Halimeda kanaloana* off Kamiloloa in 11 m (35 ft) of water. This species forms extensive meadows on the deep reef slopes off Molokaʻi and Maui. Most species of *Halimeda* are important producers of sand in the tropics. This species is among the largest *Halimeda* in Hawaii and can be more than 30 cm (12 in) tall.

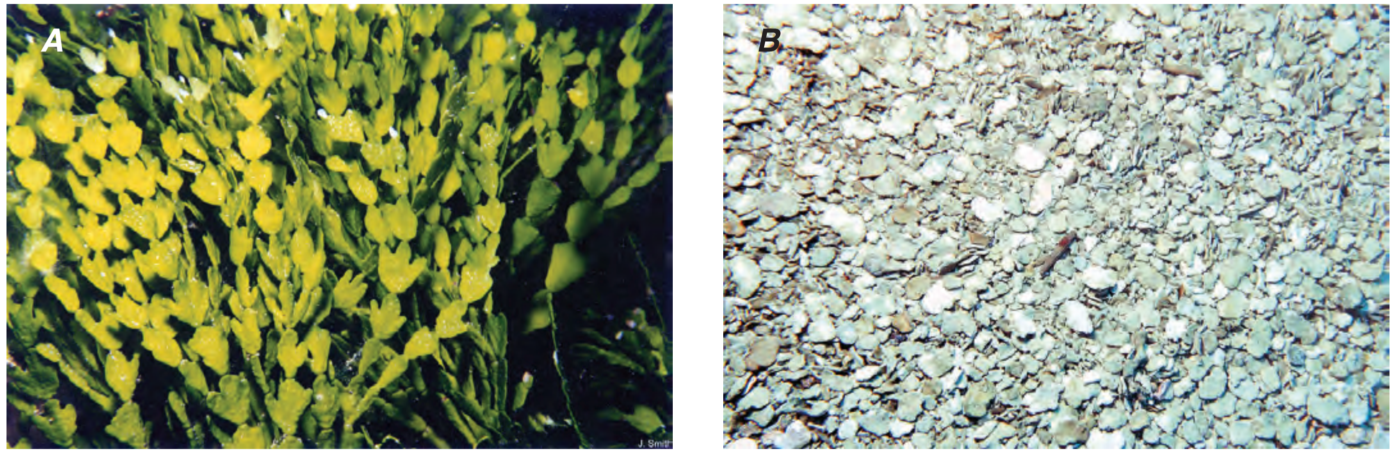


Figure 43. *Halimeda kanaloana*. *A*, A close-up of live *H. kanaloana*. *B*, Sand that is composed largely of recently dead *Halimeda* (note the oval-shaped disks).

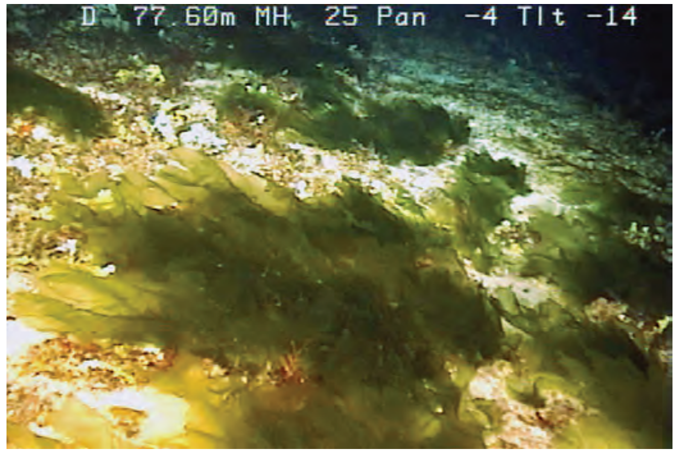


Figure 44. Large (~20 cm/7.8 in) green blades of the genus *Ulva* at 77-m (254 ft) depth. This chlorophyte covers large expanses of this deep water rubble zone.

Figure 45. Two different *Codium* species at 67-m (221 ft) depth; one is long (~15 cm/5.9 in) and lightly branched, while the other is short and more densely branched.

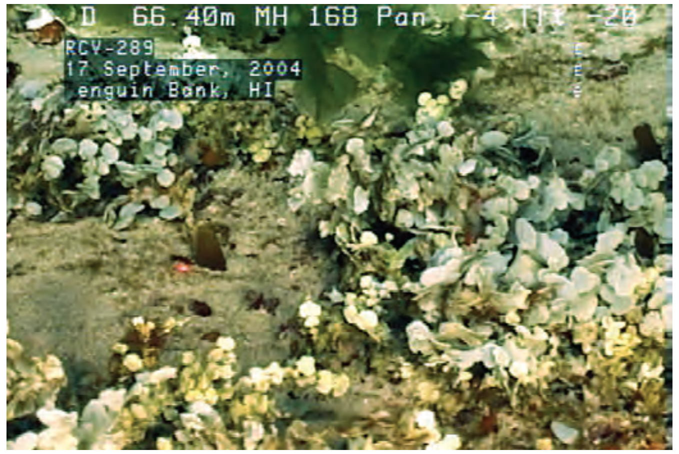


Figure 46. *Halimeda* spp. found growing on hard substrate at 67-m (221 ft) depth. These species often form clumps or large mounds in these deep-water habitats.

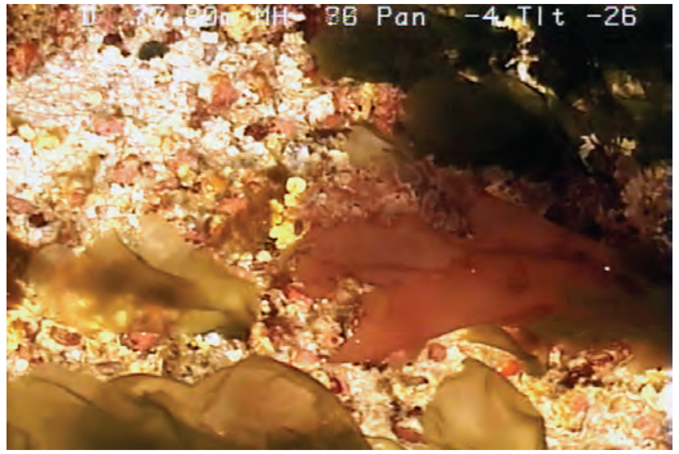


Figure 47. Unidentified red algal blades growing intermixed with the green alga *Ulva* in the rubble zone at 70-m (230 ft) depth.

Deep-Water Communities

In the deeper waters off south Moloka‘i, the bottom is a mix of soft sand, hard carbonate, rubble, and large areas covered by small balls of calcified red algae called rhodololiths. Areas that were surveyed include depths from about 60 to 120 m (~200 to 400 ft) on three different occasions in 2004 with a submersible and a remotely operated vehicle. Despite the low light levels at these depths, there was a high abundance and diversity of macroalgae. The most common large macroalgal group encountered was the chlorophyte *Ulva* (fig. 44), with *Ulva* sp. blades up to 2 m (6 ft) in length. This genus usually occurs in the intertidal zone, yet we found that it was common (as much as 25 percent cover) from 60 to 100 m (~200 to 330 ft) depths. Other common green algal genera were *Codium* (fig. 45) and *Halimeda* (fig. 46). At least three different species of *Codium* and three different species of *Halimeda* were observed, although species identifications are still pending. Many fleshy red algal blades (figs. 47, 48) were observed, but these were not collected because of strong currents. These fleshy red algae were abundant on hard substrates over the entire depth range surveyed. Large scattered clumps of the brown alga *Spatoglossum macrodentum* were also observed on hard substrate. Small filaments and clumps of the filamentous green alga *Cladophora sericea* were observed floating in the current and being transported across the bottom. A dense *Halimeda kanaloana* meadow (fig. 49) was discovered starting at 86 m (284 ft) depths in soft sediments, and it appeared to continue into shallower water.

Overall, the deep-water macroalgal community is very rich and abundant, likely forming unique habitats and acting as a food source for numerous organisms. We did not observe any invasive or introduced macroalgae in the deep-water environment, although the invasive green alga *Avrainvillea amadelpha* has been observed in similar habitats in deep water off of O‘ahu. Exploration of these unstudied environments is likely to yield the discovery of many species of algae, invertebrates, and even fishes that are new to science.

The West Shore

Very little is known about the benthic communities off the west shore of Moloka‘i. The southwest section of coast consists of a few small bays with black sand beaches and basalt points, whereas the northwest coast is largely made up of extensive carbonate sand beaches and occasional basalt outcroppings. Judging from a limited amount of field work, the intertidal communities in these areas appear to be rich with seaweeds and consist of species mentioned previously, including *Sargassum*, *Turbinaria*, *Padina*, *Galaxaura*, *Tricleocarpa*, a brown alga *Dictyopteris* (limu līpoa) (fig. 50), several species of the red algal genus *Laurencia* (fig. 51), and a surprisingly high abundance of the small calcified green alga *Neomeris annulata* (fig. 52). Overall, these communities appear to be quite diverse.

Figure 48. An unidentified red algal blade with frilly or ruffled red edges at 73-m (240 ft) depth off southwest Moloka‘i.

Summary

The marine environment of Moloka‘i is diverse and includes boulder fields, basalt tidepools, manmade fishponds (which were not surveyed here), shallow carbonate benches, extensive mud flats, coral-dominated reef slopes, macroalgal-dominated deep reefs, and various combinations of all of the above. Each of these different habitat types supports a unique assemblage of marine algae. Both the east and the west coasts are exposed to large waves, have little human impact, and support diverse algal communities in the shallow intertidal and reef-flat areas. The south shore is quite different because it is sheltered from wave action and has an extensive reef flat and many other unique types of habitats. The wide, shallow reef flat is one of the largest continuous shallow-water habitats for the endemic seagrass *Halophila hawaiiana* in Hawai‘i. These areas have been historically productive and have been invaluable collecting areas for numerous species of seaweed or “limu,” which are regularly consumed by the people of Moloka‘i. There is an indication, however, that large portions of these habitats are being overgrown by invasive macroalgal species. The actual cause of this overgrowth remains unclear, but it could be a result of increased nutrients, sedimentation, or perhaps a lack of herbivores in these areas. The deep-water reefs of Moloka‘i harbor numerous seaweed species, many of which are likely new to science. Every effort should be made to preserve the unique marine environments on Moloka‘i and the diversity of species that inhabit them.

Figure 49. An expansive meadow of the green alga *Halimeda kanaloana*. Such meadows typically occur in soft, sandy sediments and span depths from 10 m (33 ft) to more than 90 m (295 ft).

Figure 50. The brown alga *Dictyopteris* (limu lipoa) can be quite common in the shallow subtidal communities in Hawai‘i, where it often forms extensive beds. This genus is similar to *Dictyota* but has a rib that extends through the middle of each branch, rather than being completely flat like *Dictyota* (see fig. 16). Most species of *Dictyopteris* can grow up to 30 cm (12 in) in height.

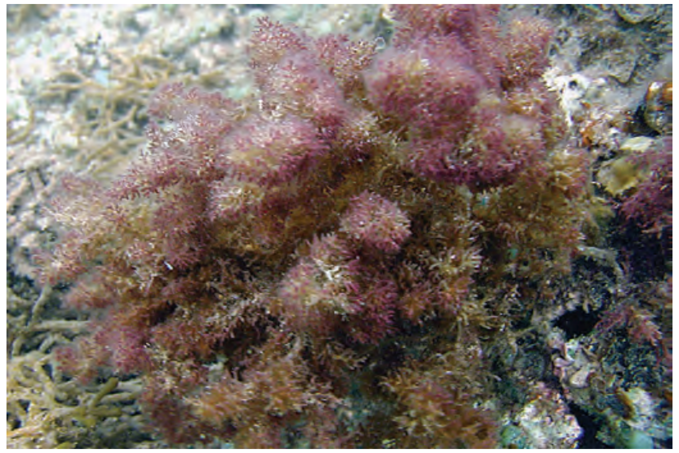


Figure 51. The red alga *Laurencia* is a common component of intertidal communities on rocky or basalt shorelines. There are more than 10 species of *Laurencia* in Hawai‘i, most of which are less than 10 cm (4 in) tall, and species identification can be quite difficult without a microscope.

Figure 52. A dense clump of the calcified green alga *Neomeris* growing along the west shore of Moloka‘i. This species usually grows alone or in clumps consisting of a few individuals less than 2 cm (0.8 in) tall; however, this photograph shows more than 50 individuals growing together.

CHAPTER 9

Benthic Habitat Maps of the South Moloka‘i Coral Reef

Susan A. Cochran[1]

To document evidence of change in any ecosystem, one must first have a starting point—a “baseline” inventory of resources. Thematic maps providing this baseline inventory are an important tool for assessing changes in coral reef ecosystems, allowing scientists to spatially document changes in coral location, percentage of cover, and relative overall health of the system. In the past decade, scientists and managers have recognized the lack of thematic maps for coral reefs worldwide. In 1998, the White House issued Executive Order 13089 establishing the U.S. Coral Reef Task Force (CRTF). Composed of several Federal agencies, including the U.S. Geological Survey (USGS), the CRTF has the primary duty of mapping and monitoring the coral reefs in the United States and U.S. Trust Territories.

One of the strategic goals of the U.S. Geological Survey is to assist land-use managers by establishing the geologic framework for ecosystem structure and function. Provide here are detailed high-resolution maps and habitat characterization of the reef off the south shore of Moloka‘i, a critical coral reef in Hawai‘i that is of concern to resource managers and the public. The threats to this reef, including excessive sedimentation and pollution, were some of the reasons for selecting this site to develop procedures for producing such maps. The USGS is in a position to provide high-resolution benthic habitat maps of the Moloka‘i reef because it is not under the 1-acre Minimum Mapping Unit (MMU) and 1:6,000 scale restrictions self-imposed on other agencies. These maps can be used as stand-alone static documents or in a geographic information system (GIS) and provide useful information to scientists, managers, and the general public.

Mapping on Moloka‘i

Before 1998, the University of Hawai‘i Marine Options Program undertook the only mapping effort of the south Moloka‘i reef, funded by the U.S. Army Corps of Engineers (Manoa Mapworks, 1984). Qualitative field data were collected over a two-week period using scuba and snorkel, and maps were plotted using 1975 black and white aerial photography at 1:6,000 and 1:24,000 scales as a base layer. These maps provide a useful background to the reef ecosystem; however, the 1975 aerial photographs were not georectified, and thus no true quantitative measurements of scale and distribution can be made.

In 1999, in response to the mandate set forth by Executive Order 13089, The National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS) implemented a program to provide digital maps of our Nation’s coral reefs for use in a GIS. The south Moloka‘i reef was mapped using orthorectified aerial photography, hyperspectral remotely sensed images, and quantitative field observations (Coyne and others, 2003). The classification scheme used to produce these maps documented 9 out of a possible 23 distinct benthic habitat types on the south Moloka‘i reef and 10 out of a possible 14 morphological reef zones. However, under the restrictions of a 1-acre (64 m by 64 m) MMU and at no finer resolution than a 1:6,000 scale, many smaller details of the reef system were overlooked. Using additional photography and bathymetric data, the USGS has now mapped the south Moloka‘i reef at a much higher resolution.

How the Maps Were Made

The Moloka‘i benthic habitat classification maps in this report were created from visual interpretation of georectified, color aerial photography and SHOALS (Scanning Hydrographic Operational Airborne Lidar Survey) bathymetric data (see Field and others, this vol., chap. 2). In addition to the remotely sensed imagery, we used knowledge from field data collected over a period of four years, from 1999 to 2003. These field data include underwater photographs, video, and visual observations and were collected using towed instruments, scuba and snorkel, and on foot. Mapping was accomplished using a GIS, and a statistical analysis of accuracy was performed. See Cochran-Marquez (2005) for a complete description of background layers, mapping methodology, and statistical accuracy assessment.

The classification scheme used was based on a scheme established by NOAA’s biogeography program in 2002 and subsequently revised in 2004 (NOAA National Centers for Coastal Ocean Science, 2005). Our maps use NOAA’s scheme as a starting point to provide some continuity to the coral-reef scientific community. However, modifications were made to the original scheme in order to better reflect the benthic habitats, geologic substrates, and historical features (such as fishponds) found on Moloka‘i.

More than 4,200 polygons covering more than 120 km^2 were digitized by interpreting features seen in both the aerial photographs and SHOALS bathymetry, with additional input from underwater video footage, photographs, and field observations. A minimum mapping unit (MMU) of 100 m^2 was used, but smaller features were mapped if they carried habitat significance (for example, an individual coral colony 2 m in diameter located in an otherwise uncolonized area). The classification scheme uses four basic attributes to describe each polygon on the benthic habitat map: (1) the dominant geomorphic structure or underlying substrate; (2) the major biologic cover found on the substrate; (3) the percent biologic coverage; and (4) the geographic zone indicating the location of the habitat (table 1). Each combination of a geomorphic structure with an overlying biologic cover may be described as a separate habitat. A geographic zone describes the cross-shelf location of a habitat, using terminology common in current coral-reef literature (fig. 1).

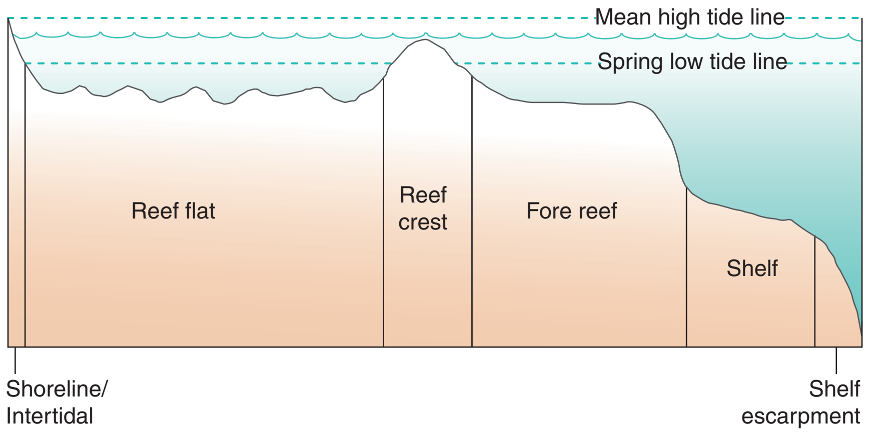


Figure 1. Schematic diagram showing the generalized cross-shelf coral reef zonation of the south Moloka‘i reef. Not shown are the zones land, channel, dredged, or vertical wall (modified from Kendall and others, 2004).

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[1] U.S. Geological Survey Pacific Science Center, 400 Natural Bridges Dr., Santa Cruz, CA 95060

Table 1. Categories of dominant structure/substrate, major biological cover, percent cover, and geographic zones used in the Moloka‘i benthic habitat classification scheme (modified from NOAA National Centers for Coastal Ocean Science, 2005).

[Less than 10 percent biological cover is considered to be uncolonized; therefore, <10 percent is not used as a percent biological cover category.]

Geomorphic structure/substrate	Biological cover	Geographic zonation
Hardbottom	Coral	Land
Aggregate reef	Coralline algae	Shoreline/intertidal
Spur-and-groove reef	Emergent vegetation	Reef flat
Aggregated patch reef	Macroalgae	Reef crest
Individual patch reef	Mangrove trees	Fore reef
Pavement	Uncolonized	Shelf
Pavement with sand channels	Unclassified	Shelf escarpment
Scattered coral/rock	(land or artificial)	Channel
Reef rubble	Unknown	Dredged
Softbottom		Vertical wall
Sand	**Percent biological cover**	
Mud	10% to <50%	
Other	50% to <90%	
Artificial	90% to 100%	
(for example, wharves)		
Artificial/historical		
(for example, fishponds)		
Land		
Unknown		

Table 2. Areas and percentages for each class of dominant structure/substrate on the south Moloka‘i reef.

Dominant structure/substrate	Area (m^2)	Area (acres)	Percent
Aggregate reef	5,718,383	1,413.043	4.69
Aggregated patch reef	683,658	168.938	0.56
Artificial	119,770	29.597	0.10
Artificial/historical	116,252	28.730	0.10
Individual patch reef	38,325	9.471	0.03
Land	2,192,241	541.715	1.80
Mud	5,142,276	1,270.678	4.22
Pavement	38,531,126	9,521.240	31.59
Pavement with sand channels	5,029,773	1,242.888	4.12
Rubble	2,428,875	600.188	1.99
Sand	47,047,502	11,625.692	38.57
Scattered coral/rock	1,387,821	342.932	1.14
Spur-and-groove	12,030,578	2,972.823	9.86
Unknown	1,511,423	373.479	1.24
Grand total	**121,978,003**	**30,141.414**	**100.00%**

Table 3. Areas and percentages for each class of major biological cover on the south Moloka‘i reef.

Major biological cover	Area (m^2)	Area (acres)	Percent
Coral	34,031,767	8,409.427	27.90
Coralline algae	179,632	44.387	0.15
Emergent vegetation	150,170	37.111	0.12
Macroalgae	16,615,684	4,105.825	13.62
Mangrove trees	2,967,857	733.366	2.43
Unclassified	234,028	57.834	0.19
Uncolonized	66,087,550	16,330.591	54.18
Unknown	1,711,315	422.873	1.40
Grand total	**121,978,003**	**30,141.414**	**100.00%**

The Maps—What They Tell Us

Dominant Structure/Substrate

The south Moloka‘i reef is classified into 14 different structures/substrates that compose the reef morphology. The maps on the following pages show the reef in nine different geographic subsets. The dominant structure/substrate and major biological cover maps have been overlaid on aerial photographs for viewing purposes. Nearly 66 km^2 (54 percent of the total area mapped) consists of combined reef and hard-bottom substrates; soft-bottom sand and mud make up just over 52 km^2 (43 percent) (table 2).

A major feature of the South Moloka‘i reef is the broad, shallow pavement platform of the reef flat, which extends nearly 1.5 km offshore in the Pālā‘au and Kamiloloa areas (see Storlazzi and others, this vol., chap. 3). A mud veneer and ancient fishponds lie close to shore on the reef flat, while sand patches and coral-covered pavement dominate the seaward edge of the reef flat.

Seaward of the reef crest, the fore reef alternates between abundant reef and barren, hard pavement. Aggregate reef growth is predominantly in the Wai a Kāne/Pālā‘au and Kawela/Kamalō regions. Spur-and-groove formations are more common to the west. The areas off Kaunakakai/Kamiloloa and Pūko‘o, however, are barren “dead zones” of hard pavement with little or no active reef development.

The base of the fore reef is around 27-m (90 ft) water depth, where it drops off into a gently sloping sand-covered plain of the shelf zone. Reef development pinches out near the east and west ends of the island, where high wave energy limits growth (see Storlazzi and others, this vol., chap. 11).

Additional structure/substrate descriptions for each geographic subset area may be found on the following pages.

Major Biological Cover

The 14 different structures/substrates are covered with 8 different biological classes. Coral covers 51 percent of the suitable hard substrate on the Moloka‘i reef (more than 34 km2 or 28 percent of the overall study area) (table 3).

Major biological cover varies geographically along the inner reef zones (shoreline/intertidal, reef flat, and reef crest). Macroalgae is most abundant on the reef flat in the Kaunakakai (eastern half), Kamiloloa and Pūko‘o areas. The majority of the mangroves may be found along the Pālā‘au and Kaunakakai shorelines (see D’Iorio, this vol., chap. 16). Wai a Kāne, Pālā‘au and Kamalō have large areas of uncolonized sand or barren pavement (fig. 2).

The coral-covered pavement at the seaward edge of the reef flat is dominated by *Porites lobata* colonies. These shallow colonies appear as knobby flat-topped mesas, with live tissue on the sides of the coral mounds. Surface exposure, wave influences, and/or relative sea-level change prevent vertical growth of these coral mounds. These flat-topped coral mounds can be exposed at low tides, making it difficult for live coral tissue to grow. The irregular surface of the knobby mounds sometimes has macroalgae or coralline algae growing on it, and it may contain sediment in the depressions (pukas).

Of the areas of suitable hardbottom available for coral growth on the Moloka‘i fore reef, the highest percentages of coral are found in the Wai a Kāne and Pālā‘au areas near the west end of the island and in the Kawela and Kamalō (western half) areas along the center of the island. Studies have shown these areas to have the highest coral coverage in the

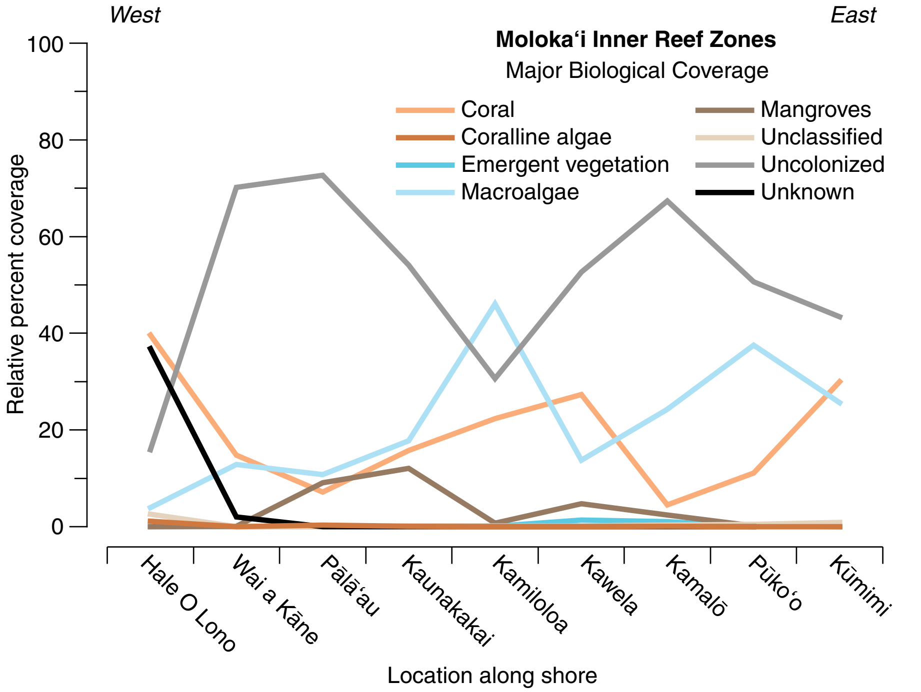


Figure 2. Graph showing the major biological coverage on the inner reef zones (shoreline/intertidal, reef flat, and reef crest) for each geographic area of the south Moloka‘i reef. The geographic locations alongshore relate to the map sections shown in the following pages. The percent coverages are relative to each map section.

main Hawaiian Islands (Jokiel and others, 2001). The fore reef in the Kaunakakai (eastern half), Kamiloloa (western half), Kamalō (eastern half), and Pūko‘o areas have large "dead zones" where most hardbottom substrate suitable for coral growth is either barren or covered with macroalgae (for example, *Halimeda* sp.) (fig. 3).

Aggregate reefs and spur-and-groove formations on the fore reef are dominated mostly by *Porites* sp. and *Montipora* sp. Large patches of the macroalgae *Halimeda* sp. may be found in the sand at the base of the fore reef. These calcareous algae are a major contributor to the sand supply on the reef shelf (see Field and others, this vol., chap. 17).

The highest percentages of coral are found at depths between 5 m and 15 m (15–50 ft) across the entire reef (fig. 4). However, abundant coral is also found at depths between 20 m and 25 m (65–85 ft) in some localized areas.

Additional biological cover descriptions of each subset area may be found on the following pages.

Accuracy of Maps

The validity of map classifications is determined with actual on-site checks at random locations and an accuracy assessment. For this project, a total of 816 map points were checked in the field. The overall accuracy of 86.27 percent (with a 95-percent confidence interval of ±2.36 percent) indicates the number of points on the map which were classified correctly according to the field check. The greatest amount of error was found in the uncolonized class. In this instance, what was originally mapped as uncolonized sand on the fore reef at depths of approximately 27 m (90 ft) was found many times to be sand with >10 percent macroalgae (*Halimeda* sp.).

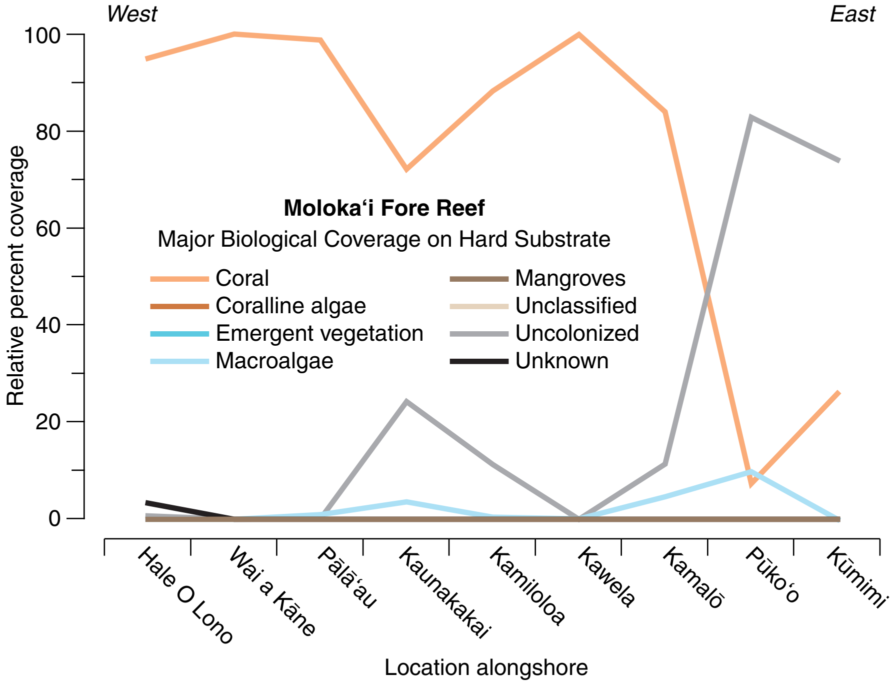


Figure 3. Graph showing the major biological coverage on hardbottom substrates for each geographic area of the south Moloka‘i fore reef. The geographic locations alongshore relate to the map sections shown in the following pages. The percent coverages are relative to each map section.

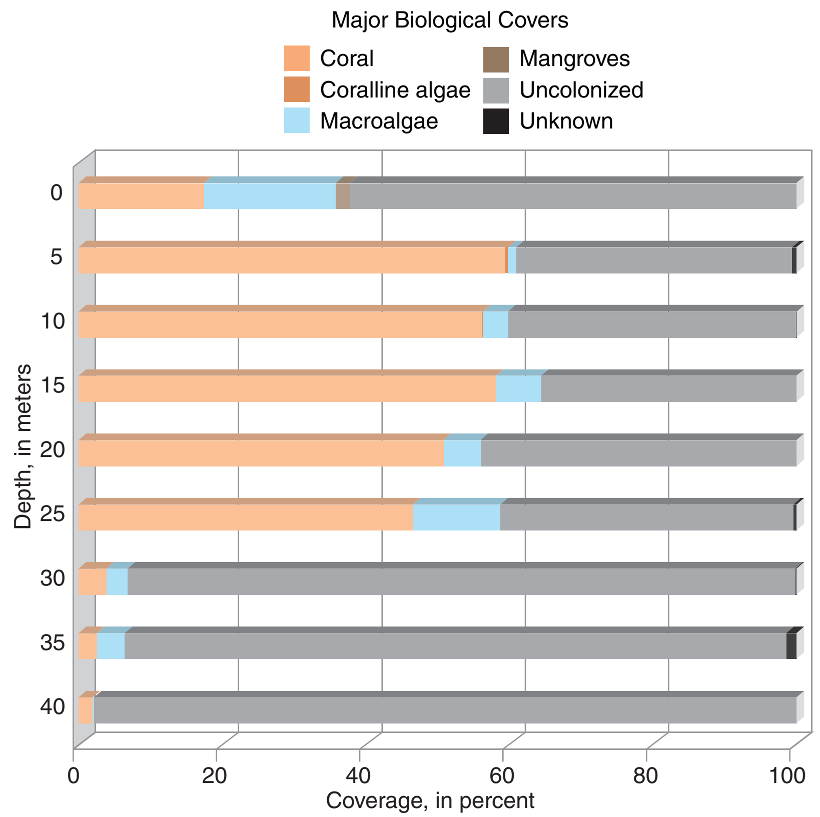


Figure 4. Graph showing the percentages of major biological covers at various depths along the south Moloka‘i reef. See text for description.

After accuracy assessment calculations were performed, any misinterpreted polygons on the Moloka‘i reef maps were corrected using the field-check data, thus increasing the accuracy of the final map to greater than 86.27 percent.

Using the Maps

The detailed high-resolution maps provided here document habitat characterization of a critical coral reef in Hawai‘i and are for use by managers, scientists, and the general public. These maps can be used by themselves (as shown in this volume), or the digital files may be used in a GIS or with other types of visualization software (fig. 5). Integration of the aerial imagery, SHOALS bathymetry, and field observations made it possible to create detailed thematic map layers reaching depths of 35 m (120 ft), encompassing the base of the Moloka‘i fore reef, which is deeper than can be mapped with standard optical remote sensing instruments.

The maps are based on an interpretation of conditions at the time the imagery was collected (1993, 1999, and 2000) and are constrained in positional accuracy by use of a standard GPS receiver (±3 m). Hence, they are not to be used for navigation and are limited in their use for recognizing small-scale changes in the ecosystem. For example, it would be difficult to discern if bleaching occurs, or if there is a loss of coral colonies due to storm waves or dredging. However, large-scale shifts in the dominant bottom type, such as a change from uncolonized pavement to a predominantly algal-covered or coral-covered environment, could be detected.

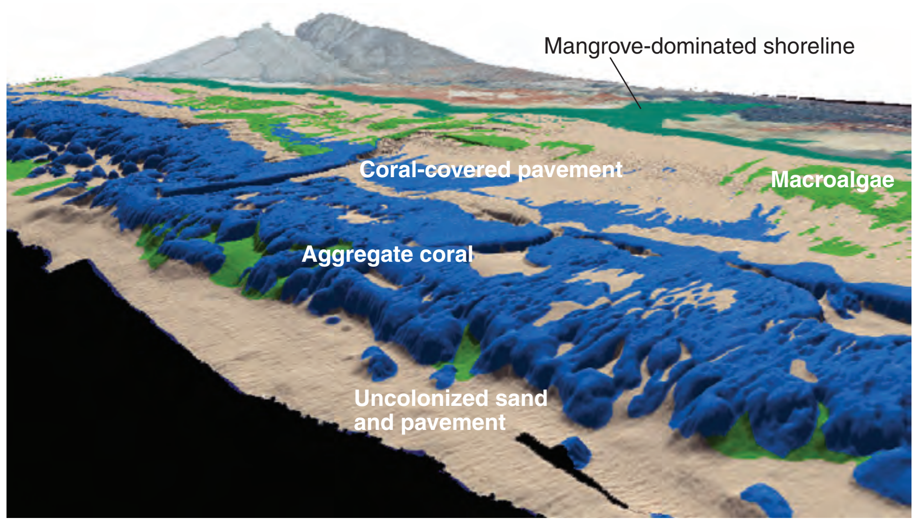
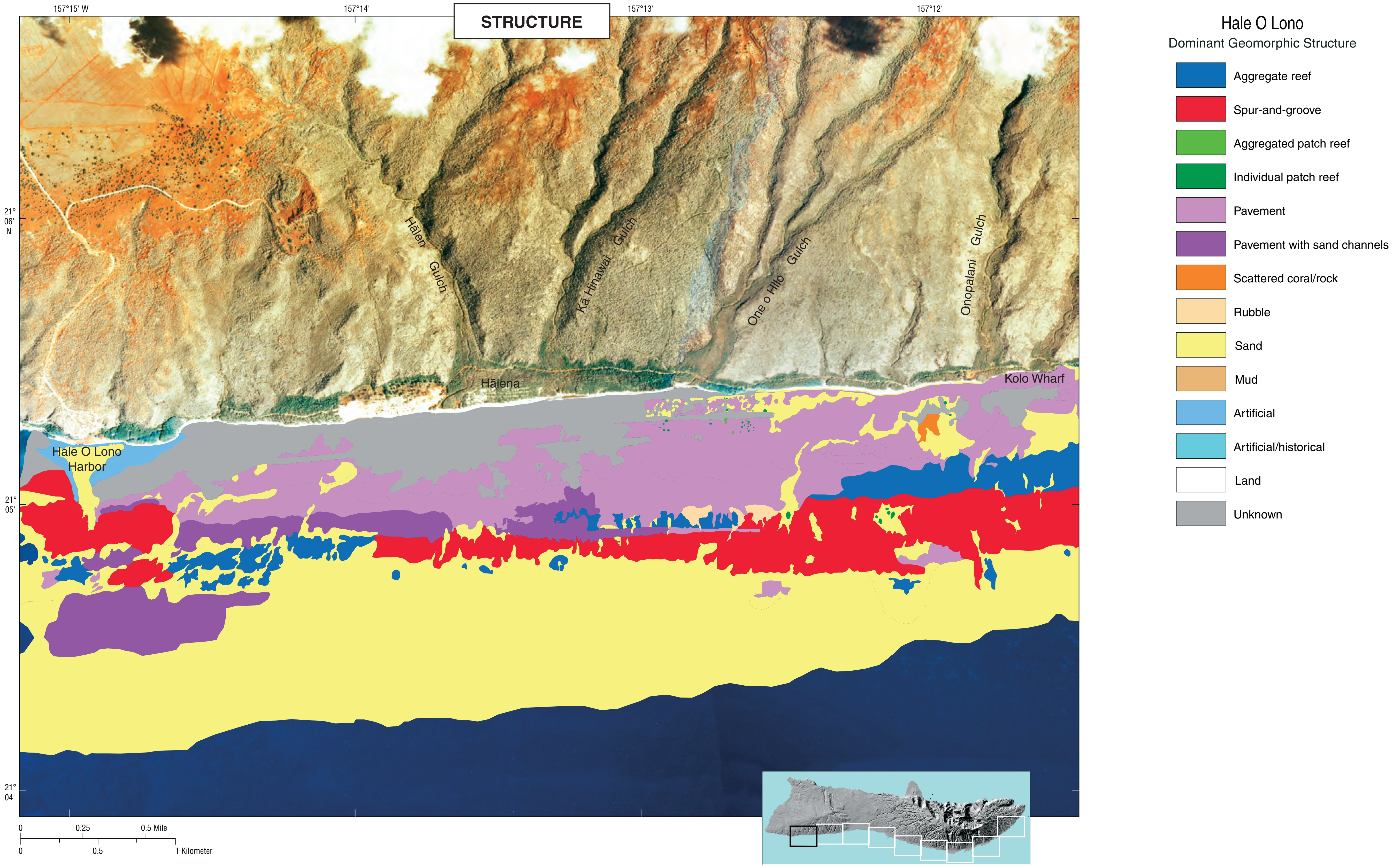
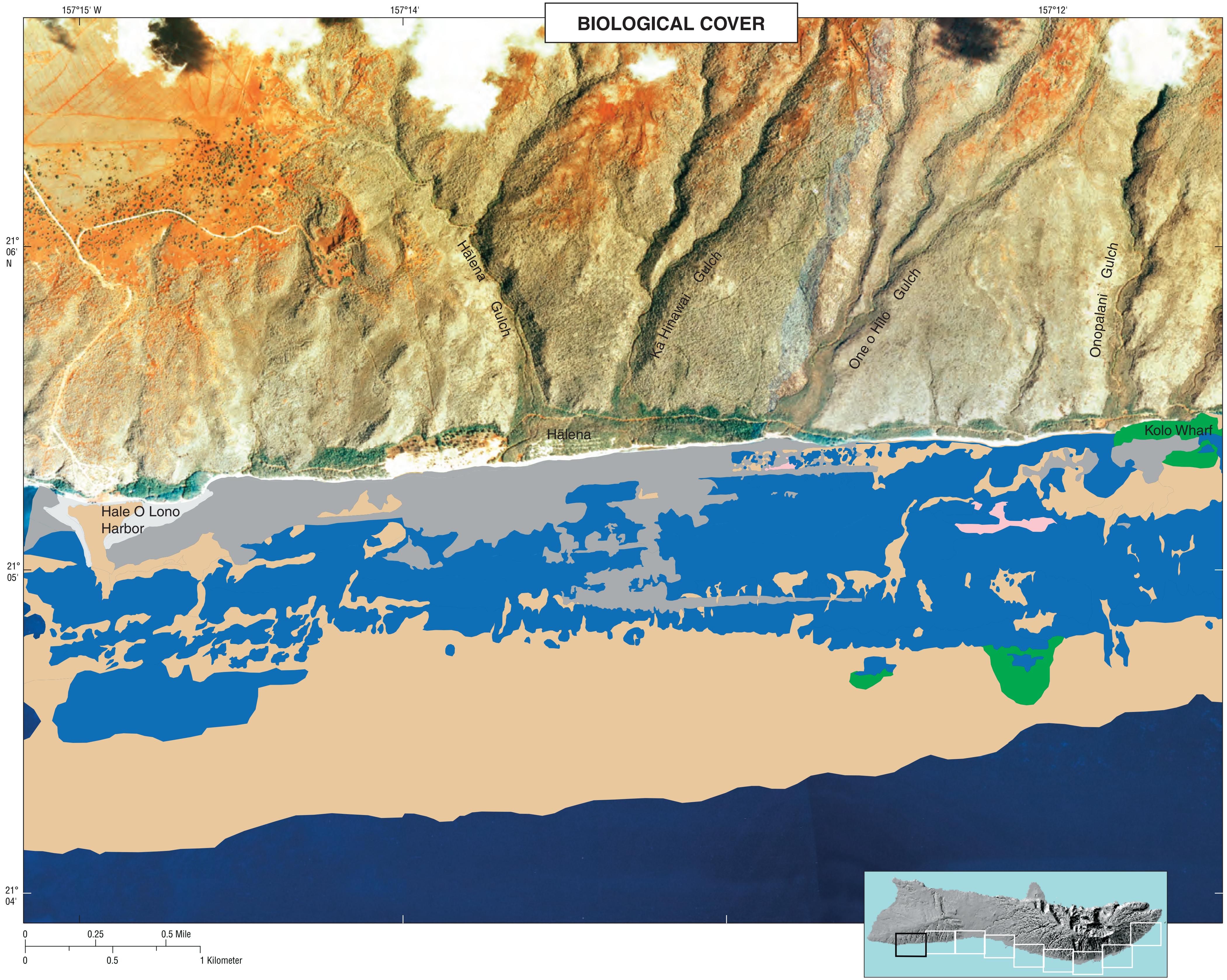
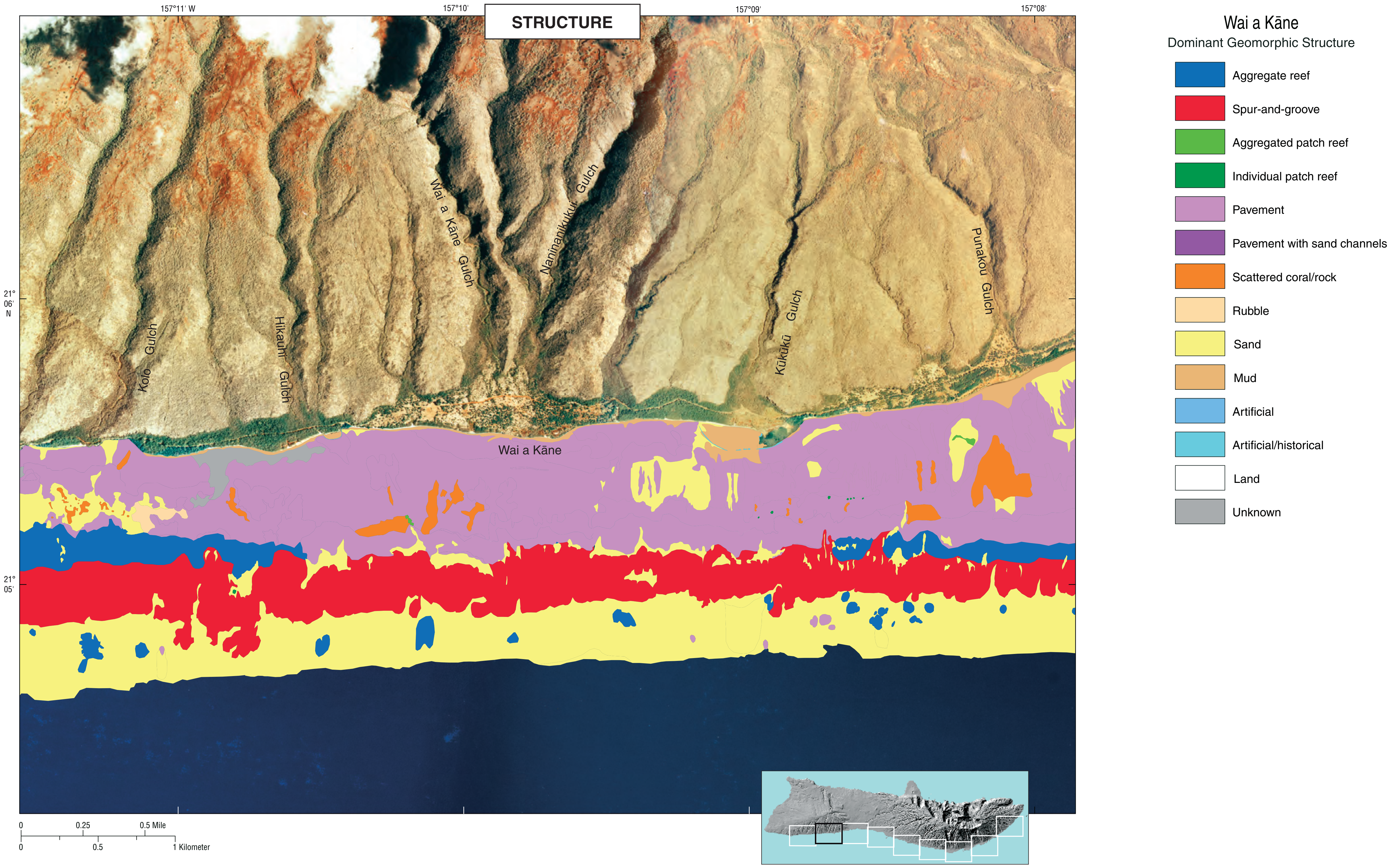


Figure 5. Three-dimensional perspective view, looking northwest, of the Pālā‘au region of the south Moloka‘i reef showing major biological cover. The natural channel leading from the mangrove-dominated shoreline (blue-green) is visible in the left-center portion of the image. Aggregate coral (blue) dominates the fore reef; the reef flat is a mix of uncolonized sand and pavement (tan), macroalgae (light green), and coral-covered pavement (blue). Approximate distance across the bottom of the image is 4.5 km (2.8 mi).

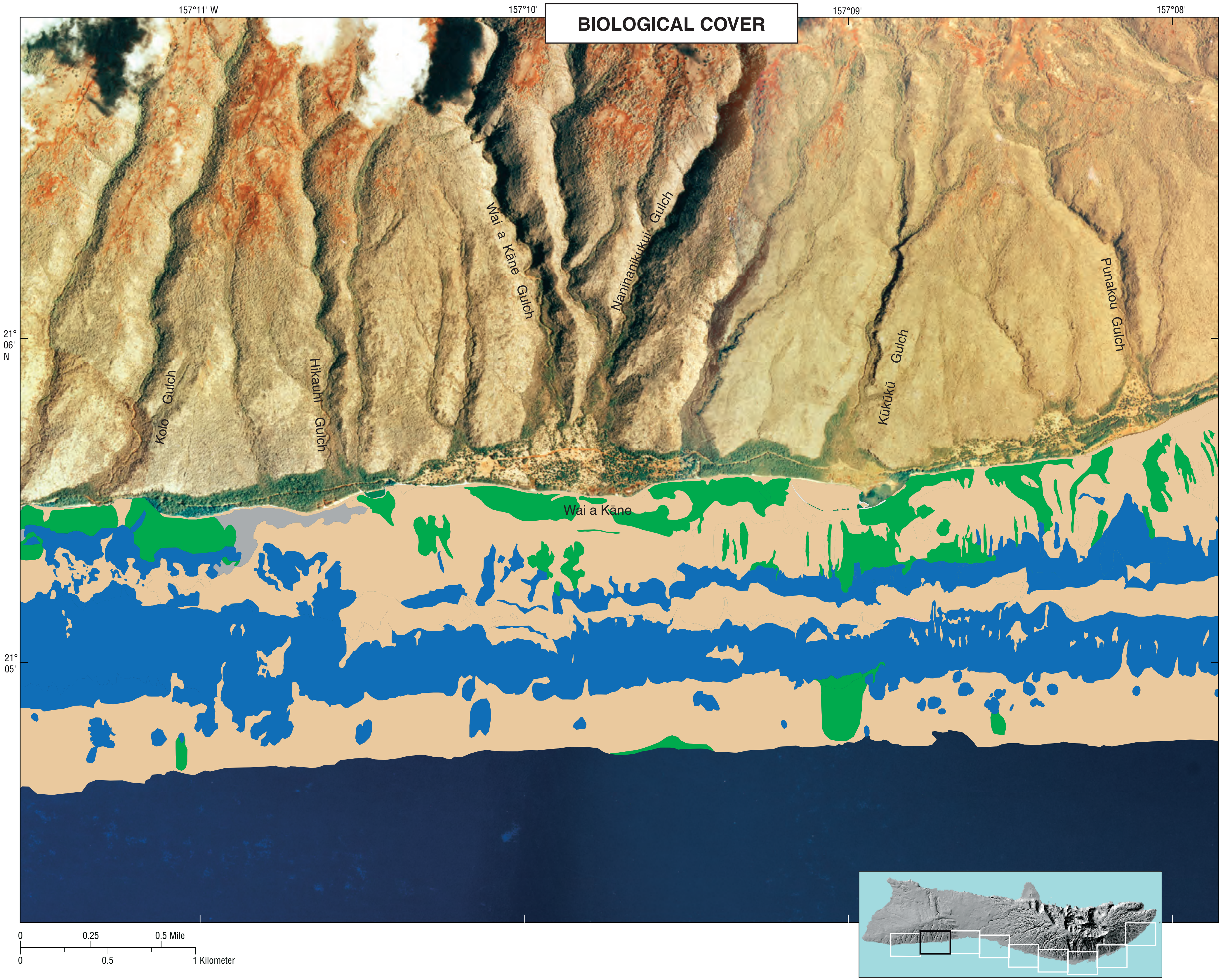

STRUCTURE
157°15' W
157°14'
157°13'
157°12'
21° 06' N
21° 05'
21° 04'
Hālen Gulch
Kā Hinawai Gulch
One o Hilo Gulch
Onopalani Gulch
Hālena
Kolo Wharf
Hale O Lono Harbor
0 0.25 0.5 Mile
0 0.5 1 Kilometer
Hale O Lono
Dominant Geomorphic Structure
Aggregate reef
Spur-and-groove
Aggregated patch reef
Individual patch reef
Pavement
Pavement with sand channels
Scattered coral/rock
Rubble
Sand
Mud
Artificial
Artificial/historical
Land
Unknown



This area marks the western extent of active coral-reef growth along the south shore of Moloka‘i. Coral-covered aggregate reef and the spur-and-groove structure of the fore reef trend progressively closer to the shoreline from east to west, before finally pinching out near Hale O Lono. Reef growth further west is limited by high-energy waves from the North Pacific Swell that wrap around the end of the island near Lā‘au Point (see Storlazzi and others, this vol., chap. 11). The reef flat here is home to a few scattered individual heads of coral and is steeper than along the central portion of the island. There is no discernable reef crest in this region.


STRUCTURE
157°11' W
157°10'
157°09'
157°08'
21° 06' N
21° 05'
Kolo Gulch
Hikauhi Gulch
Wai a Kāne Gulch
Naninanikukui Gulch
Kūkukū Gulch
Punakou Gulch
Wai a Kāne
0 0.25 0.5 Mile
0 0.5 1 Kilometer
Wai a Kāne
Dominant Geomorphic Structure
🟦 Aggregate reef
🟥 Spur-and-groove
🟩 Aggregated patch reef
🟩 Individual patch reef
🟪 Pavement
🟪 Pavement with sand channels
🟧 Scattered coral/rock
🟨 Rubble
🟨 Sand
🟫 Mud
🟦 Artificial
🟦 Artificial/historical
⬜ Land
⬜ Unknown

BIOLOGICAL COVER

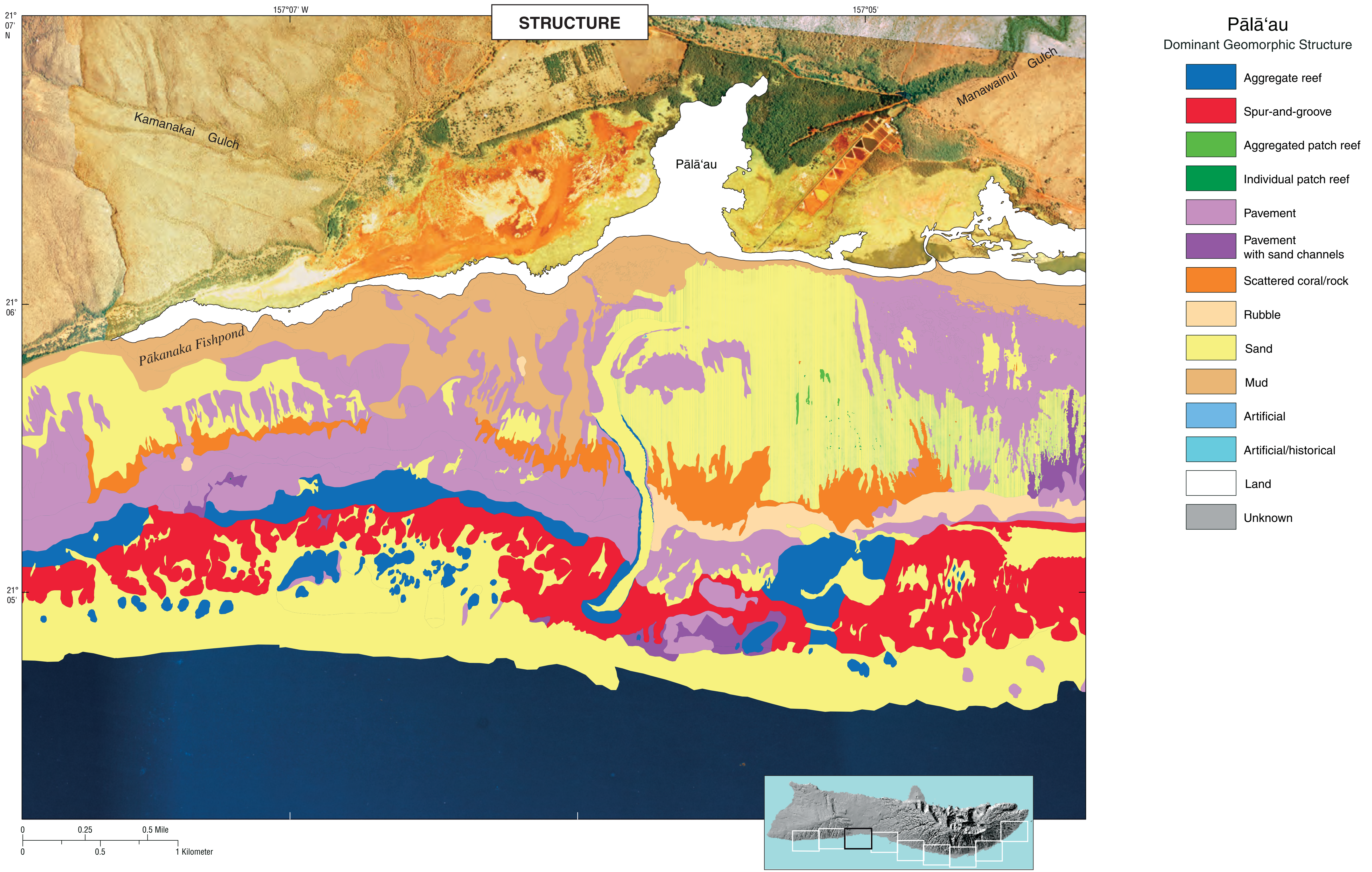


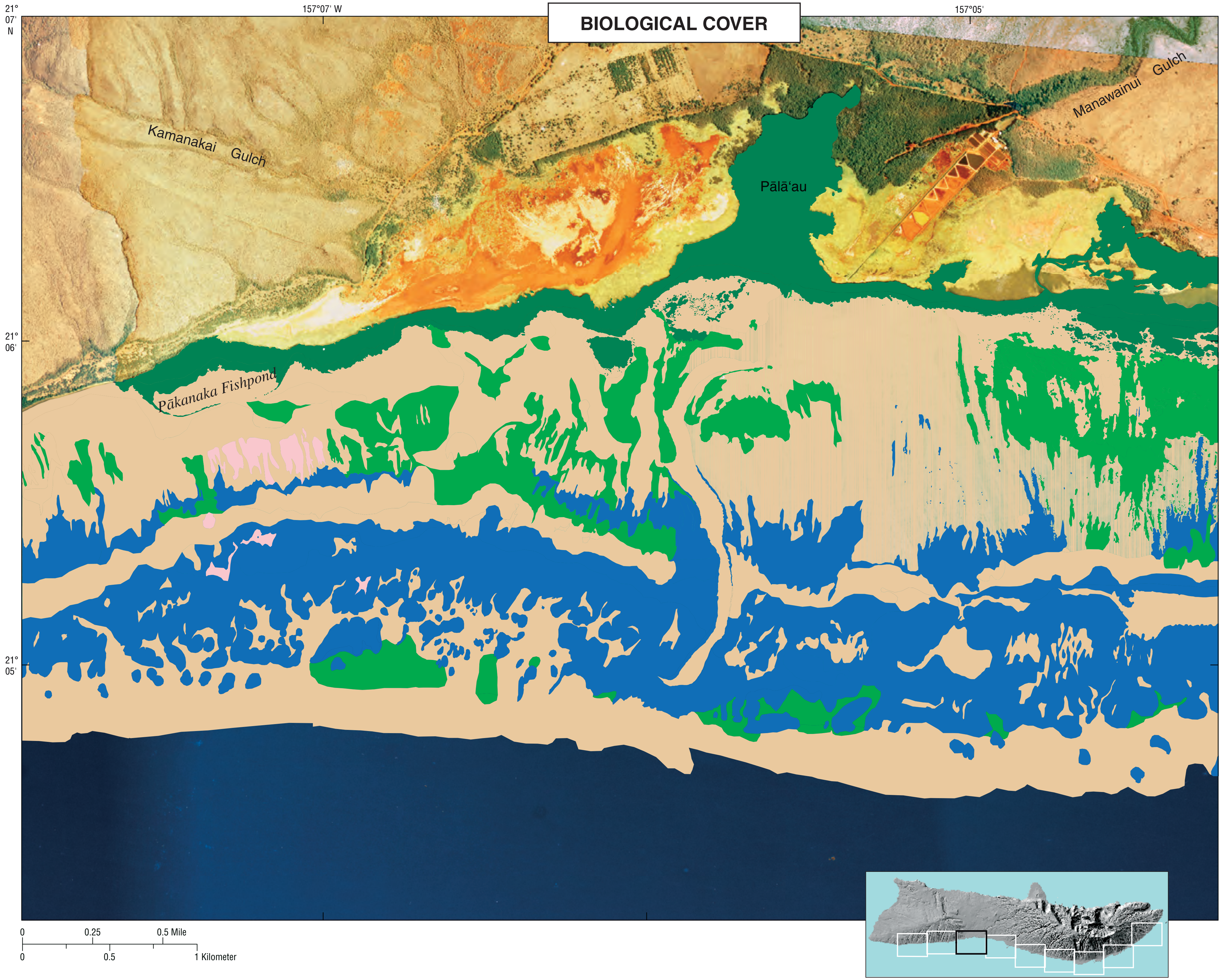
Wai a Kāne

Major Biological Cover

- ■ Coral
- ■ Coralline algae
- ■ Emergent vegetation
- ■ Macroalgae
- ■ Mangrove trees
- ■ Uncolonized
- ■ Unclassified
- ■ Unknown

Westward from Wai a Kāne Gulch the reef crest disappears and the coral-covered aggregate reef and spur-and-groove structure begin to trend progressively closer to the shoreline (see previous section). East of Wai a Kāne Gulch, coral-covered ridges are found along the seaward edge of the reef flat, which is relatively deeper here than in the central portion of the island. Several isolated coral-covered mounds are located offshore from the main aggregate fore reef on the deeper portion of the sand-covered shelf.


STRUCTURE
157°07' W
157°05'
21° 07' N
21° 06'
21° 05'
Kamanakai Gulch
Pālāʻau
Manawainui Gulch
Pākanaka Fishpond
0
0.25
0.5 Mile
0
0.5
1 Kilometer
Pālāʻau
Dominant Geomorphic Structure
🟦 Aggregate reef
🟥 Spur-and-groove
🟩 Aggregated patch reef
🟩 Individual patch reef
🟪 Pavement
🟪 Pavement with sand channels
🟧 Scattered coral/rock
🟨 Rubble
🟨 Sand
🟫 Mud
🟦 Artificial
🟦 Artificial/historical
⬜ Land
⬜ Unknown

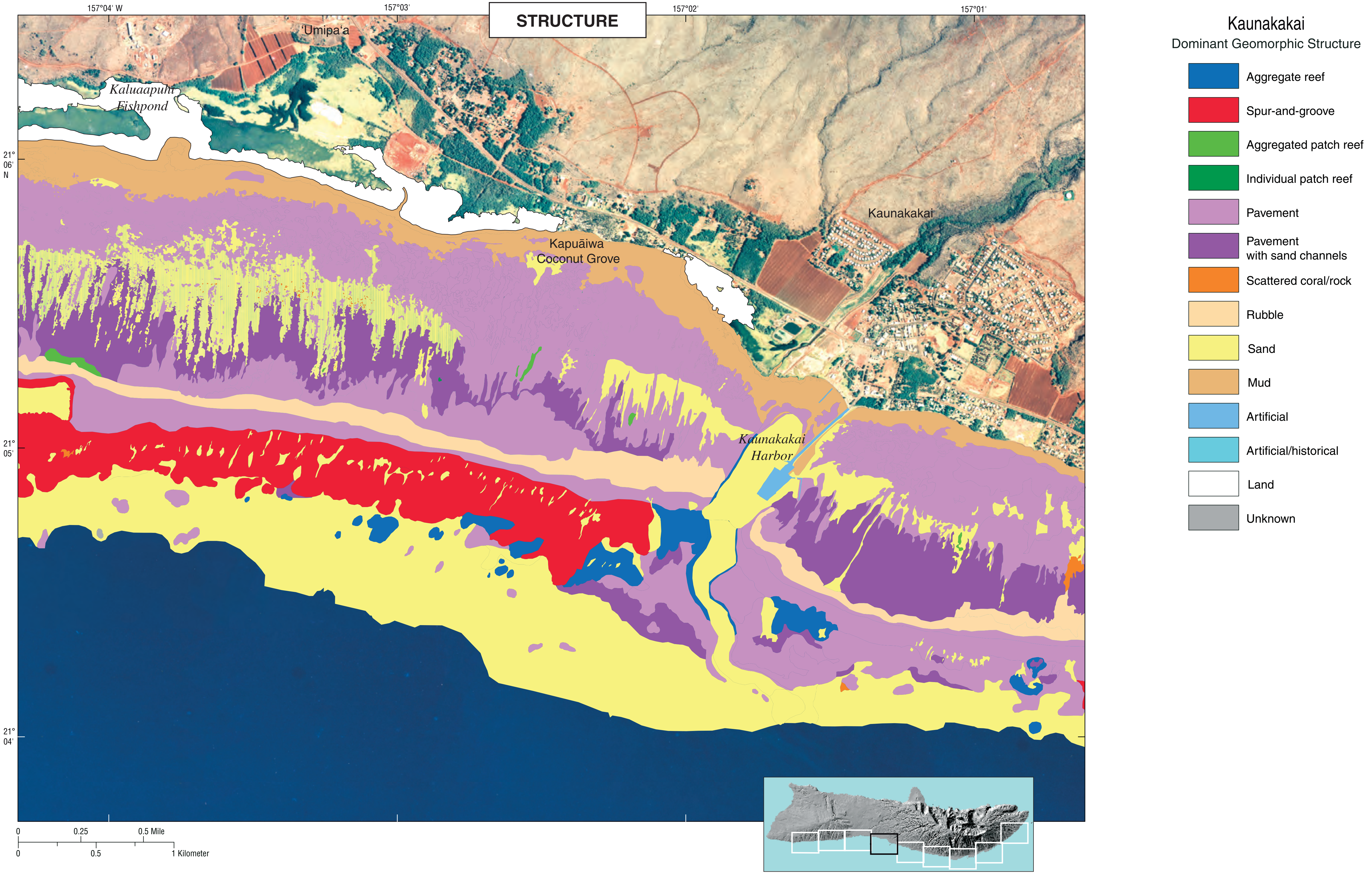


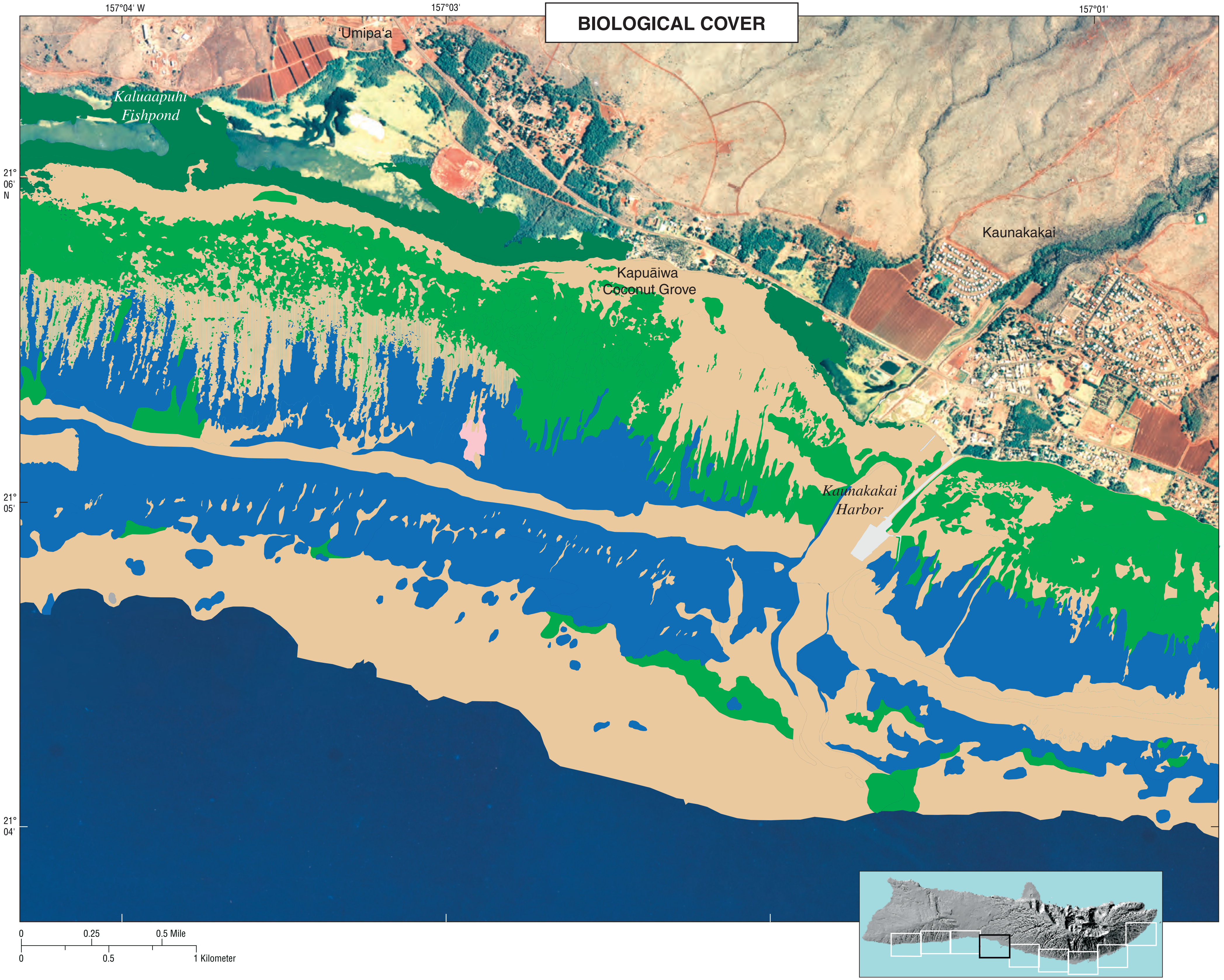
Mangrove trees, planted in an attempt to trap sediment runoff from the island, dominate the shoreline at Pālā‘au (see D'Iorio, this vol., chap. 16). However, large amounts of sediment still reach the coast and are deposited on the reef flat. A major offshore feature in this region is a channel that bisects the reef flat, reef crest, and fore reef. The vertical walls of the channel host a number of coral species, except in the turbid, muddy waters close to shore.

West of this Pālā‘au channel, the reef flat is mostly uncolonized terrigenous mud. Live coral is found along the seaward edge of the reef flat and on the portion of the reef crest near the channel. West of the channel and seaward of the coral-covered fore reef, the sand-covered shelf is dotted with isolated coral-covered mounds.

The reef flat is shallower and broader on the east side of the Pālā‘au channel. It is dominated by a large area of uncolonized, white carbonate sand. Live coral is found along the seaward edge of the reef flat, and beyond the reef crest on the fore reef.

Two large "blue holes," or pits, are found on the eastern edge of the Pālā‘au fore reef. These features were possibly formed by dissolution of the limestone reef by the subsurface percolation of fresh groundwater through the system (see Grossman and others, this vol., chap. 13). The vertical walls of these pits are covered with live coral, and the bottoms are covered with sand.


STRUCTURE
157°04′ W
157°03′
157°02′
157°01′
21° 06′ N
21° 05′
21° 04′
‘Umipa‘a
Kaluaapuhi Fishpond
Kapuāiwa Coconut Grove
Kaunakakai
Kaunakakai Harbor
0
0.25
0.5 Mile
0
0.5
1 Kilometer
Kaunakakai
Dominant Geomorphic Structure
Aggregate reef
Spur-and-groove
Aggregated patch reef
Individual patch reef
Pavement
Pavement with sand channels
Scattered coral/rock
Rubble
Sand
Mud
Artificial
Artificial/historical
Land
Unknown



Kaunakakai

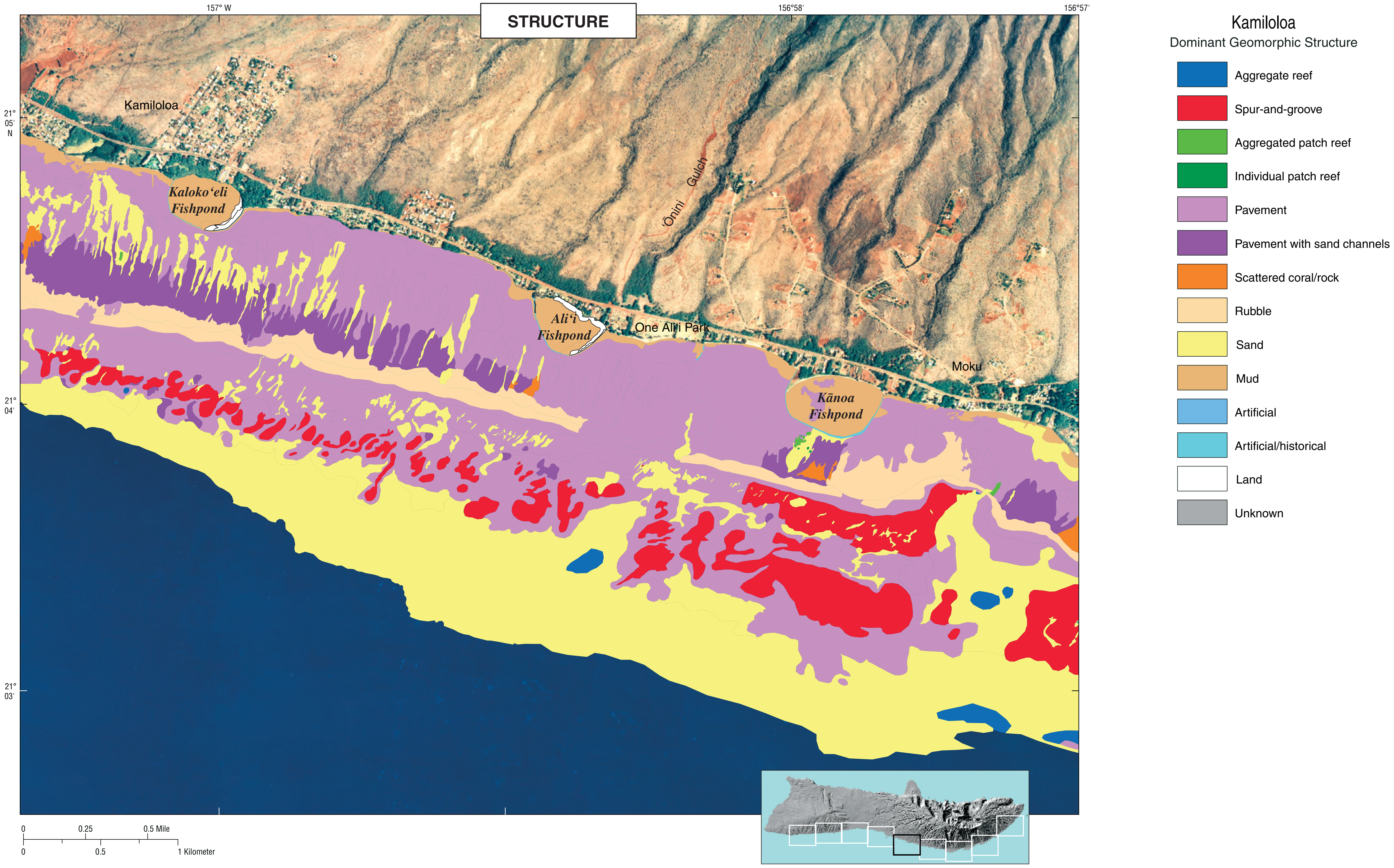
Major Biological Cover

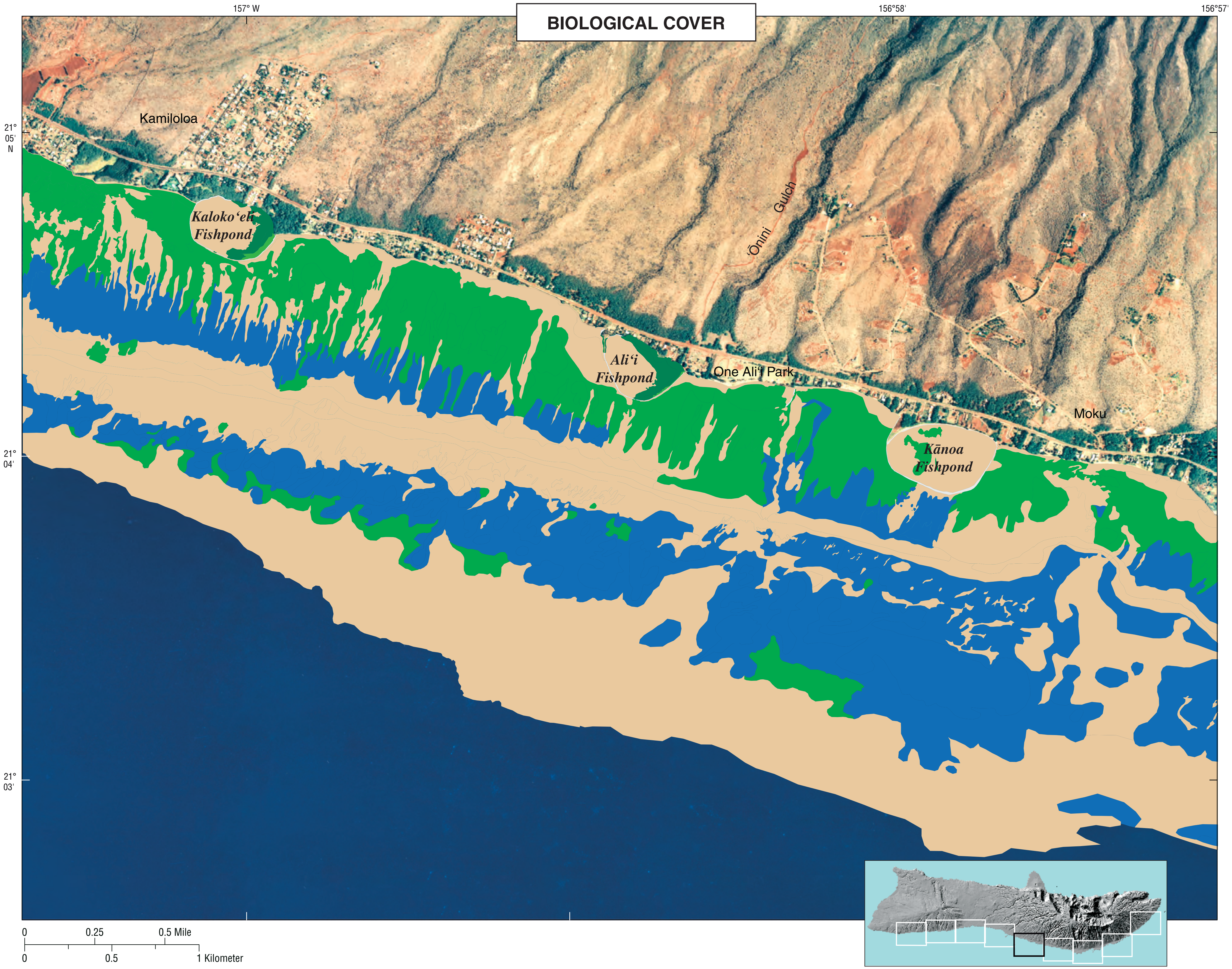
- 🟦 Coral
- 🟪 Coralline Algae
- 🟩 Emergent Vegetation
- 🟩 Macroalgae
- 🟩 Mangrove trees
- 🟫 Uncolonized
- ⬜ Unclassified
- ⬛ Unknown

Kaunakakai is the population center of Moloka‘i. The impermeable Kaunakakai Wharf extends 0.85 km (0.5 mi) offshore, blocking the east to west transport of water and sediment. The natural offshore extension of Kaunakakai Gulch, which bisects the reef flat, reef crest, and fore reef, has been enhanced by dredging to create a deep harbor next to the wharf.

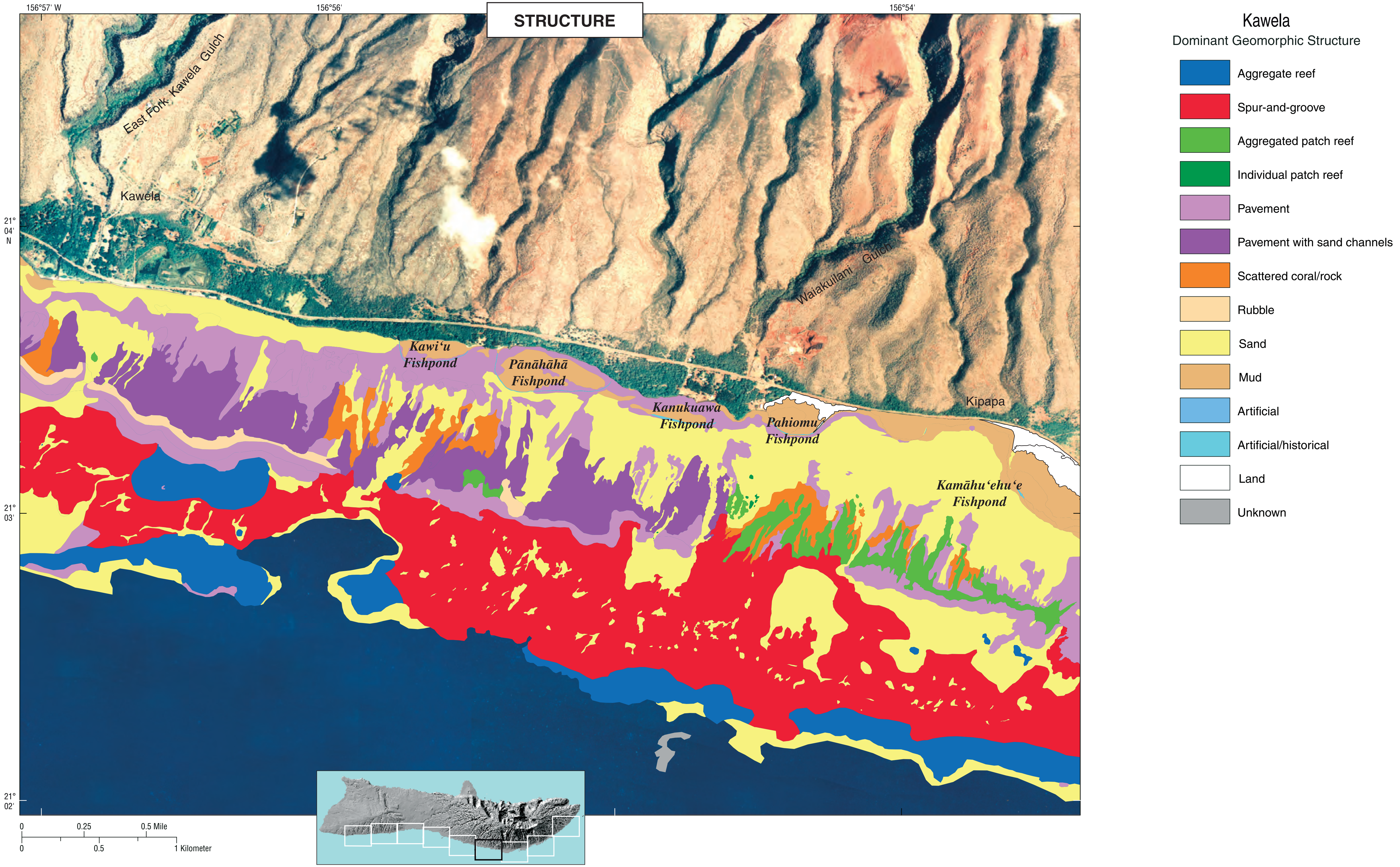
West of Kaunakakai Wharf, mangrove trees are found along most of the shoreline. A broad band of terrestrial mud covers the inner reef flat; the middle portion of the reef flat is dominated by algae-covered pavement; coral-covered ridges interspersed with sand are found on the seaward edge of the reef flat. Beyond the reef crest, the fore reef is dominated by healthy coral-covered aggregate reef and spur-and-groove structures, which have high coral coverage offshore of the Kapuāiwa Coconut Grove area. However, the fore reef just west of the channel is barren, possibly owing to dredging activities.

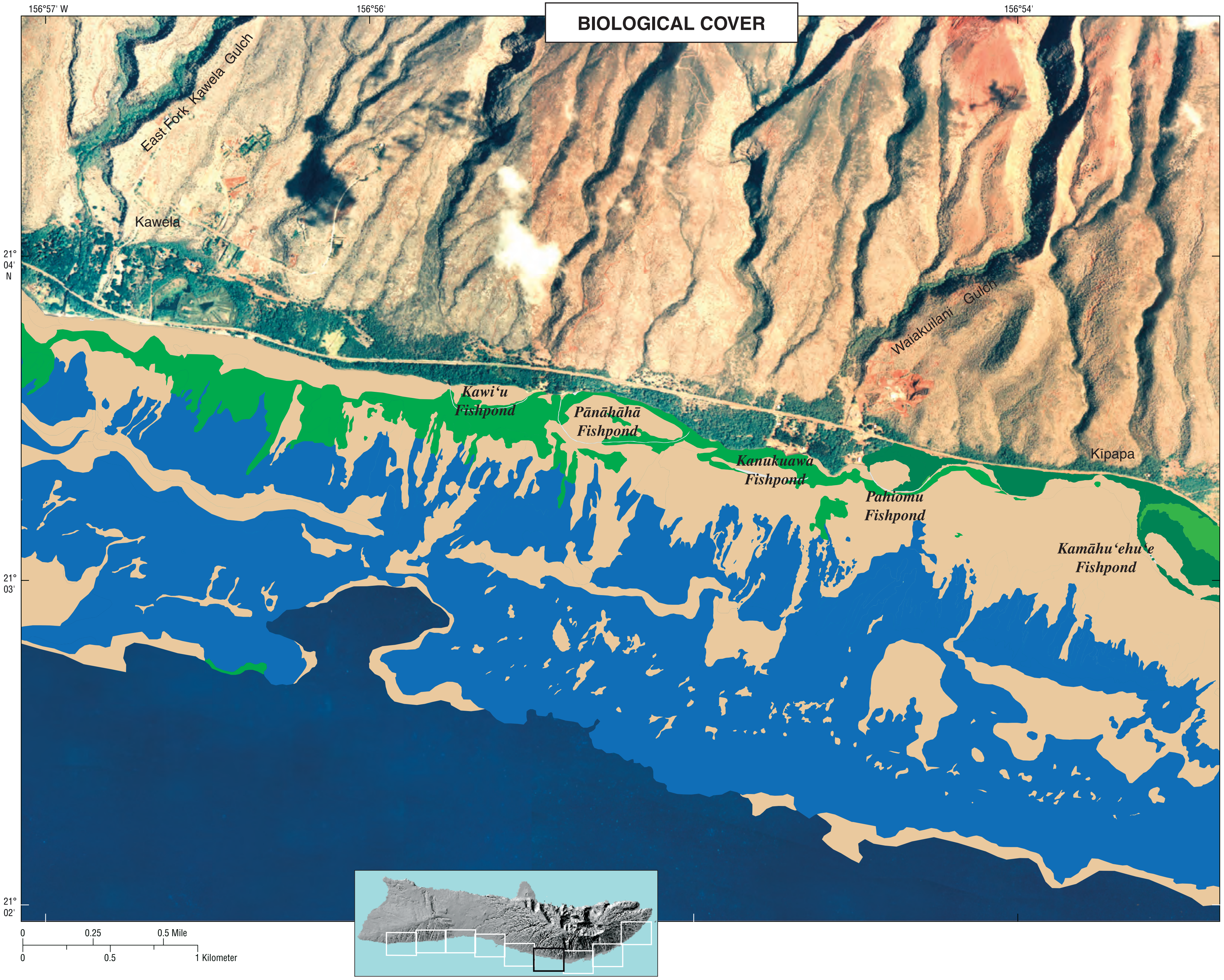
East of Kaunakakai Wharf, the reef flat is dominated by algae and terrestrial mud on hard pavement. A few live corals grow on ridges near the seaward edge of the reef flat. Beyond the reef crest, the fore reef is mostly barren pavement; however, some aggregate reef growth may be found at deeper depths.


STRUCTURE
157° W
156°58'
156°57'
21° 05' N
21° 04'
21° 03'
Kamiloloa
Kalokoʻeli Fishpond
ʻŌnini Gulch
Aliʻi Fishpond
One Aliʻi Park
Moku
Kānoa Fishpond
0
0.25
0.5 Mile
0
0.5
1 Kilometer
Kamiloloa
Dominant Geomorphic Structure
Aggregate reef
Spur-and-groove
Aggregated patch reef
Individual patch reef
Pavement
Pavement with sand channels
Scattered coral/rock
Rubble
Sand
Mud
Artificial
Artificial/historical
Land
Unknown



A narrow band of terrestrial mud is found along the shoreline of Kamiloloa, transitioning into the predominately algae-covered platform of the middle reef flat. A few live corals grow on ridges near the seaward edge of the reef flat. The barren fore-reef platform of Kaunakakai (see previous pages) continues eastward through Kamiloloa to One Ali‘i (center of this area), with coral-covered spur-and-groove structures found only at greater depths. East of One Ali‘i, the shallower areas of the fore reef have increasing coral growth continuing toward the Kawela area (see next pages).


STRUCTURE
156°57' W
156°56'
156°54'
21° 04' N
21° 03'
21° 02'
East Fork Kawela Gulch
Kawela
Waiakuilani Gulch
Kawiʻu Fishpond
Pānāhāhā Fishpond
Kanukuawa Fishpond
Pahiomu Fishpond
Kipapa
Kamāhuʻehuʻe Fishpond
0
0.25
0.5 Mile
0
0.5
1 Kilometer
Kawela
Dominant Geomorphic Structure
Aggregate reef
Spur-and-groove
Aggregated patch reef
Individual patch reef
Pavement
Pavement with sand channels
Scattered coral/rock
Rubble
Sand
Mud
Artificial
Artificial/historical
Land
Unknown

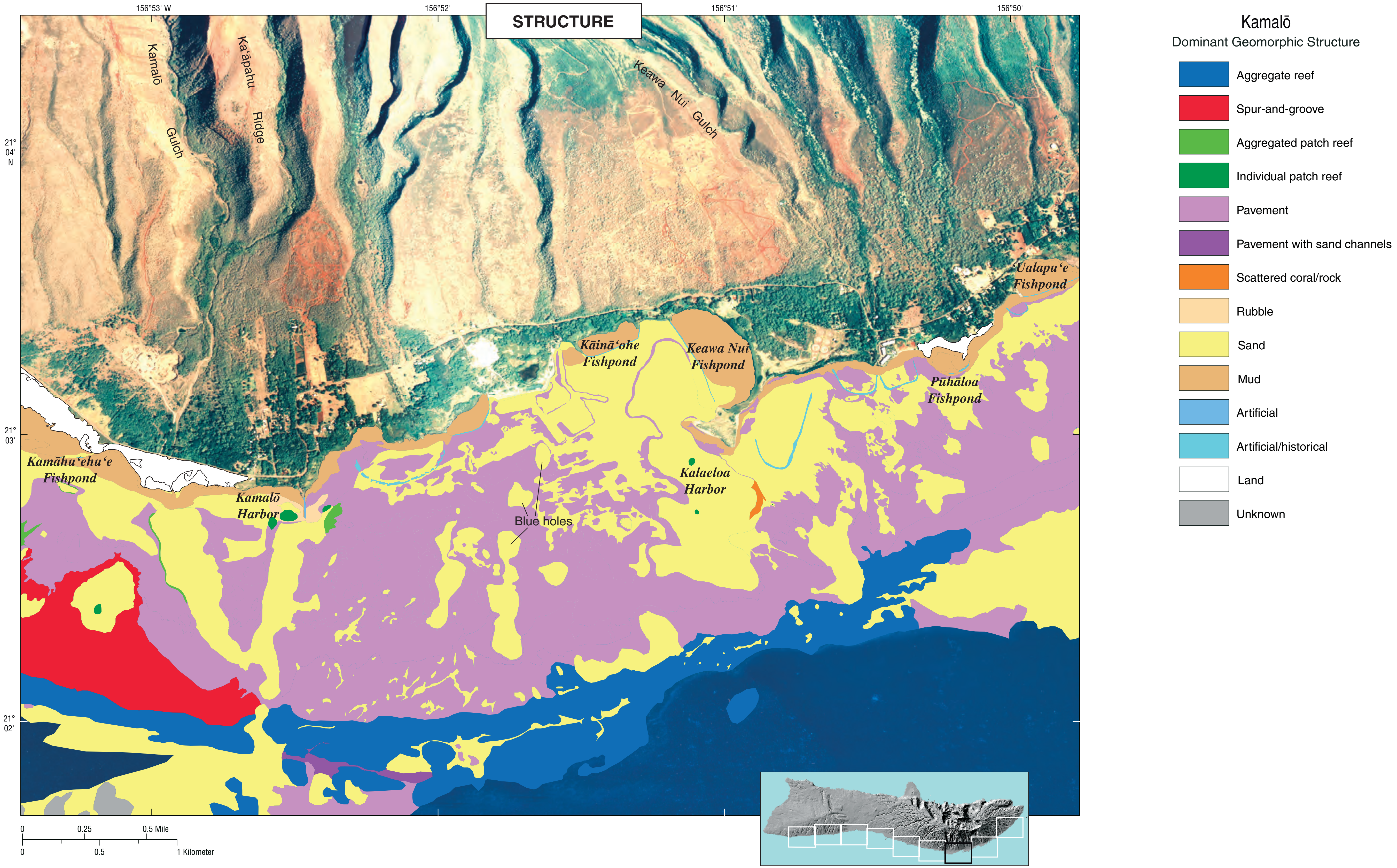


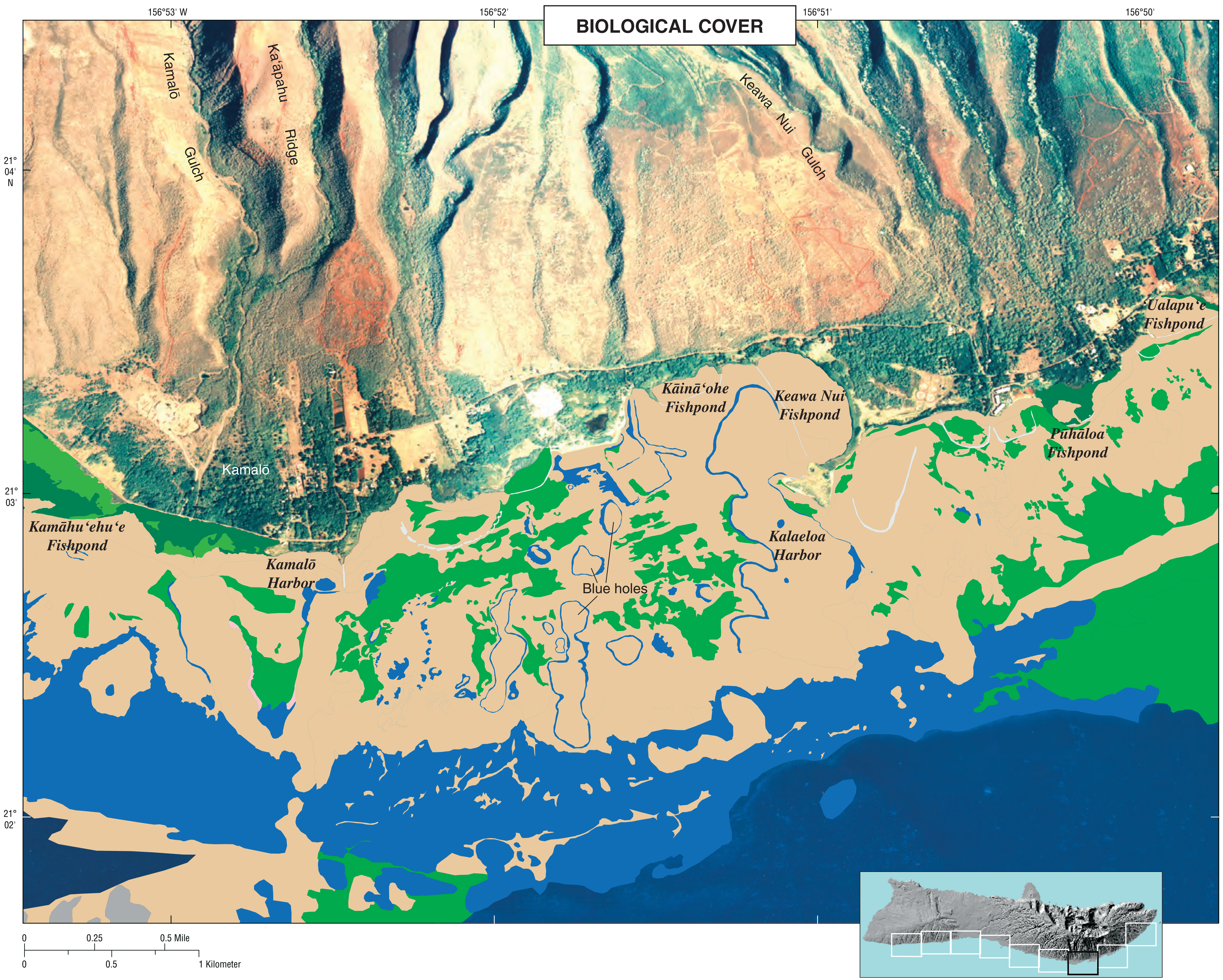
Kawela

Major Biological Cover

- 🟦 Coral
- 🟪 Coralline Algae
- 🟩 Emergent Vegetation
- 🟩 Macroalgae
- 🟩 Mangrove trees
- 🟫 Uncolonized
- ⬜ Unclassified
- ⬛ Unknown

The inner and middle portions of the reef flat at Kawela are a mixture of terrestrial mud, algae-covered platform, and uncolonized sand. Live corals grow on ridges near the seaward edge of the reef flat. The reef crest is discontinuous in this region. The fore reef is dominated by coral covered spur-and-groove structures. The deep embayment southeast of Kawela was possibly created from a major drainage during a period of lower sea-level (see Grossman and others, this vol., chap. 10, for discussion of historical sea-level rise).


STRUCTURE
156°53′ W
156°52′
156°51′
156°50′
21° 04′ N
21° 03′
21° 02′
Kamalō Gulch
Kaʻāpahu Ridge
Keawa Nui Gulch
ʻUalapuʻe Fishpond
Kāināʻohe Fishpond
Keawa Nui Fishpond
Pūhāloa Fishpond
Kamāhuʻehuʻe Fishpond
Kamalō Harbor
Kalaeloa Harbor
Blue holes
0
0.25
0.5 Mile
0
0.5
1 Kilometer
Kamalō
Dominant Geomorphic Structure
Aggregate reef
Spur-and-groove
Aggregated patch reef
Individual patch reef
Pavement
Pavement with sand channels
Scattered coral/rock
Rubble
Sand
Mud
Artificial
Artificial/historical
Land
Unknown



Kamalō

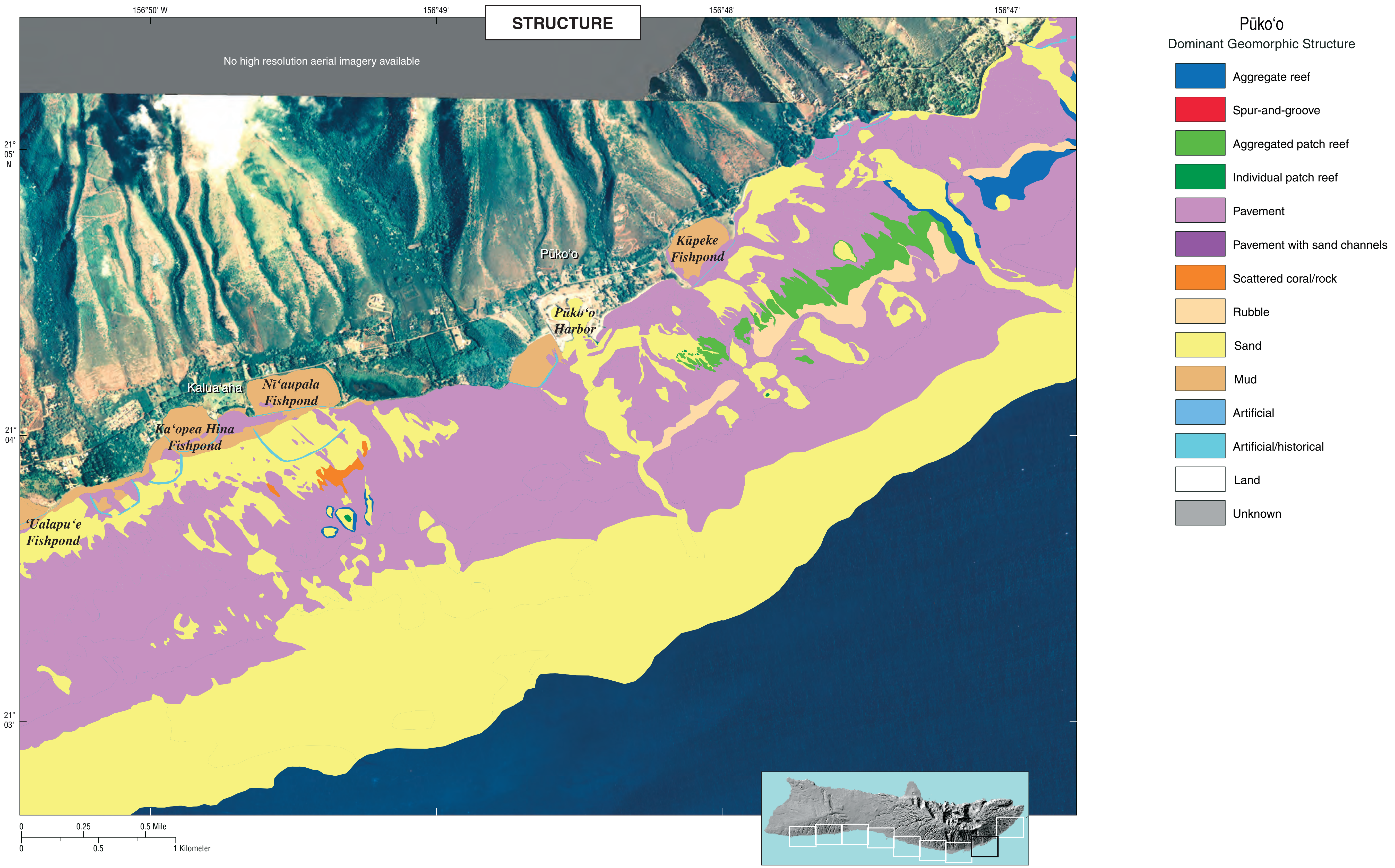
Major Biological Cover

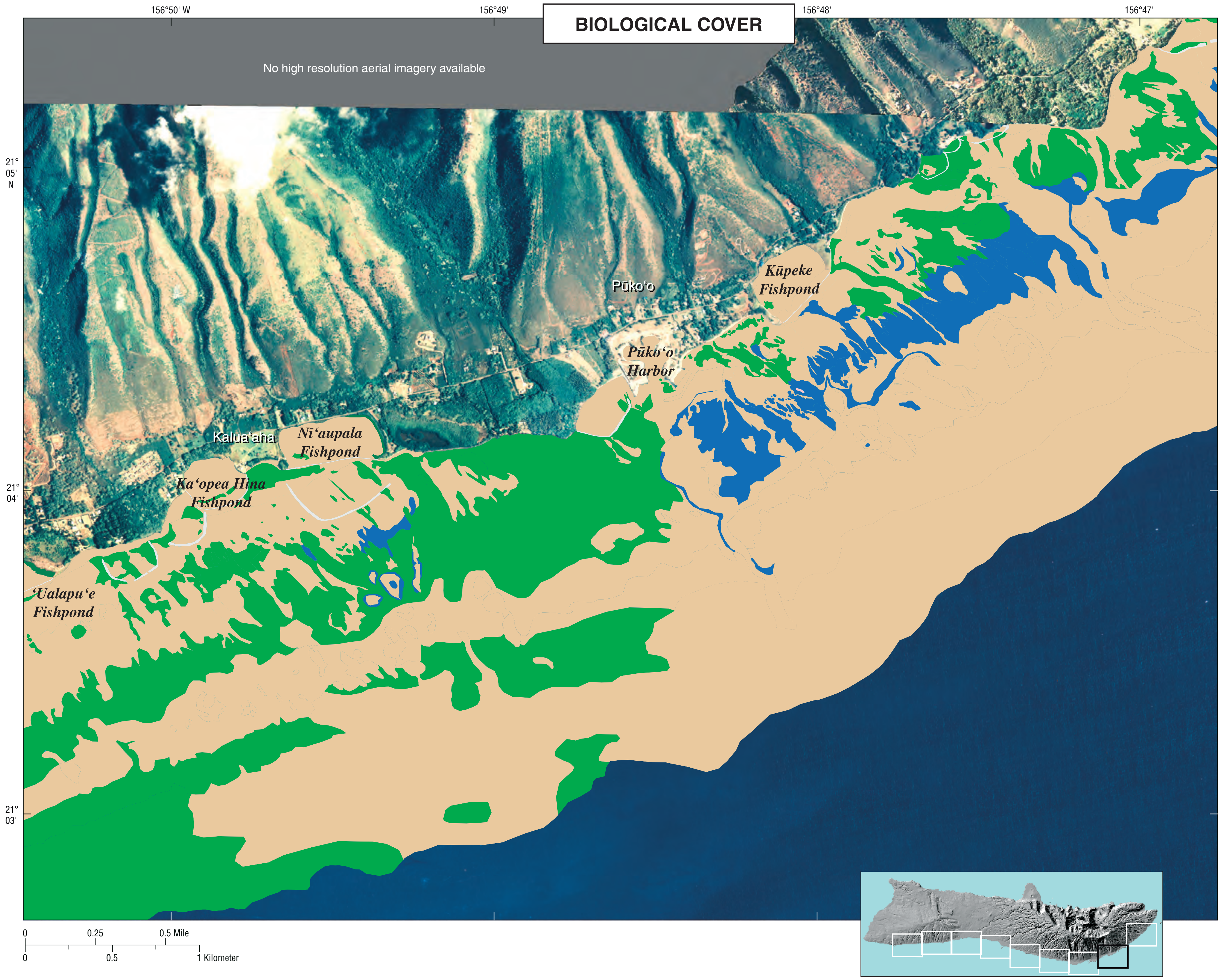
🟦 Coral
▨ Coralline Algae
🟩 Emergent Vegetation
🟩 Macroalgae
🟩 Mangrove trees
🟫 Uncolonized
⬜ Unclassified
⬜ Unknown

The Kamalō region marks a transition in the shoreline orientation along the south shore of Moloka‘i. East of Kamalō, the southeast-facing shoreline and reef flat are more susceptible to constant wave action from the daily trade winds. Siltation from a dredging operation in the 1960s (the rectangular outline of which is still visible) resulted in damage to the reef flat between Kamalō and Kalaeloa and to the downstream Kamalō fore reef (Capt. Joe Reich, oral commun., 2000). Although the fore reef has since regenerated, the reef flat is still mainly uncolonized, bare pavement with some algae-covered areas.

A unique feature of the reef flat in this area is a series of “blue holes.” The alignment of the blue holes suggests that they may be old stream channels, formed during a time of lower sea level, that were subsequently segmented by new coral growth after sea level attained its present position. An alternative hypothesis is that they were formed by dissolution of the limestone reef by the subsurface percolation of fresh ground water through the system (see Grossman and others, this vol., chap. 13). The vertical walls of the blue holes are covered with live coral, and the bottoms are covered with carbonate sand.

There is no reef crest in this region, possibly because of the higher wave activity experienced on this part of the island. The algae-covered pavement of the deep fore reef directly off Kamalō is a remnant of damage from the dredging operations. The shallower portions of the fore reef have regenerated and show substantial aggregated coral; however, this coral growth ends abruptly just east of Kalaeloa, where the fore reef transitions into an algae-covered pavement.


STRUCTURE
156°50′ W
156°49′
156°48′
156°47′
21° 05′ N
21° 04′
21° 03′
No high resolution aerial imagery available
Pūkoʻo
Kūpeke Fishpond
Pūkōʻo Harbor
Kaluaʻaha
Nīʻaupala Fishpond
Kaʻopea Hina Fishpond
ʻUalapuʻe Fishpond
0 0.25 0.5 Mile
0 0.5 1 Kilometer
Pūkoʻo
Dominant Geomorphic Structure
Aggregate reef
Spur-and-groove
Aggregated patch reef
Individual patch reef
Pavement
Pavement with sand channels
Scattered coral/rock
Rubble
Sand
Mud
Artificial
Artificial/historical
Land
Unknown

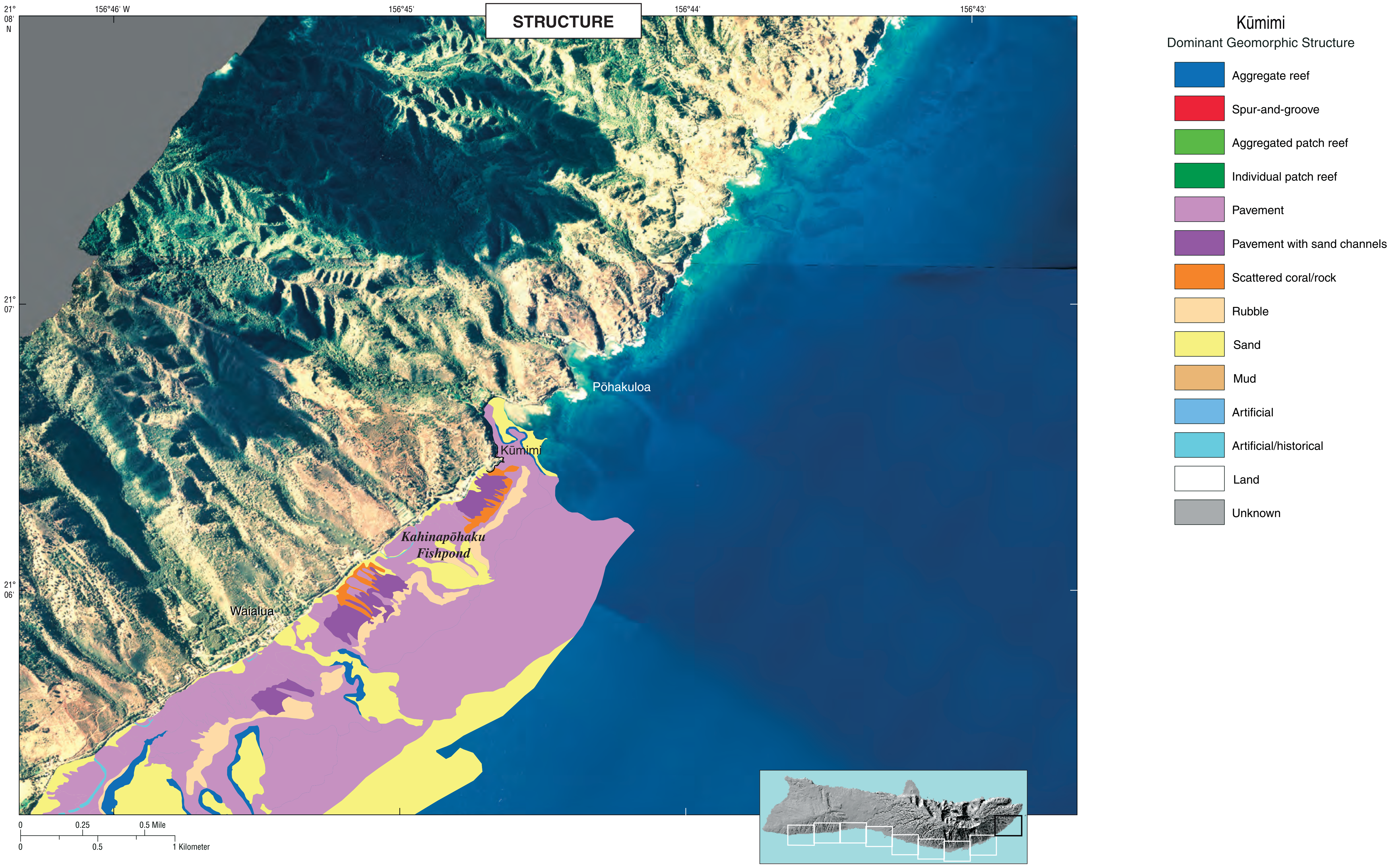


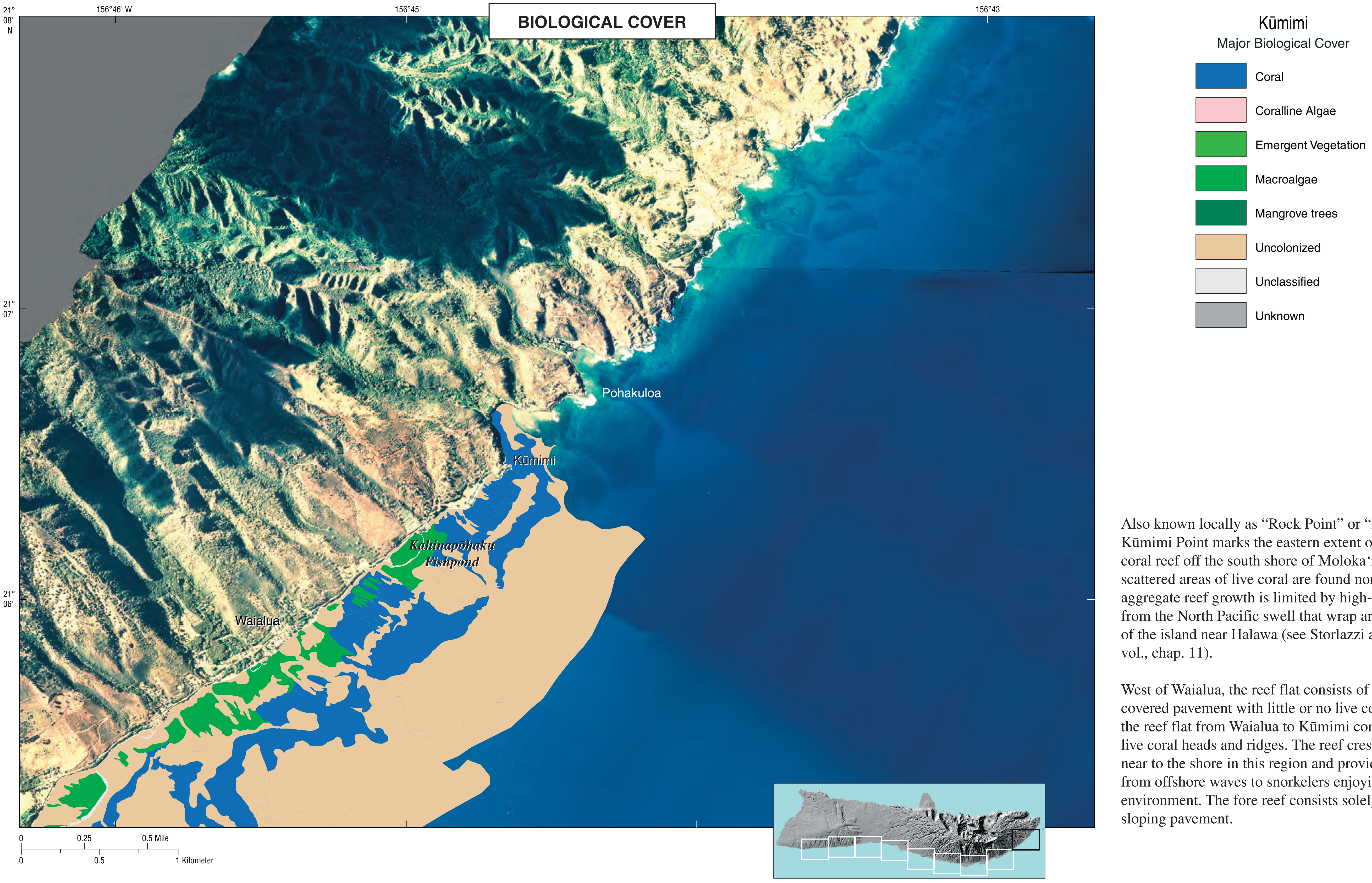
Pūko'o
Major Biological Cover

- 🟦 Coral
- 🟪 Coralline Algae
- 🟩 Emergent Vegetation
- 🟩 Macroalgae
- 🟩 Mangrove trees
- 🟫 Uncolonized
- ⬜ Unclassified
- ⬛ Unknown

The reef flat west of Pūko'o Harbor is a mixture of algae-covered and sand-covered pavement with rare bits of live coral on scattered rocks. Ridges of aggregated patch reef are found along the seaward edge of the reef flat east of the harbor; however, the actual fore reef is only an algae-covered pavement. Several deep channels that correspond to onshore drainages bisect the reef flat, reef crest, and fore reef, and live coral is found on the vertical walls of the channels.

The reef crest is nonexistent west of Pūko'o Harbor, possibly owing to higher wave activity; however, it is present east of the Harbor. East of Pūko'o Harbor, the reef crest and fore reef begin to trend closer to the shoreline as they approach the eastern extent of aggregate coral growth along the southeast shore of the island.


STRUCTURE
21° 08' N
156°46' W
156°45'
156°44'
156°43'
21° 07'
21° 06'
Pōhakuloa
Kūmimi
Kahinapōhaku Fishpond
Waialua
0
0.25
0.5 Mile
0
0.5
1 Kilometer
Kūmimi
Dominant Geomorphic Structure
Aggregate reef
Spur-and-groove
Aggregated patch reef
Individual patch reef
Pavement
Pavement with sand channels
Scattered coral/rock
Rubble
Sand
Mud
Artificial
Artificial/historical
Land
Unknown



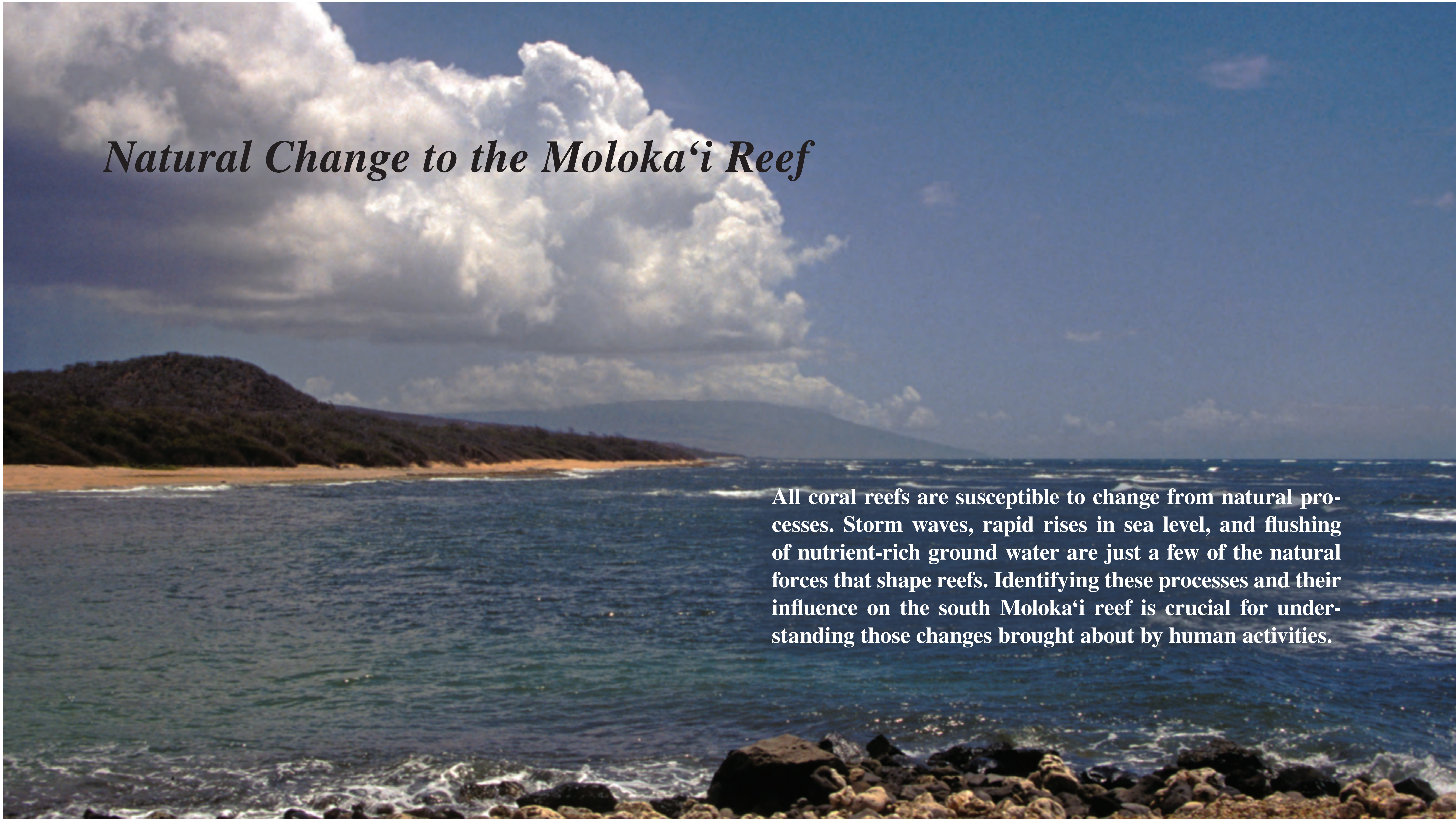
Also known locally as “Rock Point” or “20 Mile Beach,” Kūmimi Point marks the eastern extent of the fringing coral reef off the south shore of Moloka‘i. Although scattered areas of live coral are found northeast of here, aggregate reef growth is limited by high-energy waves from the North Pacific swell that wrap around the end of the island near Halawa (see Storlazzi and others, this vol., chap. 11).

West of Waialua, the reef flat consists of sand and algae-covered pavement with little or no live coral. However, the reef flat from Waialua to Kūmimi consists of many live coral heads and ridges. The reef crest is found fairly near to the shore in this region and provides protection from offshore waves to snorkelers enjoying the reef flat environment. The fore reef consists solely of a barren, sloping pavement.

Pālā‘au channel on the south-central coast of Moloka‘i.

Natural Change to the Moloka‘i Reef

All coral reefs are susceptible to change from natural processes. Storm waves, rapid rises in sea level, and flushing of nutrient-rich ground water are just a few of the natural forces that shape reefs. Identifying these processes and their influence on the south Moloka‘i reef is crucial for understanding those changes brought about by human activities.



View of south Moloka‘i, looking eastward from Hale O Lono harbor.


Kahinapōhaku fishpond on the east end of Molokaʻi.

CHAPTER 10

Sea Level and its Effects on Reefs in Hawai‘i

Eric E. Grossman[1]

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

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

Late Quaternary and Postglacial Eustatic Sea-Level History

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

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

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

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

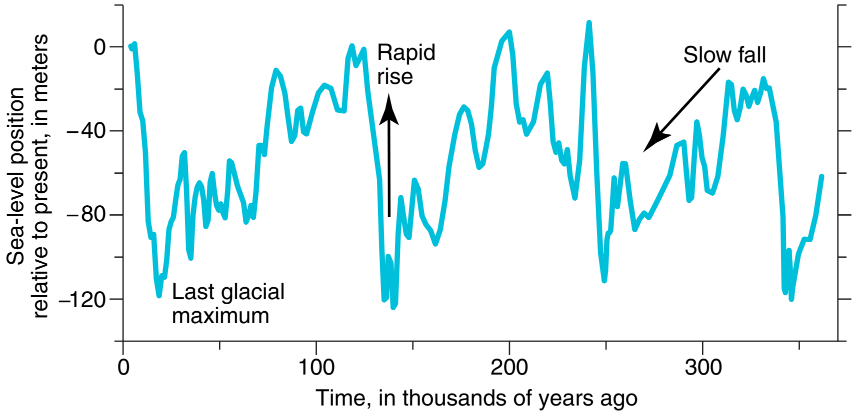


Figure 1. Late Quaternary sea level (after Lea and others, 2002) is marked by 100,000-year oscillations that on average range through 120 m (394 ft). Periods of warm climate like that of today are characterized by high sea level, while during glacial conditions like those of the last glacial maximum,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

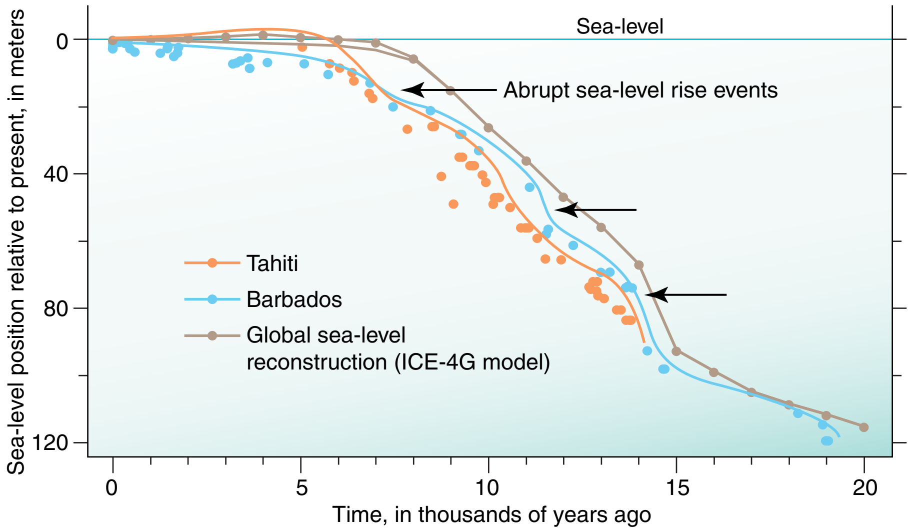


Figure 2. Curves of postglacial eustatic sea level derived from coral reef studies from Tahiti (orange symbols; Bard and others, 1996) and Barbados (blue symbols; Bard and others, 1990). The curves are marked by three periods of abrupt rise at approximately 14,500, 11,500, and 8,000 years ago. These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

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

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

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

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

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

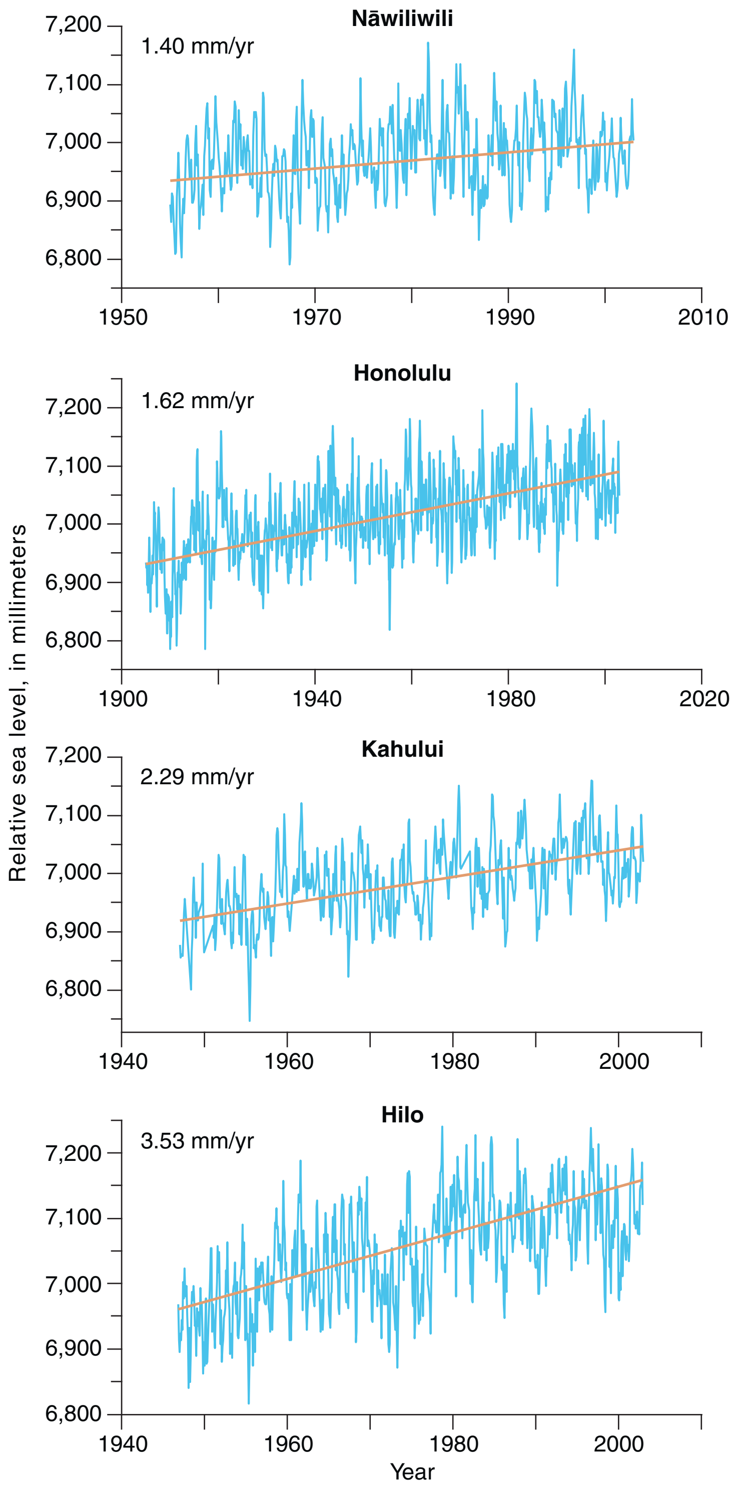


Figure 3. Least median of squares regression of tide-gauge data from Nāwiliwili (Kaua‘i), Honolulu (O‘ahu), Kahului (Maui), and Hilo (Hawai‘i), showing that the rate of relative sea-level rise increases toward the Big Island of Hawai‘i. The difference in the rates is thought to be related to differential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

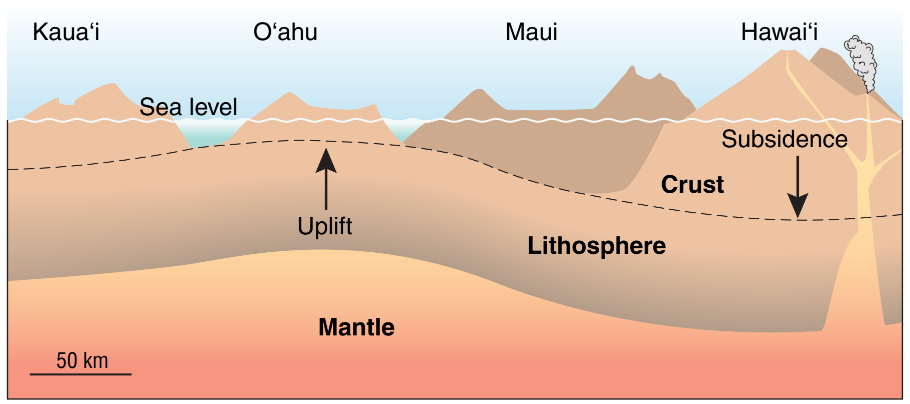


Figure 4. Lithospheric flexure is a hypothesis that is largely validated by tide-gauge measurements as shown in figure 3, studies of fossil shorelines that indicate uplift near O‘ahu and subsidence near the Big Island of Hawai‘i, and modeling of plate interactions at hot spots. Lithospheric flexure leads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

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

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

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

Postglacial Sea Level and its Impact on Hawaiian Reef Development

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

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

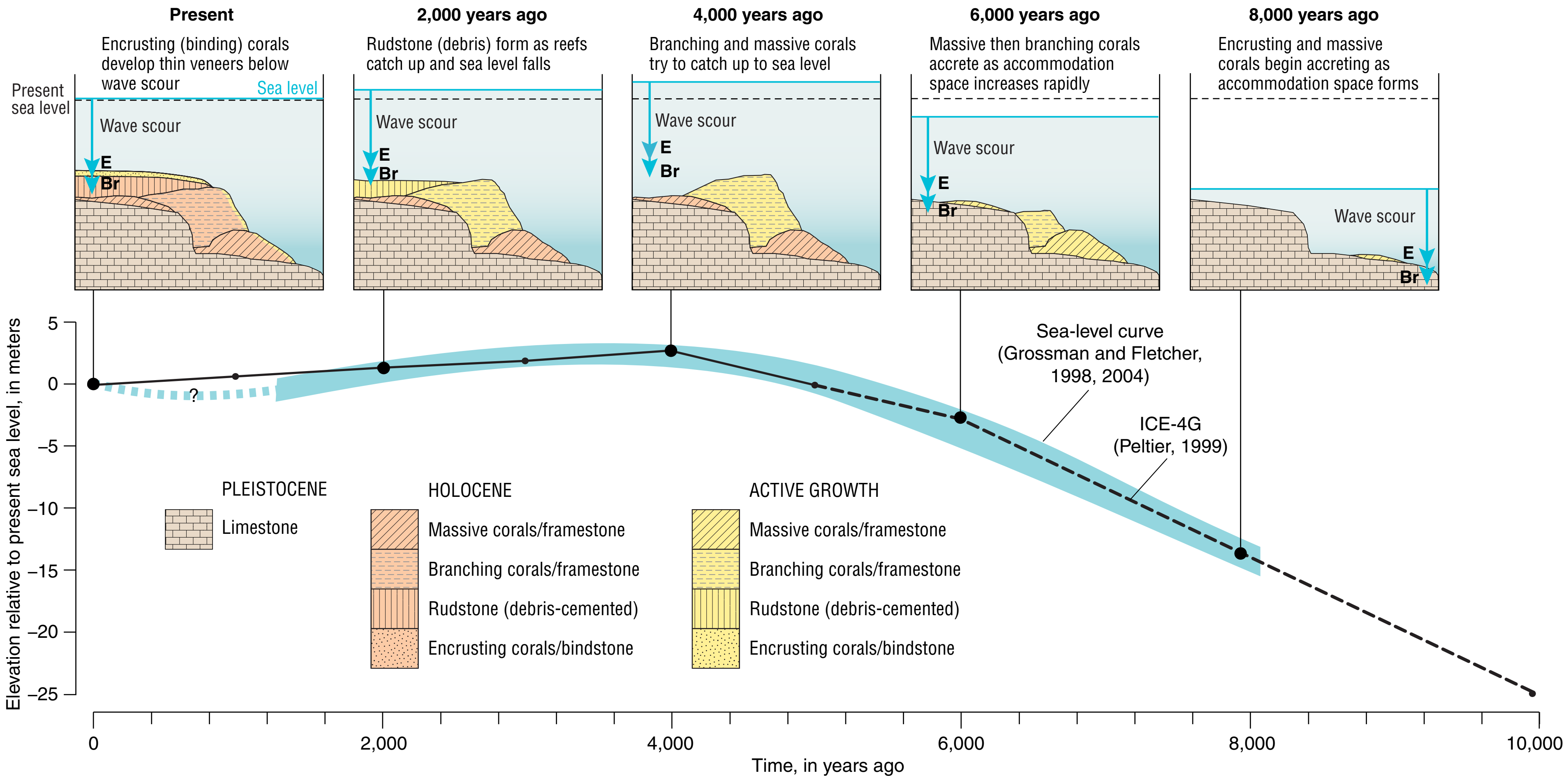


Figure 5. Model of Holocene reef development (after Grossman and Fletcher 2004; Grossman and others, 2006) in relation to accommodation space. Accommodation space for reef accretion is controlled by erosive forces, including wave scour, and occurred throughout the Holocene largely below the rising sea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

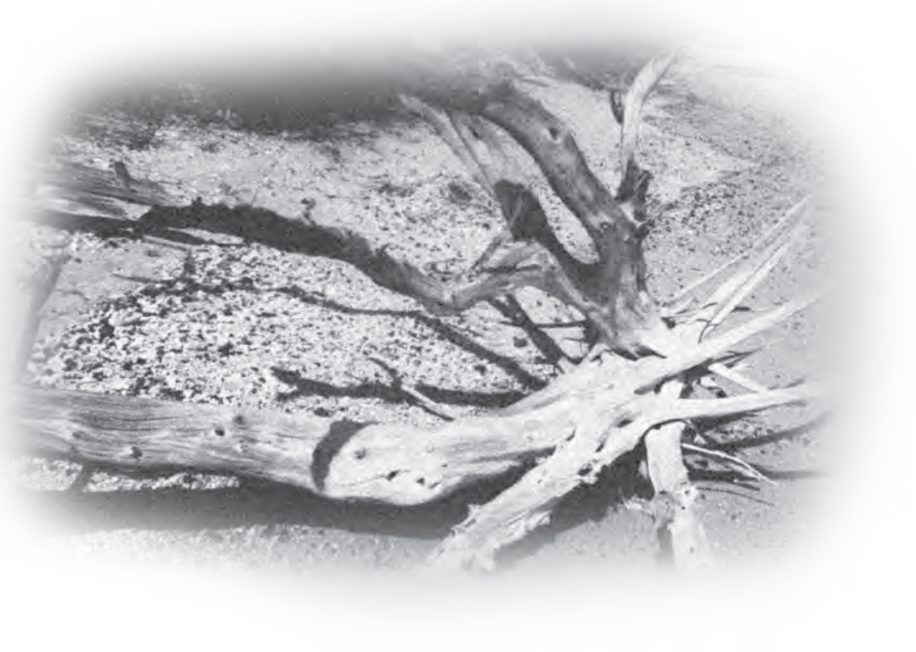
From analyses of the current inventory of coral core samples in Hawai‘i, we have determined that modern reefs began to develop with encrusting and massive framestone accretion between 9,000 and 8,000 years ago (fig. 5) as sea level inundated the insular shelves (framestone is limestone that is organically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

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

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

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

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



Summary

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

CHAPTER 11

Waves and Their Impact on Reef Growth

Curt D. Storlazzi[1], Michael E. Field[1], Eric K. Brown[2], and Paul L. Jokiel[3]

It has been known for some time that there are strong qualitative correlations between wave energy and coral distribution (Rosen, 1975; Geister, 1977; Vosburgh, 1977; Dollar, 1982; Done, 1983; Massel and Done, 1993; Rogers, 1993; Blanchon and Jones, 1997). Grigg (1998) has most recently discussed the interplay between wave energy and reef properties in the Hawaiian Islands, but as in most past studies, wave-energy is classified in terms of the loosely divided categories of “low,” “medium,” and “high” wave energy regimes. Jokiel and others (2004) show that maximum wave height in Hawaiʻi is negatively correlated with coral cover, diversity, and species richness. There has yet to be, however, a large-scale quantitative investigation of these relationships that compares the motions exerted by waves upon the reef to the distribution of different stony coral species. Our goal here is to better quantify the interplay between wave-induced forces, reefs, and corals.

Waves

Wave Observations and Modeling

In order to provide accurate wave data for the entire south shore of Molokaʻi, we used the U.S. Naval Oceanographic Office’s Spectral Wave Prediction System (SWAPS) version 4.0 wave model (Storlazzi and others, 2005). This model generated a gridded field of wave height, wave period, and wave direction for analysis. Real-time output of wave height and wave period were compared to concurrent observations of wave height and wave period made at two U.S. National Oceanographic and Atmospheric Administration (NOAA) offshore deep-water buoys (#51001 and #51002; National Data Buoy Center, 2002) and five wave/tide gauges that we deployed in 11-m (36 ft) mean water depth off the south shore of Molokaʻi (fig. 1). Wave heights and wave periods calculated from the wave model differed from the measurements by less than 10 percent and verified that the model’s estimation of energy loss due to refraction and shoaling worked properly. The modeled wave heights and wave periods produced by the wave model for the shallowest grid cells that were closest to the south shore of Molokaʻi were then used for input into the coral force-balance model. When the orbital motion of the water as a wave passes interacts with the sea floor, it imparts a force or stress (stress = force/area) on the sea floor; this stress is better known as a wave-induced shear stress. Table 1 gives examples of how variations in wave height, wave period, and water depth affect wave-induced shear stresses on the sea floor. These peak wave-induced near-bed shear stresses were calculated following the methodology presented by Jonsson (1966).

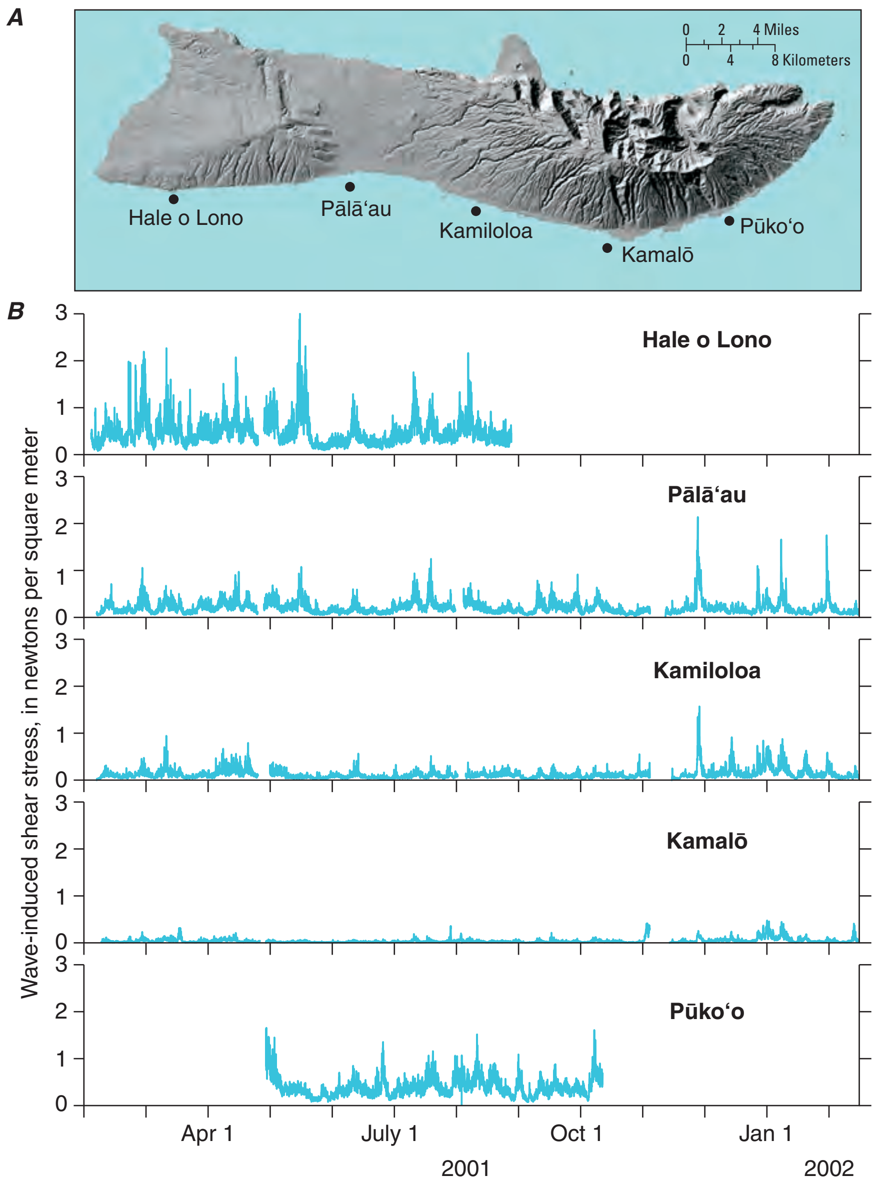


Figure 1. U.S. Geological Survey (USGS) wave data for south coast of Molokaʻi. *A.*, Location of USGS wave and tide gauges deployed along the 11-m (36-ft) isobath. *B*, Calculated peak wave-induced near-bed shear stresses from the USGS wave and tide gauges. Gaps in the individual gauges’ records are a result of instrument failures.

Table 1. Examples of variations in wave-induced shear stresses caused by variations in wave height, wave period, and water depth.
[Peak wave-induced near-bed shear stresses calculated as per Jonsson (1966)]

Variable	Wave height (m)	Wave period (s)	Water depth (m)	Resulting shear stress (N/m^2)
	1	10	15	0.42
Wave height	2	10	15	1.36
	3	10	15	2.72
	1	5	15	0.04
Wave period	1	10	15	0.42
	1	15	15	0.54
	1	10	5	1.38
Water depth	1	10	15	0.42
	1	10	25	0.20

The wave events modeled corresponded to the largest waves observed for each wave-energy regime over the previous 15 years for which the boundary-condition data were of a high enough quality to run the wave model (table 2). We chose to use these events because 15 years approaches the recovery time for the dominant coral species observed off Molokaʻi (Dollar, 1982; Grigg, 1983) and corals and their resulting reefs generally develop under the environmental conditions observed over the time necessary for their recovery (Graus and others, 1984; Rogers, 1993). The North Pacific swell model run displayed a strong shadowing effect by the island of Molokaʻi along its south coast (fig. 2). The north, east, and west sides of the island were exposed to the brunt of this large swell, which could generate peak wave-induced near-bed shear stresses greater than 1.75 N/m^2 (newtons per square meter) along most of Molokaʻi’s shoreline. The area off the south

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Table 2. Modeled wave conditions.

[Based on data from the National Data Buoy Center (2002)]

Wave regime	Date (month/day/year)	Wave height (m)	Wave period (s)	Wave direction from (deg)	Wind speed (m/s)
North Pacific swell	01/28/1998	8.4	20	320	6.1
Trade-wind waves	06/23/1998	3.2	8	50	13.8
Southern Ocean swell	06/08/2000	2.5	20	180	6.2

shore, which contains the large fringing reef, is a shadow zone for North Pacific swell, with modeled peak wave-induced near-bed shear stresses less than 0.25 N/m^2. Along most of the fringing reef, these peak stresses were less than 0.10 N/m^2 in 10 m (33 ft) of water. At both the east and west ends of the island, where the reef narrows, peak wave-induced near-bed shear stresses rapidly increase fivefold to more than 0.50 N/m^2 as some wave energy refracts around the ends of the island (fig. 3).

Kona storm waves (not shown), which were modeled to observe how the south shore of Moloka‘i would be affected by an unrefracted swell from the south, did not generate high near-bed wave orbital velocities (peak wave-induced near-bed shear stresses = 0.08 N/m^2) anywhere along the island. The Southern Ocean swell, on the other hand, produced intermediate values of peak wave-induced near-bed shear stresses (~0.25 N/m^2) along almost the entire length of Moloka‘i’s fringing reef, and these waves have been observed to resuspend high quantities of fine-grained terrestrial sediment on the reef flat (Storlazzi and others, 2000). The modeled northeast trade-wind waves appear to affect primarily the east and southeast coast of the island. The coastline between the southernmost point of the island at Kamalō and the east end of the island is directly exposed to trade-wind waves. This resulted in peak wave-induced near-bed shear stresses being 50 percent to 100 percent higher than to the west of Kamalō, where the coast is protected from direct impact of trade-wind waves. The short wave period characteristic of trade-wind waves is reflected in the greater disparity between the peak wave-induced near-bed shear stresses for the different isobaths east of Kamalō than to the west of Kamalō, where the coastline is not directly affected by these waves (fig. 4). These waves produce rather low values of peak wave-induced near-bed shear stresses to the west of Kamalō, on the order of 0.15 N/m^2. However, the modeling suggests that trade-wind waves, in combination with a typical North Pacific swell, can generate much higher peak wave-induced near-bed shear stresses along the east and southeast shore of Moloka‘i, on the order of 0.40–0.50 N/m^2, in the area where the reef starts to pinch out.

Gordon Tribble, USGS

Figure 3. Aerial photograph looking north over Moloka‘i’s west end, showing North Pacific winter swell waves wrapping around Lā‘au Point and propagating east along the southwest shore.

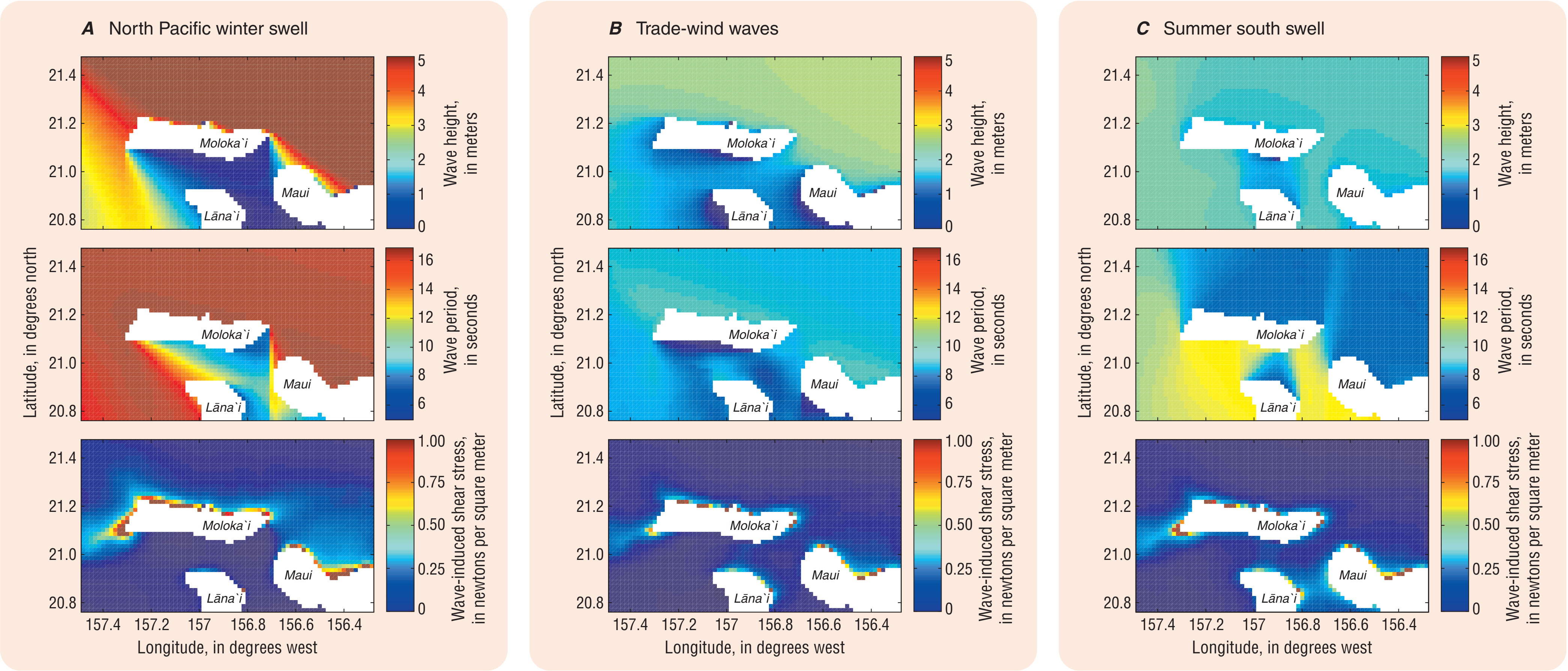

Figure 2. Wave model runs for three of the main wave climates for Moloka‘i. Note how the different combinations of wave heights, wave periods, and wave directions result in different areas being affected by high peak wave-induced near-bed shear stresses. *A*, North Pacific winter swell. *B*, Trade-wind waves. *C*, Summer south swell.

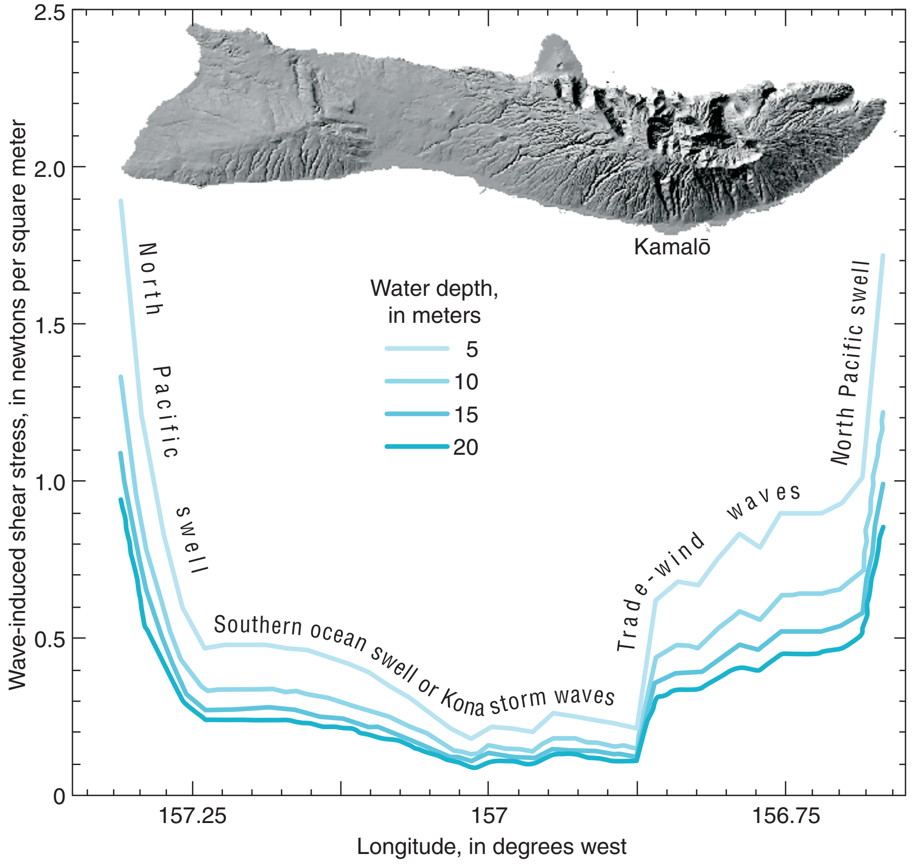

Figure 4. Modeled peak wave-induced near-bed shear stresses at different depths off Moloka‘i’s south shore. Also noted are the different types of waves that dominate each section of coastline.

Relationship Between Waves and Reef Morphology

Overall Reef Morphology

A strong inverse exponential relationship ($r^2 > 0.81$) exists between the modeled peak wave-induced near-bed shear stresses and the width of the reef flat at different locations along the south shore of Moloka‘i (fig. 5). This correlation implies that reef-flat width, and thus very likely the overall reef width, decreases exponentially with increasing wave energy.

Spur-and-Groove Morphology

Computed mean spur heights and spur widths for the south Moloka‘i reef were compared to the modeled wave-induced peak bed shear stresses to determine if there are any relations between spur-and-groove morphology and wave forces. Mean spur height along the 5-m, 10-m, 15-m and 20-m (16-ft, 33-ft, 49-ft, and 66-ft) isobaths was shown to decrease logarithmically with increasing modeled peak wave-induced near-bed shear stresses (fig. 6*A*). Mean spur width along the same four isobaths showed a similar relation to wave energy, decreasing logarithmically with increasing peak wave-induced near-bed shear stresses (fig. 6*B*). However, at shallow depths (5 m), spur height and spur width both displayed a trend opposite to the data for the four isobaths, with a slight increase in height or width with increasing peak wave-induced near-bed shear stresses (not shown).

The ratio of spur height to spur width decreased logarithmically with increasing peak wave-induced near-bed shear stresses (fig. 6*C*); this relation is significant above the 1-percent level. The low percentages of variability indicated by these correlations between waves and spur-and-groove morphology are likely due to a number of factors. These include natural variability in a complex biogeomorphological system, the disproportionate spatial resolutions of the SHOALS data (on the order of meters) and the wave model output (on the order of kilometers), and other important controls like variations in light availability for photosynthesis due to turbidity.

Spur-and-groove features appeared to occur in two distinctly different morphological groups correlated with different wave energies (fig. 7). Overall, spur-and-groove structures tended to be more than twice as high (1.1 m or 3.6 ft) and slightly wider (93 m or 305 ft) in lower energy environments as compared to those in higher energy environments (0.5 m and 87 m, or 1.6 ft and 285 ft, respectively). In regions of low wave energy, numerous short, narrow spur-and-groove structures are observed in shallow water depths (fig. 7*B*), whereas in mid water depths (fig. 7*C*), fewer, broader, and taller spurs dominated, followed by a reversal back to more numerous, short and narrow spurs lower on the fore reef along the 20-m isobath. The numerous short, narrow spur-and-groove structures either truncated or merge together to form the fewer, broader and taller spur-and-groove structures along the 15-m isobath.

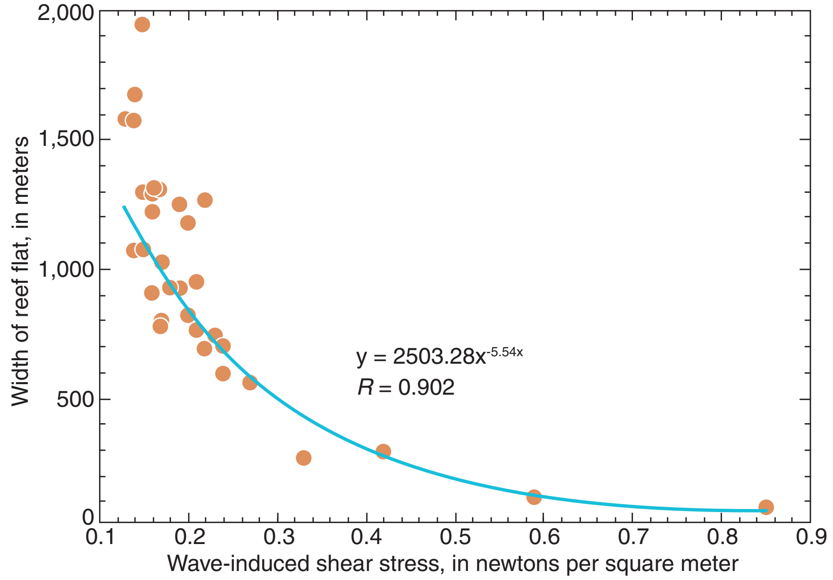

Figure 5. Plot showing the relation between peak wave-induced near-bed shear stress and the width of the reef flat off Moloka‘i’s south shore. The exponential curve fit is significant above the 0.1-percent level. This trend demonstrates that the reef flat is widest where the wave energy is lowest.

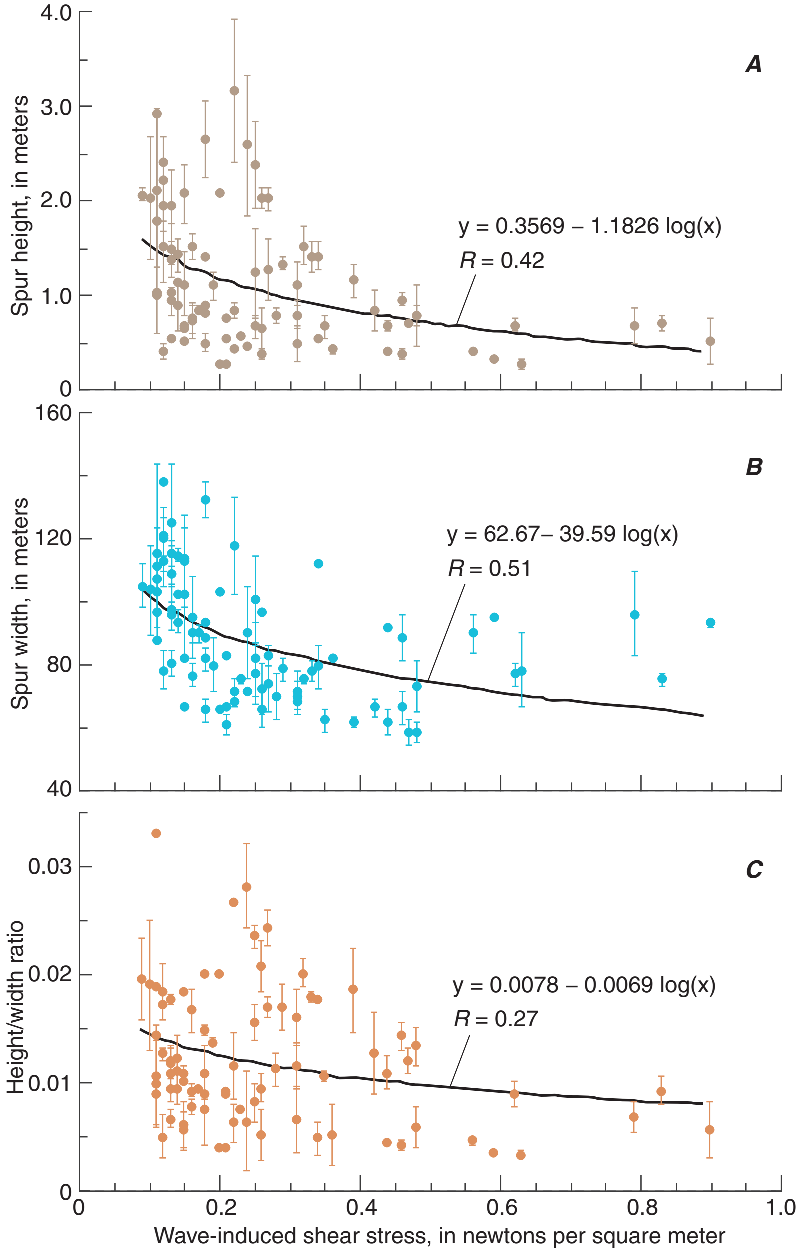

Figure 6. Relations between peak wave-induced near-bed shear stress and shape parameters of coral spurs: spur height (*A*), spur width (*B*), and ratio of spur height to spur width (*C*). The error bars denote ±one standard deviation. The exponential curve fits in *A*, *B*, and *C* are significant above the 0.1-percent, 0.1-percent, and 2-percent levels, respectively. Spur height and width are variable, but spurs tend to be higher and wider at low wave-induced shear stresses and become shorter and narrower at high shear stresses. The data suggest that waves are the dominant factor controlling spur-and-groove morphology, but they explain only a relatively low percent of the variability. Natural variability in the system and other factors, such as light availability for photosynthesis, turbidity, and the high resolution of the measurements as compared to the low spatial resolution of the wave model, are likely other sources of variability.

In higher energy environments, however, spur-and-groove structures tended to be roughly similar in height and width regardless of water depth, with the tallest spurs typically being observed in the shallowest water depths (fig. 7*D–E*). The spur-and-groove measurements in shallow water (5 m) agree with the observations made by Munk and Sargent (1954) along atolls in the western Pacific Ocean and by Roberts (1974) along Grand Cayman in the Caribbean Sea. At greater depths (15–20 m or 49–66 feet) off Moloka‘i, the relation of spur-and-groove morphology to wave energy was the exact opposite of that found by Roberts and others (1980) and Blanchon and Jones (1997) along the deeper shelf-edge reef off Grand Cayman. The population of reef-forming corals in both the Caribbean and western Pacific is distinctly different from those of Hawai‘i. It is not clear what role different species may play in influencing the morphology of spur-and-groove structures.

Implications of Results to Understanding Processes of Reef Formation

The relations shown here between modeled wave parameters and reef morphology suggest that peak wave-induced near-bed shear stresses are a dominant control on the distribution and morphology of the reef off southern Moloka‘i. The central portion of the reef is protected from the direct impact by large waves, and thus the reef framework is able to develop into an extensive shallow reef flat and broad fore reef. The east and west ends of the island are exposed to larger, longer period waves that generate high orbital wave velocities and thus strong near-bed shear stresses. This appears to limit substantial reef development because of physical breakage of the coral and high abrasion by both bedload and suspended sediment (Dollar, 1982; Grigg, 1998).

In order to explain the variability in spur-and-groove morphology at a given water depth, where light availability remains relatively constant, other physical factors must come into play (fig. 7). The slightly higher and more widely spaced spurs in higher energy shallow areas (fig. 7*D*) relative to lower energy shallow regions (fig. 7*B*) may be explained by the interaction between sediment and coral. The spurs in the shallow, high-energy portions of the reef are likely constructed in part by the binding of coral rubble by diagenetic cementation or coralline algae as described by Shinn and others (1981), Macintyre (1997) and Rasser and Riegl (2002). These studies and others (Tribble and others, 1990, 1992; Brainthwaite and others, 2000) have shown that such processes are dominant along low-slope energetic shallow reef crests and upper fore reefs but are absent along the more quiescent deeper portions of the steep fore reef. The large amount of coral rubble and coarse-grained sediment resulting from the weathering of broken coral may effectively increase the abrasion experienced by corals closer to the sea bed. Consequently only those spurs with enough height to avoid this abrasion likely promote coral growth. Thus, higher wave energy in more exposed shallow areas may advance spur development through cementation and binding of coral rubble, whereas at depth intact coral development may be retarded by wave stresses where these processes are absent and in-place coral growth dominates.

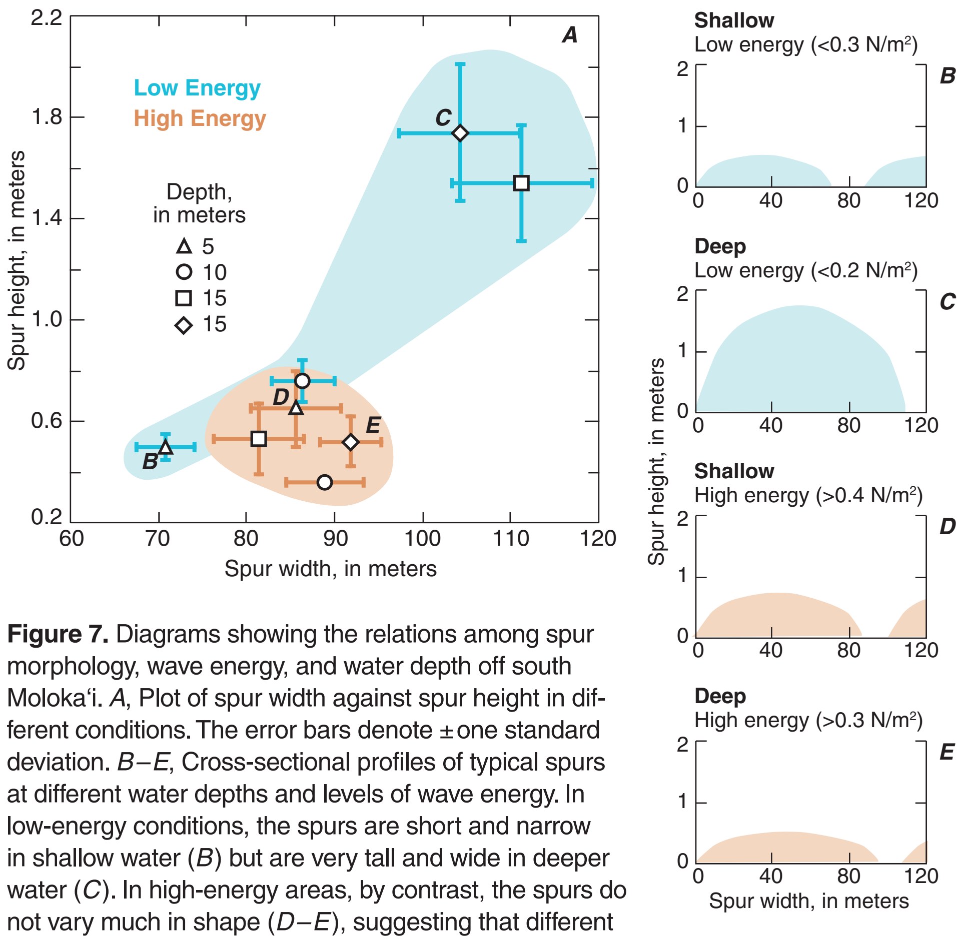

Figure 7. Diagrams showing the relations among spur morphology, wave energy, and water depth off south Moloka‘i. *A*, Plot of spur width against spur height in different conditions. The error bars denote ± one standard deviation. *B–E*, Cross-sectional profiles of typical spurs at different water depths and levels of wave energy. In low-energy conditions, the spurs are short and narrow in shallow water (*B*) but are very tall and wide in deeper water (*C*). In high-energy areas, by contrast, the spurs do not vary much in shape (*D–E*), suggesting that different processes might be more important in defining coral-spur morphology in calm areas versus high-energy areas.

Another significant factor shown to control reef development is antecedent topography. While a lower gradient shelf would result in a greater cross-shore extent of the shelf being situated in the zone optimal for coral growth in terms of light availability and wave energy, reef development in this space would still be contingent on low enough wave energy to allow reef growth. This is why well-developed active reefs are not observed off northern O‘ahu or Maui. These areas have similar coastal configurations to south Moloka‘i but are directly impacted by the large North Pacific swell that generates extremely high (>1.5 N/m^2) peak wave-induced near-bed shear stresses (Grigg, 1998).

These analyses clearly show that waves are the primary control on both large-scale reef morphology and smaller scale spur-and-groove morphology where high peak wave-induced near-bed shear stresses are present. In these areas light, water depth, and antecedent topography are subordinate. The higher morphologic variability at lower peak wave-induced near-bed shear stresses demonstrates that when wave-induced water motions are low enough as to not dominate reef and spur-and-groove morphology, other factors such as light availability for in-place coral growth and the ability to bind or cement rubble increase and may become the dominant factors.

CHAPTER 12

The Freshwater Cycle on Moloka‘i

Gordon Tribble[1] and Delwyn S. Oki[1]

Rain is the source of all freshwater on Moloka‘i. Most of the rain falls in the upland (mauka) areas at higher elevations, generally above 600 m (2,000 ft). Figure 1 shows the average amount of daily rainfall per square mile in four zones of the island; also shown is the amount of rain that runs off as surface water, evaporates and transpires back to the atmosphere, and recharges the aquifer. The wettest part of the island, the upper slopes of East Moloka‘i Volcano, receives an average of nearly 4 m (more than 150 in) of rain per year (fig. 2). The driest parts of the island, such as coastal areas of West Moloka‘i, receive an average of less than 0.4 m (15 in) per year (Giambelluca and others, 1986; fig 3).

On an average day, the entire island receives about about 2 billion liters (552 million gallons) of rain. Of this amount of rainwater, about 50 percent evaporates or is transpired by plants, about 16 percent runs off to streams, and the remaining 34 percent infiltrates into the ground and becomes ground water. Drier areas of the island (such as the West Aquifer Sector; fig. 1) tend to have a higher percentage of rainwater going to evaporation and transpiration and a lower percentage going to runoff and recharge, whereas the wetter areas (such as the Northeast Aquifer Sector; fig. 1) tend to have a higher percentage of rainwater going to runoff and recharge and a lower percentage going to evaporation and transpiration (Shade, 1997).

Figure 1. Map of Moloka‘i showing average annual rainfall per square mile in different areas of the island. The percentage distribution of the rainwater into runoff, evaporation and transpiration, and ground-water recharge is shown in pie charts. The size of each pie chart indicates the total amount of rainwater. The map also shows the locations of stream (continuous-record and peak-flow) and spring-discharge monitoring stations operated by the U.S. Geological Survey in 2007. Data from these stations can be found at http://hi.water.usgs.gov/ (last accessed April 29, 2008).

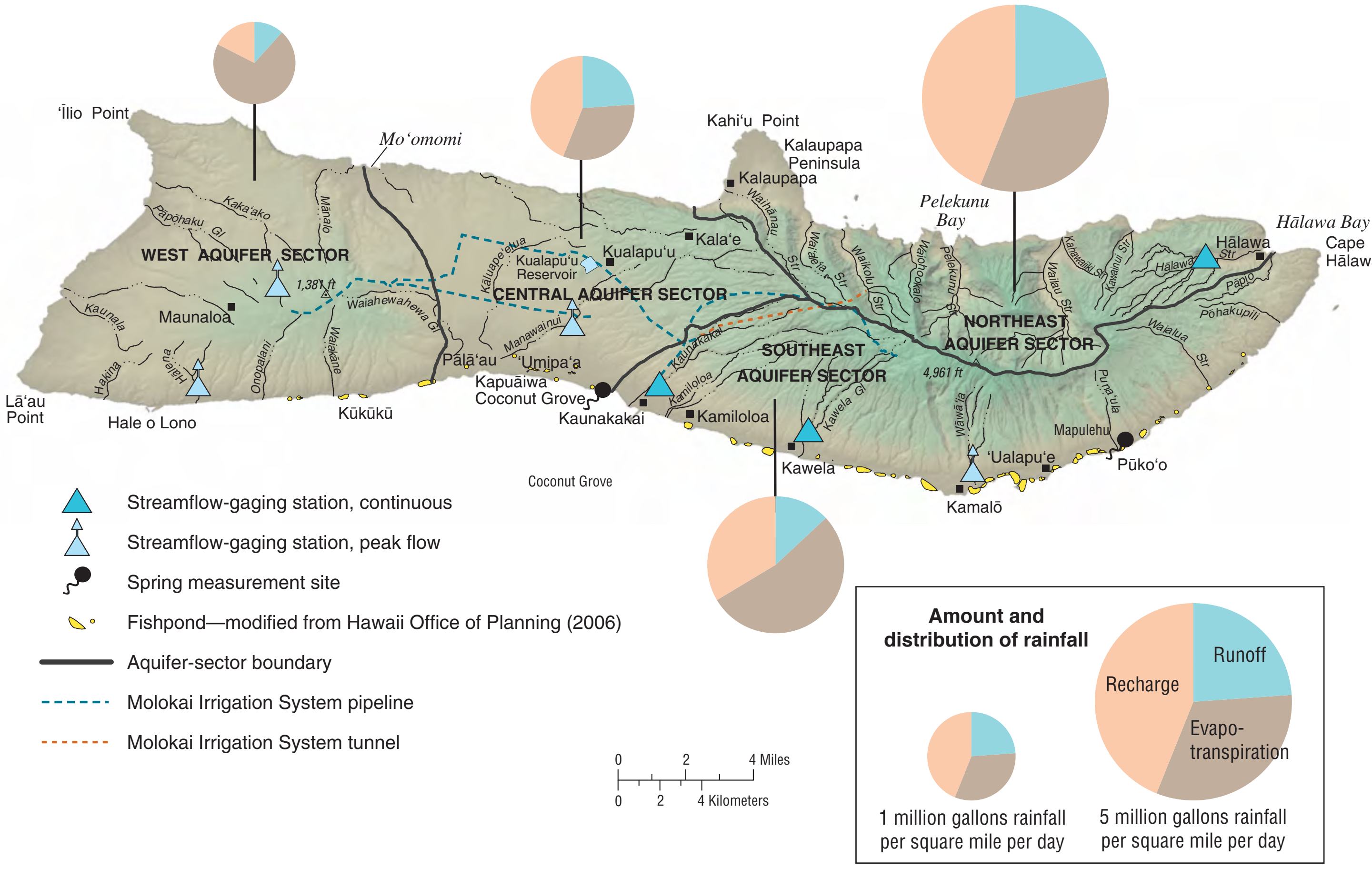

Figure 2. View of Pelekunu Valley, on the northeast coast of Moloka‘i, showing lush vegetation and deep erosion in the valleys resulting from the wet climate in the northeastsern part of the island.

Figure 3. View of the south coast of Moloka‘i from Kamiloloa to Lā‘au Point as seen from Kawela, showing the subdued landscape and sparse vegetation that result from the arid climate in the southwestern part of the island. The fringing coral reef, coastal fishponds, and mudflats at Pālā‘au are also visible.

Recharge is important because it replenishes underground aquifers with freshwater. This fresh water flows slowly through the aquifers and eventually discharges from springs and seeps into streams or the ocean. Under natural conditions, the average rate of recharge to an aquifer balances the amount of discharge. Water removed from aquifers by pumping is no longer available to discharge to streams or the ocean. Such ground water pumped from aquifers supplies most of the freshwater for drinking and other uses on Moloka‘i. For the period 2000 to 2002, about 4.2 million gallons (about 16 million liters) a day was pumped for domestic use on the island. About 50 percent of this water is pumped from the Kualapu‘u area. To assist in managing the supply of ground water, computer models are used to simulate the flow of ground water and evaluate the effects of pumping (Oki, 1997, 2000, 2006). Water use on the island of Moloka‘i is regulated by the State of Hawai‘i Commission on Water Resource Management, which designated the entire island as a Ground Water Management Area in 1992.

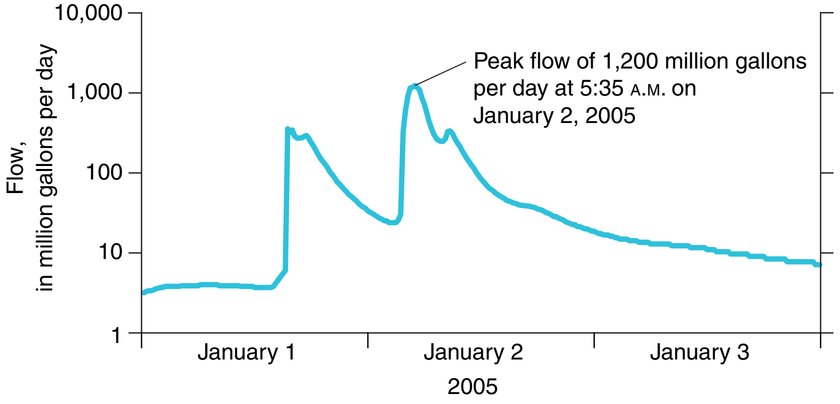

Figure 4. Flow in Hālawa Stream during January 1–4, 2005, showing rapid changes in flow from less than 10 million to more than 1,000 million gallons per day. The high rates of flow are caused by direct runoff of rainfall, whereas the sustained low rates are caused by the base-flow discharge of ground water into the stream.

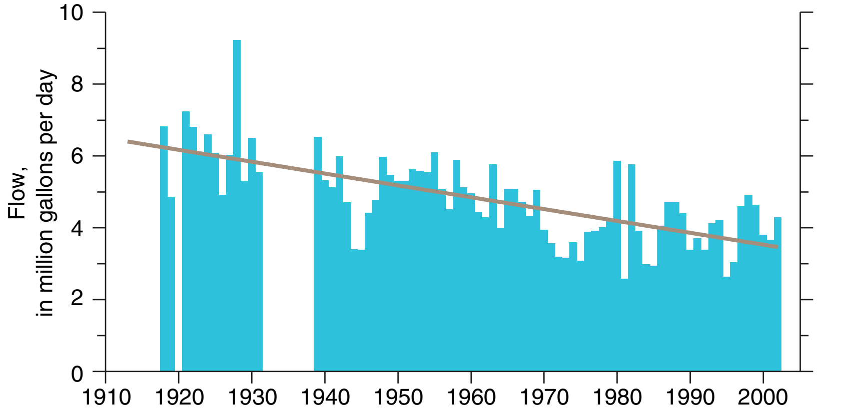

Figure 5. Average annual base flow in Hālawa Stream since 1918. The solid brown line shows the long-term trend of declining flow (from Oki, 2004). Base flow is estimated from daily records of total flow using computerized methods that separate the measurement of total flow into direct runoff and base flow. Note: data are missing for the years of 1920 and 1932 to 1938.

The U.S. Geological Survey (USGS) has measured flow in both perennial and ephemeral streams on Moloka‘i since 1917. At one time (1968), 9 continuous and 11 peak-flow stream gages were in operation on the island, but as of 2007 only 3 continuous and 4 peak-flow stream gages were in operation. The locations of these sites are shown in figure 1. Data from most of these sites are available on the internet at www://hi.water.usgs.gov/ (last accessed July 11, 2007). Funding to operate these stations currently comes from the State of Hawai‘i Department of Land and Natural Resources, the State of Hawai‘i Department of Transportation, Maui County Department of Water Supply, and the USGS Cooperative Water Program.

Ground-water discharge along the south shore of Moloka‘i is much higher on the east because of the greater amount of rain that falls on that part of the island. For example, between Kawela and Pūko‘o the discharge of freshwater is estimated to be approximately 4.0 million gallons per day per mile (about 9.4 million liters per day per kilometer) of coastline. On the west side, between Hale O Lono and Kūkūkū Gulch, the discharge of freshwater is only one-tenth as much, approximately 0.39 million gallons per day per mile (about 0.9 million liters per day per kilometer) of coastline.

Water in streams comes both from the direct runoff of rainfall and from the discharge of ground water from springs and seeps (which is called base flow). Streams on the northeast side of the island flow continuously (perennial streams) and are sustained by base flow because their valleys have eroded deeply enough over time to cut into the water table (fig. 2). Hālawa Valley, on northeast Moloka‘i, contains a good example of a perennial stream. Streamflow in Hālawa Valley has been measured for most of the time since 1917 at a site where the stream drains an area of about 11.9 km^2 (about 4.6 mi^2) that receives an average of 2 m (80 in) per year of rainfall. Since 1917, the median flow at that site has been about 8.4 million gallons (about 32 million liters) per day. However, flow has varied from a daily low of 0.56 million gallons per day to a peak flow of 17,400 million gallons per day (about 2.1 million to 65,900 million liters per day). Figure 4 shows an example of how flow can change very rapidly. Such extremes in the amount of flow are typical of streams in Hawai‘i, and a rapid increase in flow can be very dangerous if people are crossing or playing in the stream. Great caution should be exercised around any stream during periods of rain.

Flow can also change over a period of many years. For example, from 1918 to 2002, the average annual base flow in Hālawa Valley has decreased by an average of 0.53 percent per year; this equals a cumulative decline of 44 percent (fig. 5). This decline is a result of lower rainfall in the second half of the 20th century (Oki, 2004), but it is not known if this trend is part of a long-term cycle or represents a distinct change in climate.

Most streams on Moloka‘i have no base flow and are ephemeral; they flow to the ocean only when there is enough rain to generate runoff. Runoff from watersheds carries sediment and other materials from the land to the ocean. In 2004 a gage was built to measure the amount of water and sediment flowing in Kawela Stream about 600 m (about 2,000 ft) inland from the coast. The flow at the gage is from a drainage area of about 13.7 km^2 (about 5.3 mi^2) with an average annual rainfall of about 1.1 m (45 in). The amounts of water flow and sediment load measured by the gage are shown in figure 6.

For the one-year period from October 1, 2004, to September 30, 2005, water flowed in the stream 29 percent of the time. The median flow, during times when the stream was flowing, was 2.2 million gallons (about 8.3 million liters) per day, and the peak flow was 345 million gallons (about 1,300 million liters) per day. The concentration of suspended sediment ranged from 1 to 1,700 mg/L. The total amount of sediment carried towards the ocean at this site during this period was 2,789 tons, and the highest amount for a single day was 1,030 tons on March 9, 2005. The five days with the highest sediment load contributed more than 90 percent of the total sediment load for the year. Information from this site will be used to estimate the amount of sediment reaching the coral reefs along the south coast of Moloka‘i and provide information on how the coral reefs are being affected by processes in the watershed. This information can also be used to assess the effectiveness of watershed management plans because it will be possible to measure reductions in the rate of erosion over time.

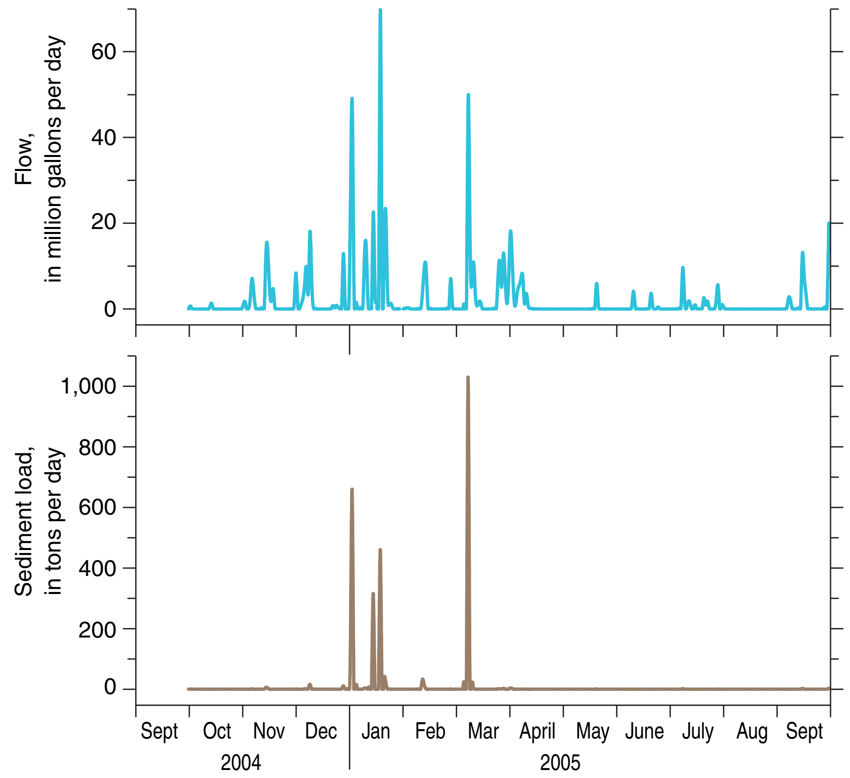

Figure 6. Graphs of daily flow (top) and sediment load (bottom) for Kawela Stream during the one-year period from October 1, 2004, to September 30, 2005. Streamflow occurred only intermittently, and most of the sediment load occurred during a few periods of wet weather. Instantaneous values can differ substantially from daily values because streamflow can vary greatly even during one day.

CHAPTER 13

Ground Water and its Influence on Reef Evolution

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Ground water—water that is stored in and transported through the rocks and sediment below the Earth's surface—is an important resource of water as well as a site for biologic, geologic, and chemical processes (fig. 1). The influence of human activities on this resource is of particular concern because such activities can produce nutrients and contaminants that may infiltrate the ground water and move with it to areas of discharge at the coast. Unlike streams and lakes, ground-water discharge is much more difficult to access and measure, and therefore our understanding of its quantity, character, fate, and ultimate role on coastal environments is still limited.

Because water flowing through rocks often moves slowly, it can have a long residence time within the rocks. As a result, the water can acquire a unique chemical signature, which can be used to distinguish its source. Where land-use activities (industry, agriculture, urbanization) are intense, ground water may contain concentrated levels of terrestrially derived nutrients, trace metals, and other organic and inorganic contaminants, including many synthetic compounds and those associated with human waste.

Ground water commonly plays a vital role in structuring coastal habitats and ecosystems. When either ground-water composition or ground-water discharge rate changes, it is likely to induce alteration of the environmental conditions at the coast. Submarine ground-water discharge (SGD) is that portion of ground water that enters the ocean below sea level and may be composed of fresh ground water or a mixture of fresh ground water and seawater (for example, brackish water). As a result, studying SGD and determining its effects on coastal ecosystems is very challenging.

Exciting advances in the technology of airborne sensors, submersible instruments, and marine chemistry are enabling better mapping of SGD along the coast and providing means to calculate the quantity, composition, and fate of SGD into the coastal ocean. These tools can help differentiate processes and pathways of contamination associated with land-use activities from those of natural phenomena by examining the chemistry of SGD. Analyzing compounds collected in the annual growth bands of coral skeleton may help determine past levels of discharge and temporal changes in them. Freshwater from surface or ground water has long been known to be more acidic than seawater and, as a result, is notable for dissolving coral reefs on many scales: on the microscopic scale, submillimeter cements form within coral skeleton, and over tens to hundreds of kilometers, entire reef systems dissolve to produce karst landscapes.

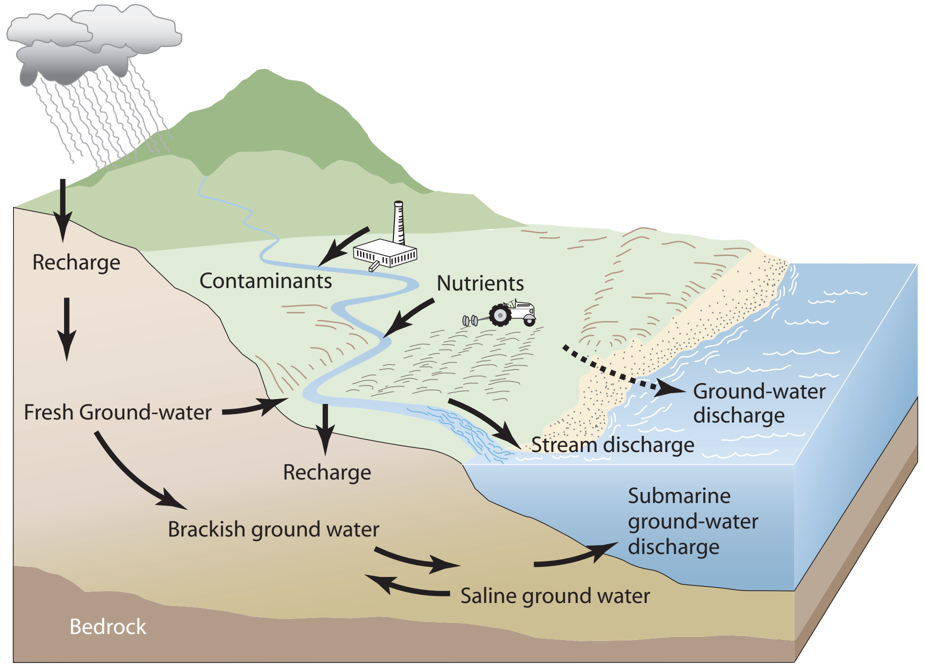

Figure 1. Diagram of the hydrologic cycle showing how upland precipitation and streams infiltrate into the soil and recharge ground water. Ground water is composed of fresh, brackish, and saline types, and their zonation fluctuates with changes in recharge and pumping through wells. Many land-use activities can add nutrients and contaminants to ground water, which eventually discharges to the coast.

Determining the role of ground water on Hawaiian reefs, and the south Moloka‘i reef in particular, is important for understanding the reef's current health and future fate. A growing concern is the impact of excess nutrients derived from land-use activities, especially inorganic nitrogen in the form of nitrate and nitrite. These chemicals are often found in higher concentration in ground water and are considered a limiting nutrient in coastal waters. The addition of excessive amounts of nitrogen to relatively nutrient-poor coastal waters surrounding coral reefs therefore can have significant ecosystem impacts. In many reef settings, excess inputs of nutrient have led to a shift from coral-rich communities to excessive algal and plant growth, which can smother and kill reefs (Hughes and others, 2003b; Szmant, 2002).

Understanding Submarine Ground-Water Discharge in Coastal and Reef Settings

Our understanding of ground-water discharge and its effects on coastal and reef settings is derived in four primary ways: (1) local knowledge and observation, (2) physical property surveys of the water column, (3) chemical analyses of water samples, and (4) hydrologic modeling. Specific sites of SGD in the shallow coastal zone of Hawai‘i, and of Moloka‘i specifically, as in many island settings, are often known from local observations of fisherman and coastal residents. Many legends are also validated today by observation of cold and/or fresh water emanating from the ground (fig. 2*A*–*D*) and through the shallow sea floor at sites known in Hawai‘i as "water holes" (lua wai), like the many cold-water springs around Kona on the Big Island of Hawai‘i and in Waikīkī (which means "spouting-water" in Hawaiian) on the island of O‘ahu.

Modern instruments, including airborne thermal infrared (thermal IR) imaging systems and CTDs (submersible instruments that measure water conductivity, temperature, and depth) are now sensitive enough to map and quantify physical properties of the water, including temperature and salinity (the dissolved salt content of water) at specific depths and over large areas rapidly. Thermal IR systems image Earth's surface temperatures (in soil, water, and vegetation) by measuring the amount of radiation reflecting back to space in the thermal portion of the spectrum. Thermal IR imaging systems are typically flown on small aircraft and measure only the uppermost layer of the water column, whereas CTDs are often deployed from a boat to measure temperature and salinity through the entire water column. CDTs can also be fastened to a tripod on the sea floor to record temperature and salinity variations at a single point over time. These types of data allow discrete water masses to be mapped in order to examine pathways of freshwater into and through the coastal ocean, along with characteristics of its mixing. In Hawai‘i the shallow sea floor is commonly composed of porous coral reefs, and CTD data can be especially useful to help identify where SGD, characterized by being colder and of lower salinity, flows out to the sea through the reef.

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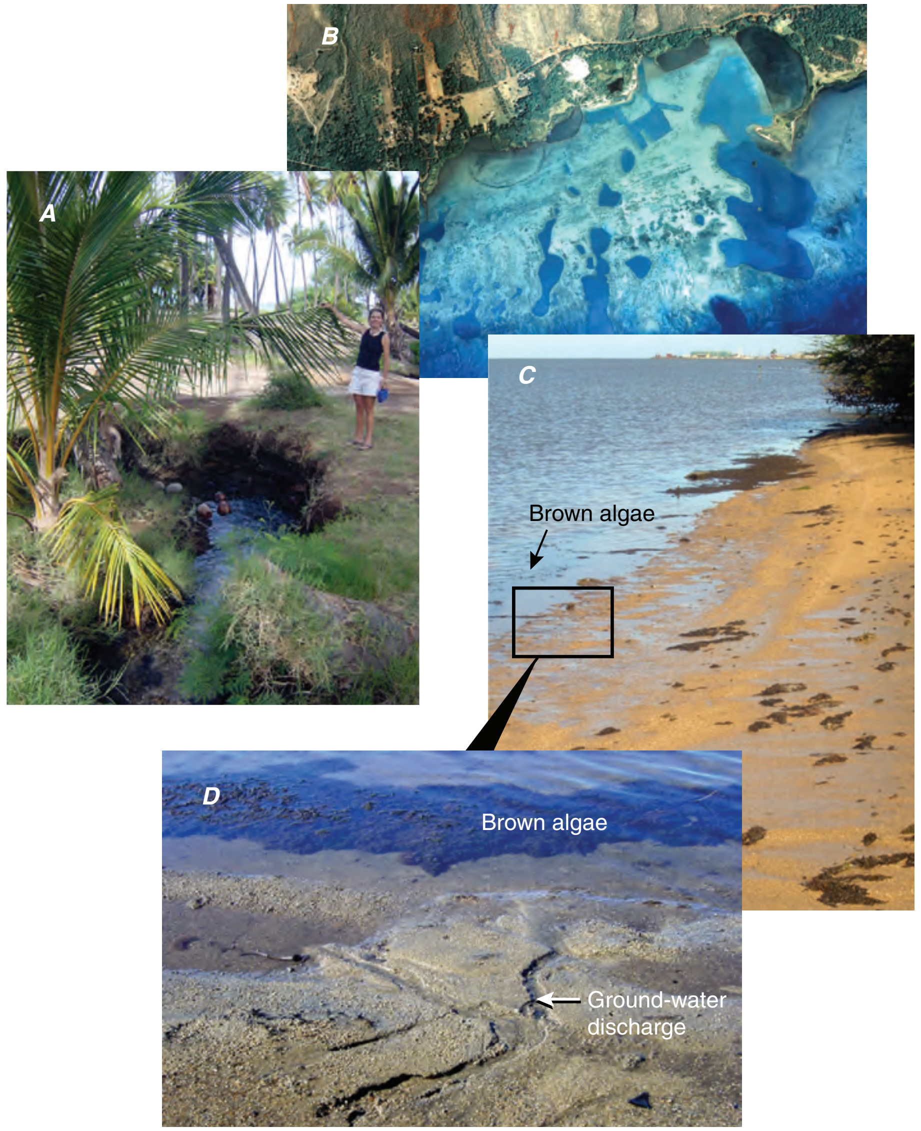


Figure 2. Photographs of landscape features associated with ground-water discharge. *A*, Ground water discharging through springs at the shoreline of Kapuāiwa coconut grove. *B*, The “blue holes” off Kamalō, characteristic of karst (dissolution) features. *C*, Ground water discharging through the beachface at Kamiloloa during low tide. *D*, Fleshy brown and/or green algae commonly found in coastal waters with high nutrient concentrations.

New chemical methods that determine the concentration of specific compounds and elements are used to determine the composition of water. Many chemicals and compounds can be used as tracers to differentiate water masses and sources, including SGD, in the coastal ocean. Several constituents, including barium, silica, lead, and iron, are indicative of freshwater and/or ground water, and recently the naturally occurring radioactive elements radon (Rn) and radium (Ra) have proven of excellent utility in identifying SGD to the coast (Moore, 1996). Rn and Ra occur in several isotopes (different forms of the same element having slightly different masses resulting from different numbers of neutrons in their nuclei) that radioactively decay at specific rates. Knowing the rate of decay and activity of these isotopes in water samples enables calculations that help identify the source and mixing rate of fresh ground water (using Rn) and brackish ground water (using Ra). In Hawai‘i, Rn and Ra are often concentrated in ground water and are associated with nutrient concentrations, especially nitrogen as nitrate and nitrite (Garrison and others, 2003; Soicher and Peterson, 1997; Paytan and others, 2006). Other chemical methods include the use of stable isotopes of carbon (^{13}C) and nitrogen (^{15}N). These can be used to identify a wide range of sources and processes that influence the fate of nutrients, including terrestrial plant or organic material, fertilizers, sewage, and waste products, and to track the mediation of those nutrients through biologic uptake and geochemical cycling (Leichter and others, 2003; Umezawa and others, 2002; Yamamuro and others, 2003). Using a combination of stable isotopes, radioactive isotopes, and concentrations of various nutrients and elements, scientists can determine and in many cases quantify (1) SGD at the coast, (2) nutrient fluxes, and (3) nutrient sources.

Hydrologists and geologists use the rock properties and structure of coastal environments, rainfall patterns, and water levels in wells to map the distribution of ground water below the surface. By the use of tracers and a knowledge of ground-water behavior, the rate of ground-water flow from areas of recharge (where rainfall and infiltration are greatest) to the ocean can be determined (fig. 1). Using these data, models are constructed to estimate and describe flow patterns and locate suitable areas for ground-water development. In island settings like Hawai‘i, these models and direct observations reveal that within the island mass a freshwater lens commonly floats above more saline ground water and seawater. In times of high rainfall and recharge, freshwater discharge to the ocean increases. During times of drought and/or in areas of heavy well-water use, saline waters from the ocean intrude into the freshwater reservoirs, sometimes contaminating freshwater resources needed for local consumption. Understanding these processes and the nutrient and contaminant concentrations associated with freshwater discharging across coastal ecosystems is of critical importance as human activity increasingly alters the quality and composition of freshwater and coastal ocean water.

Results—Submarine Ground-Water Discharge Across the Moloka‘i Reef

There are multiple indicators of submarine ground-water discharge (SGD) to the Moloka‘i reef. These include morphologic evidence, remote sensing data (thermal IR), direct measurements of temperature and salinity, studies of chemical radioactive (Ra and Rn) and stable (C and N) isotopes, and measurements of nutrients.

Morphologic Evidence of Submarine Ground-Water Discharge

The “blue holes” of Kamalō (fig. 2*B*) are characteristic of karst topography, sculpted limestone terraines formed by dissolution by freshwater. They probably formed during periods of subaerial exposure (lower sea level). It remains uncertain if the Kamalō blue holes are indeed karst, but significant freshwater outflow along the coast there, and at other sites such as the Kapuāiwa coconut grove, 2.5 km (1.5 mi) west of Kaunakakai, and Pālā’au where similar features occur, points to ground-water dissolution as a likely cause for erosion of the holes. Subsequent reef accretion around the edges may add reefal material to the perimeter of the blue holes in time. Dissolution of carbonate reefs by freshwater occurs much as chalk is dissolved when dropped in a carbonated beverage, which is slightly acidic. Freshwater is relatively acidic compared to seawater and will dissolve calcium carbonate, which is the dominant mineral in reefal limestone. Karst features are found across the entire Moloka‘i reef in the form of isolated sand-filled circular basins. A prominent blue hole referred to herein as “The Pit” occurs near the reef crest between Pālā’au and the Kapuāiwa coconut grove (Field and other, this vol., chap. 2). Local knowledge of its longtime existence suggests that this feature was naturally formed. Several other large karstlike features occur along the reef crest offshore of Kawela (Storlazzi and others, this vol., chap. 3). Drilling through the outer reef flat at the Kapuāiwa coconut grove (Engels and Fletcher, this vol., chap. 4) revealed a cavity or cave just below the sea floor extending to nearly 20 m (60 ft) below the reef surface. This type of cavity is uncommon in living reefs and is likely due to dissolution, probably during times of lower sea level. The blue holes of Moloka‘i offshore of the Kapuāiwa coconut grove and Kamalō have been the focus of conductivity, temperature, and depth (CTD) measurements and water analyses to determine if they are active conduits of SGD escaping through the reef. The reef flat and fore reef offshore of Kamiloloa also has been studied to examine SGD and potential nutrient flux where the reef shows signs of extensive deterioration and high algal growth.

Spatial Patterns of Submarine Ground-Water Discharge

Thermal IR images collected by scientists from the U.S. Geological Survey and University of Hawai‘i in 2001 using the Airborne Hyperspectral Imager (AHI) show the large-scale pattern of cool surface waters along the Moloka‘i south shore relative to further offshore (fig. 3). This version of the AHI data is qualitative and shows relative temperature variations of the surface water in the top 1 cm (0.4 in) across the reef. In the absence of surface-water runoff through rivers and streams during most of the year, cool surface waters along the coast suggest extensive SGD. Thermal IR data also show the cross-shore influence of fresh surface water near stream mouths, where active subsurface flow is likely concentrated because ground-water levels are higher than the elevation of the incised stream channel. On the island of Moloka‘i, modest rainfall in the upper elevations recharges ground-water levels sufficiently to maintain ground-water flow at the coast (fig. 4).

Measurements of surface-water temperature, conductivity, and salinity from 325 CTD casts and 50 point measurements using a temperature and conductivity probe across the Moloka‘i reef made during two different surveys (May and August, 2002) reveal a persistent pattern of freshwater discharge and mixing across the reef flat and inner reef crest (fig. 5). These

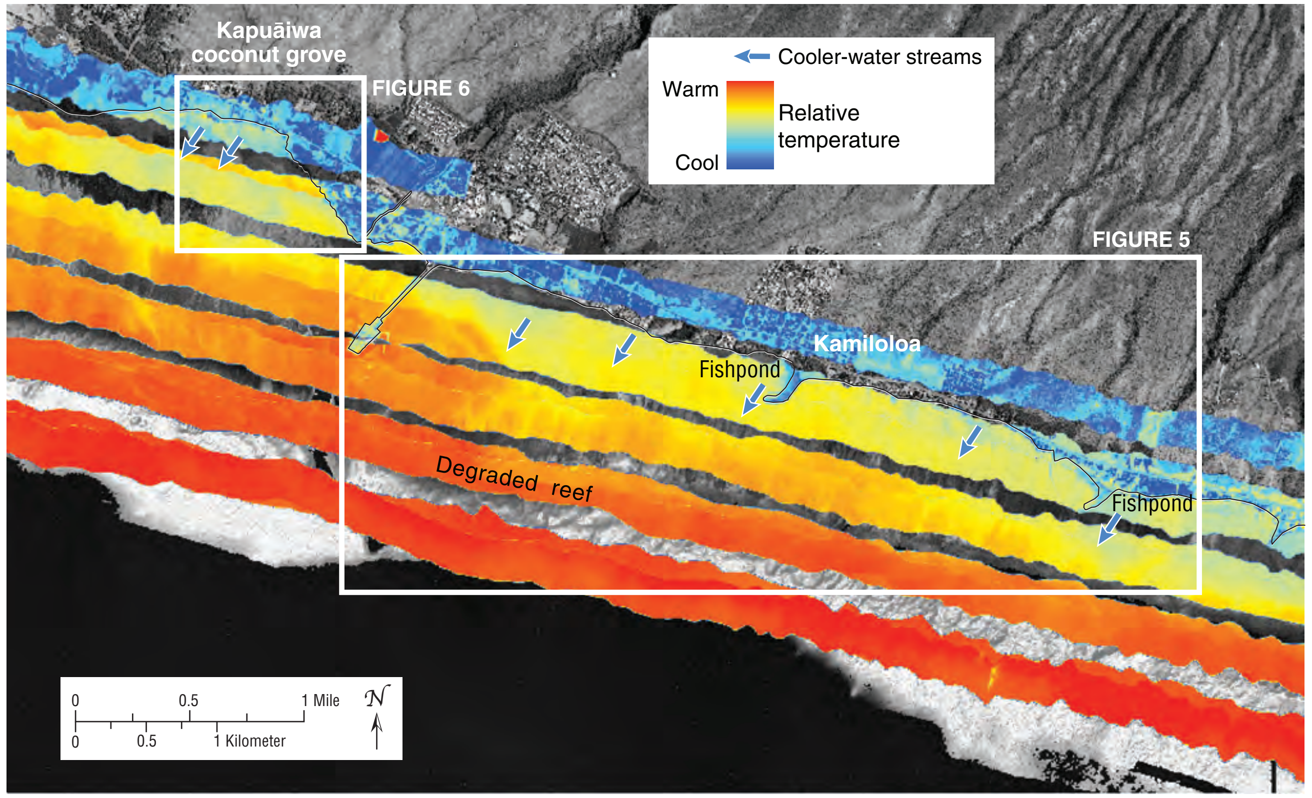


Figure 3. Map showing uncalibrated thermal infrared imagery collected March 8, 2001, across the south shore Moloka‘i reef. The rainbow color codes represent relative temperature variations, where red is warm and blue is cool. Offshore of Kapuāiwa coconut grove several streams of cool water are observed flowing out across the reef flat (blue arrows). Along the Kamiloloa coast, several areas of cooler water are found flowing as streams across the reef flat (blue arrows) and are commonly associated with fishponds. In the absence of surface runoff from streams, these cooler water masses are best explained by ground-water discharge along the shore.

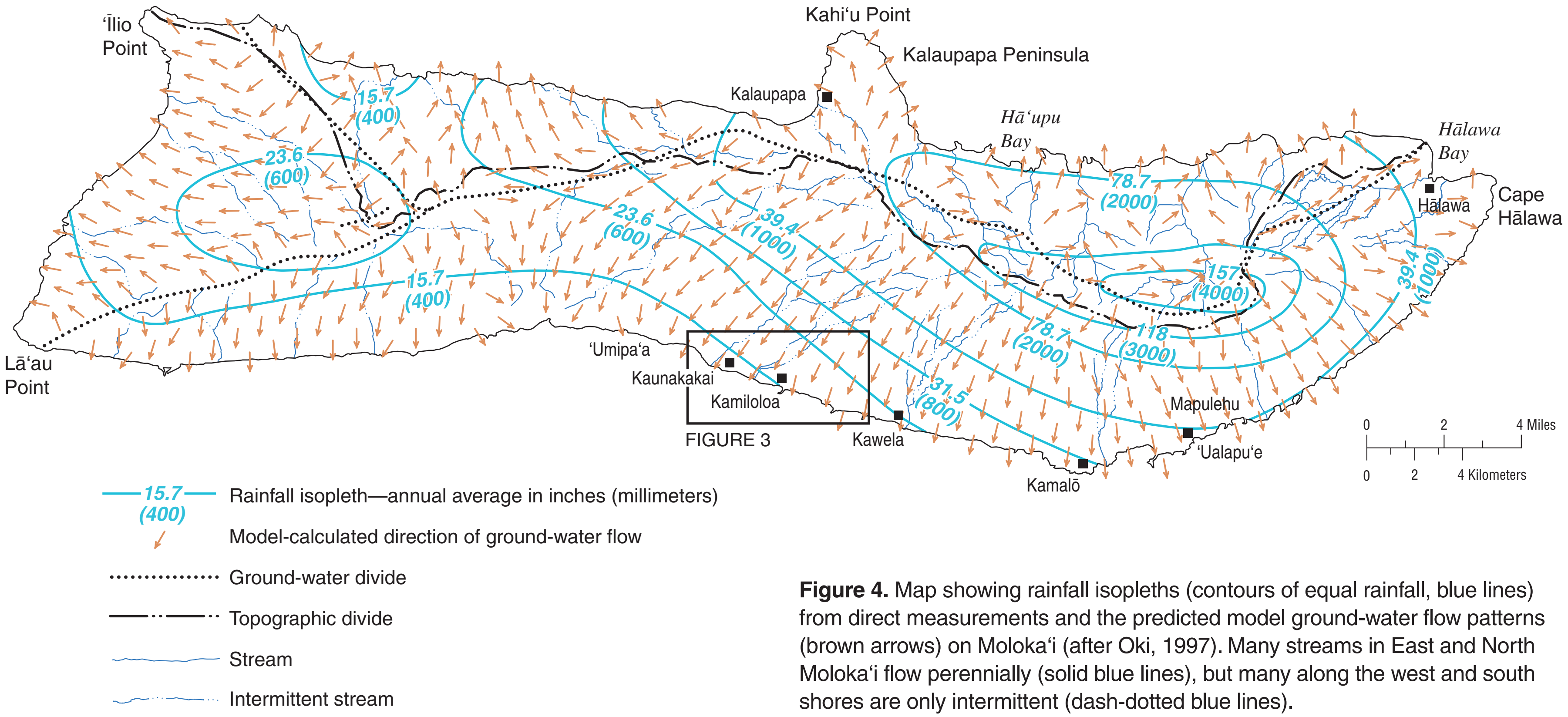


Figure 4. Map showing rainfall isopleths (contours of equal rainfall, blue lines) from direct measurements and the predicted model ground-water flow patterns (brown arrows) on Moloka‘i (after Oki, 1997). Many streams in East and North Moloka‘i flow perennially (solid blue lines), but many along the west and south shores are only intermittent (dash-dotted blue lines).

results are similar to what the thermal IR data show and suggest that freshwater is discharging along the south Moloka‘i shoreline. In the absence of inflowing surface waters via streams, these data are a strong indication that ground water is the source of this freshwater.

At Kapuāiwa coconut grove, the influence of freshwater from springs and SGD is dramatic based on surveys collected in August 2004 (fig. 6). Cold freshwater emanates from the springs and extends more than 0.5 km (0.3 mi) offshore at the surface. This ground water rapidly warms over the shallow reef flat. In addition, ground water can be seen discharging through the reef (black arrow, fig. 6*B*) 0.5 km (0.3 mi) offshore of the coconut grove. Interestingly, however, cooler temperatures are not always indicative of freshwater, because marine water associated with the incoming tide may be cooler than freshwater that warms rapidly near shore on the reef flat (fig. 6*C*, *D*).

Across the reef offshore of Kamiloloa, sensors were mounted on tripods and left recording at the same location for several years. The resulting measurements show that water temperature and salinity vary both daily and seasonally. Although temperature varies by only a few degrees, salinity varies as much as ~10 practical salinity units (psu), whereas marine waters commonly have values around 35 psu (Ogston and others, this vol, chap. 20). Each day, as the tide rises it brings slightly cooler, more saline marine waters toward shore. They mix with surface waters across the shallow reef flats, which become warmer throughout the day as they are heated by the sun. Episodic decreases in temperature and salinity, however, may be related to discrete periods of high rainfall. Whether these variable conditions adversely affect coral directly remains uncertain.

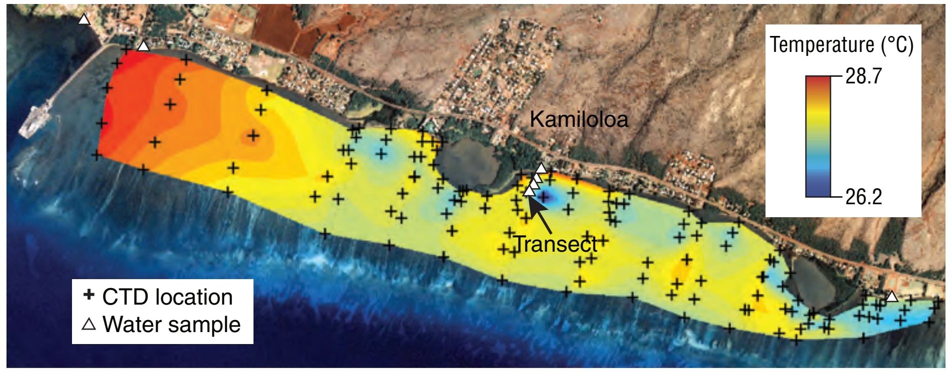
Radiochemical Signatures of Submarine Ground-Water Flux

Elevated activities of radium isotopes measured in nearshore waters provide strong evidence of widespread SGD to the fringing reef along south Moloka‘i. Water samples were collected on July 12, 2003, approximately 1 m (3 ft) from the shoreline at 12 sites between Kapuāiwa coconut grove and ‘Ualapu‘e fishpond east of Kamalō (fig. 5). ^{223}Ra and ^{224}Ra activities measured in these samples ranged from 0.3 to 2.5 and 9 to 47 decays per minute per 100 liters (dpm/100 L), respectively, showing a high degree of variability. Because these isotopes are evenly present in very low concentration in seawater, this likely reflects an uneven distribution of SGD along the coast. Peak Ra activities were measured just west of the Kaunakakai Wharf in high-salinity waters, and Ra activities at all sites were 10 to 100 times greater than those measured in the open ocean.

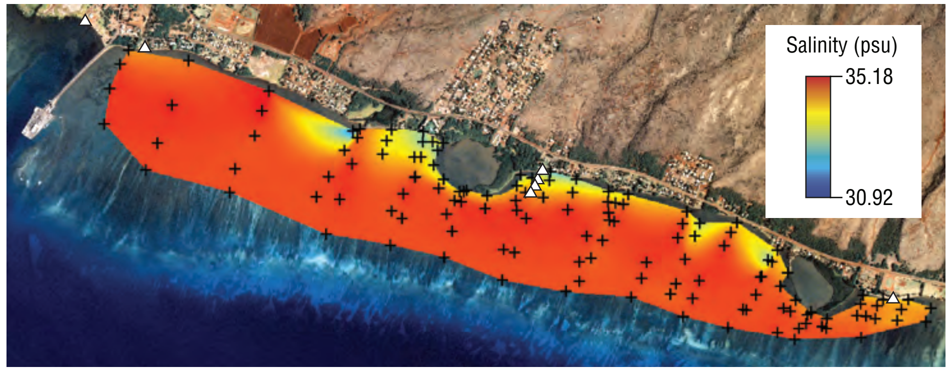
Samples were also collected along cross-shore transects at three sites along the south coast: Kapuāiwa coconut grove, Kamiloloa, and near ‘Ualapu‘e fishpond (two are shown in figure 7). Elevated ^{224}Ra activities (17–34 dpm/100 L) were detected in samples as much as 60 m offshore on the reef flat. Assuming slow mixing rates and water residence times of 2–3 days (several tide cycles) in the protected back-reef areas (Ogston and others, 2004; Presto and others, 2006), the persistence and elevated activities of ^{223}Ra and ^{224}Ra offshore suggest high discharge of brackish ground water. The discharge may be occurring through the sea floor over a broad area of

Figure 5. Diagrams showing depth-averaged water temperature and salinity (measured in practical salinity units, or psu) across the Kamiloloa reef flat from direct measurements during high tide. Sample locations include conductivity, temperature, and depth (CTD) casts (crosses) and water samples (triangles, see also figure 7). High-tide temperatures in August 2002 (*A*) are generally cooler along the shoreline than farther offshore on the reef flat and reef crest and are considerably higher near the Kaunakakai Wharf than to the east near One Ali‘i. Similarly, salinities in August (*B*) and May (*C*) are significantly lower along the coast than offshore, consistent with a persistent input of freshwater at the shore.

A Temperature, August, 2002



B Salinity, August, 2002



C Salinity, May, 2002

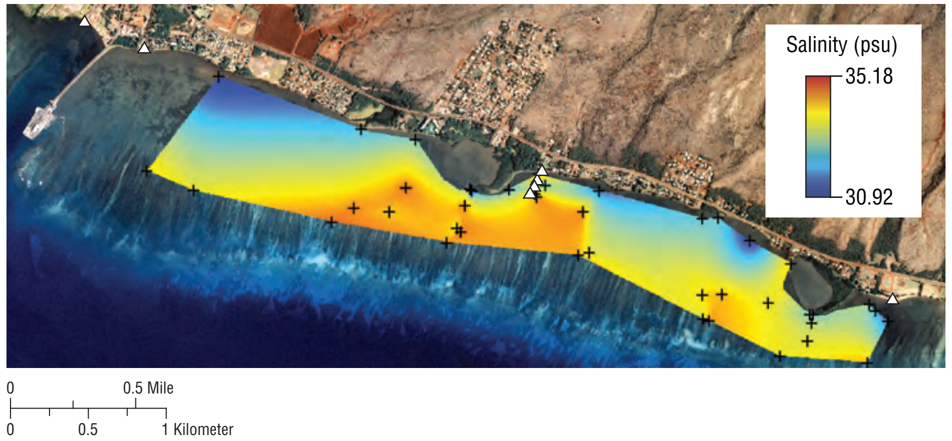


Figure 6. Diagrams showing seawater salinity (measured in practical salinity units, or psu) and temperature on the reef flat offshore of Kapuāiwa coconut grove in August 2004 during the initial stages of a rising tide. Sample locations include conductivity, temperature, and depth (CTD) casts (crosses) and water samples (triangles, see also figure 7). *A*, Sea-surface salinity shows a tongue of freshwater extending across more than 0.5 km (0.3 mi) of the inner reef flat, with values as low as 5 psu at the spring along the shore. *B*, Bottom salinity (~0.5 m or 1.6 ft above the sea floor) shows that freshwater in the form of submarine ground-water discharge (SGD) emanates from the springs along the shore as well as from a spring out in the middle of the study area (white arrow). *C*, Sea-surface temperatures reveal that the plume of freshwater is cool near the spring but quickly warms over the shallow inner reef flat. *D*, Bottom temperatures reveal that water is warmest in the shallowest parts of the reef flat and coldest near the offshore spring.

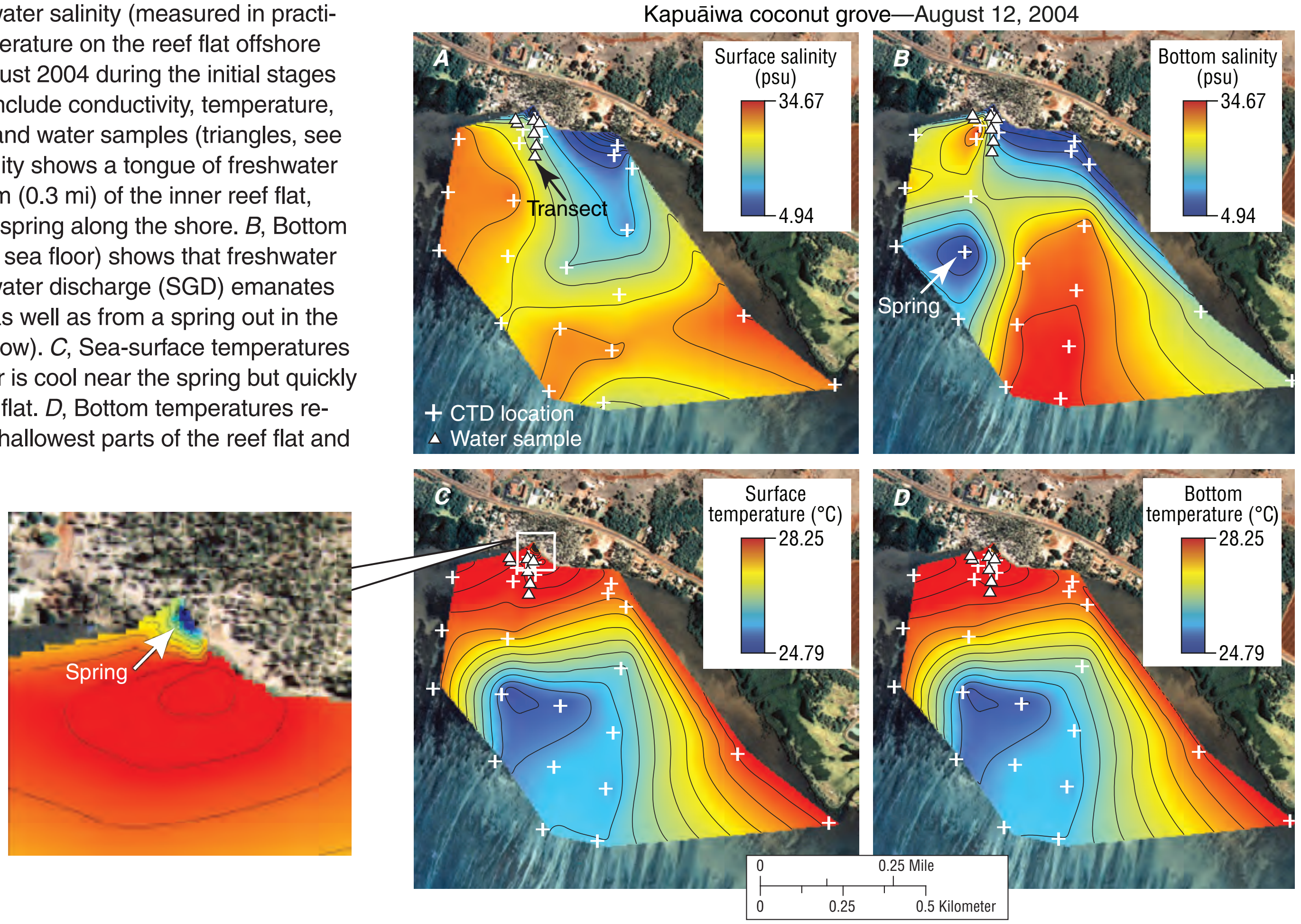
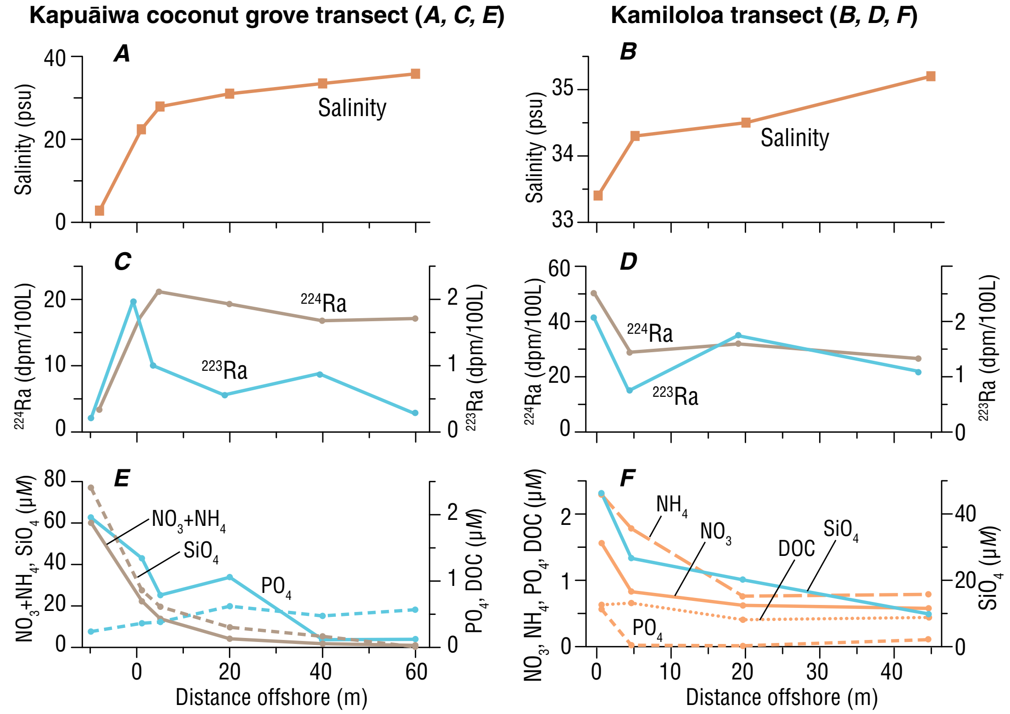


Figure 7. Plots of surface salinities, radium activities, and nutrients along transects offshore of Kapuāiwa coconut grove and Kamiloloa measured on July 10, 2003 (see figures 5 and 6 for locations). Salinity (*A*, *B*) generally increases away from the shore as expected with increasing influence of marine water (psu, practical salinity units). Activities of ^{223}Ra and ^{224}Ra (*C*, *D*) are higher near shore and correlated with each other as they decrease offshore with increasing salinity, suggesting a terrestrial source of Ra, likely from uranium and thorium decay in basalt source rocks. An exception at Kapuāiwa coconut grove, where Ra is lower in the fresh coastal spring, is consistent with a fresher source of ground water there and a more brackish source emanating from the offshore spring. Similarly, offshore of Kamiloloa a slight increase in Ra activities 20 m offshore may indicate submarine ground-water discharge (SGD) through the reef flat. Unit of activity is (radioactive) decays per minute per 100 liters (dpm/100 L).All nutrients measured (*E*, *F*) are significantly higher close to shore and, taken with the Ra results, indicate that the source of these nutrients is ground water. Dissolved organic carbon (DOC) is relatively uniformly distributed across the reef flat.



the reef flat, rather than from a discrete, onshore source. This observation is consistent with a subterranean source of ground water composed of a mixture of both terrestrial ground water and recirculated seawater discharging offshore, like the situation observed in figures 5 and 6.

A brackish to saline mixing zone is usually present within ground-water systems of many islands. This mixing zone migrates back and forth in a cross-shore direction under the influence of the tides and rainfall. These factors modulate the gradient of hydraulic head (equal to water level in unconfined systems) that drives ground-water discharge. At low tide, when ground-water flow across the reef flat is strongest (greatest water-level gradient), the brackish zone migrates offshore. Conversely, at high tide, or during dry periods when ground-water flow is weaker, the brackish zone moves inland. Because desorption (leaching) of radium from rocks and sediment is suppressed in freshwater, Ra isotopes are primarily tracers of saline ground water. They thus can show the location of the discharge of brackish mixing-zone water. This model of coastal aquifer dynamics on Moloka‘i is consistent with the observation that Ra activities in nearshore waters are much higher than in onshore samples taken from the coastal aquifer at low tide. The spring at Kapuāiwa coconut grove (fig. 2*A*) was sampled at low tide and was found to have ^{223}Ra and ^{224}Ra activities of only 0.26 dpm/100 L and 3.19 dpm/100 L, respectively, and a salinity of only 2.9 psu. Just a few tens of meters offshore, where the saline ground water discharged, Ra activities and salinities on the reef flat were four to seven times greater.

Nutrient Concentrations Along the South Moloka‘i Reef

Ground water discharging along the south Moloka‘i shoreline is a major source of new nutrients, including inorganic nitrogen (N), phosphorus (P), and silica (SiO_2) to the Moloka‘i reef (fig. 7). The mean molar concentration of inorganic nutrients in three low-tide samples of undiluted ground water collected from springs at Kapuāiwa coconut grove were 63.7±3.3 µ*M*, 2.20±0.18 µ*M*, and 823±32.6 µ*M*, for nitrate, orthophosphate, and silicate, respectively. These concentrations are 10 to 1,000 times greater than those measured in open-ocean samples. Elevated concentrations were also measured in the surface pool sampled near ‘Ualapu‘e fishpond (7.20 µ*M* NO_3^-, 4.03 µ*M* PO_4^{3-}, 593 µ*M* $Si(OH)_4$), although nutrient concentrations of the original ground water there are likely modified by internal cycling and/or inputs and uptake by nearby vegetation. In the coconut grove ground-water samples, the N/P ratio is approximately 29, whereas in the ‘Ualapu‘e fishpond the ratio is less than 2, suggesting that biologic uptake of N within the pond is depleting the nitrogen.

Submarine Ground-Water and Nutrient Flux to the South Moloka‘i Reef

We calculate submarine ground-water discharge (SGD) and nutrient fluxes to the Moloka‘i reef at Kamiloloa and Kapuāiwa coconut grove using Ra isotope-tracer and salinity mass-balance methods adapted from Moore (1996) and our understanding of residence time of water on the reef, the time required to replace water on the reef through tidal exchange or currents. Given the measurement uncertainties in the activities of ^{224}Ra and ^{223}Ra, it would take at least 1.5 days to detect a change in the ratio of ^{224}Ra to ^{223}Ra. Because we do not observe these ratios to vary across shore, it is assumed that there is negligible Ra decay within the residence time of water on the reef, and that the decrease in activities offshore is due to dilution with seawater. The dilution occurs with mixing through tidal exchange and currents. Because of uncertainties in our understanding of currents and water exchange in the shallow reef flat, we calculate SGD on the basis of residence times of water at two sites where we measured Ra activities across the inner reef flat—a box at Kamiloloa 45 m (148 ft) long (across shore) by 1 m (3.3 ft) wide (along shore) by 1 m (3.3 ft) deep and a box at Kapuāiwa coconut grove 60 m (197 ft) long, 1 m (3.3 ft) wide, 1 m (3.3 ft) deep (fig. 7). The residence times for these boxes range from 1.5 days (based on our Ra measurements) to 37 minutes (based on net cross-shore currents of 2 cm/sec) (Presto and others, 2006).

Calculations of SGD based on Ra decay and salinity mass balance range from 8.8 to 638 L/min/m (liters per minute per meter of shoreline) (2.3 to 169 gal/min/m) at Kamiloloa and from 4.7 to 204 L/min/m (1.2 to 54 gal/min/m) at Kapuāiwa coconut grove (fig. 8). A key difference between the sites is the presence of natural springs at Kapuāiwa coconut grove, which can be observed to discharge freshwater directly to shore. The SGD estimates derived from using current measurements of Presto and others (2006) are significantly higher than those derived from the Ra activity and salinity mass balance. This may result from the fact that the current measurements, like most instantaneous observations, are biased toward higher rates (for example, higher flushing rates, lower residence time across reef). In contrast, the extrapolations of residence time across larger portions of the reef via the Ra activity and salinity mass-balance methods tend to average out instantaneous rates over longer time and space scales. It is probable that the residence time of water across the reef used in our Ra activity and salinity mass-balance calculations is closer to 1.5 days because of incomplete exchange within one tidal cycle. However, during periods of strong currents caused by high trade winds and/or large waves, the residence time of water across the reef may be shorter and on the order of hours, as reflected by Presto and others (2006). The results here based on tidal exchange are in close agreement with estimates based on ground-water models, which predict regional trends (fig. 4). The model predictions of SGD range from 1.7 cubic feet per second per mile of shoreline (1.9 L/min/m) at Kamiloloa to 3.2 cubic feet per second per mile (3.4 L/min/m) at Kapuāiwa coconut grove (Oki, 1997; D.S. Oki, written commun., 2007).

We calculate nutrient fluxes to the South Moloka‘i reef by multiplying the concentration of nutrient in SGD by the SGD flux rates noted above. For example, the nitrogen flux to the reef is the product of total inorganic nitrogen (TIN, nitrate plus ammonium) concentration in ground water emanating to the reef (fig. 7) and the SGD rate converted to grams of elemental nitrogen flux per day to the reef. At Kamiloloa, we calculate a range of TIN between 0.7 and 50.2 grams of nitrogen per day (g/d of N) entering the reef with ground water. At Kapuāiwa coconut grove, TIN flux to the reef in ground water ranges from 5.9 to 255 g/d of N. Again, the TIN fluxes based on current measurements are higher than those from the other two methods, reflecting the more rapid SGD flux estimated by the process measurements. The measured concentrations of N found here are comparable to nutrient concentrations found in ground water in other areas of the Hawaiian coastal zone, which range from 13.2 to 63.6 µ*M* (at Kahana; Garrison and others, 2003), 60 to 95 µ*M* (at Waikoloa and Keahou; Dollar and Atkinson, 1992), and 0.45 to 1.7 µ*M* (at West Maui; Soicher and Peterson, 1997). More importantly, the nutrient concentrations found in ground water at Kamiloloa and Kapuāiwa coconut grove are 10 to 100 times higher than concentrations found in open ocean water. The higher levels of nutrients discharging from the spring at Kapuāiwa coconut grove are likely a result of being associated with fresh ground water, while at Kamiloloa nutrients discharging in brackish to saline ground water may be diluted by recirculated seawater.

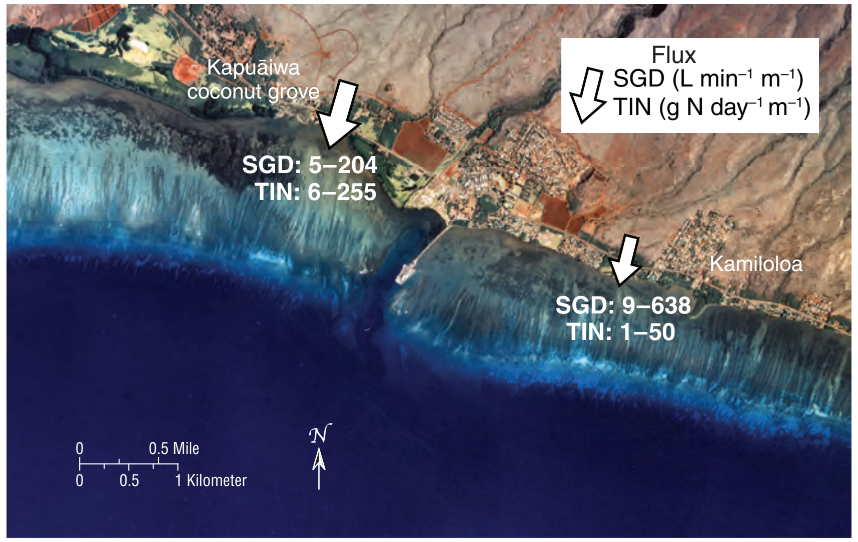


Figure 8. Map showing calculated submarine ground-water discharge (SGD) and total inorganic nitrogen (TIN) flux at the Kapuāiwa coconut grove and Kamiloloa. Although ranges of SGD are higher for Kamiloloa, nitrogen flux to the reef is higher at Kapuāiwa because of higher nitrogen concentration in the fresh ground water there. Estimates range considerably because of our limited knowledge of residence times of water on the reef and because of the complex mixing of fresh and brackish ground water with recirculated seawater in the coastal aquifer.

Dissolved Carbon and Carbon-Isotope Signatures of Water Source and Mixing

Ground-water discharge appears to be only a minor contributor of dissolved organic carbon (DOC) to the Moloka‘i reef (fig. 7*E*, *F*). The average DOC concentration and standard deviation for all nearshore and back-reef samples collected during July 2003 are 0.66±0.24 ppm (54.6±20.2 µ*M*, n=30). This places the Moloka‘i reef within the lower to middle portions of the range of DOC (9 to 290 µ*M* in coral-reef sites globally; Atkinson and Falter, 2003. This result is consistent with the semiarid climate of the Hawaiian region. Samples collected within a few meters of the Moloka'i shore are on average slightly enriched in DOC (0.73±0.30, 60.6±25.8 µ*M*, n=15) relative to samples from farther offshore, likely reflecting carbon from mangroves and terrestrial plant debris, although the springs at the Kapuāiwa coconut grove contain a lower average concentration of DOC (0.35 ppm, 29.0 µ*M*, n=3). These data suggest that some other source, such as export of DOC from the fore reef and reef crest, are necessary to support the higher observed DOC concentrations in the nearshore and on the reef flat.

Measurements of stable-isotope ratios ($\delta^{13}C$) of DOC also suggest that ground water is not a dominant source of carbon to the Moloka'i reef. The vast majority of nearshore samples have $\delta^{13}C$ signatures of DOC in the range of –17 to –24 permil (parts per thousand), consistent with the $\delta^{13}C$ signatures of marine phytoplankton (–18 to –24 permil) and marine algae (–15 to –22 permil) (Michener and Schell, 1994). These values fall within the broad range of published values for marine and estuarine systems (see, for example, Coffin and others, 1994), the DOC of which is commonly enriched in ^{13}C relative to rivers and freshwater. Exceptions occur within the 'Ualapu'e fishpond (–26.77 permil) and in a shoreline sample collected between Kawela and Kamalō (–30.92 permil), where an abundance of emergent terrestrial vegetation (mangroves) that have low $\delta^{13}C$ values (–22 to –30 permil) is likely exporting carbon to the reef flat (Michener and Schell, 1994). The $\delta^{13}C$ values in spring-water samples from Kapuāiwa coconut grove average –21.46±0.99 permil (n=3), a signature not distinguishable from most inner reef-flat samples.

Gaps in our Knowledge of SGD Flux, Phasing, and Impact to the Moloka'i Reef

It is evident from the foregoing that submarine ground water does discharge on the south shore of Moloka'i and that the discharge contains high concentrations of nutrients. It may also contain contaminants, but this is not yet documented. Understanding the variability of ground-water composition, flux, and circulation processes that determine its fate is important to predict impacts to coastal ecosystems. A particularly challenging issue is being able to identify (1) the origin of ground water and contaminant additions, (2) transport pathways, and (3) the timing of discharge relative to rainfall and recharge. To these ends, scientists are actively pursuing experiments to quantify these processes. With suitable measurements, adequate models can be developed and applied to societally relevant issues concerning ground-water effects on coastal ecosystems. For example, ground-water flow models can predict travel times, discharge rates, and nutrient fluxes to the coast that are important parameters to resource managers tasked with balancing the needs of human water supplies and coastal ecosystems.

Summary

Submarine ground-water discharge (SGD) to the coast is highly variable along the shore and through time because of the complex nature of subsurface flow through a variety of different rock and sediment types. Along the Moloka'i reef, evidence in the form of legends, reef morphology, thermal infrared imaging, CTD (conductivity, temperature, and depth) studies, water chemistry, and modeling studies indicate that a significant amount of freshwater discharges at the shoreline or below sea level on the nearby reef flat. Although springs like those at the Kapuāiwa coconut grove have only a localized effect on the reef, their persistent nature may shape nearshore reef communities and at the same time dissolve the reef below, as has been observed in drill cores. Localized areas of SGD occur across the reef, although the timing and amount of this flow remains uncertain. Further inquiry into the range of nutrient sources to ground water and nutrient concentrations reaching the coast in ground-water discharge will aid in future planning and resource management.

Mike Field, USGS

Kapuāiwa coconut grove.

CHAPTER 14

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

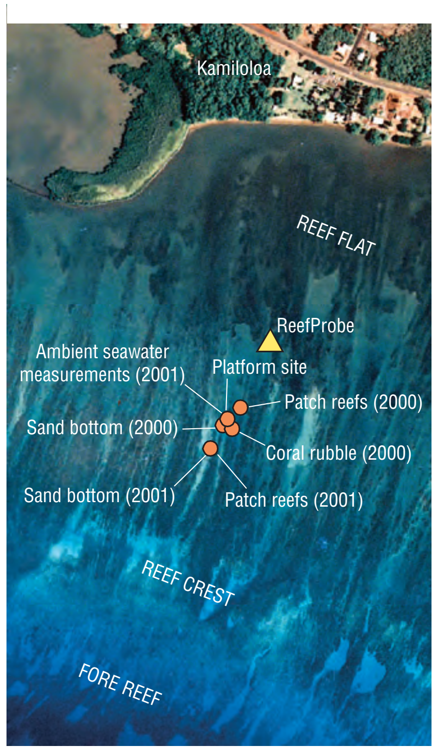
Robert B. Halley[1] and Kimberly K. Yates[1]

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.



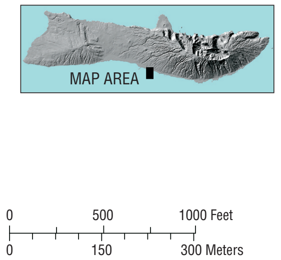


Figure 1. Aerial photograph of a portion of the Moloka‘i reef flat at Kamiloloa showing SHARQ chamber sampling locations (red dots) for this study in 2000 and 2001. The samples were collected in an area approximately 200 m landward of the reef crest and 300 m seaward of the ReefProbe (yellow triangle), 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.

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

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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 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).

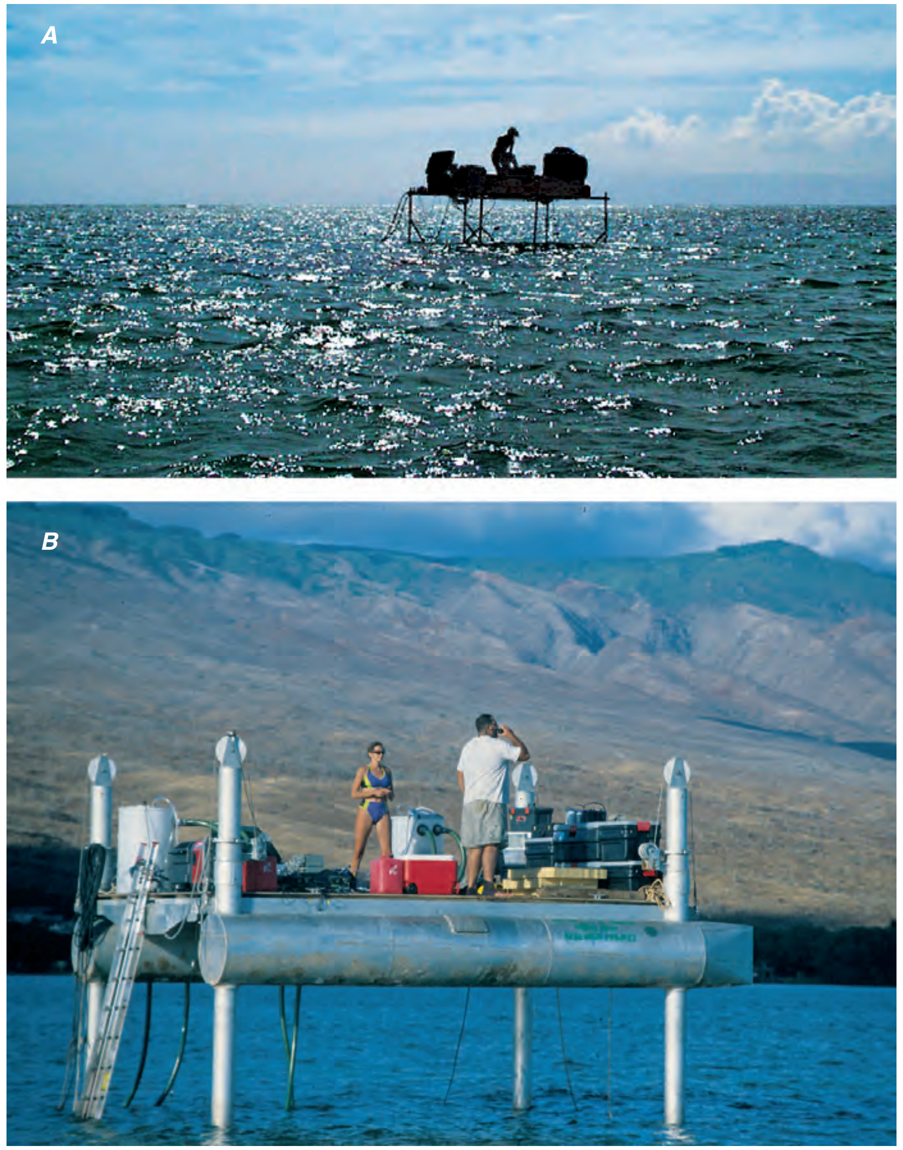


Figure 2. Platforms were erected on the reef flat and used for SHARQ support systems and as a field laboratory. *A*, Scaffolding with a plywood top used during February 2000. *B*, The University of Hawai‘i drill platform used during July 2001.

The 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. 6*A*).

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. 6*B*). 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 mollusks; (2) calcareous macroalgae (such as *Halimeda* sp. and *Porolithon* sp.); (3) fleshy (noncalcareous) macroaglae (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.

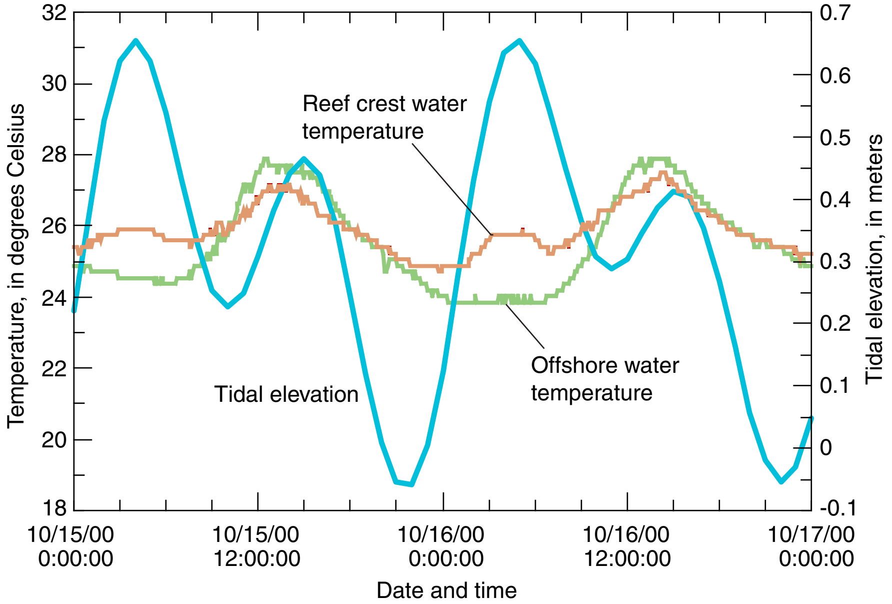


Figure 3. A 48-hour record (October 15 to 17, 2001) of tide and temperature on the inner and outer Moloka‘i reef flat. Tide range (blue line) is about 0.7 m during this period. Water temperature 50 m offshore (green line) shows a daily cycle, with a range of 4°C and maximum temperatures in the afternoon.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

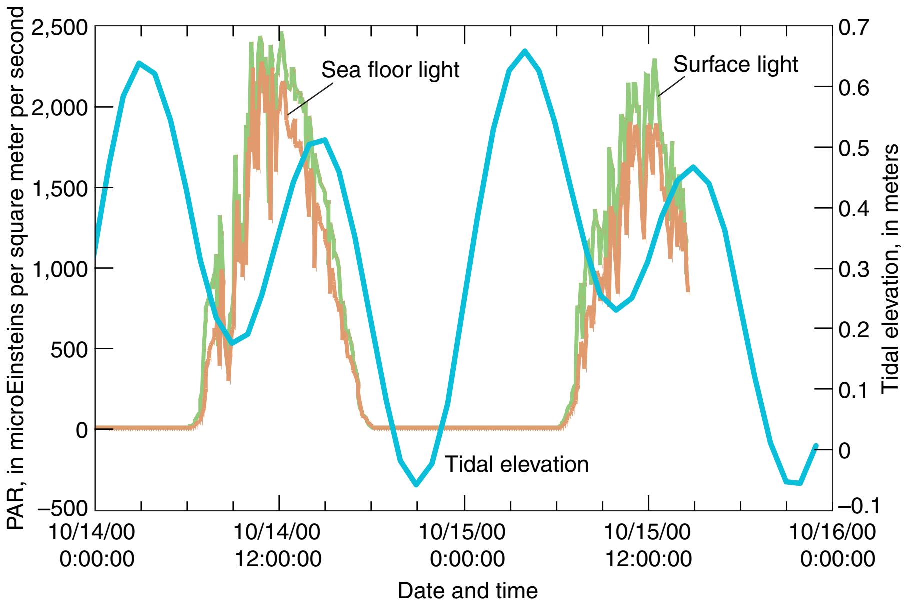


Figure 4. A 48-hour light and tide record (October 14 to 16, 2001) at the ReefProbe location. Light measurements are of photosynthetically active radiation (PAR) measured in microEinsteins. Light reaching the sea floor (orange line) is only slightly reduced from surface light (green line) at this shallow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

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 (Pmax) 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 production 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).

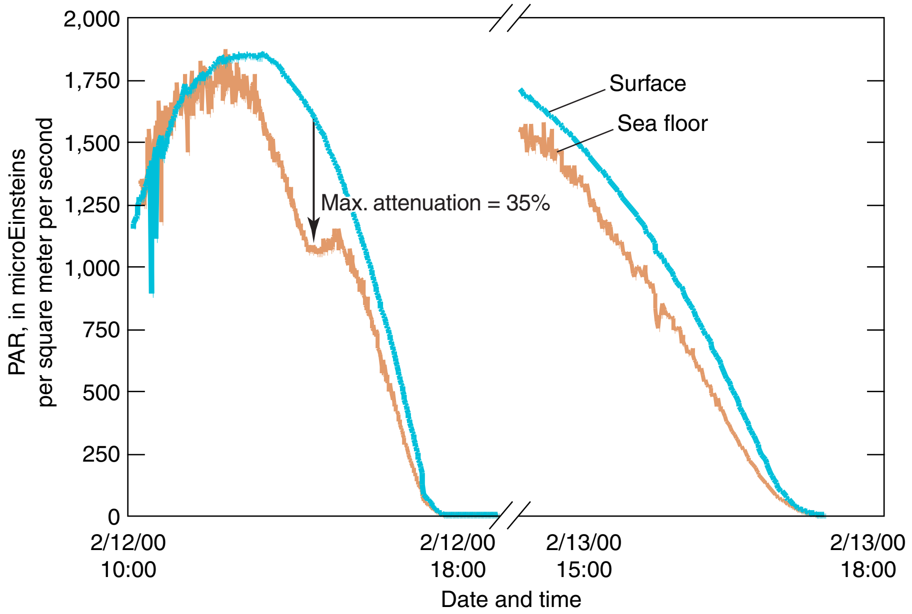


Figure 5. Partial 48-hour light record from coral-rubble SHARQ site in February 2000. Light (PAR, photosynthetically active radiation) reaching the sea floor (brown) is more reduced from surface light (blue) in the deeper water (2.2 m) at this study site. Windy conditions and increased turbidity on the 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.

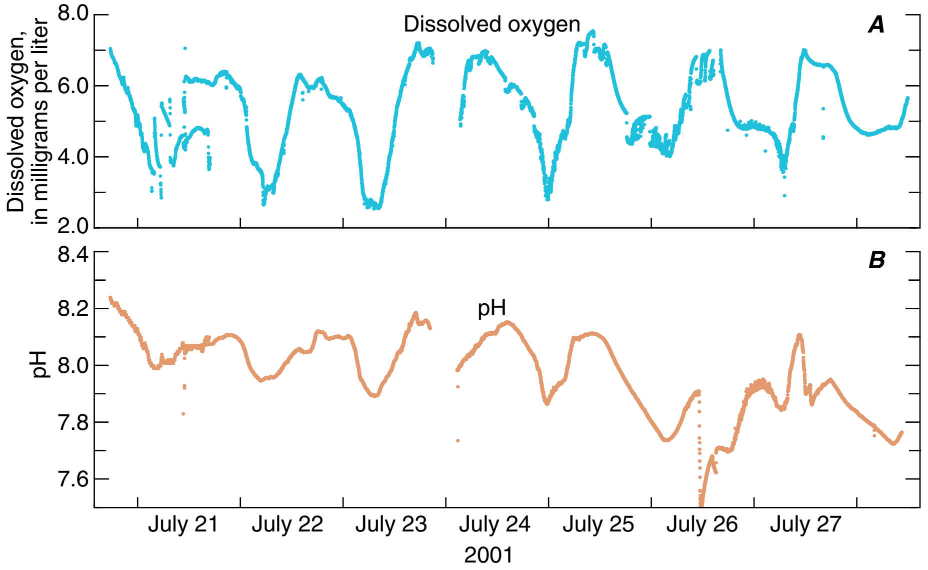


Figure 6. Daily cycles of dissolved oxygen and pH record for the Moloka‘i reef flat, July 20–28, 2001. The daily metabolic activities on the reef flat induce chemical changes in the overlying water. Erratic nature of these cycles is partially due to variations in light, wind, and other naturally occurring 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.

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

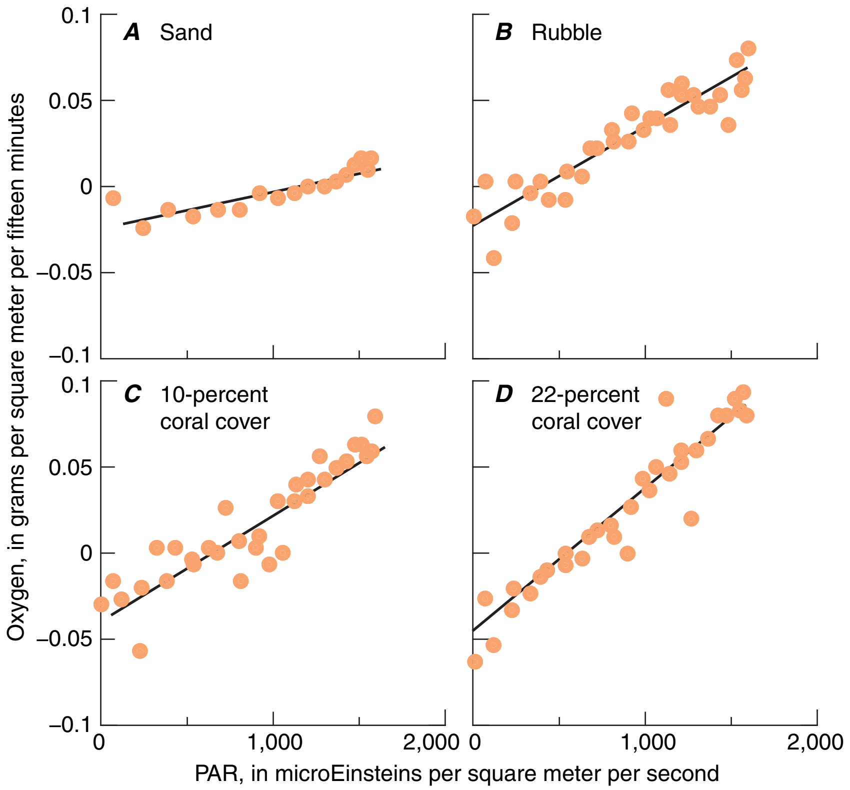


Figure 7. Photosynthetically active radiation (PAR) and oxygen (O_2) production on the Moloka‘i reef flat. These graphs show the relationships between available light and photosynthesis or respiration for sand (*A*), rubble (*B*), 10-percent coral cover (*C*), and 22-percent coral cover (*D*). Note that 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, Engles 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).

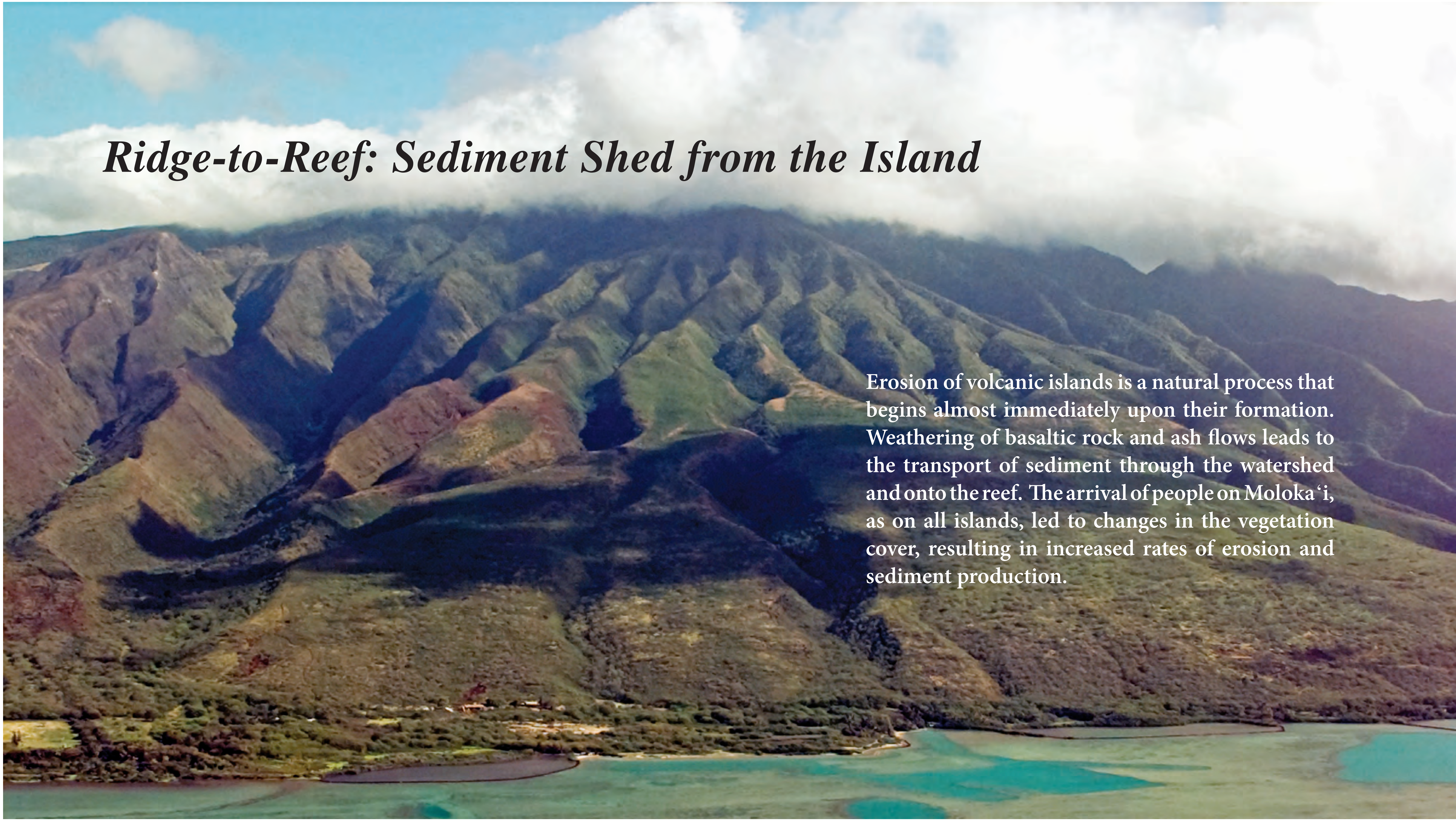
Sediment production and accumulation in reefs and related carbonate sedimentary environments continues to be an active area of research, often approached within the framework of a sediment budget (Hubbard and others 1990; Harney and Fletcher, 2003; Yates and Halley, 2006b). These studies, typically with 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.

Ridge-to-Reef: Sediment Shed from the Island



Erosion of volcanic islands is a natural process that begins almost immediately upon their formation. Weathering of basaltic rock and ash flows leads to the transport of sediment through the watershed and onto the reef. The arrival of people on Moloka‘i, as on all islands, led to changes in the vegetation cover, resulting in increased rates of erosion and sediment production.

Moloka‘i shoreline just east of Kamalō.

Boats in Kaunakakai Harbor.

CHAPTER 15

People, Land, and the Reefs of South Moloka‘i

Lucile M. Roberts[1] and Michael E. Field[2]

Waters along the southern shore of Moloka‘i are frequently turbid, a result of large quantities of suspended sediment. The most dominant factor contributing to this condition is the legacy of several hundred years of human activities on the island. We have examined archaeological and historical evidence to understand the impact that evolving societies had on Moloka‘i, from the watersheds to the reefs. This chapter takes a look at activities that have influenced the rate, volume, and extent of soil erosion and deposition and the overall changes to the south-facing slopes and coast. These activities include land settlement and clearing, construction of shoreline fishponds, interisland war, livestock introduction, farming practices, and the effects of fire and feral grazers.

Impacts of Human Occupation on Moloka‘i

Early Human Activities

The first people arrived on Moloka‘i 1,400 years ago and through their settlement began to alter the surface of the land. For much of early Hawaiian history, the southeastern coastal plain or kona district (fig. 1) carried most of the population (de Loach, 1975). Hawaiians eventually settled other parts of the island, including the Ho‘olehua Saddle (the area between the east and west volcanoes), the upper reaches of the south-facing slopes, and much of the south-central coastal plain.

Although no written records were kept during the early period of human habitation, there are indicators of how settlement proceeded. We can combine knowledge of the social organization in the Pacific Islands where the settlers lived before traveling to Moloka‘i, and archaeological evidence found on Moloka‘i (Weisler and Kirch, 1985), to provide a sense of conditions and processes during the time of the early settlers.

The earliest Polynesian voyagers to settle on Moloka‘i arrived around the year 600 C.E.[3] in the area now known as Hālawa, at the eastern tip of the island. As settlers began to explore the island, they discovered the gentler slopes and broad reef areas to the south and west. Here, long-term stream erosion had produced low-lying coastal plains and alluvial fans mantled with loose, rich soil that was easy to cultivate. The resources of the adjacent reef were also valued, and settlements gradually spread westward along the south coast.

The early Hawaiian settlers brought with them their customs and traditions, including a system of land use and organization still used today in many Pacific island nations. In this feudal scheme, an ali‘i (chief) assigned the use of an ahupua‘a (a portion of the land) to a small group or family unit (fig. 2). The ahupua‘a commonly included a valley and the adjoining hillsides, running from the top of the watershed to the nearshore waters and the adjacent reef. Each ahupua‘a provided access to everything the people might need: water from a stream or springs, wood from the higher elevations, forage on the lower slopes, land along the coast for cultivating, and access to the full resources of the reef flats and shallows.

Early clearing and farming activities centered on planting traditional staples the settlers brought from their previous homes in Polynesia: taro and sweet potatoes. They also introduced many other plants: sugar cane, bananas, coconut, breadfruit, ginger, pepper, and mulberry (Bryan, 1954). Little evidence of formal villages has been found from this very early period, only signs of occasional small huts and perhaps a community heiau (altar or sacred site). Although the clearing process may have included some burning, with few people and a broadly scattered population, the impact of the people on the land was likely minimal for the first four centuries of human habitation.

Building on the Edge of the Sea

During the next 400 years, starting about 1,000 C.E., changes in the evolving society began to leave visible changes on the landscape. Early in this period the ali‘i nui (high chiefs) of the larger Hawaiian islands seem to have ignored the small, lightly populated island of Moloka‘i as they battled over larger prizes elsewhere in the islands. This was the period when many stone works were completed on Moloka‘i, including terraces on the hillslopes to keep soil and water in place for growing taro and other

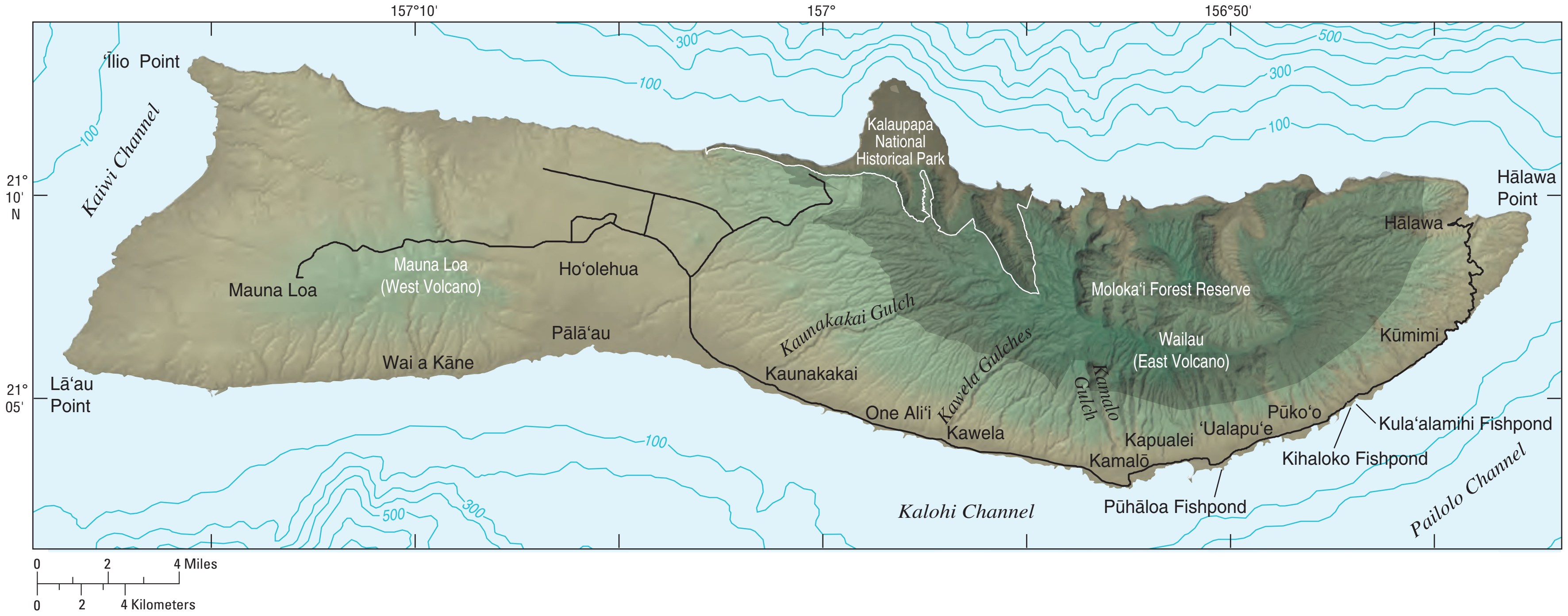


Figure 1. Map of Moloka‘i, showing locations mentioned in the text. Bathymetric contour interval, 100 m.

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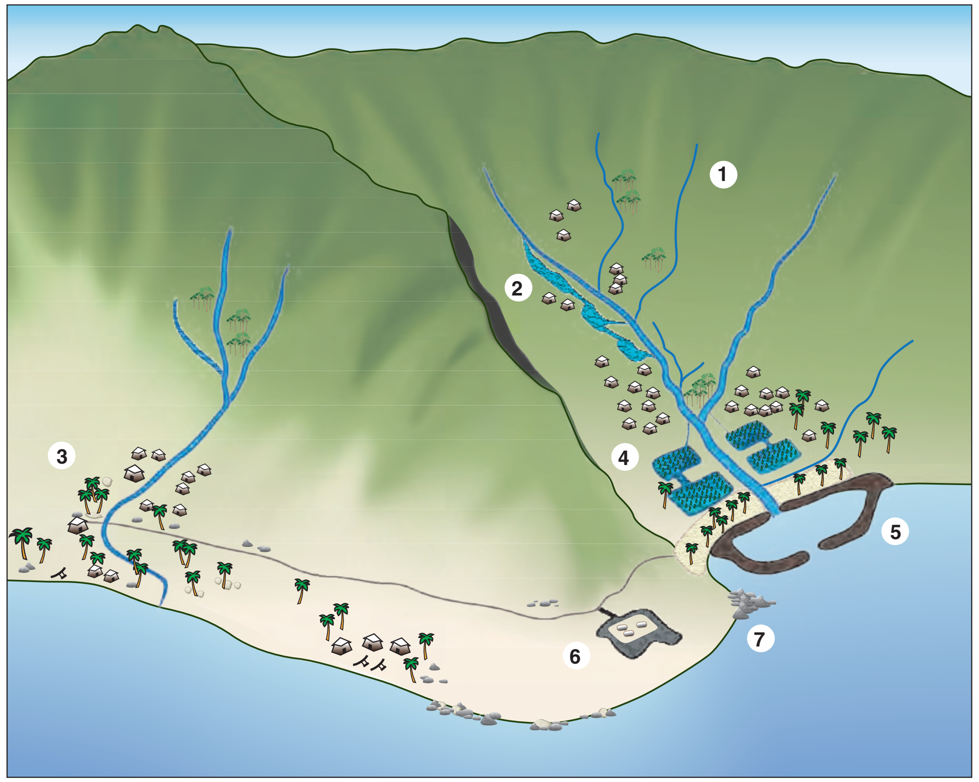
[3] C.E. (Common Era) and B.C.E. (Before Common Era) are often used by social scientists to refer to what others call A.D. (Anno Domini or in the year of the Lord) and B.C. (before Christ), but without religious connotation.

Figure 2. Drawing of an ahupua‘a (modified from HawaiiHistory.org, http://www.hawaiihistory.org, last accessed April 29, 2008). The ahupua‘a is based on a traditional Polynesian style of land management that divides an island into segments running from the mountainous interior to the edge of the reef, cutting through all the ecological zones (Weisler and Kirch, 1985, p. 129). Each ahupua‘a provides for all the needs of a family or small group of people. 1, Streams carry mountain rainwater from ridges down steep slopes. 2, Stream water is diverted in narrow taro fields in the upper valley. 3, Coconut trees provide food and drink. 4, Broader taro fields fill the wider valley mouth. 5, Coastal fishpond is open to the sea. 6, Fishing village heiau (sacred altar). 7, Rock marker at ahupua‘a boundary.



crops (de Loach, 1975). More than 50 fishponds for raising fish were built on reef flats along the south coast, most of them completed by the early 15th century.

Although other islands also had fishponds, Moloka‘i had perhaps the greatest concentration, in large part because of the extensive shallow reef flat along the south shore (fig. 3). Some fishponds occupied several hundred acres, with enclosing walls averaging 1.5 m (5 feet) high and 3 m (10 feet) thick (Kepler and Kepler, 1991). Most fishponds were relatively shallow (1 m or 3 feet) but some were as deep as 10 m (33 feet). The presence of fishponds on the reef flat altered the natural pathways for water and sediment. Sediment flushed to the coast during rainy periods was deposited in the ponds, requiring constant tending to prevent them from filling and becoming unusable for raising fish (as in fig. 3*A*) for the island ali‘i.

A Time of Extremes—Quiet Prosperity or Invasion

During the time between the first fishponds and the arrival of outsiders from Europe and America in the late 1700s, the people of Moloka‘i developed a comfortable level of prosperity. Crops were plentiful and the ponds filled with fish. However, in this same period the ali‘i nui of the larger islands fought many battles. Because it was located between the warring factions of Hawai‘i, Maui, and O‘ahu, Moloka‘i served as both a refuge and a source of provisions. The island was conquered, perhaps many times, by ali‘i nui of other islands. One of the conquering ali‘i nui was Kapi‘iohokalani, who ruled O‘ahu in the 1730s. According to de Loach (1975, p. 27), “Kapi‘iohokalani invaded Moloka‘i somewhere around 1736. He attacked with a large force, and his army broke down sea walls and destroyed many fishponds.” Conflict among the ali‘i nui continued for at least 30 years after the outsiders came. Then, in the late 1700s, Kamehameha I used Western firearms and small, fast boats to conquer his opponents and declare his power over all the islands. It is said of his taking of Moloka‘i that, “Kamehameha’s descent upon it had desolated the country” (Menzies, 1920, p. 118). Robert Louis Stevenson, visiting Moloka‘i several years after the battles ended, painted a vivid word picture of the devastation: “...upon this island a battle was fought in which it has been computed that thousands were engaged; and he who made the computation, though

Bruce Richmond, USGS

Bruce Richmond, USGS

National Oceanic and Atmospheric Administration, 1993

Figure 3. Aerial photographs of fishponds on the southeastern coast of Moloka‘i. Constructed in the 11th through 15th centuries, these fishponds have great cultural and historical value to the people of Hawai‘i. *A*, Pūhāloa fishpond between Kalaeloa and ‘Ualapu‘e, showing the large amount of sediment infilling that has occurred here. As vegetation takes hold, trapping of sediment and infilling rates increase. *B*, Kihaloko (left) and Kula‘alamihi fishponds east of Pūko‘o link together to form a nearly continuous armored shoreline. This photograph shows the lower part of several ahupua‘a as well. *C*, Submerged remains of fishpond walls are shown by arrows.


Susan Cochran, USGS

Figure 4. A historical lua moku ‘iliahi, or sandalwood measuring pit (outlined by dashed line), on the Moloka‘i high slopes. Approximately 23 m (75 ft) long, the pit was dug in a size and shape that mimicked the size of the hold of sailing ships that carried the sandalwood back to New England. Sandalwood was cut and stacked in the pits, and then hauled to ships waiting at anchor.

he lived long after, has seen and counted, when the wind blew aside the sands, the multitude of bones and skulls” (Stevenson, 1973, p. 75).

A Faster Rate of Change

While the ali‘i nui were battling for power, Europeans, beginning with Cook and Vancouver in the 1770s, entered the islands, bringing with them irrevocable change to the people and the habitat. Along with firearms and fast ships, the explorers from Europe and America introduced grazing animals and commercial farming. Both ideas caused rapid changes to the hillsides and reefs of Moloka‘i over the next 100 years. Animals were initially introduced by explorers to be used as a food source on their return. The ali‘i quickly realized that they could also raise animals to use and to sell. Goats, swine, sheep, cattle, and horses were introduced and began to thrive on Moloka‘i by the end of the 1800s. In 1870, Kamehameha V sent his small herd of deer to Moloka‘i, where they also flourished (Judd, 1936).

Hawaiian vegetation evolved without native grazing animals. Trees, ferns, and bushes developed soft bark, tender greenery, and lacked thorns—and were therefore defenseless against grazing animals (Bryan, 1954). As the number of animals increased on Moloka‘i, the distribution of native vegetation was altered, particularly in the cooler upper reaches of the island’s watersheds. Goats, sheep, and cattle are known to graze heavily on dense vegetation wherever it is available, leading to increased susceptibility of exposed areas to the effects of wind and rain. This is consistent with conditions noted on the higher slopes of Moloka‘i. Increasing amounts of soil were transported and deposited on the low southern slopes and, eventually, on the reef flat. The loss of soil in the uplands led to further habitat destruction and changes in local microclimates. Without the heavy vegetation to capture the moist, rising winds, rainfall decreased in upland areas. Many springs dried up (Kepler and Kepler, 1991), and people abandoned efforts to raise grazing animals. Pigs and goats turned feral (wild) and migrated to the rugged, hard-to-reach areas of the high slopes, where they, along with deer, fed on small saplings and grasses and dug for roots, further contributing to soil loss. As the animal population grew, the human population declined. From early estimates of 10,500 people on Moloka‘i in 1779 (Summers, 1971), the population dropped to 2,307 by 1896 (Bottenfield, 1958), leaving fewer people to hunt the animals and keep them in check.

Two other early activities adversely affected the south slopes of Moloka‘i: the sandalwood trade and plantation-style agriculture. Early in the 1800s, sandalwood—highly prized in the Orient—became a great trade commodity. Moloka‘i stands of this tree were smaller than those found on other islands but considered large enough to warrant logging, as evidenced by the digging of at least one ‘sandalwood pit’ (a hole in the ground the size of a ship’s hold, used for measuring the amount of wood needed to provide a full cargo; see fig. 4). To support this venture, the ali‘i directed the men to leave their fields and focus on harvesting the trees (Bottenfield, 1958). According to Cooke (1949, p. 61), “It is said that the extinction of sandalwood was caused by the natives destroying young sandalwood plants. They did not wish their descendants to undergo the hardship of obtaining the sandalwood from the cold, wet mountains and having to transport it to the shore.” The removal of sandalwood and exposure of soil for agriculture, especially in the area of Ho‘olehua Saddle, contributed to additional erosion.

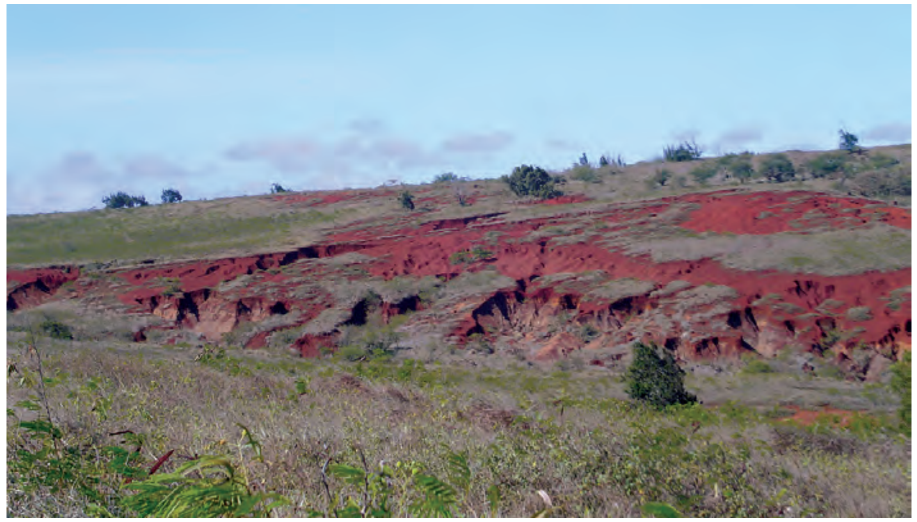

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Figure 5. Characteristic severe erosion on west Moloka‘i, just west of the Ho‘olehua Saddle. The red-brown soils are eroded during heavy rainfall and transported to the coast through gulleys and by overland flow. This type of erosion is typical of areas that have had the forest canopy removed.

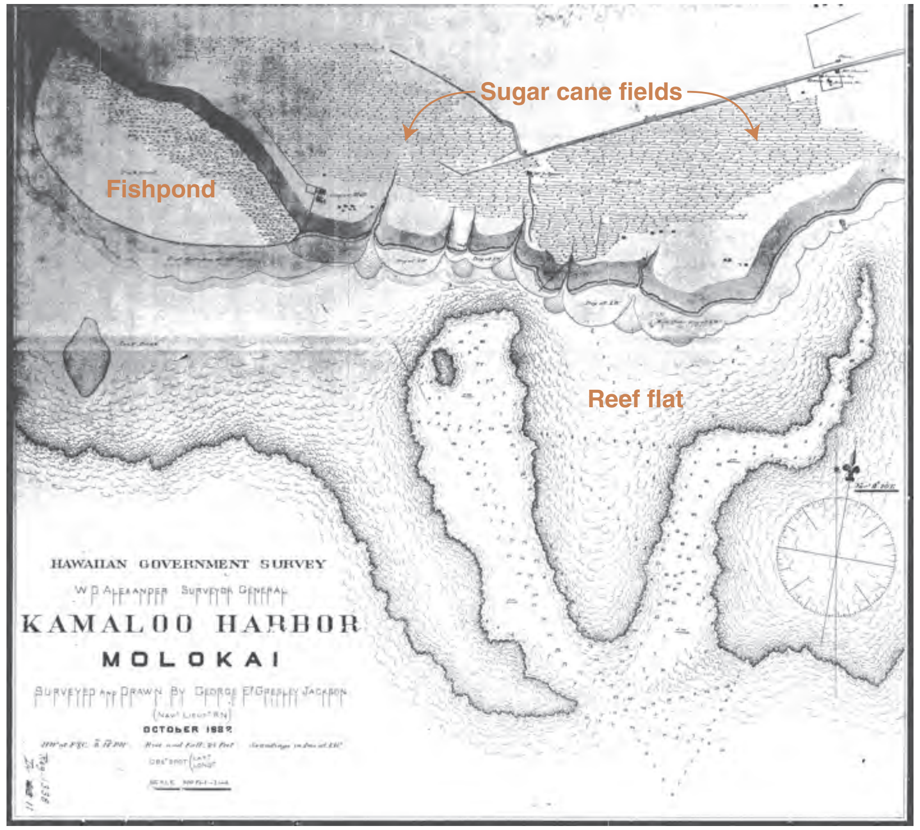
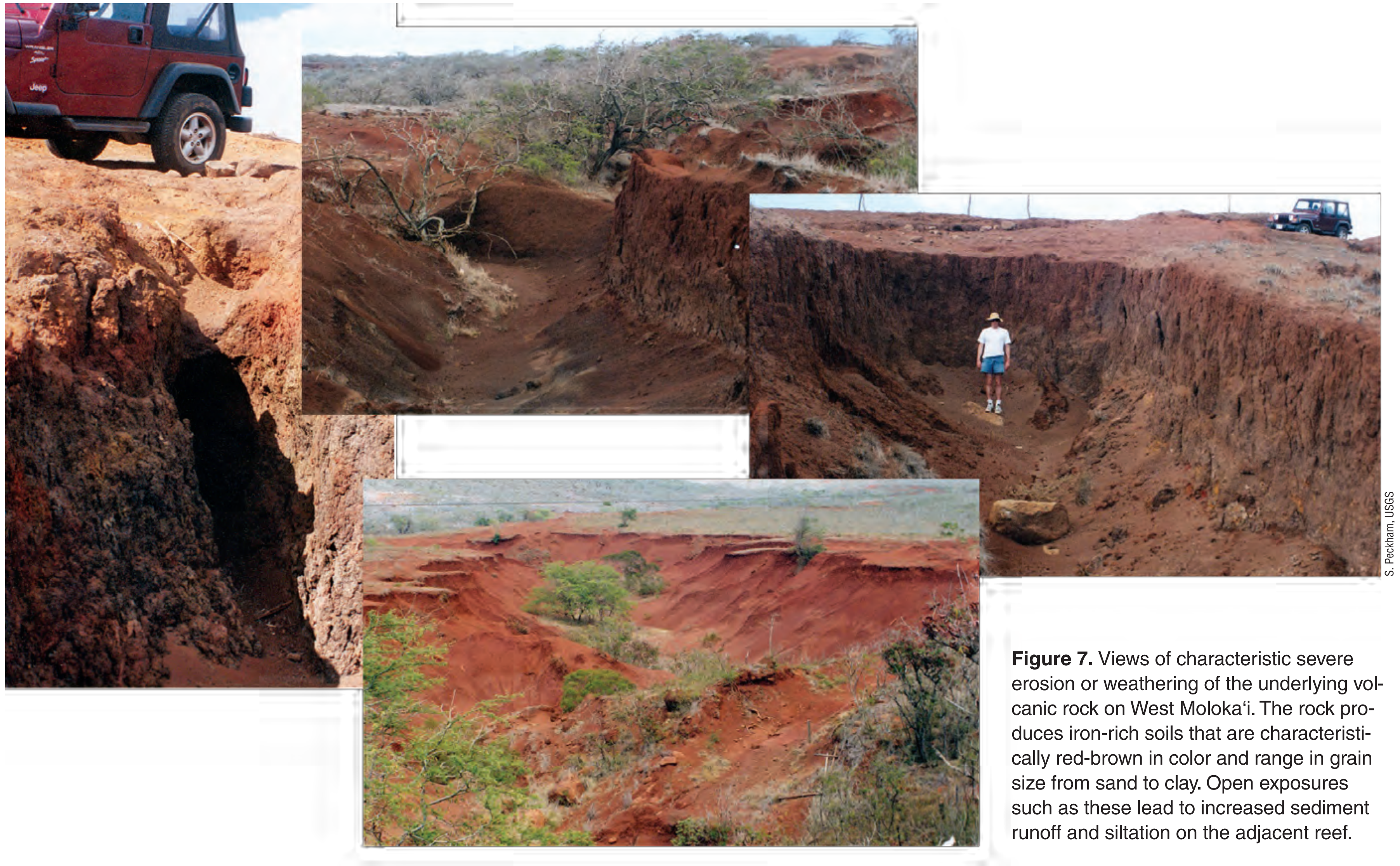


Figure 6. Map of Kamalo‘o (as it was called then; today it is Kamalō) showing the shape of the coast in 1882 and the sugar cane fields near the shoreline (from Jackson, 1882). Sediment derived from the erosion of the exposed sugar cane fields was transported to the coast, resulting in a change in shape of the shoreline.

Soil loss likely accelerated in the mid 1800s when cattle ranching intensified on the upper reaches of Ho‘olehua Saddle. Low-quality cattle, sold for hides and tallow, were raised in large numbers and driven south to Pālā‘au for shipment. The damage done by the trampling of driven herds added to the damage done by grazing (fig. 5). By the end of the 1800s, sediment was deposited in the central lowland plain at a rate of one foot (30 cm) every six years (Cooke, 1949; D’Iorio, this vol., chap. 16).

Plantation monoculture was also introduced during the 1800s. Sugar cane was one of the first such crops and was grown in several areas along the southeastern coastal plain (Jackson, 1882; fig. 6), “but the holdings were abandoned when it was found that the artesian water being used was too salty” (Keesing, 1936, p. 27). This system left lasting problems. Between the destruction of native vegetation necessary for plantations and the insects and diseases associated with the introduced species, even taro and some vegetables could no longer be grown in certain areas. Changes in land-use patterns were visible long after the sugar plantations disappeared (Gast, 1982). Thus



S. Peckham, USGS

Figure 7. Views of characteristic severe erosion or weathering of the underlying volcanic rock on West Moloka‘i. The rock produces iron-rich soils that are characteristically red-brown in color and range in grain size from sand to clay. Open exposures such as these lead to increased sediment runoff and siltation on the adjacent reef.

the clearing necessary for such monoculture heightened the susceptibility of the soils to erosion in the lower coastal areas as well.

Modern Actions, For Better or Worse

By the twentieth century, the damage to the landscape and soil cover (fig. 7) caused by ranching and sugar cane farming had become evident, and some corrective measures were introduced. At the same time, some damaging activities continued and new ones were introduced. Repairing centuries of damage has proved challenging:

- Between 1898 and 1905, Moloka‘i Ranch, the largest landholder on the island, shifted from open country grazing to a paddock system in an effort to limit the impact of cattle on the vegetation in selected areas (Henke, 1929). This measure was only marginally successful, and erosion caused by destruction of overlying vegetation can still be seen today (fig. 5).
- In 1902, mangroves (*Rhizophora mangle*) were introduced by the American Sugar Company in an effort to stabilize the coastal mudflats at Pālā‘au in south-central Moloka‘i and hold back the soil washed down by heavy rains into the sea (Allen, 1998, p. 62).
- By 1907, the sheep population on Moloka‘i reached 17,000 animals, grazing mostly on the grasses of the Ho‘olehua Saddle and denuding large areas of pasture. Sheep-raising was finally discontinued “only because of reduced grazing areas and a poor wool market” (Henke, 1929, p. 18).
- In 1912, the Moloka‘i Forest Reserve was created, covering a large part of the eastern uplands of the island as a cooperative effort of government and local landowners. Fencing and volunteer restraint were used to give the upper slopes of the south-draining watersheds a chance to recover from the livestock damage. Effectiveness of conservation and remediation efforts varied with the dedication of those involved.
- In the 1920s, much of the Ho‘olehua Saddle was set aside as Hawaiian Homestead lands and was opened to farming. Clearing the land for farming made the loose, red soil more susceptible to the eroding effect of the prevailing northeast trade winds, while the planting of windbreaks was only marginally successful in mitigating the damage. Ironically, the homesteaders found it more lucrative to lease their parcels to the big pineapple producers than to farm them individually, leading to the additional environmental damage associated with extensive monoculture.
- By 1930, much of the island was devoted to either pineapple cultivation or to grazing. Both activities continued to alter the land of the Ho‘olehua Saddle and the coastal plain. As Handy (1931) noted, most fishponds by this time had been abandoned and were filled with mud.
- In 1934, the modern pier at Kaunakakai was built (Kepler and Kepler, 1991). This large-rock structure had a base substantial enough to carry a two-lane road, and it supported an expanded landing facility. Its position, jutting as it did at least 800 m (nearly 0.5 mi) south across the reef flat along the eastern edge of a natural channel in the reef, disrupted the along-shore flow of water.
- In 1948, the Moloka‘i-Lāna‘i Soil Conservation District was formed by the U.S. Department of Agriculture to help local residents reverse the environmental damage and improve the management of their lands. A Moloka‘i field office was established to disseminate information and assistance to landowners, farmers, and tenants to promote their conservation efforts by a broad variety of means (S. Cox, oral commun., 2000).
- The Nature Conservancy established an office on Moloka‘i in 1983 (E. Misaki, oral commun., 2000), adding their efforts to those of others attempting to reverse centuries of environmental damage and halt its progress. Since that time they have been working with local hunters and State and Federal agencies to try to control the feral goat population.

The Late Twentieth Century

Although agriculture has been the main land use influencing erosion rates on Moloka‘i, increased construction and road building have added to the runoff of water and sediment. Road cuts expose layers of loose soil that

National Oceanic and Atmospheric Administration, 1993

Bruce Richmond, USGS

Figure 8. Aerial photographs of the reef flat east of Kamalō showing impact of coastal development. Dredging of coastal materials and reef deposits produces high levels of turbidity and sedimentation locally. These two projects generated tons of sediment that washed across the reef, and according to local accounts, killed acres of corals. *A*, 1993 aerial photograph shows an irregular pit in the reef flat (straight-edged area of deeper, dark blue water) that was the site of excavation in the 1950s for a proposed marina. *B*, Oblique 1998 photograph of Pūko‘o Harbor is an example of shoreline modification. Construction of the harbor resulted in a large volume of fine sediment being released onto adjacent coral covered areas.

is easily eroded and transported to the coast, often via the sloped, paved surfaces or drainage ditches cut alongside the roads.

In the second half of the 1900s, residents and visitors alike increased in number, resulting in the construction of hotels, condos, and housing developments. In the early 1970s, sections of the reef flat at Kamalō and Pūko‘o were dredged for marina development (fig. 8). Some of the excavated material was used to alter the shape of the remains of a large fishpond, and some of it was discharged onto the reef. After completion of the dredging and reshaping of the coast, these marina projects were abandoned.

Additional development along the southern shoreline began with small-scale residential units, including low-rise condominiums and private homes. This was followed by upslope development involving large-scale clearing and grading and the building of roads, houses, walls, parking lots, and driveways. These activities altered the runoff patterns. Less water was absorbed into the ground, and surface flows became larger, more frequent, and more erosive.

Population growth on Moloka‘i also led to an increase in sewage discharge, another potential impact to the reef. The county sewage treatment plant serves only the town of Kaunakakai (J. Souza, oral commun., 2000) and uses injection wells on the plant site west of town and a quarter mile north of town, in Kaunakakai Gulch. Newer residences outside the town have septic systems, while the older ones have cesspools. Condominiums have their own small primary treatment systems with on-site injection wells. There is a potential—as yet undocumented—impact on the reef from the migration of sewage through ground-water seepage. Nutrients in the sewage may contribute to blooms of undesirable algae and cyanobacteria along the inner reef flat near residential areas.

The Twenty-First Century

Centuries of human activity have clearly had an impact on water quality and reef condition along the Moloka‘i south coast. Human activities that have adversely affected much of the south coast include coastal dredging at Pūko‘o in the east, wharf construction and sugar cane farming in the central part of the coast, and heavy cattle grazing on the west end. Although the impact from these activities has been severe, evidence indicates that once the activities ended, water quality improved and the adjacent reef began to recover. Assessment will continue for many years in an effort to discern the degree of improvement in both the water and the reef. Coastal waters off Pālā‘au, for example, are relatively clear compared to those off Kawela, and the coral cover on the reefs is increasing.

Many activities that occur in watersheds have a lingering effect, or legacy. Muddy sediment introduced into gullies, stream channels, and the coastal plain remains there for many years, but ultimately it is eroded and transported to the reefs. The greatest threats to reefs and to water quality are activities that expose upland soils to accelerated erosion and transport. Two of the principal causes of current soil loss from south Moloka‘i watersheds are the stripping of vegetation by fires and the destructive grazing of feral goats (fig. 9).

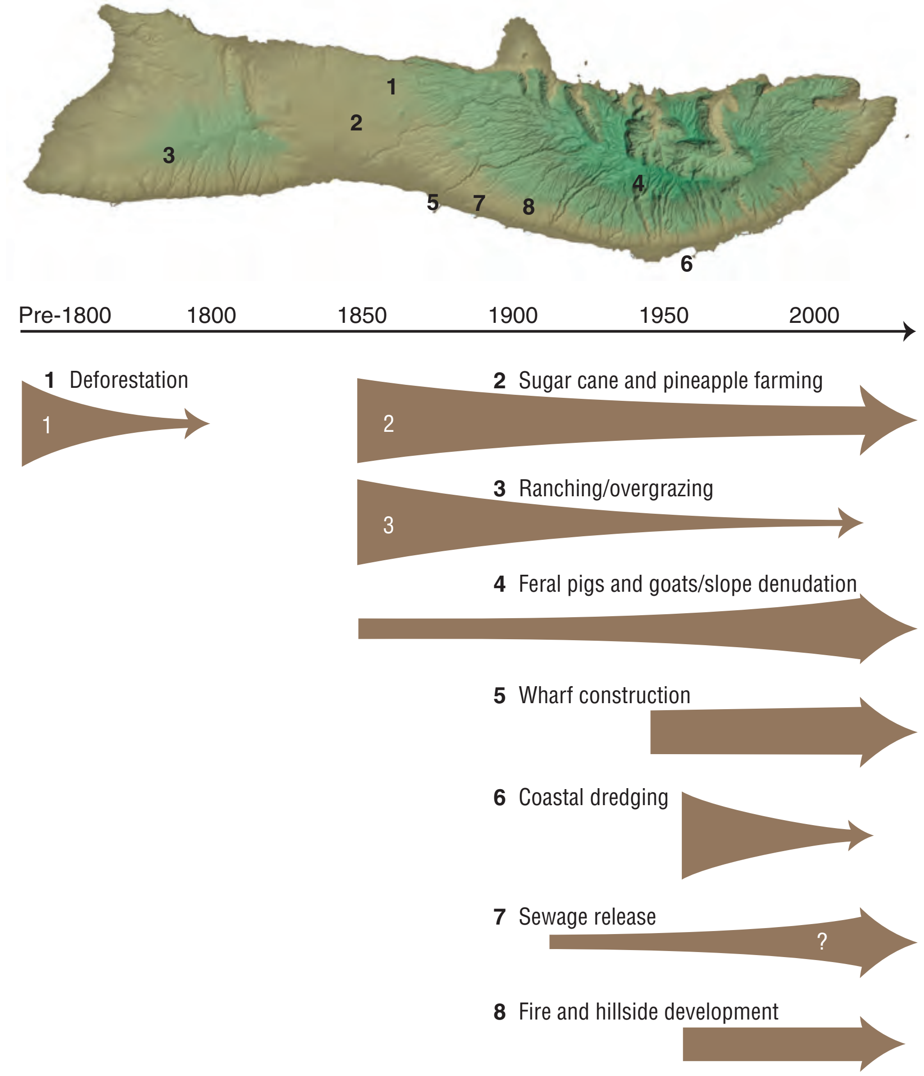


Figure 9. This map and chart summarize the human activities that have influenced watershed character and soil loss on Moloka‘i over several centuries. The locations are somewhat generalized; although the locations of some activities are well known (farming in the Ho‘olehua Saddle, for example), the locations of others, such as fires and feral grazers, are widespread and change through time. The time line illustrates the approximate timing for each activity that has caused soil loss and altered conditions on the Moloka‘i reef. Although some past activities seem to have had a severe impact, the reef appears to be recovering now that the activity has ceased or diminished. Some activities, in particular feral grazing, fire, and hillside and coastal construction still have the potential to continue degradation of the reef. Ongoing studies by U.S. Geological Survey scientists show that in some upland areas the damage to the terrain will be difficult to repair. Loss of vegetation leads to erosive overland flows and soil loss, making it difficult for vegetation to become reestablished. Note that the impact from sewage release into the subsurface is essentially unknown, and that at present, damage from feral goats is a leading contributor to soil loss and reef degradation.

G. Tribble, USGS

Figure 10. The denuded hill slopes of eastern Moloka‘i upslope from Kamalō. Feral goats strip the grasses and young shoots before they can develop sufficient root structures to hold soil or a canopy to protect against direct rain action. Infrequent fires exacerbate the problem of vegetation loss.

Federal, State, and local organizations have recognized the threat to Hawaiian coral reefs from land-derived sedimentation. Together they have developed a Local Action Strategy (LAS) under the auspices of the U.S. Coral Reef Task Force to address land-based pollution. The LAS focuses on three areas in Hawai‘i, one of which is the Kawela to Kapualei area of east Moloka‘i. The LAS is watershed based and incorporates the native management system for lands and natural resources, the ahupua‘a. The objectives of the LAS are threefold: (1) reduce pollutant load to surface water and ground water, (2) improve understanding of the link between land-based pollution and coral-reef health, and (3) increase awareness of pollution prevention. The LAS proposes specific positive actions to address the problems of soil erosion in the Kawela-Kapualei area and the consequent damage to coastal water quality and the reef:

- fencing and other procedures to control feral grazers and reduce the impact of grazing,
- educating and training local residents about fire management,
- restoring the watersheds with native vegetation, and
- constructing sediment basins to capture land-derived silt before it reaches the ocean.

Construction of sediment basins is costly, and thus it is uncertain whether they will be built. The other measures, along with a program to reduce the total number of goats, will likely reduce sediment runoff.

Summary

Although landscape change is a continuous and anticipated part of all natural systems, the rate of erosion, deposition, and coastal change in South Moloka‘i has been altered significantly by human activities that range from farming and ranching to the introduction of feral grazers. These activities were not confined to any one part of the island, nor was any single activity responsible for the changes to the watersheds. The changes visible today result from the cumulative effects of many different activities over decades or, in some cases, centuries (fig. 10).

During the past few years, the residents of Moloka‘i have recognized the extent to which they affect the rate of change in their environment and have initiated efforts to understand and possibly reverse the effects. Today scientists continue to study the upland regions and the processes that erode and transport sediment to the reef. On the reef, they examine physical evidence of the impact of upland watershed change on the coral community. They seek to identify and quantify the rate of change and learn the causes of both past and present change. The goal is a worthy one: knowledge of Moloka‘i’s past will help the residents deal more effectively with present and future threats to their coral reefs.

CHAPTER 16

Invasive Mangroves and Coastal Change on Moloka‘i

Mimi D’Iorio[1]

Mangroves are salt-tolerant, woody plants that grow on island shores and along low-relief coastlines throughout the world’s tropical and subtropical oceans (fig. 1). Often found in association with coral reef environments, mangroves form coastal forests that exist in a dynamic equilibrium between the ocean and the land (fig. 2). The term “mangrove” refers to an individual mangrove plant, but is more generally used in an ecological context to describe an entire plant community, including approximately 70 different species of trees and shrubs, that inhabits the brackish land-sea margin along low-latitude coastlines (Duke, 1992). Not native to the Hawaiian Archipelago, mangroves were introduced to Moloka‘i in the early 20th century to help stabilize eroding coastal mudflats on the south coast near Pālā‘au (MacCaughy, 1917; Wester, 1981; Allen, 1998). Their subsequent colonization of the island’s south shore has altered the structure of the coastal margin, influencing a variety of changes to surrounding nearshore habitats and coastal infrastructure.

Figure 1. Red mangrove (*Rhizophora mangle*) juvenile tree growing on the reef flat off Moloka‘i’s south coast near Pālā‘au.

Regarded as land builders and known for their ability to promote sedimentation in coastal settings, mangroves play a valuable role in protecting and stabilizing eroding coastlines worldwide. They are most prolific in sediment-rich areas where freshwater and terrestrial runoff are abundant, such as near the mouths of coastal rivers and streams and in coastal wetlands. Mangroves trap sediment being transported seaward, thereby reducing water turbidity and decreasing the amount of sediment flowing into adjacent coastal ecosystems. Water flow is decreased in the vicinity of the extensive aerial root systems, allowing silt (fine-grained terrigenous sediment) to deposit. The high abundance of microbial communities within mangrove forests also plays an important role in trapping and binding sediment, as fine particles settling out from reduced water velocity are aggregated and mineralized by biological activity (Alongi and McKinnon, 2005).

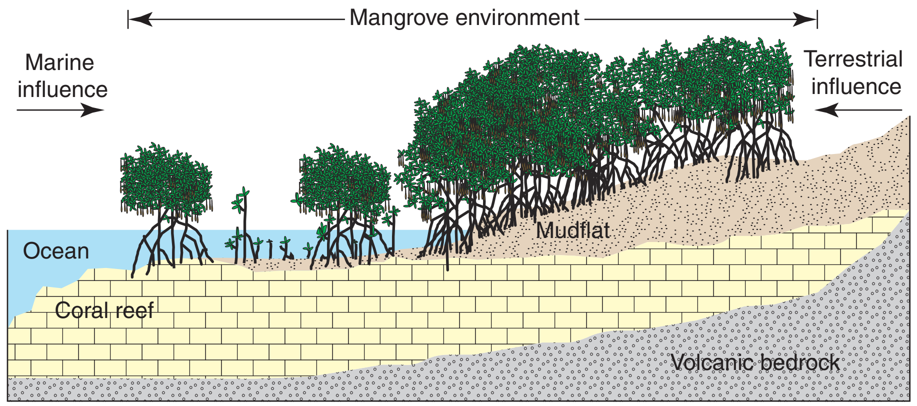


Figure 2. Schematic diagram illustrating the dynamic relation that exists between coral reef and mangrove environments because of the complex interaction of marine and terrestrial processes at the land-sea margin.

Mangroves are unique plants that have evolved special physiological and morphological adaptations which allow them to thrive in the relatively harsh environmental conditions that exist within the intertidal zone. Increased water salinity, the presence of anaerobic substrates, high-energy wave action, and frequent tidal inundation are all factors that contribute to the severe nature of the mangrove environment. Their ability to survive in these relatively adverse conditions sets mangroves apart from other plant species and allows them to occupy a niche within the coastal zone where they have little to no competition among other plants.

History of Mangroves on Moloka‘i

Although no mangrove species are native to the Hawaiian Islands, 25 species exist naturally elsewhere in the Pacific, with 9 species identified on Guam and 12 on both the Republic of Palau and the Federated States of Micronesia (Ellison, 1999). Because of the relatively young geological age of the Hawaiian Islands and their geographic and oceanographic isolation from large continental land masses, the various mangrove species that evolved and radiated throughout the Indo-Pacific during the Cretaceous Period and have since colonized many island coasts throughout the South Pacific, Atlantic, and Indian Oceans did not naturally disperse to the Hawaiian Islands.

In 1902, however, the Florida red mangrove, *Rhizophora mangle*, was introduced to the south coast of Moloka‘i by the American Sugar Company. Young mangrove trees were planted on the Pālā‘au mudflats to help protect the shoreline and adjacent coral reef environment from the increased agricultural runoff associated with the cultivation of the uplands for sugar cane (Allen, 1998). Since its introduction, *Rhizophora mangle* has become well established on Moloka‘i, migrating eastward along the coastline, colonizing tidal mud flats, shallow embayments, and the rock walls and muddy interiors of coastal fishponds. The species has also spread to other nearby islands in the Hawaiian chain but is most prolific on Moloka‘i. It now dominates the

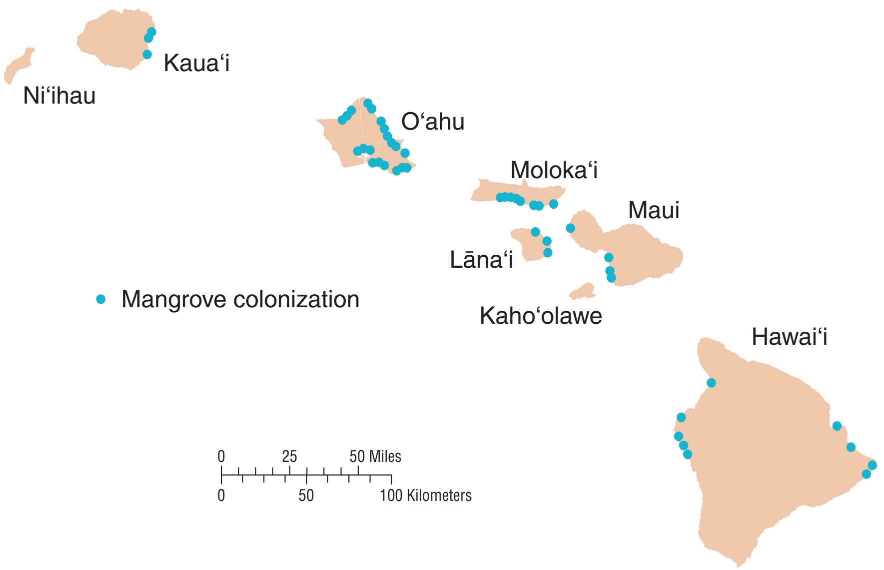


Figure 3. Map showing the approximate sites (blue dots) of known mangrove colonization throughout the eight main Hawaiian Islands. Sites updated from Allen (1998) and Wester (1981).

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Figure 4. Large mature red mangrove tree growing on the reef flat at Pālā‘au. Note the dense matrix of prop roots that extend from the tree’s main stem onto the sediment-covered reef flat.

island’s south coastline at Pālā‘au, and localized coastal colonies are identified as far as Pauwalu on the island’s east end.

In most of the world, native mangrove systems are declining as a result of overharvesting, land reclamation, and aquaculture (Spalding and others, 1997; Alongi, 2002), and large-scale efforts focus on restoring degraded mangroves and preserving remaining natural mangrove forests (Saenger and Siddiqi, 1993; Islam and Wahab, 2005). In Hawai‘i, however, the alien mangrove is not threatened, but is spreading, colonizing coastal property on at least six of the eight main islands (fig. 3; Allen, 1998). The proliferation of introduced mangroves has contributed to loss of habitat for four endemic waterbirds, including the endangered Hawaiian stilt (*Himantopus mexicanus knudseni*), damage to sensitive archaeological sites, premature infilling of historic fishponds, and restructuring of the native coastal wetland ecosystem. Management of *R. mangle* is of concern in many of the national parks and wildlife refuges on the islands, where native habitats, nesting grounds, and important archaeological sites are threatened by encroaching mangroves. These effects of alien mangroves on the native systems have encouraged local agencies to consider and implement alien-species management strategies. Mangrove removal projects have already been initiated in the Kaloko-Honokōhau National Historic Park on the Island of Hawai‘i (Pratt, 1998) and in the Nu‘upia Ponds Wildlife Management Area (NPWMA) within the Kāne‘ohe Bay Marine Corps Base on O‘ahu (Cox and Allen, 1999).

Characteristics of Mangroves on Moloka‘i

All mangrove species are considered facultative halophytes, meaning that they can survive in both saltwater and freshwater environments. In native mangrove environments, where multiple species exist and compete for space, the mangrove habitat exhibits species zonation in response to local cross-shore environmental gradients of salinity, substrate composition, and elevation. Each zone is dominated by the mangrove species that is best adapted to survive in the given conditions. On Moloka‘i, however, there is a monospecific distribution of *R. mangle*, a species that is characteristically found at the water’s edge, along the turbulent boundary of the intertidal zone. As a result, the species zonation evident in native systems is not observed on Moloka‘i, and *R. mangle* has been able to successfully migrate and colonize outside its traditional niche.

Rhizophora mangle, or red mangroves, are easily distinguished from other mangroves throughout their reproductive cycle by their prominent aerial prop roots, their thick, waxy leaves, and their pencil-shaped fruit or propagules, which grow in dense, low-hanging clusters. These propagules, which include embryonic root structures, germinate while still attached to the parent tree and grow into long greenish-brown seedlings that drop into the water, where they float upright and are dispersed by currents. After an often lengthy water-borne dispersal period (that can be as long as a year), during which they continue to grow and develop, the germinated seedlings eventually encounter land or are stranded on tidal flats, where they plant their roots, grow leaves, and flower (fig. 4). The dense system of prop roots, extending up to a meter above the soil surface, provide stability from wind and waves and are equipped with pores called lenticels that promote respira-

Figure 5. Features of red mangrove (*Rhizophora mangle*) on Moloka‘i’s south coast. *A*, Propagules hanging from mature red mangrove tree at the coastal margin near Pālā‘au. *B*, Young mangrove seedlings at various stages of root development colonizing the reef flat just offshore of the Kapuāiwa coconut grove. *C*, Mangrove seedling that has taken root on the reef flat near the Kapuāiwa coconut grove. Notice the aerial prop roots that have begun to grow laterally away from the main stem toward the substrate. *D*, Red mangrove tree establishing a stronghold on the reef flat at Pālā‘au. Note the young seedling in the foreground that has yet to grow any prop roots. The prop roots collect algae and sediment around their base, forming a unique and protected environment for marine microfauna.

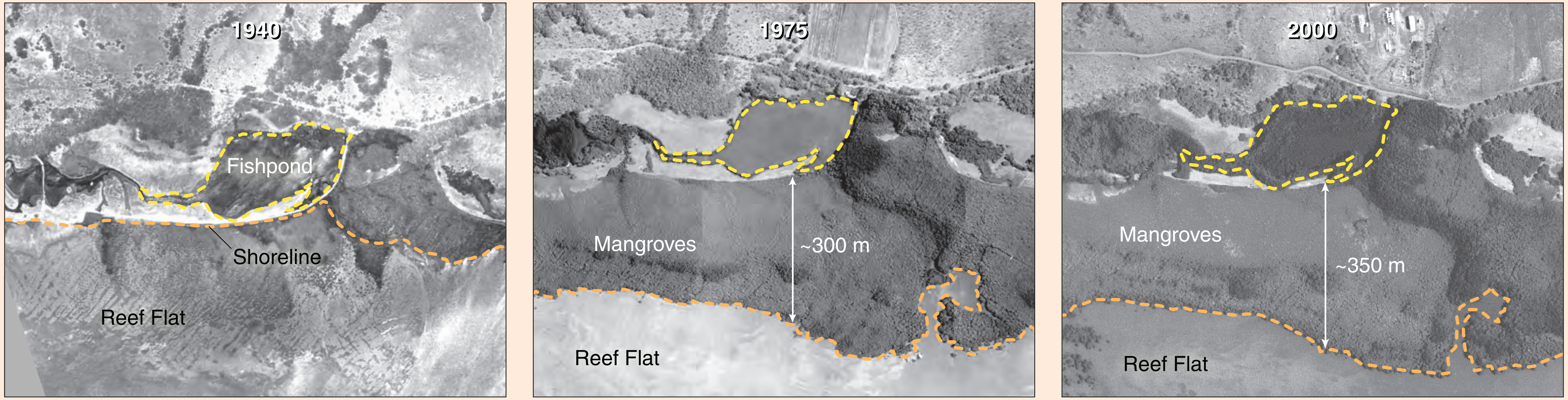


Figure 6. Historical aerial photographs showing the relative location of the shoreline (orange dotted line) to the Kaluaapuhi Fishpond (yellow dotted line) near ‘Umipa‘a in 1940, 1975, and 2000. Note the lack of mangroves on the tidal reef flat in 1940.

tion in anerobic (low-oxygen) soils by diffusing oxygen down to the buried roots when exposed at low tide. Figure 5 shows the features of *R. mangle* trees in various stages of development.

Fishponds are easy targets for mangrove encroachment, providing root support within rock walls and protection from surface currents and northeasterly trade winds. Shoreline change associated with mangroves and fishponds is most evident in the ‘Umipa‘a region, where a number of previously shoreline-bound fishponds (loko ‘ume iki) are now separated from the coastline by hundreds of meters of mangrove forest (fig. 6).

Mangroves and Shoreline Change

To understand how the invasion of *Rhizophora mangle* influenced coastal change on Moloka‘i, rates of shoreline progradation were calculated across various time scales to assess the temporal and spatial variability in mangrove colonization throughout the 20th century. Remote sensing and geographic information systems (GIS) techniques were used to interpret satellite data, aerial photographs, historical maps, and coastal surveys in order to identify the position of the south coast shoreline and to map its seaward migration since the introduction of *R. mangle* in 1902.

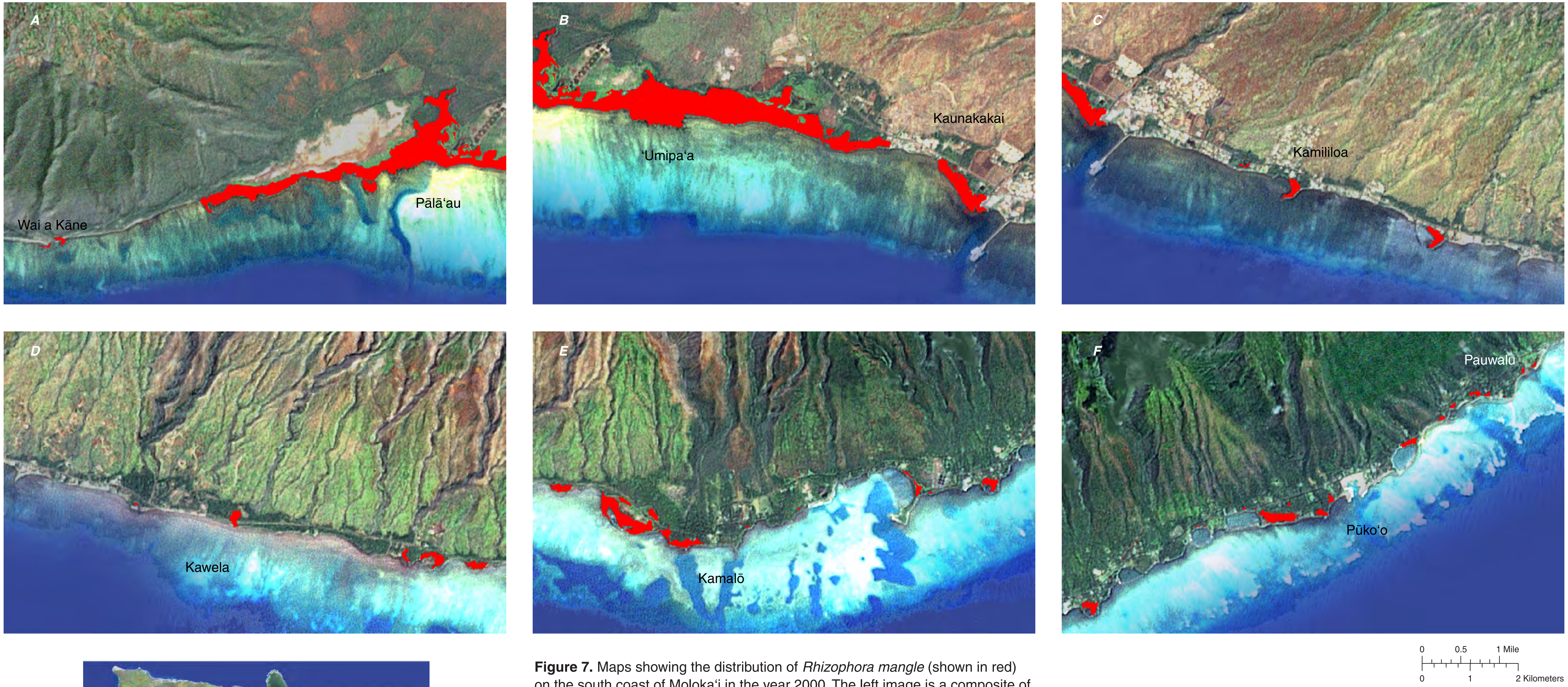
Historical maps and aerial photography offer a perspective into the past that can be digitally recreated in a GIS environment to assess spatiotemporal patterns of change in coastal systems. Topographic coastal surveys (T-sheets), published by the National Oceanic and Atmospheric Administration’s (NOAA) Coastal Services Center (and previously by NOAA’s National Ocean Service), are the oldest reliable representation of the shoreline, providing a valuable point of reference for defining historical coastal features and shoreline positions. Quantification of coastal change involves the acquisition and digitization of these historical resources, their rectification and/or georegistration, digital extraction of shoreline position, and the calculation and interpretation of change rates. Additionally, satellite data and aerial imagery were processed to extract species coverage and distribution information for assessing the spatial extent of *Rhizophora mangle* as observed from space and airborne imaging sensors.

In the year 2000, mangroves occupied 2.4 km^2 of coastal land on Moloka‘i, with the Pālā‘au and ‘Umipa‘a regions exhibiting the most extensive coverage of dense mangrove canopy. The western portion of the island’s south coast exhibits greater overall coverage, whereas mangroves in the east preferentially colonized in coastal fishponds. The geographic boundaries of mangrove habitat alongshore are from Wai a Kāne in the west to Pauwalu in the east (fig. 7).

The distribution of *R. mangle* may be both naturally and anthropogenically influenced. The red mangrove prefers muddy, protected settings for colonization, but it is likely that mangrove colonization has been prevented on some suitable substrates by clearing of the propagules as they begin to encroach onto private property. In support of this, anecdotal evidence through discussion with local residents indicates that at least some fishponds are routinely cleared of mangrove pods to maintain operability and prevent overgrowth and excess sedimentation.

Mangrove propagules are dispersed into the water column and are transported by winds and surface currents, influencing the coverage of mangroves along the south coast of Moloka‘i. With predominantly east-to-west surface flow and northeasterly trade winds, material and seedlings deposited at the coast are generally transported westward (see Ogston and others, this vol., chap. 20, for further discussion about surface flow and transport). This may account for the greater mangrove coverage at the west end of the island. Additionally, observations at the Kaunakakai Wharf show a substantial accumulation of pods along the east side of the causeway, suggesting that further westward transport is blocked by the presence of this long structure that extends across the shallow reef flat.

Shoreline change rates are highly variable both alongshore and over time. From 1915 to 2000, mangrove progradation in regions of the south coast accounted for shoreline change rates in excess of 14 m (45.9 ft) per year (fig. 8). Long-term trends of shoreline change rates show an overall decrease in progradation from west to east, which appears to be related to the distribution of coastal fishponds alongshore. Interval rates for the Pālā‘au and ‘Umipa‘a regions suggest that there was an early period of rapid mangrove expansion that occurred from 1915 to 1940, during which a majority of the currently existing mangrove habitat was established (fig 9). Maximum rates calculated over this period are found in Pālā‘au, where shoreline progradation rates exceeded 44 m (144.4 ft) per year. Interval change trends



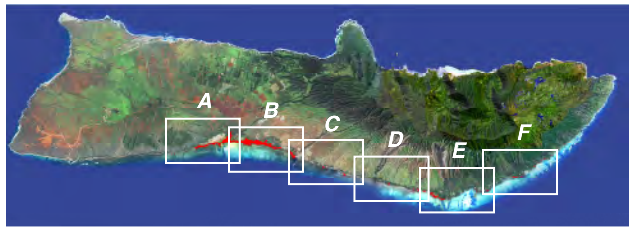


Figure 7. Maps showing the distribution of *Rhizophora mangle* (shown in red) on the south coast of Moloka‘i in the year 2000. The left image is a composite of Landsat 7 data showing the mangrove distribution for the entire south coast of Moloka‘i, with rectangles outlining the extents of the six insets presented above (*A*–*F*). Each red pixel represents an area 10 m by 10 m (32.8 ft by 32.8 ft) that is predominantly occupied by the red mangrove. The total coverage for *R. mangle* in the year 2000 was approximately 240 hectares (2.4 km^2).

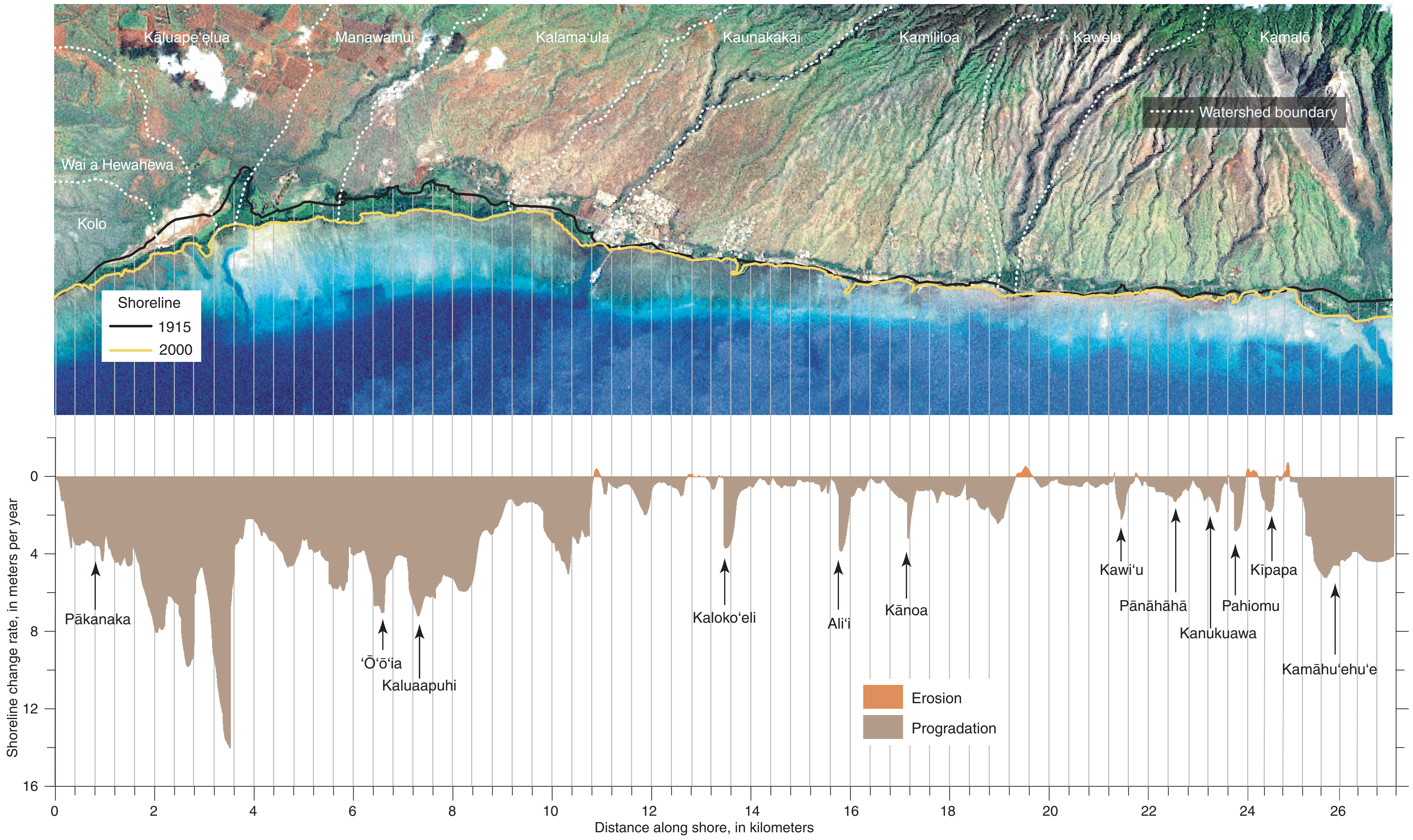


Figure 8. Landsat composite image of a 27-km (16.7 mi) section of coastline of southeastern Moloka‘i from the Pākanaka Fishpond (west) to the Kamalō Harbor (east), showing the position of the shoreline in 1915 and 2000. Below the image is a histogram of long-term shoreline change rates (1915–2000) along this stretch of coast. White dotted lines on the image represent boundaries of coastal watersheds named along the margin of the image (watershed boundaries from Hawai‘i State GIS Program, http://www.state.hi.us/dbedt/gis/, last accessed April 29, 2008). The arrows on the plot identify the locations of coastal fishponds alongshore.

show an overall decrease in shoreline progradation rates and an increase in rates of erosion of mangrove habitat (fig. 9). From 1915 to 1961, a majority of the shoreline showed progradation, with a maximum rate of 27 m (88.6 ft) per year near the channel at Pālā‘au. Erosional trends were more evident between 1961 and 1975, when approximately 35 percent of the shoreline studied showed varying rates of retreat as great as 4 m (13.1 ft) per year. Average rates of change decayed exponentially through time, starting high in the early 20th century at 4.1 m (13.4 ft) and decreasing to modern rates of less than 0.1 m (0.3 ft) per year.

Summary

No mangroves were present on the Hawaiian Islands before their introduction (the species *Rhizophora mangle*) in 1902. Since that time, shoreline change along the leeward (south) coast has been dominated by seaward growth and progradation at specific locations, most notably the Pālā‘au and ‘Umipa‘a regions of the south-central coastline. Over the 20th century, *R. mangle* has colonized vast areas of the coastal interface, leading to seaward progradation of the shoreline across the reef flat, filling ancient fishponds, and encroaching onto private beachfront property. These effects are typical of invasive species, which often have devastating impacts on native habitats and species' distributions, phenomena that are often exacerbated on remote islands with already low species diversity.

The invasive mangroves on Moloka‘i have both positive and negative feedbacks on the dynamics of the coastal system. They reduce the area of wetland habitat important for endemic waterbirds and encroach onto the reef flat, coastal beaches, and fishponds, yet at the same time they stabilize coastal land, create new fishery and aviary habitat, and inhibit cross-shore sediment transport onto the reef. With so many intertwined potential effects on the coastal system, understanding how the patterns of this invasive species migration, colonization, and habitat conversion proceed is an essential part of developing effective alien- species policy and coastal management practices.

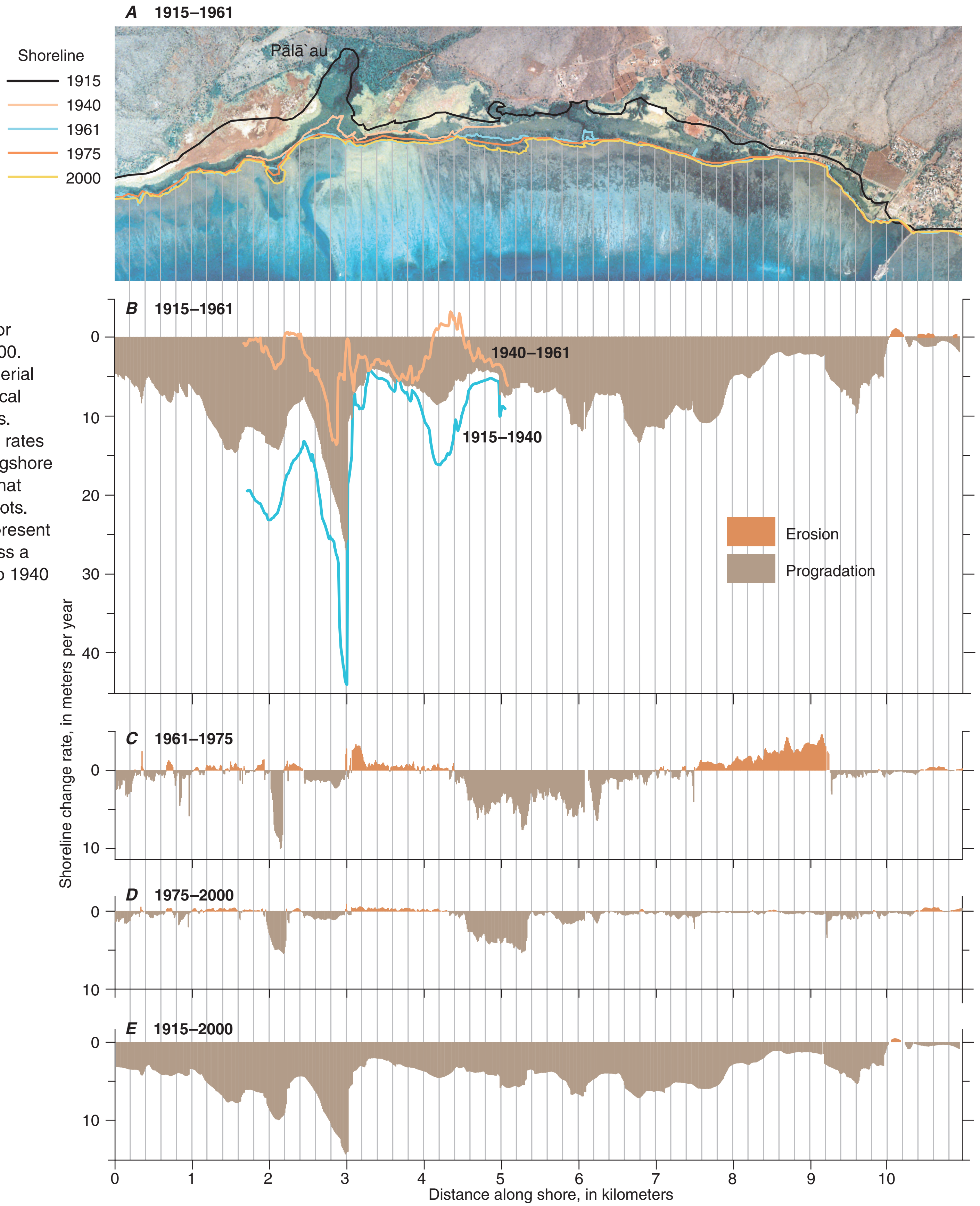
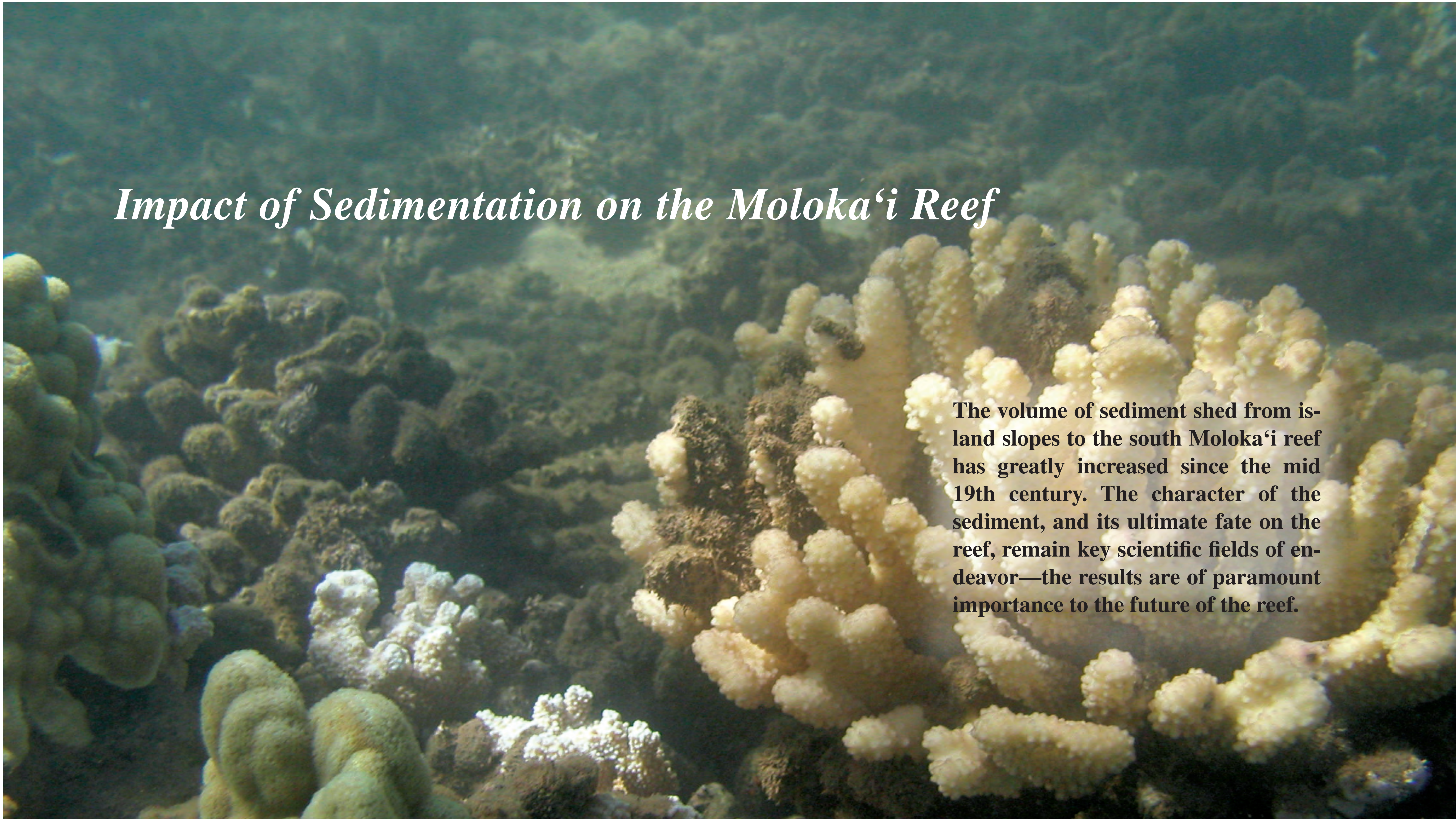


Figure 9. Shoreline change rates for the Pālā‘au region from 1915 to 2000. *A*, Orthophotomosaic of the 2000 aerial imagery overlaid with the five historical shorelines used for change analysis. *B–E*, Plots of the end-point change rates measured at 10-m increments alongshore in the defined time intervals. Note that the vertical scale varies between plots. The blue and orange lines on *B* represent the end-point rates calculated across a limited area of Pālā‘au from 1915 to 1940 and 1940 to 1961, respectively.



Impact of Sedimentation on the Moloka‘i Reef

The volume of sediment shed from island slopes to the south Moloka‘i reef has greatly increased since the mid 19th century. The character of the sediment, and its ultimate fate on the reef, remain key scientific fields of endeavor—the results are of paramount importance to the future of the reef.

Bleached and sediment-covered corals on the Moloka‘i reef.

View of suspended sediment on the Moloka‘i reef flat as seen from Kawela.

CHAPTER 17

Sediment on the Moloka‘i Reef

Michael E. Field[1], R. Scott Calhoun[2], Curt D. Storlazzi[1], Joshua B. Logan[1], and Susan A. Cochran[1]

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.

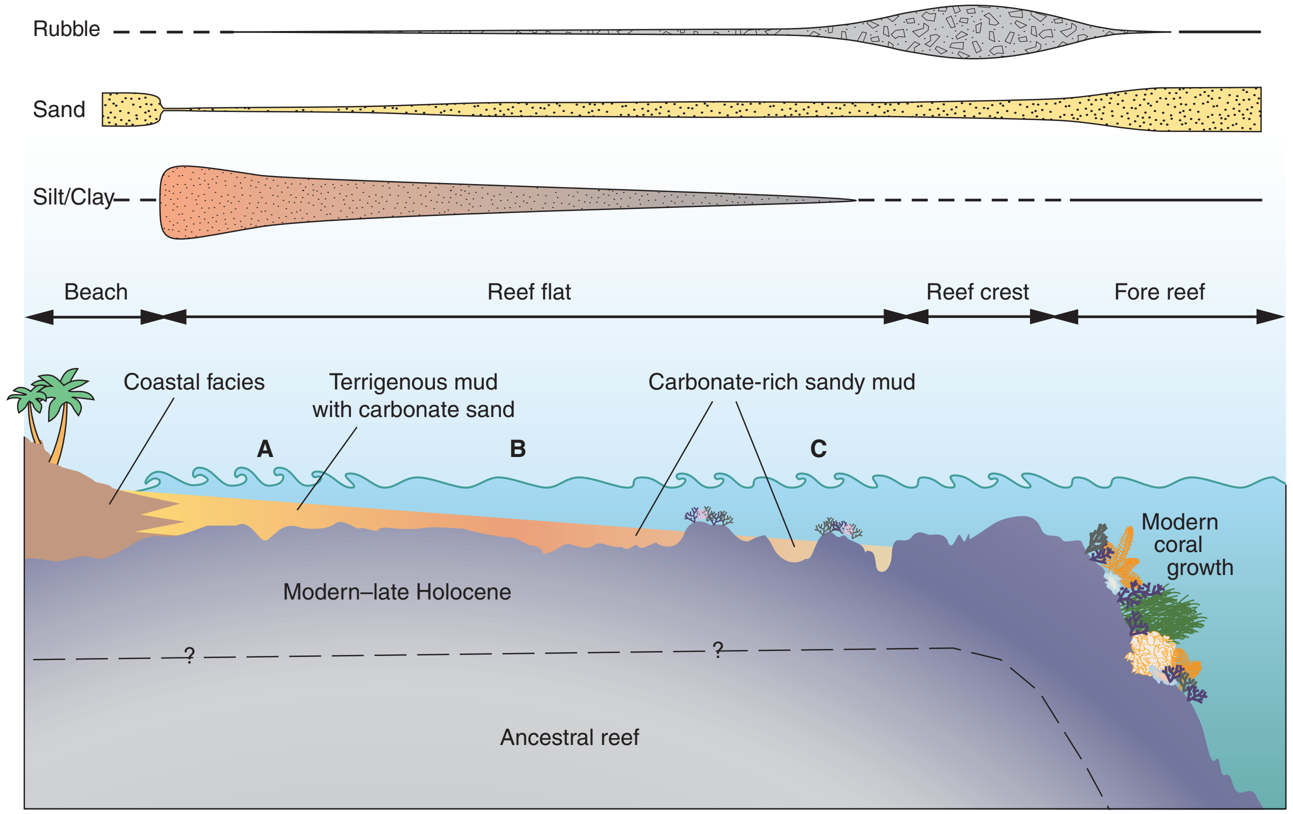


Figure 1. Cross section of the south Moloka‘i reef system showing the transition from the sediment-covered inner reef flat to the coral-rich fore reef. The relative abundances of rubble, sand, and mud are shown schematically from the beach across the reef flat and reef crest onto the fore reef. A, B, 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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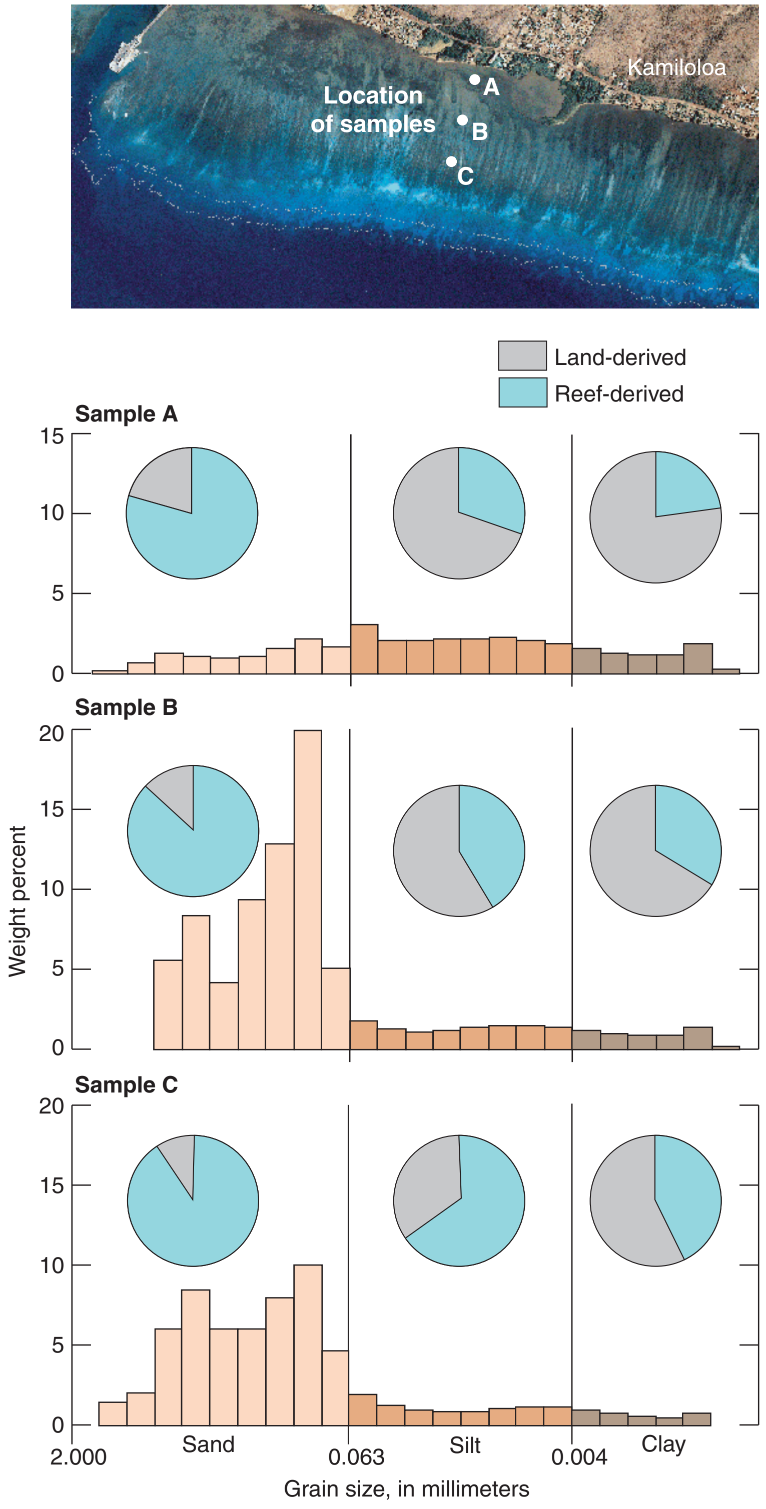


Figure 2. Size and composition of three typical sediment samples from the south Moloka‘i reef flat; the rubble fraction is not shown. The land-derived (terrigenous) and reef-derived (carbonate) fractions were determined by HCl acid solution, a standard laboratory procedure. Note: the x-axis is a decreasing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

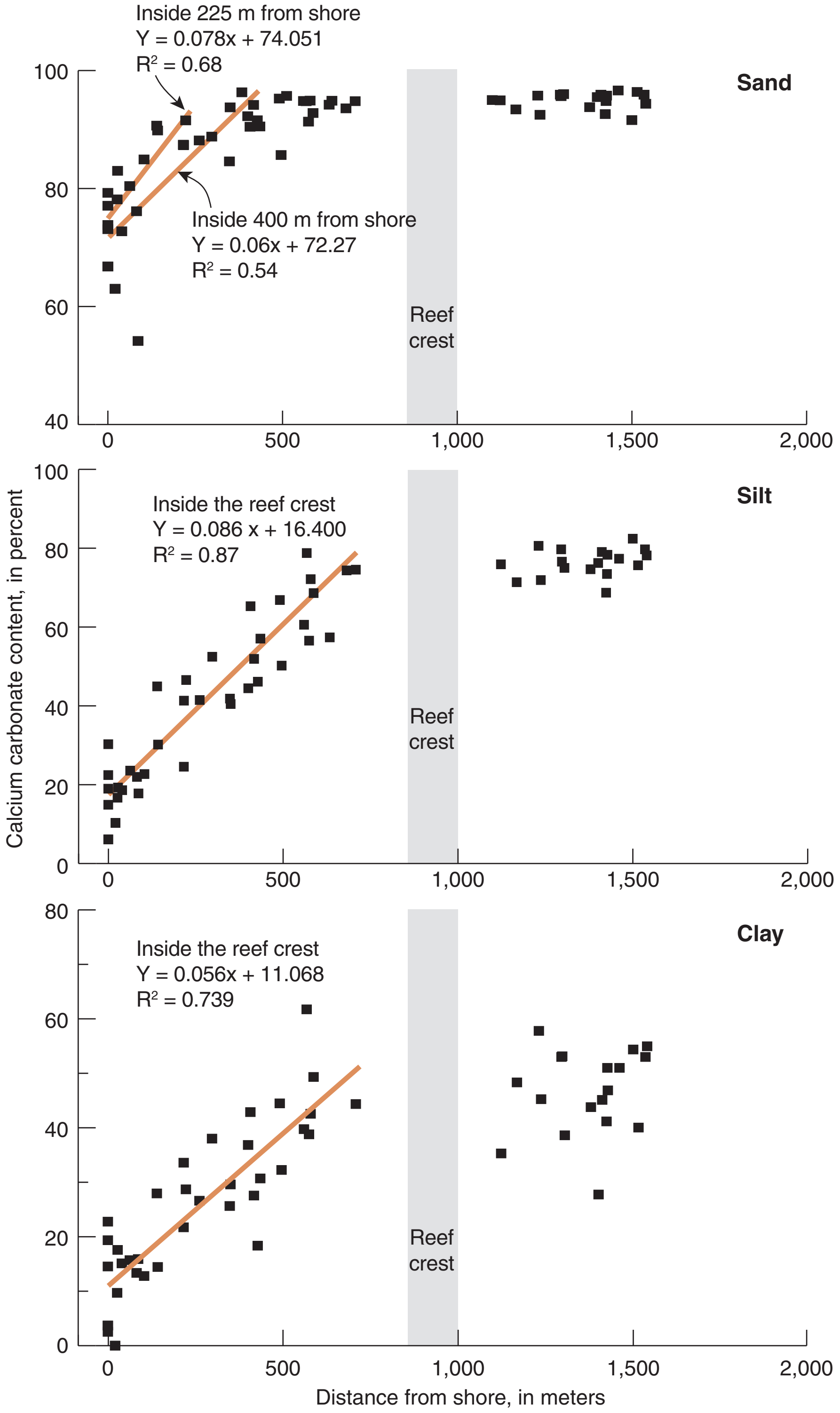
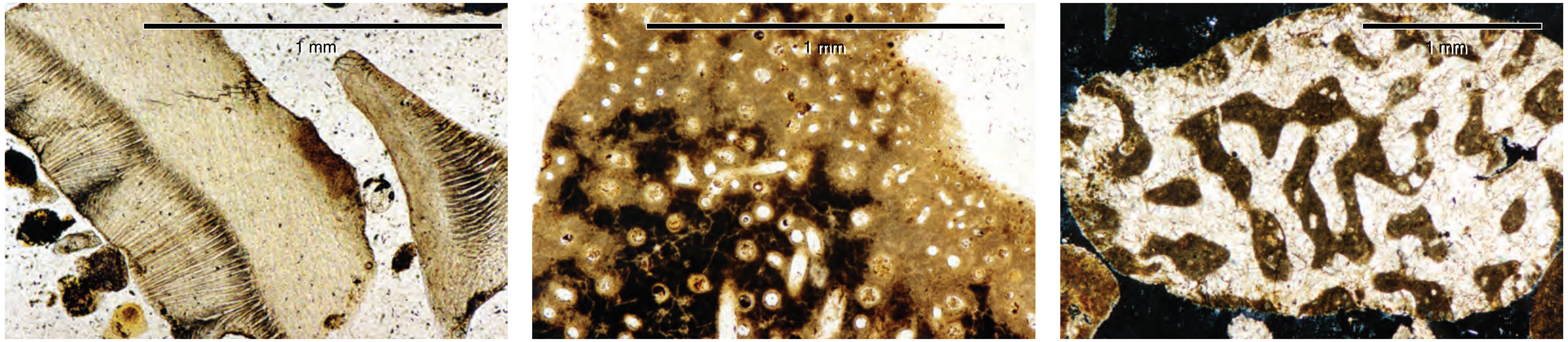


Figure 3. Calcium carbonate content of sand, silt, and clay fraction. The calcium carbonate contents increase with distance from the shoreline, reaching their fore-reef levels at approximately 400 m (1,312 ft) for sand, 500 m (1,640 ft) for clay, and 650 m (2,133 ft) for silt.

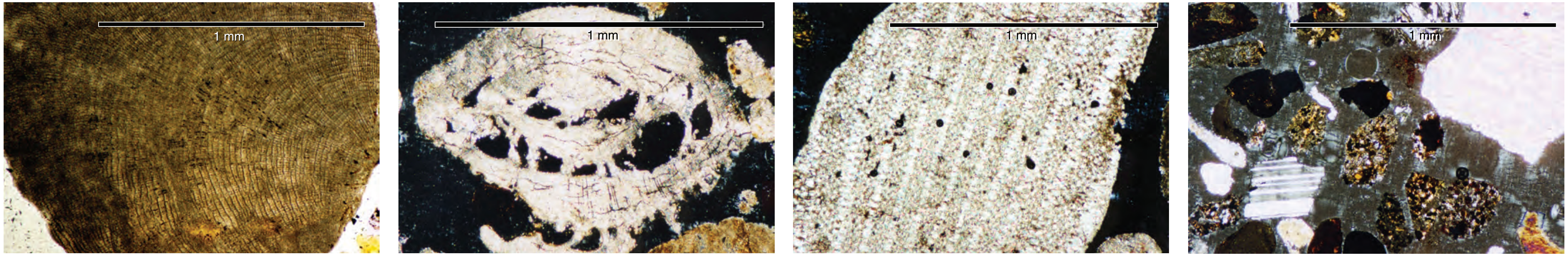
Figure 4. Photomicrographs of sand grains of various origins from sediment on the south Molokaʻi reef (Calhoun and Field, 2008).



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.

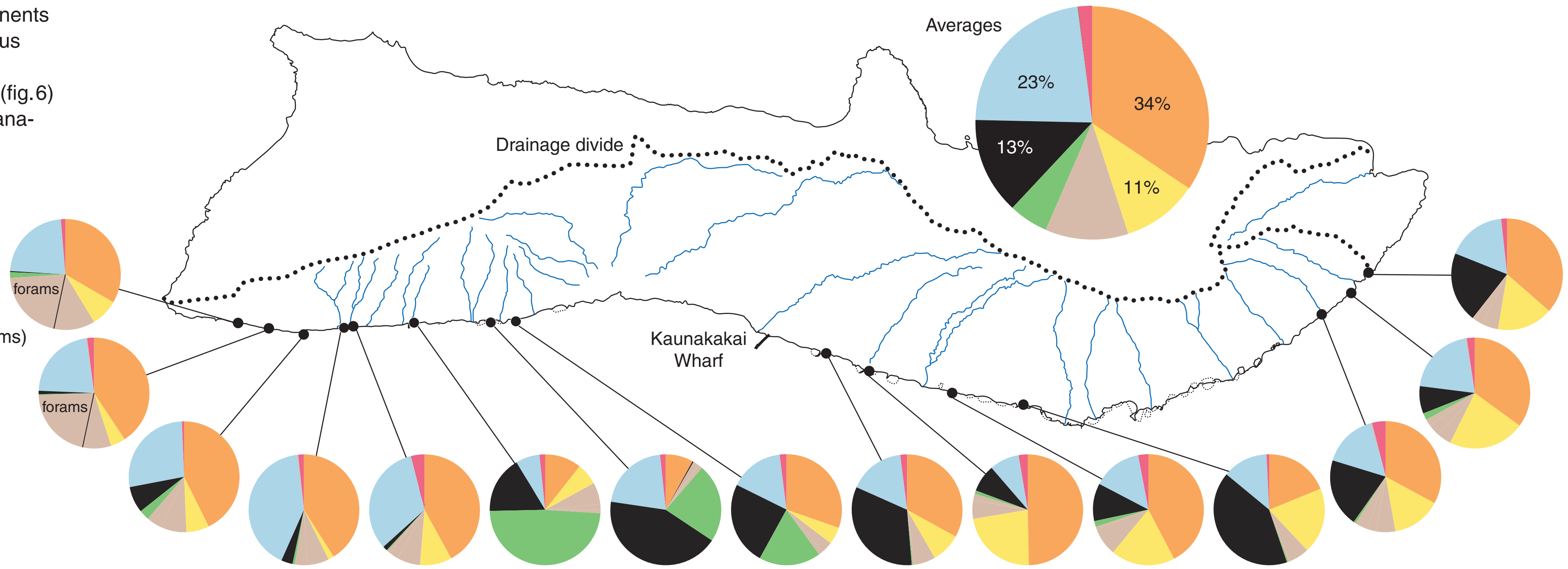


Figure 6. Composition of reef-flat sand on the south Moloka‘i reef. The most important components are chemically altered (micritized) carbonate grains, terrigenous grains, coralline algae, and coral. Streams draining to the south side of Moloka‘i shown in blue.

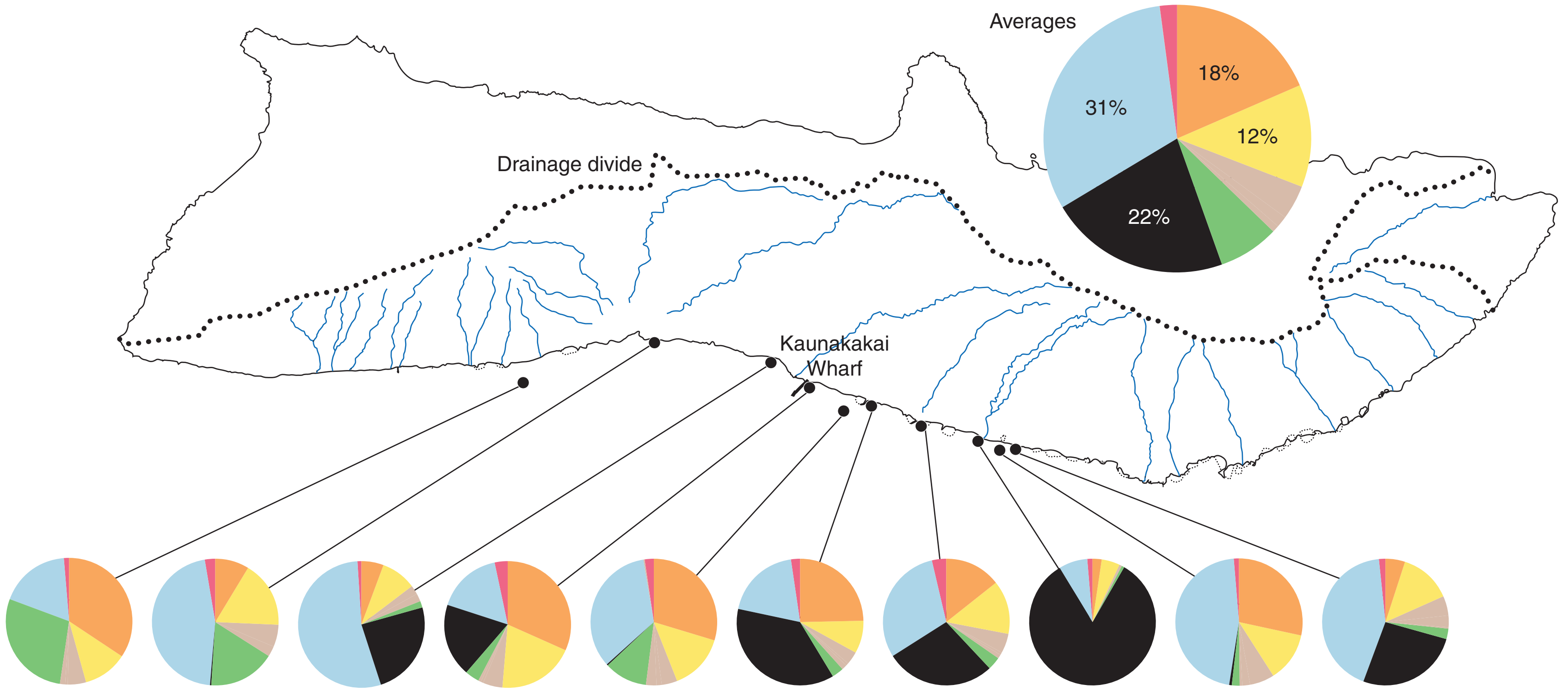
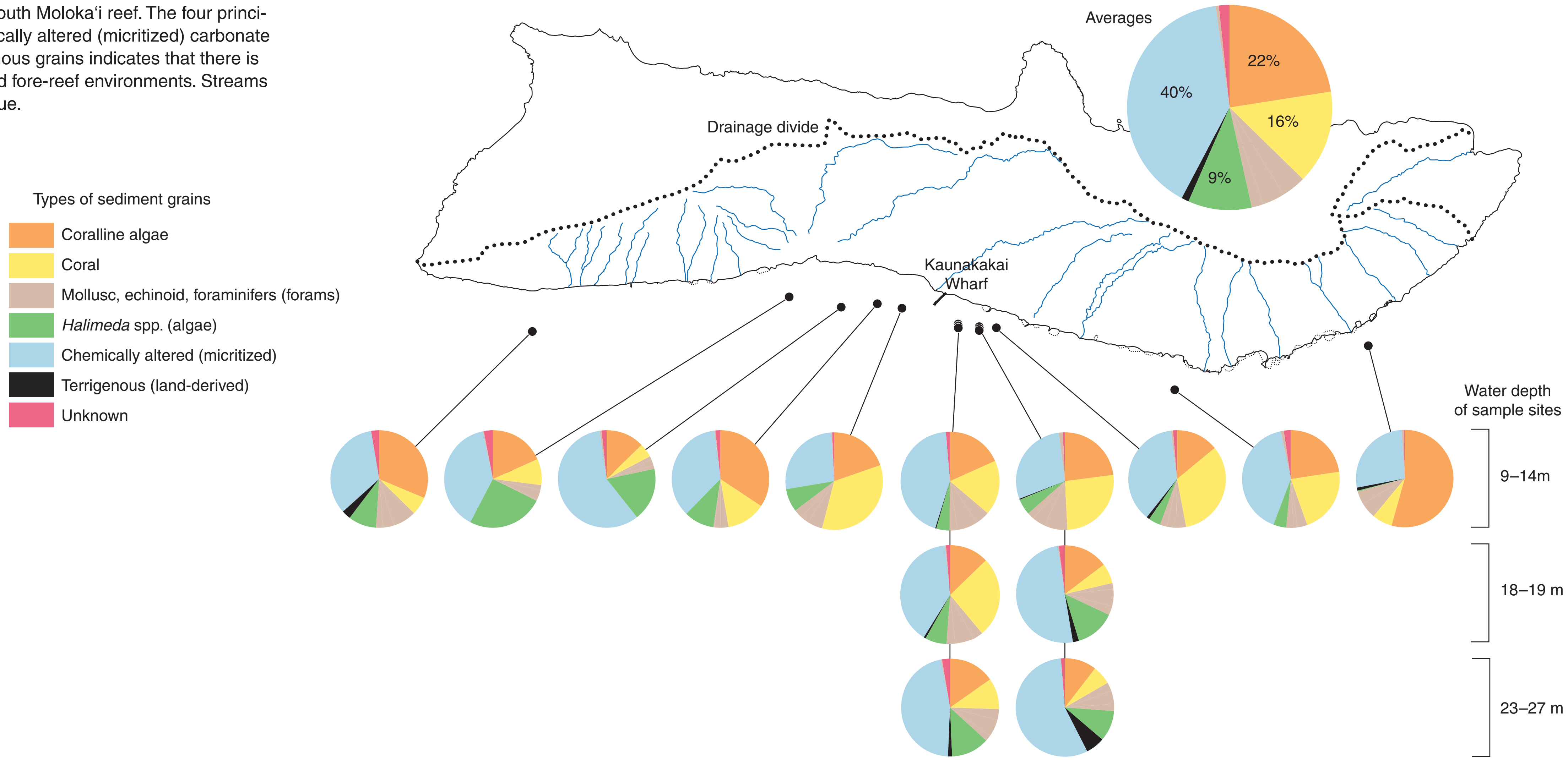


Figure 7. Composition of fore-reef sand on the south Moloka‘i reef. The four principal components are coralline algae, coral, chemically altered (micritized) carbonate grains, and *Halimeda*. The scarceness of terrigenous grains indicates that there is little sediment exchange between the reef-flat and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

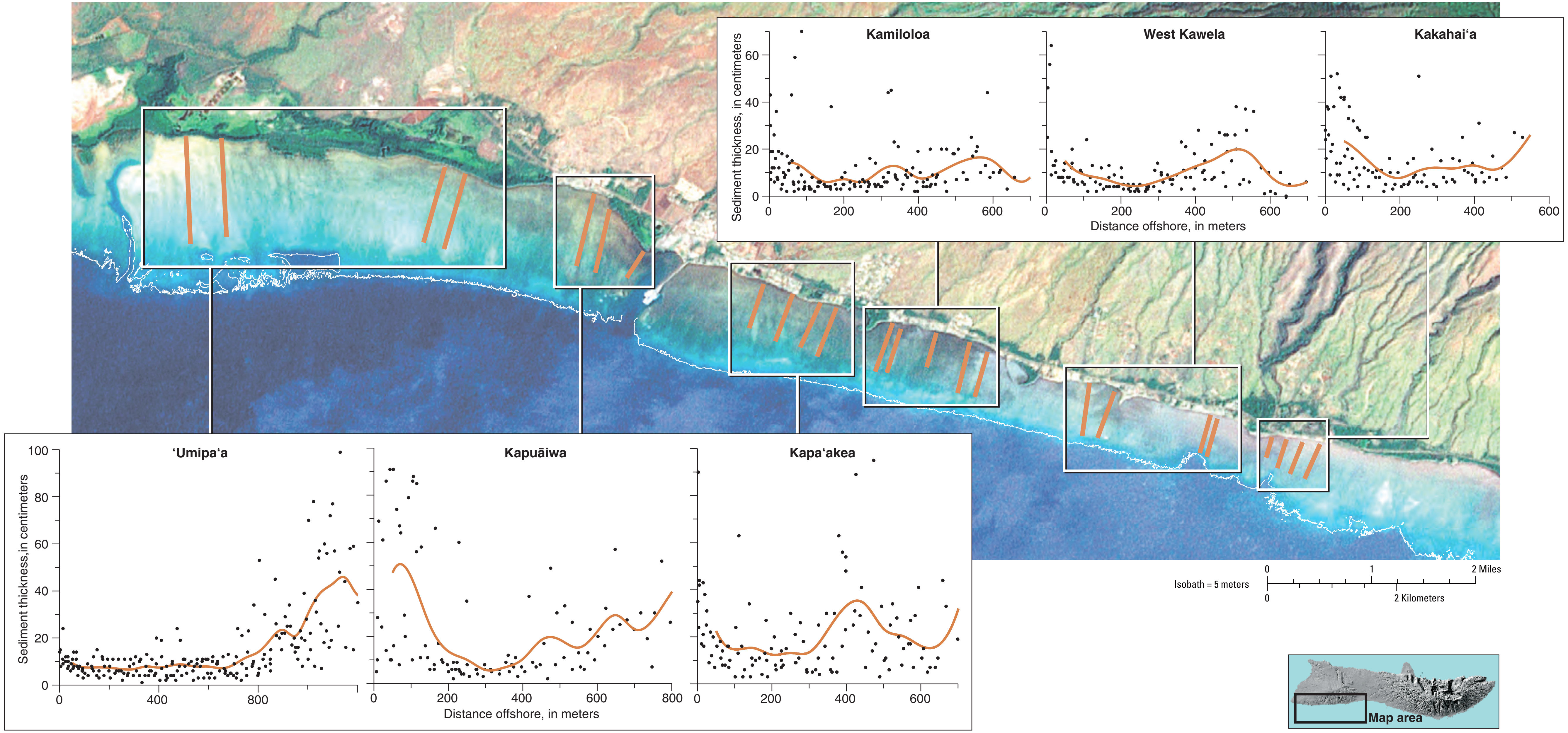


Figure 8. Sediment thickness on the Moloka‘i reef flat. Red lines on map show locations of sampling transects. Red lines on graphs are best-fit averages. Sediment thickness off **Kakahai‘a**: The thick sediment within 100 m (328 ft) of the shoreline is a reflection of the proximity of Kawela Gulch and 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 Moloka‘i 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 Pālā‘au; 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 Moloka‘i 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 Moloka‘i 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 Pālā‘au 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, Kakahai‘a).

- 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 Moloka‘i 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 Moloka‘i have very limited sources available for natural replenishment.

On the south shore of Moloka‘i, 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 Moloka‘i 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 Moloka‘i 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

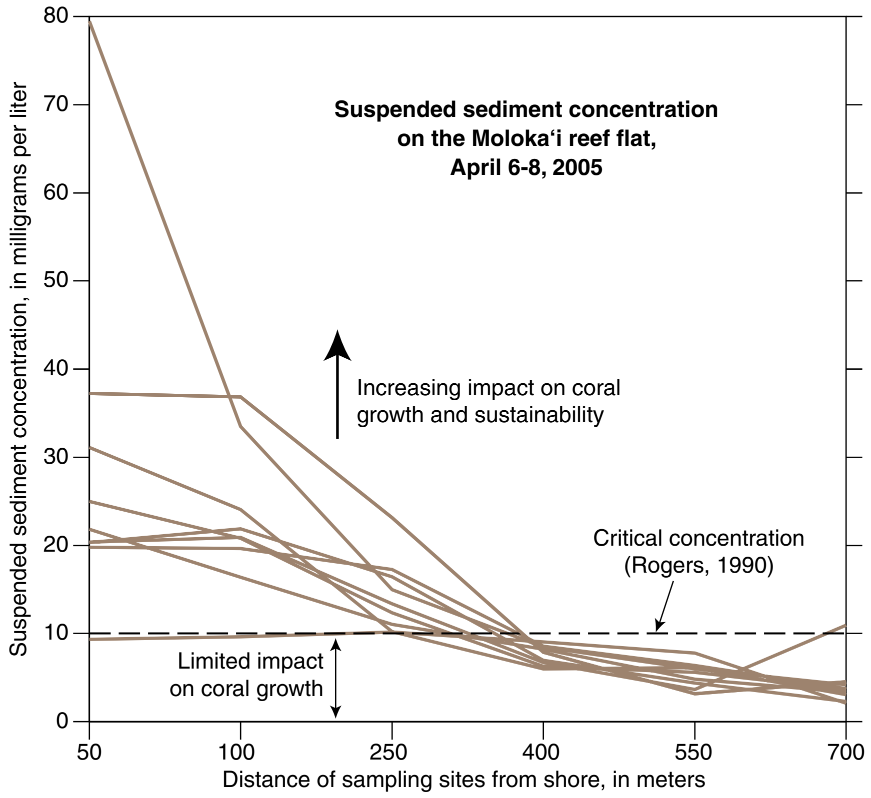
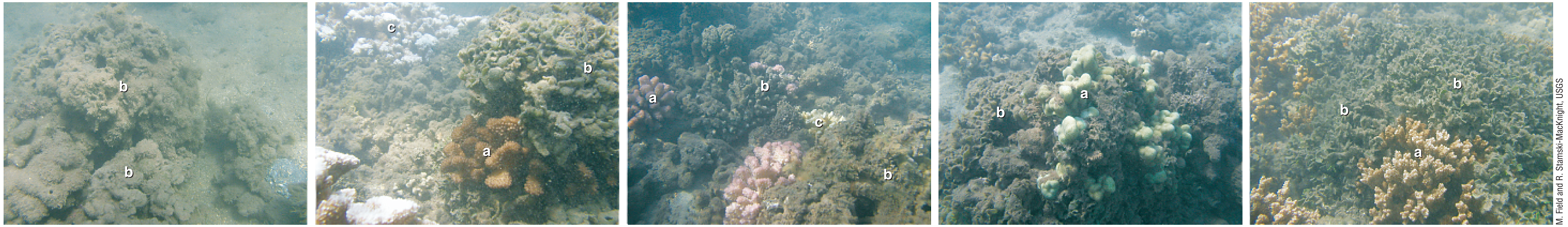


Figure 9. Diagram of suspended sediment concentrations across the reef flat between Kamalō and the Kaunakakai Wharf measured at 1-mile intervals along the shore in April 2005. All of the profiles show high levels of suspended sediment (typically 10 to 40 mg/L and higher). The values steadily decrease 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.



M. Field and R. Stamski-MacKnight, USGS

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.

CHAPTER 18

Measurement of Toxicity in Reef Sediments

R. Scott Carr[1] and Marion Nipper[2]

The shoreline of the south coast of Moloka‘i is composed of narrow sandy beach deposits and muddy mangrove habitats that border the wide, low-energy reef flat. Such a setting is prone to the deposition of fine-grained particles, and increased siltation has occurred on the reef in historical times as a result of several factors (see Roberts and others, this vol., chap. 15, for a discussion of historical siltation). Terrigenous sediment runoff and deposition on coral reefs is recognized as a hazard to coral health. In addition to the smothering effect, terrigenous runoff can contain contaminants from urban and agricultural activities (fig. 1) that have the potential to affect the health and survival of the coral reef with its associated flora and fauna.

The probable biological effects of sediment-associated contaminants can be determined using porewater toxicity tests, which allow an assessment of the presence of bioavailable contaminants in toxic amounts (Carr, 1998; Carr and Nipper, 1998; Carr and others, 2003; Nipper and Carr, 2001). A sediment quality survey was conducted to assess the presence of bioavailable contaminants in toxic amounts in surficial sediments off the southern coast of Moloka‘i, Hawai‘i. The specific objectives of this study were to measure porewater toxicity by analyzing fertilization and embryological development success using the sea urchin *Arbacia punctulata* in conjunction with measurements of water-quality parameters (salinity, dissolved oxygen, pH, sulfide, temperature, ammonia, and dissolved organic carbon).

Materials and Methods

The toxicity of sediment collected from 10 stations was assessed using porewater tests during 2001, and a more focused study was conducted in 2002. Pore water was extracted on site using a diver-held syringe with an aquarium airstone attached (fig. 2). The syringe was inserted approximately 6–8 cm (2–3 in) below the sediment surface. Toxicity of the sediment pore water was determined using the fertilization and the embryological development tests with the sea urchin *Arbacia punctulata* (Carr and others, 2003). Complete methodology may be found in Carr and Nipper (2001, 2003).

Figure 1. Aerial view, looking south, of agricultural activities in south-central Moloka‘i.

Toxicity Test Results

The toxicity test results for the 2001 survey are presented in figure 3. Porewater samples from stations 2, 4, 6, 9, and 10 were significantly toxic in the sea urchin fertilization test at a concentration of 100 percent, and samples from stations 2 and 9 were also toxic at a 50-percent dilution, denoting a higher concentration of bioavailable contaminants. Only the sample from station 9, on the fore reef off Kamiloloa, was significantly toxic even when diluted to 25 percent pore water, indicating a very high concentration of bioavailable contaminants.

The toxicity test results for the more focused 2002 survey are presented in figure 4. Only two samples from this survey were toxic to sea urchin early life stages. The sample from station 1 near Kapuāiwa coconut grove was marginally toxic to sea urchin fertilization at 100 percent pore water, and the sample from station 3 just east of Kaunakakai Wharf was significantly toxic to sea urchin embryological development at a concentration of 100 percent. Water-quality data and dissolved oxygen concentrations for the porewater samples have been reported elsewhere (Carr and Nipper, 2001, 2003) and were well within acceptable ranges.

What the Tests Showed

The primary objective of the initial study in 2001 was to determine if erosion problems in Moloka‘i have led to the deposition of contaminants in toxic amounts in the vicinity of the extensive coral reef system along the south shore. Porewater toxicity test results suggest that station 9 on the fore reef off Kamiloloa had the highest amount of bioavailable contaminants, with toxic effects in the sea urchin fertilization and embryological development tests at 50-percent and 25-percent porewater concentrations, respectively (fig. 3). If the contaminants occurring at station 9 originated from direct runoff from land-based activities, as opposed to an underground spring exiting offshore, the same chemicals would be expected to occur at stations 10 and 1, closer to shore. However, stations 10 and 1 were much less toxic. The higher toxicity at station 9 could be due to higher bioavailability of contaminants as a result of the apparent coarser nature of the sand at that station. Finer sediment was observed at stations 10 and 1. The role of both total and dissolved organic carbon (DOC) in binding organic contaminants (Di Toro and others, 1991; Haitzer and others, 1998) as well as some metals (Mahony

Figure 2. Diver conducting porewater extraction on the sea floor using a syringe with an aquarium airstone attached.

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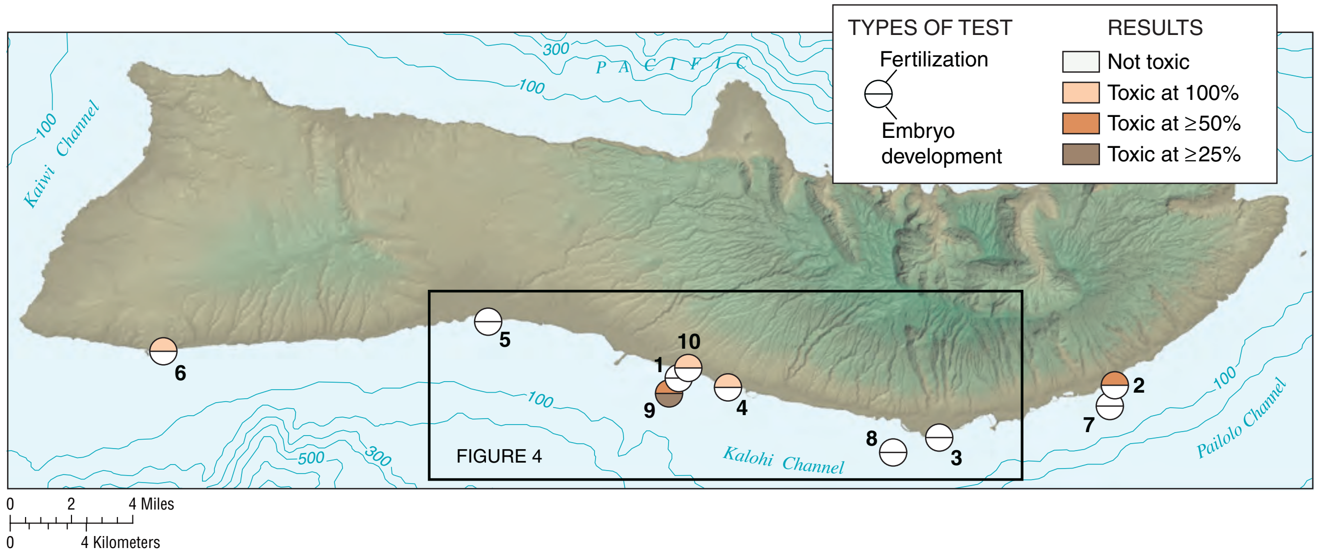

Figure 3. Toxicity test results on sea urchin fertilization and embryo development for sampling sites 1 to 10 on south coast of Moloka‘i in 2001 survey.

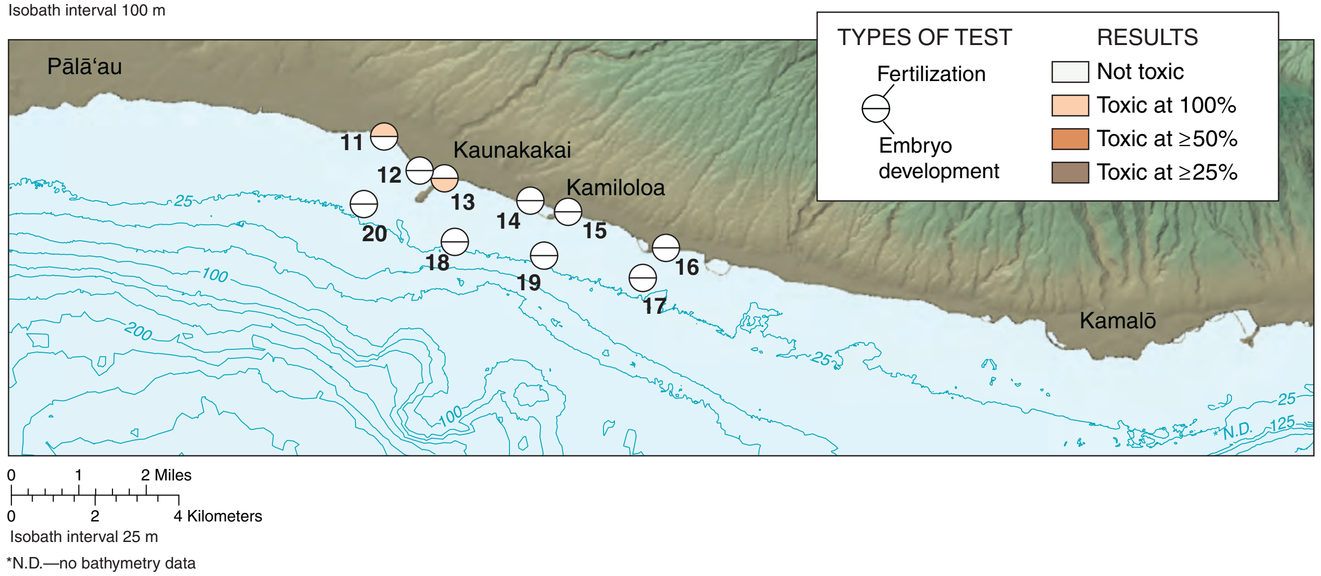

Figure 4. Toxicity test results on sea urchin fertilization and embryo development for sampling sites 11 to 20 on central south coast of Moloka‘i in 2002 survey.

and others, 1996) and reducing their bioavailablity is well recognized (Nipper and others, 2002). For the three stations mentioned above, the porewater DOC concentration was highest at station 1 (not toxic), and lowest at station 9 (highly toxic), with an intermediate value at station 10 (moderately toxic to sea urchin fertilization). This supports the suggestion that organic carbon content may have been at least partially responsible for the toxicity test results. Chemical analyses for the assessment of specific contaminants and their concentrations were not performed in this study.

Nearshore stations 4 (at One Ali‘i Park) and 6 (near Hale O Lono) were moderately toxic to sea urchin fertilization, and station 2 (at Pūko‘o) was also toxic at the 50 percent porewater dilution. The reason for the toxicity to the fertilization test only, and not to sea urchin embryological development, is likely to be related to the type of contaminants present at the sites. For instance, the sea urchin fertilization test is more sensitive than urchin embryos to a variety of metals, including copper, mercury, zinc, and silver (Nacci and others, 1986; Carr and others, 1996). It was not the objective of this initial survey to establish the category of contaminants present in the marine sediment tested.

The primary objective of the followup study in 2002 was to conduct a more focused survey in the region exhibiting toxicity previously and to attempt to identify the contaminants at a site that was highly toxic in 2001. Porewater toxicity test results for samples collected in August 2001 suggested that station 9 (offshore Kamiloloa) had the highest amount of bioavailable contaminants. That sample exhibited toxic effects in the sea urchin fertilization and embryological development tests at 50-percent and 25-percent porewater concentrations, respectively. However, a new porewater sample collected in August 2002 at this station (fig. 4, station 19) did not exhibit any toxic effects in either test. These data suggest that the contaminants that caused toxicity in the previous year were from a transient source and had been dispersed a year later. Dispersion of contaminants from such a coarse sand substrate, where the porewater DOC concentration was among the lowest measured from all the stations sampled on Moloka‘i, is not particularly surprising. Toxicity would only be expected to persist in such an environment if a continuous source of contaminants existed in the area, which apparently is not the case. Nearshore stations 11 and 13 were toxic to urchin fertilization and development, respectively, in 2002 (fig. 4). Station 11 was near a freshwater seep at Kapuāiwa Park, which might have brought land-based or ground-water contaminants to the area. Station 13 was on the eastern side of Kaunakakai Wharf, and the observed toxicity could be the result of runoff of contaminants generated by urban activity.

In conclusion, this study did not demonstrate the consistent presence of bioavailable contaminants in toxic amounts in most areas off southern Moloka‘i. Therefore, it appears that the degraded reefs are not the result of persistent contaminants or chronic contaminant inputs. These results, in conjunction with previous studies, suggest that transient events from ground water or runoff can introduce contaminants at toxic concentrations at some locations, but these inputs do not appear to be continuous.

CHAPTER 19

Sediment Mobility Along Moloka‘i’s Fringing Coral Reef: Evidence From Sediment Traps

Michael H. Bothner[1], Richard L. Reynolds[2], Michael A. Casso[1], Curt D. Storlazzi[3], and Michael E. Field[3]

There is concern about the potential negative impact of suspended sediment and sedimentation on the health of the coral reef off Moloka‘i (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 Moloka‘i 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.

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

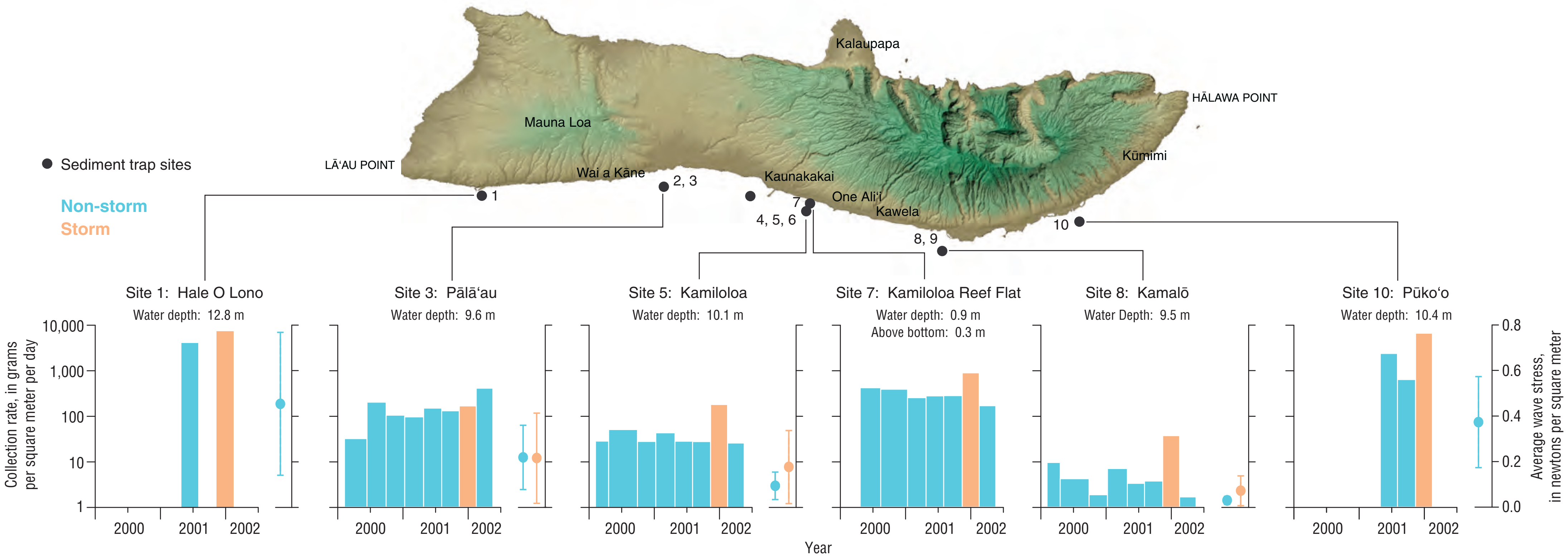

Figure 1. Location of sediment traps along the south shore Moloka‘i reef, along with collection rates (bars, log scale) during successive roughly three-month periods. Collection rates from nonstorm periods are shown in blue, and data from the deployment period containing Kona storms are shown in orange (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.

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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

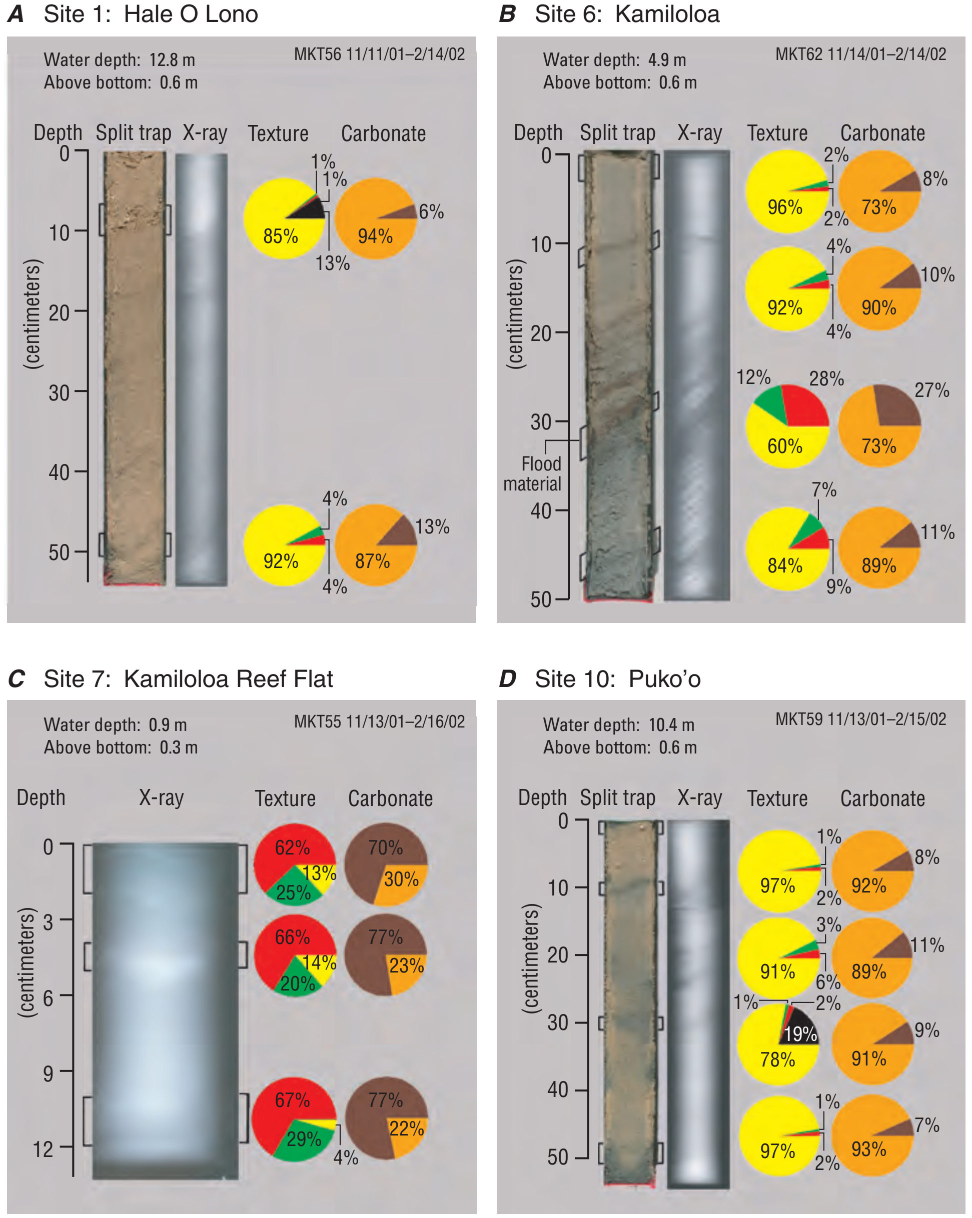


Figure 4. Characteristics of sediment trapped during the deployment in which Kona storms occurred. Traps were X-rayed, split, and photographed. Selected layers were analyzed for sediment grain size and for calcium carbonate content. Traps shown in *A*, *B*, and *D* were full when recovered. *A*, The 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 Moloka‘i.

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 Pālā‘au (site 3) to 39 times higher at Kamalō. The tube traps at Hale O Lono (site 1) and Pūko‘o (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 Pūko‘o, on the wave-exposed western and eastern ends of the reef, and lowest at Kamalō. Sediment collection rates were intermediate at Kamiloloa and Pālā‘au. 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 Pālā‘au, 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.

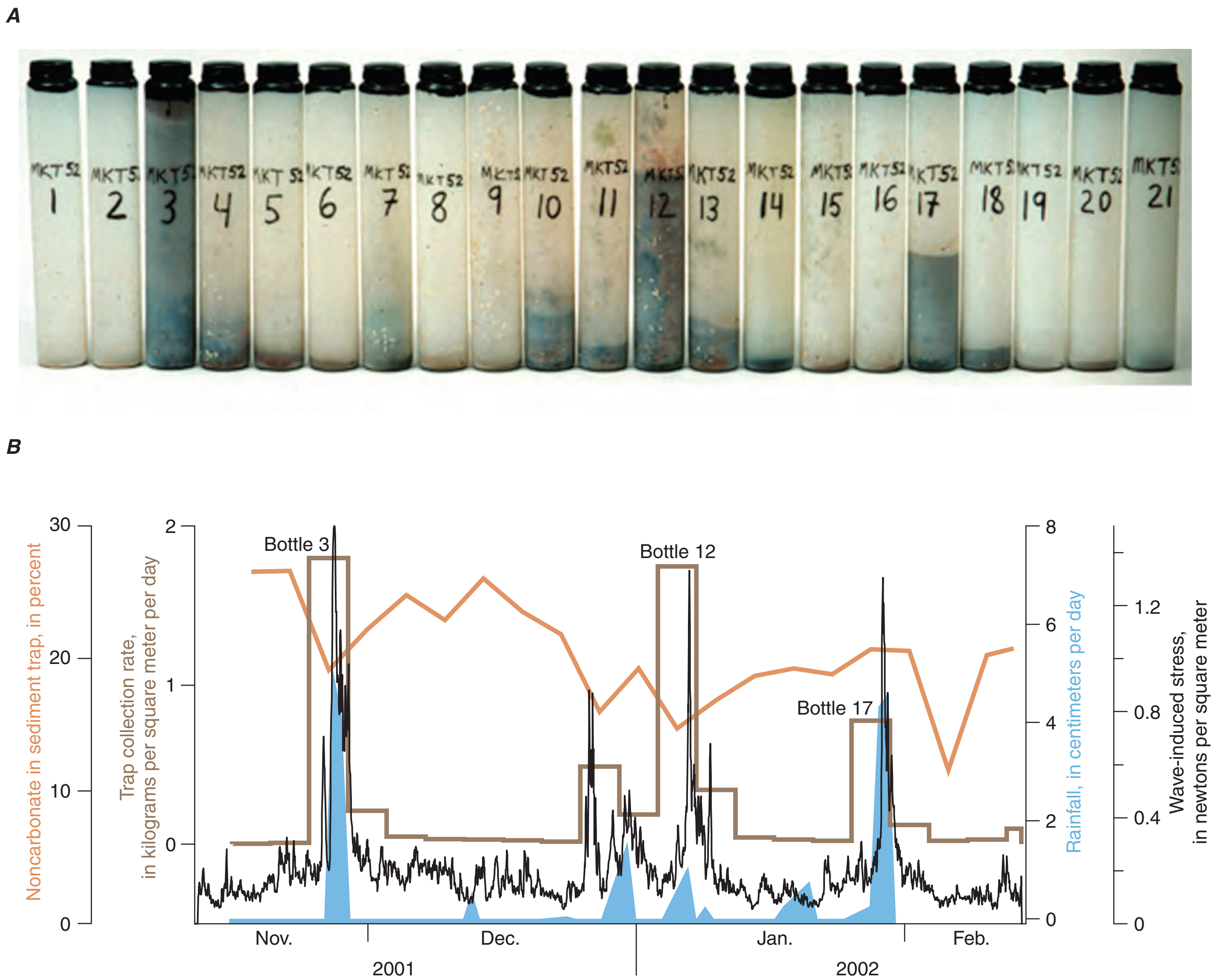


Figure 5. Sediment collection at Pālā‘au at 12.6 m (41.3 ft) water depth. *A*, Photograph of sample bottles with various amounts of gray sediment collected at Pālā‘au during successive 4.5-day intervals between November 15, 2001, and February 14, 2002. *B*, Plots of trap-collection rate, rainfall, wave-induced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

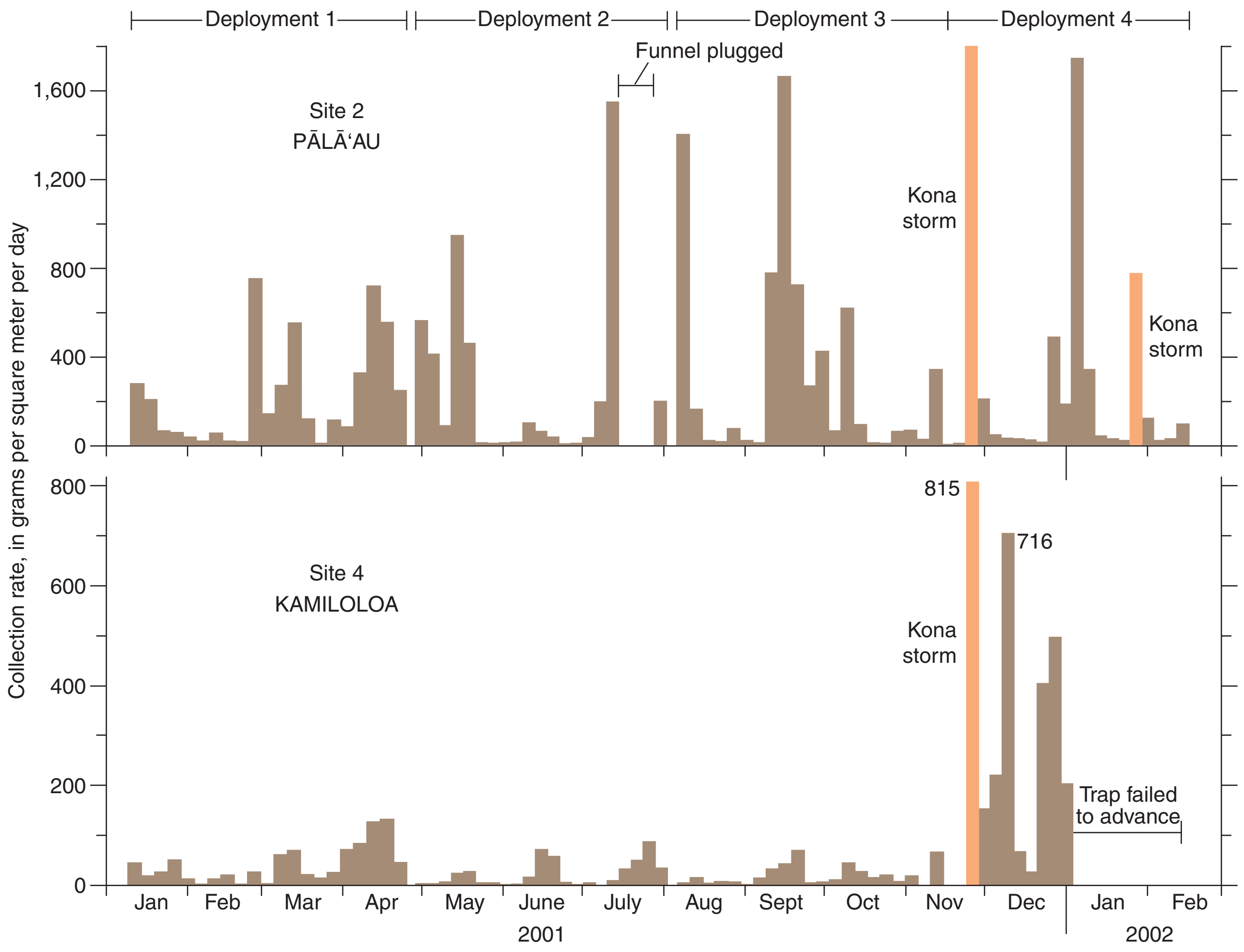


Figure 6. Collection rates determined in time-series traps were consistently higher at Pālā‘au (top) than at Kamiloloa (bottom) in response to higher wave-induced bottom stress. Orange bars represent intervals during which Kona storms occurred. The similarities in timing of many peaks in collection rate 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

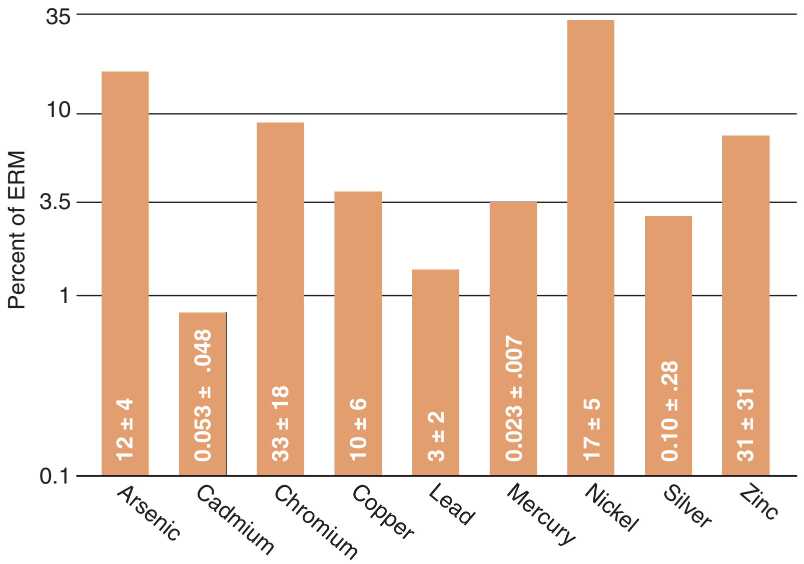


Figure 7. Histogram showing the average metal concentration (in parts per million, mean ± one standard deviation) in sediments trapped off south Moloka‘i as a percentage of the Effects Range-Median (ERM), a guideline for sediment toxicity (Long and others, 1995).

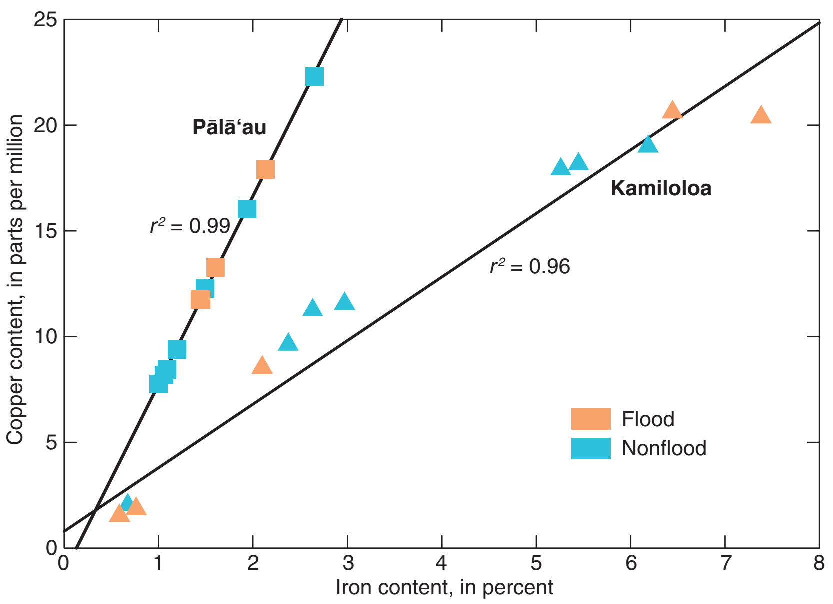


Figure 8. Concentrations of iron (percent dry weight) and copper (parts per million = µg/g) are highly correlated within trap samples from Pālāʻau and Kamiloloa. Samples collected during flood periods (orange) plot on the same line as those collected during non-flood periods (blue). These data suggest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

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 Molokaʻi 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.

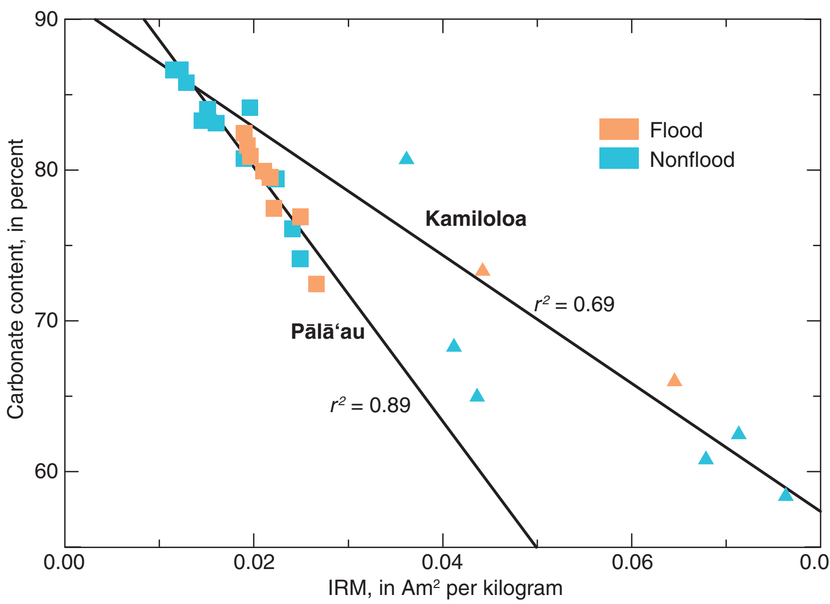


Figure 9. The different regression lines for isothermal remanent magnetization (IRM in units of ampere meter squared per kilogram) versus percent calcium carbonate in trap samples from Pālāʻau and Kamiloloa indicate a higher magnetite content in the land-derived fraction of Kamiloloa traps. Data from 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.

The time-series sediment traps at Pālāʻau and Kamiloloa (fig. 6) provide two pieces of new information. First, the collection rates are consistently higher at Pālāʻau 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 Pālāʻau 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 Pālāʻau 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 Pālāʻau. 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 Molokaʻi, 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, Molokaʻi, oral commun., 2004).

The concentrations of most heavy metals correlate with concentrations of iron, one of the main elements in Molokaʻi'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 Pālāʻau 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 Pālāʻau 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 Pālāʻau.

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.

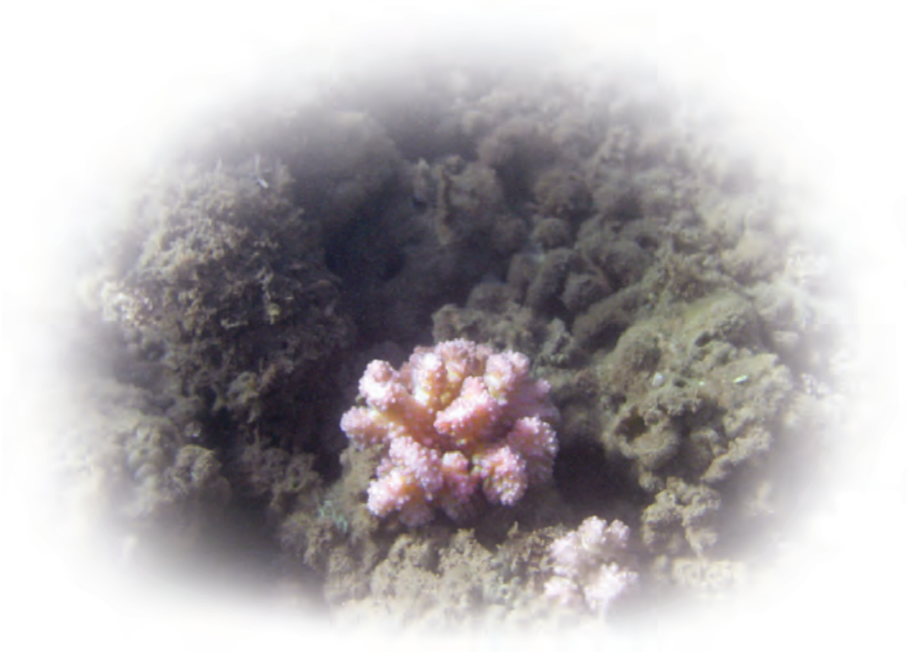
Following the Kona storms and floods beginning in late November 2001, we measured a significant increase in the land-derived fraction of trapped sediment on the reef flat at Kamiloloa, and a much weaker “flood signal” at sites on the fore reef at 4.9-m and 11.5-m water depth. At other sites along the 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.



CHAPTER 20

Causes of Turbidity on the Moloka‘i Reef Flat and Resulting Sediment-Transport Patterns

Andrea S. Ogston[1], M. Katherine Presto[2], Curt D. Storlazzi[2], and Michael E. Field[2]

Turbidity and sedimentation are generally recognized as important factors that can impair coral health (Acevedo and others, 1989; Fortes, 2000; Rogers, 1990; Buddemeier and Hopley, 1988). Turbidity on reefs is a difficult parameter to characterize, because it concerns not only the amount of sediment suspended in the overlying water column (suspended-sediment concentration), but also the frequency and duration of resuspension and the types of particles in suspension. In general, the physical environment controls the factors that regulate turbidity on reefs. Four important factors that control the sedimentary regime are tides, waves, currents, and amount of available sediment, all of which vary over time on hourly, daily, seasonal, and longer scales.

Between January 2000 and August 2002, we studied these processes and their influence on turbidity on the Moloka‘i reef flat (fig. 1), a topographically rough, nearly horizontal surface ranging from 0 to 2 m (0 to 6.5 ft) in depth, that extends almost 1 km (0.6 mi) from the shoreline outward to the reef crest. The reef crest itself is a shallow, irregular barrier between the reef flat and the open ocean. Our studies identified a suite of processes and their temporal changes, using a small instrumented tripod (ReefProbe, fig. 2) deployed at 1-m (3.3 ft) water depth approximately midway across the reef flat. The instruments collected a 2-year record of water-surface elevation, water properties (temperature and salinity), currents (due to waves, tides, and winds), and suspended-sediment concentration. To complement the single-point time-series data, in May and August 2002 we used a portable instrument package (Backpack, fig. 3) to measure currents and water properties for a few minutes at multiple sites along transects spanning the reef flat and reef crest between One Ali‘i Park and Kaunakakai Wharf (fig. 1).

In this chapter, we summarize the results of these investigations to illustrate the processes that contribute to turbidity on the Moloka‘i reef flat and the resulting sediment-transport patterns. For a more detailed analysis, see reports by Ogston and others (2004), Storlazzi and others (2004), and Presto and others (2006).

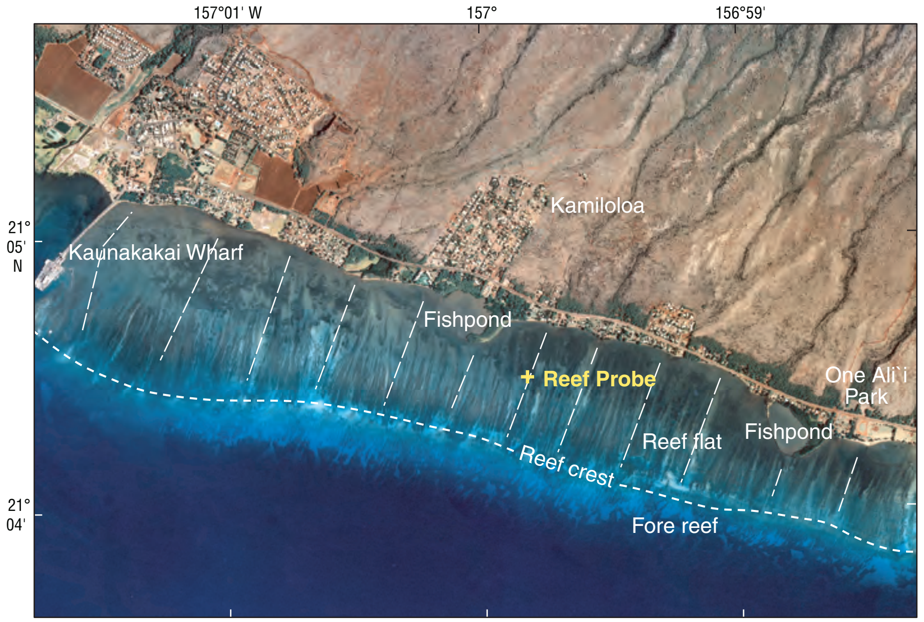


Figure 1. Moloka‘i reef flat, showing general location of study area. Data were obtained from two sources: (1) a small instrumented tripod, the ReefProbe, placed on the mid reef flat collected time-series data for almost 2 years; and (2) a portable instrument package, the Backpack, was used to collect measurements at multiple sites along transects (dashed lines) during high and low tides when trade winds were active.

Transport of Sediment and Water on the Reef Flat

Typical Environmental Conditions

The amount of sediment suspended in the water column and how rapidly sediment transport occurs depend on environmental conditions related to the weather. The most conspicuous feature of the weather pattern in the tropical Pacific Ocean is the persistent trade winds that blow generally northeast to southwest. Their effect is greatest across Hawai‘i during the trade-wind season (May-November), when they are prevalent 80–95 percent of the time; during the non-trade-wind season (November-May), trade winds still blow across the islands much of the time, though with decreased frequency. Storms bring heavy rains and strong winds to the Hawaiian Islands, generally during the non-trade-wind season. In particular, Kona storms from the south generate large waves offshore and rainfall that brings freshwater and sediment from the uplands to the reef on southern Moloka‘i. Storms over the open ocean to the south of the Hawaiian Islands generate large waves that can propagate as swell to the south coast of Moloka‘i.

To illustrate the effect of environmental conditions over the year, we classified the data from the ReefProbe according to the four environmental conditions that occur most frequently on the Moloka‘i reef flat: (1) trade winds, (2) storms, (3) swell, or (4) light winds of varying direction without swell (referred to simply as light winds). We compared the magnitude, direction, and duration of winds, as well as offshore wave conditions, during the period May 2001–May 2002 to evaluate which environmental condition dominated. We divided the periods over which each of these environmental conditions occurs by season (fig. 4). For example, during the trade-wind season, the trade-winds environmental condition occurred 83 percent of the time, while the swell environmental condition occurred only 13 percent of

Figure 2. Time-series data on the Moloka‘i reef flat were obtained by using the ReefProbe deployed on the mid reef flat at 1-m (3.3 ft) water depth. The ReefProbe contained sensors that measured current (electromagnetic current meter), tidal elevation and wave height (pressure sensor), turbidity or suspended-sediment concentration (optical-backscatter sensor and transmissometer), and salinity and water temperature (conductivity and temperature sensor).

Instrument	Height above bed (cm)
Electromagnetic current meter	20
Pressure sensor	30
Optical-backscatter sensor	20
Transmissometer	20
Conductivity and temperature sensor	55

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Figure 3. The Backpack, used for spatial studies, provided a perspective on sediment-transport processes along and across the Moloka‘i reef flat under specific conditions. The instrument package contained sensors that measured the same properties as the ReefProbe (fig. 2).

Instrument	Height above bed (cm)
Electromagnetic current meter	20
Pressure sensor	50
Optical-backscatter sensor	20, 50
Transmissometer	70
Conductivity and temperature sensor	Profiling

the time, although historically the swell environmental condition is much more frequent (Andrews and Pickard, 1990). Sheltering of the south-central coast of Moloka‘i by other islands (Maui and Lana‘i) partly accounts for the limited occurrence of the swell environmental contribution. The light-winds and storms environmental conditions rarely occurred (2 percent each).

During the non-trade-wind season, the light-winds environmental condition dominated the record (51 percent), while the trade-winds environmental condition occurred 37 percent of the time and the swell environmental condition 7 percent of the time. The storms environmental condition, which occurred only 5 percent of the time, was more prevalent during this season; a strong Kona storm struck Moloka‘i in November 2001, and smaller storms in December 2001 and January 2002. Although their strength varies, trade winds are the principal factor controlling sediment-transport processes on the Moloka‘i reef flat throughout the year, as is also true on other shallow-reef-flat environments where tidal currents and wave energy are relatively small (Pickard, 1986; Andrews and Pickard, 1990).

Currents and What Drives Them

Currents provide the stress (force per unit area) required to erode sediment from the seabed, create turbidity in the water column, and move the sediment elsewhere. On the Moloka‘i reef flat, currents are principally driven by winds, tides, and waves, each producing a different sediment-transport pattern.

Wind-Driven Currents

In general, wind-driven currents are the strongest unidirectional currents on the reef flat. Throughout the year, these currents are driven by trade winds (Nov. 16–26, 2000, figs. 5*A*, *B*), with flow toward the west and offshore at the ReefProbe site (fig. 1). The offshore component is not a persistent feature along the reef flat but can be explained by the position of the instruments relative to the orientation of the shoreline, as indicated in the Backpack studies discussed below. During the trade-winds environmental condition (fig. 5*A*), mean currents at the ReefProbe site were influenced by the speed and duration of the winds, resulting in a flow (>10 cm/s) to the west and slightly (~2 cm/s) offshore on the reef flat, regardless of tidal cycle. These currents occurred predominantly during the afternoon for approximately 70 percent of the year, during both the trade-wind and the non-trade-wind seasons. Under the light-winds environmental condition, slow (1–3 cm/s) currents were observed. During Kona storms, wind speeds were high, and currents were strong (>10 cm/s) but varied in direc-

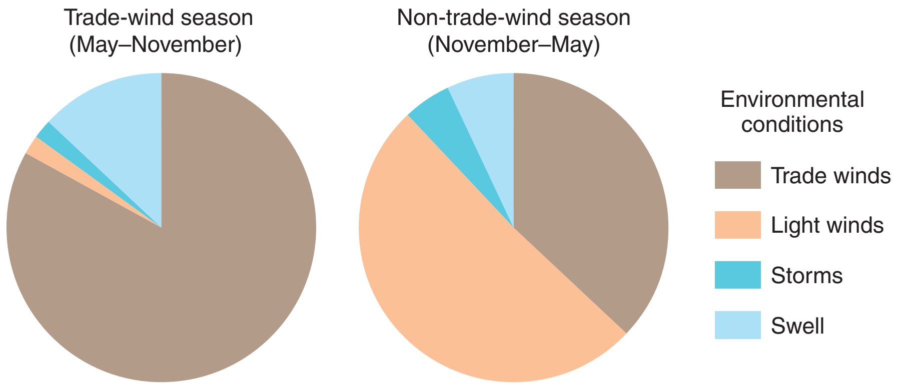

Figure 4. The distribution of four environmental conditions as measured by the ReefProbe on the Moloka‘i reef flat in a typical 1-year period (2001-2002) during trade-wind (May-November) and non-trade-wind (November-May) seasons. Environmental conditions were determined by examining the direction, speed, and duration of winds as measured by a sensor at the end of Kaunakakai Wharf, as well as by offshore wave conditions.

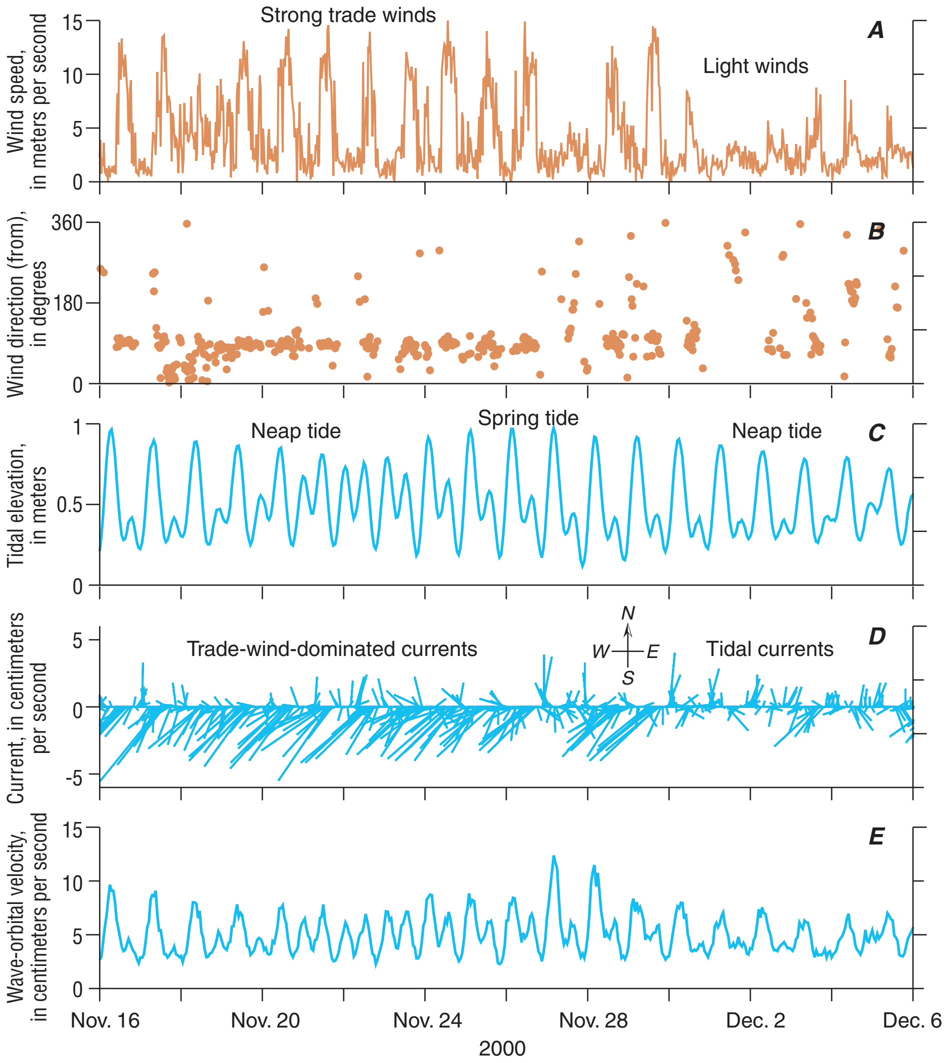

Figure 5. Environmental factors that contribute to sediment resuspension on the Moloka‘i reef flat include winds and tides. In this example from a time series in late November 2000, both trade-winds and light-winds environmental conditions are prevalent. During the trade-winds environmental condition, winds were strong and varied on a daily cycle, peaking in the afternoon (*A*), and were in a direction along the reef flat of ~110˚ (*B*). During light-winds environmental condition, the winds were weaker and had no specific direction. Tides are defined as microtidal and have a range of ~0.6 m (~2 ft) with a mixed semi-diurnal signal, varying on a fortnightly cycle between neap and spring tides (*C*). Response of water on the reef flat to trade winds and tides is complex. Trade winds generate along-reef currents with a small offshore component (*D*). During light winds, currents are weak and vary in direction. Winds also create waves on the sea surface that, in turn, cause wave-orbital motions at the sea bed; wave-orbital velocities (*E*) are controlled by both winds and water depth.

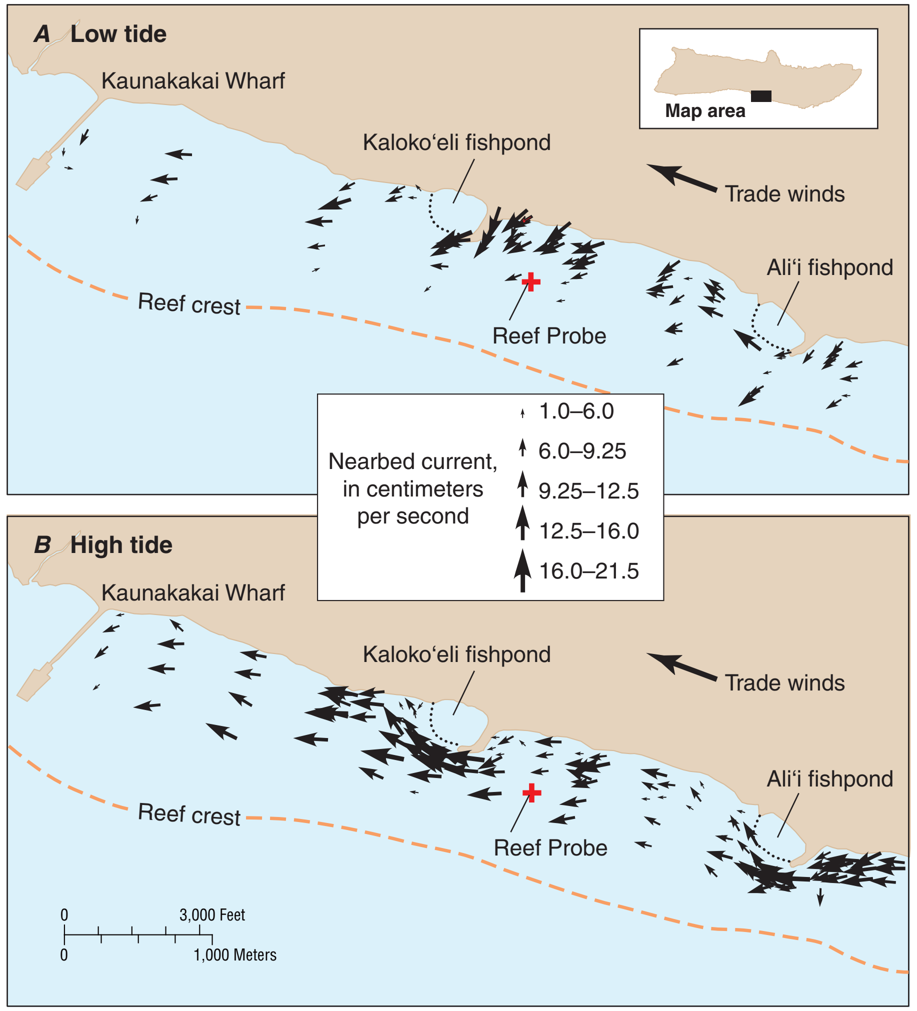

Figure 6. Observed nearbed (20 cm or 7.9 in above seabed) mean currents on the Moloka‘i reef flat during trade-winds environmental condition vary spatially and with tidal stage, as seen in measurements at low tide (*A*) and high tide (*B*). Dominant current direction is alongshore to the west at most survey points on the reef flat, with a slight offshore flow on the east (upwind) side of fishponds and onshore flow on the west (downwind) side at both tidal stages. All measurements were taken in <2-m (<6.6 ft) water depth.

tion as the storms passed, resulting in relatively minor net currents in both the alongshore and cross-shore directions. Under the swell environmental condition without the presence of trade winds, wind-driven currents were slow (<5 cm/s), with flow slightly eastward and shoreward.

From Backpack measurements, the pattern of trade-wind-driven currents over the Moloka‘i reef flat was observed to be strongly alongshore to the west, following the coastline in the direction of the trade winds, with a minor offshore component at the fishponds and wharf (fig. 6). Currents ranged from ~1 to 25 cm/s, faster where the reef flat is narrow and deep, slower over the broader, shallower parts of the reef flat, and significantly slower near Kaunakakai Wharf, indicating some stagnation of water against the wharf. A more detailed analysis of these data was presented by Presto and others (2006).

The spatial maps of currents in figure 6 allow an approximation of a water-transport rate for various sections of the Moloka‘i reef flat by moving water at the speed and in the direction measured at one transect to a position on the next transect. For a pathway approximately halfway across the reef flat, water is transported from One Ali‘i Park to the Kaunakakai Wharf (fig. 1), a distance of ~5 km (3.1 mi), in 13 hours (average speed, 9.7 cm/s) during high-tide and high-wind conditions. Typically the trade-winds environmental condition occurs, on average, 6 hours per day. Thus, a parcel of water flowing on the mid reef flat would take about 2 days to travel the 5 km from One Ali‘i Park to the wharf. For a pathway on the inner reef flat, water is transported during high tide and under the trade-winds environmental condition in about twice the time (>4 days), owing to the much slower currents (average speed 6.4 cm/s) and the slightly longer pathlength due to obstructions (fishponds). Because water moves slower on the inner reef flat than on the mid reef to outer reef flat and the distance traveled in the pathway around the fishponds is greater, alongshore flushing rates are significantly slower on the inner than on the outer reef flat.

Tidal Currents

The tides in Hawai‘i are defined as microtidal (tidal range, <2 m or 6.5 ft) and have a mixed semidiurnal signal, with two daily highs and lows, dominated by one extreme high and low each day (fig. 5*C*). Though small in range, the changing tidal elevation is particularly important because of its influence on waves and currents on the Moloka‘i reef flat, owing to the reef's broad, shallow shape. The observed tidal range on the reef flat was typically 0.6 m (2 ft), with a maximum of ~1.0 m (3.3 ft). Although the tidal range off southern Moloka‘i is small relative to elsewhere in the world, it represents more than a doubling in water depth over much of the reef flat. This tidal variation over the reef flat is important for sediment resuspension and transport because wave heights are limited by the depth of water. At higher tides, the effects of offshore waves are greater on the reef flat because more offshore wave energy can be transferred through the deeper water over the reef crest. The greater water depth also allows for larger local wave formation on the reef flat.

Tidal currents on the reef flat have both semidiurnal (12.4 h) and diurnal (24.8 h) components. We evaluated data recorded at the ReefProbe site (fig. 1) during light-winds environmental conditions to estimate the tidal currents. Tidal currents on the reef flat were generally slow (3–5 cm/s) relative to wind-driven currents (max 15 cm/s; fig. 5*D*).

Wave-Orbital Currents

The waves on the Moloka‘i reef flat are small and result from offshore waves that propagate over the reef crest, from waves that are generated locally by wind stresses, or from some combination of both factors. Wave heights in the open North Pacific Ocean can be large because they are not influenced by the landmasses of the islands, and significant wave heights average 2 to 3 m (6.6 to 9.8 ft) throughout the year. The waves offshore of the south-central coast of Moloka‘i are much smaller, typically averaging ~0.5 m (~1.6 ft), because the surrounding islands of Lana‘i and Maui protect south Moloka‘i from large, open-ocean waves. As waves off the coast approach the reef, they significantly decrease in height as they

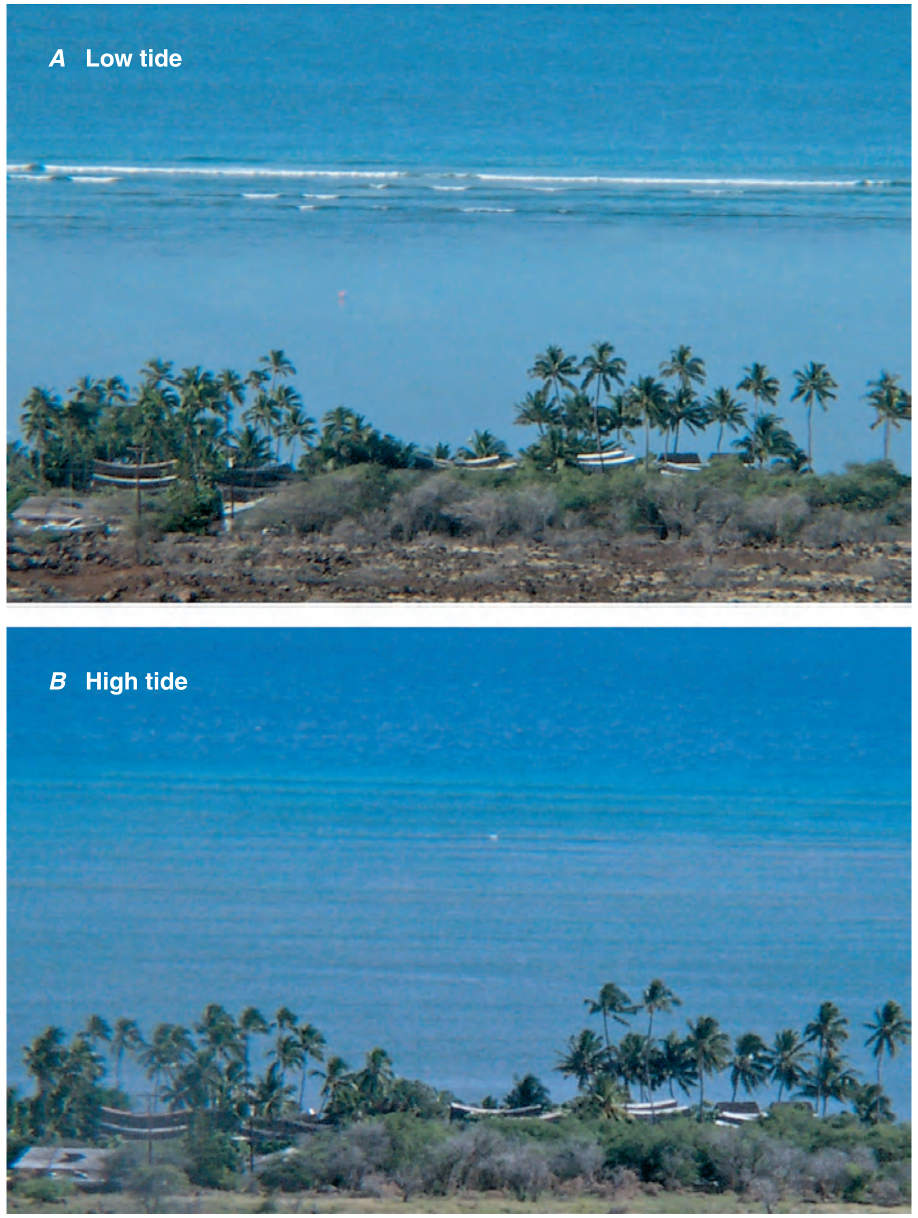

Figure 7. Photographs taken from an autonomous camera mounted above Kamiloloa show the difference in waves breaking on the Moloka‘i reef crest at low (*A*) and high (*B*) tides. At low tide, waves break on the reef crest, and little wave energy from offshore waves reaches the reef flat, whereas at high tide, some offshore wave energy can propagate through the reef crest to generate wave-orbital velocities on the reef flat.

break on the reef crest. The waves that we observed on the reef flat were small (~0.1–0.2 m or ~0.3–0.7 ft during high tide), and their height was more influenced by tidal elevation than offshore wave height (fig. 7).

Waves cause the water to move in oscillating (or orbital) patterns, which were measured on the Moloka‘i reef flat as the wave-orbital velocity. Nearbed wave-orbital velocities varied on a daily basis at tidal periods (fig. 5*E*), with a maximum of ~15 cm/s. At low tidal elevations, the wave-orbital velocity was low (<5 cm/s), whereas at high tidal elevations, it was higher (max 10–15 cm/s) and less predictable. The high degree of correlation between tidal elevation and wave-orbital velocity implies that the wave-orbital velocity on the reef flat is strongly controlled by water depth, irrespective of whether the waves are generated offshore or locally on the reef flat by trade winds.

The combination of high water elevation (due to tides and storm surge—an increase in water elevation caused by wind and low atmospheric pressure) and high offshore waves caused the highest wave-orbital velocity at the seabed of the reef flat; however, this combination of factors occurred only over relatively short periods. The trade-winds environmental condition, with lower wave-orbital velocities on the reef flat, occurs persistently during the trade-wind season and intermittently during the non-trade-wind season.

Suspended-Sediment Concentrations

The amount of sediment suspended in the water column (suspended-sediment concentration) can be attributed to resuspension of sediment from the seabed or its advection (transport) from another area, or a combination of both these processes. Suspended-sediment concentration, which is expressed in units of weight per volume of seawater (milligrams per liter), increases in response to stresses on the seabed caused by wave-orbital velocities and/or mean currents. Currents measured on the reef flat are generally insufficient alone to resuspend even fine silt from the seabed. Wave-orbital velocities observed on the Moloka‘i reef flat, in the absence of currents, also are generally insufficient to resuspend the finest seabed sediment. When waves and currents act together (wave-current interaction), however, their combined stress is sufficient to resuspend sediment on the reef flat. Thus, the daily resuspension of sediment observed on the reef flat is typically generated by wave-current interaction.

Suspended-Sediment Concentrations Under Typical Environmental Conditions

Suspended-sediment concentrations on the Moloka‘i reef flat are responsive to the daily variations in winds, tides, and waves under the four typical environmental conditions. Thus, during the trade-winds environmental condition, sustained strong winds generate currents of >10 cm/s that flow westward alongshore, regardless of the tidal cycle. Peak suspended-sediment concentrations during the trade-wind season were measured at high tide, when the greater water depth over the reef flat allowed the generation of substantial wind-driven waves in addition to strong alongshore wind-driven currents. A typical daily peak in suspended-sediment concentration during the trade-wind season was ~20 mg/L on the mid reef flat (fig. 8).

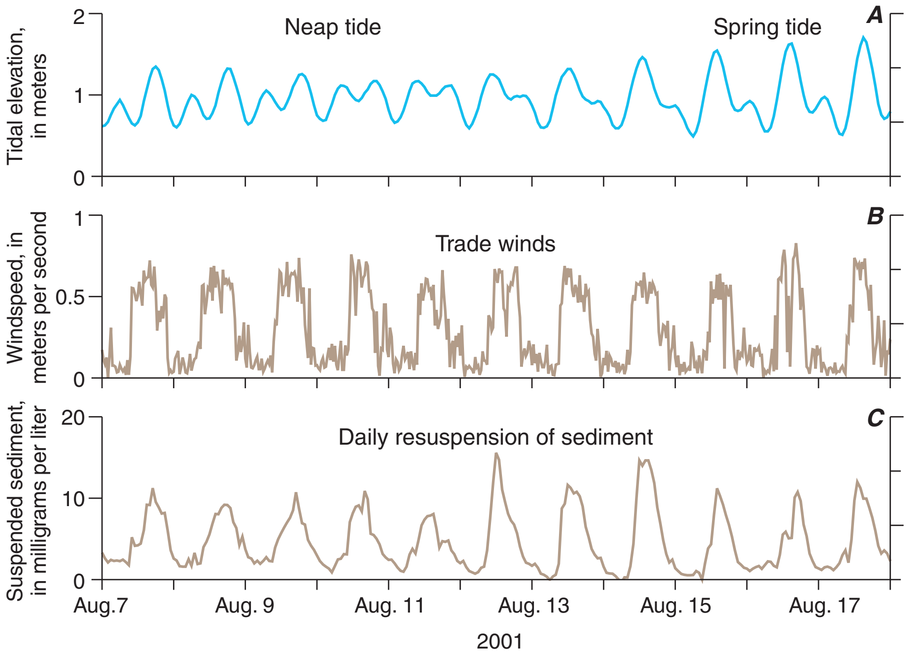

Figure 8. During trade-winds environmental condition, sediment is resuspended from the seabed, owing to a combination of wave-orbital velocities and wind-driven currents. During the period shown here, the water-surface elevation varies because of the tides (*A*) and strong trade winds (*B*), which control the wave-orbital velocity and wind-driven current (not shown). Resulting suspended-sediment concentrations (*C*) measured at the ReefProbe site on the Moloka‘i reef flat vary on a daily basis, with peak suspended-sediment concentrations resulting from strong winds and high tidal elevation.

Storms environmental conditions on the reef flat were infrequent, but the large storm waves that propagated onto it during high tide resuspended large amounts of sediment from the seabed, with peak suspended-sediment concentrations of 100 mg/L on the mid reef flat. Similarly, suspended-sediment concentrations under the swell environmental condition were also high (~40 mg/L) because wave-orbital velocities were high (>10 cm/s), especially during high tides, when larger deep-water waves are able to propagate over the reef crest and onto the reef flat. The nearbed mean currents under the swell environmental condition, in the absence of trade winds, were small and driven primarily by tides. Under the light-winds environmental condition, mean and tidal currents and wind-generated wave-orbital velocities were minimal. Although some sediment was still suspended, concentrations were quite low (<10 mg/L) and generally fluctuated with the tidal cycle (fig. 9).

Patterns of Suspended-Sediment Concentration

Backpack measurements at low and high tides under the trade-wind environmental conditions show the spatial relation between tidal stage and suspended-sediment concentration over the study area (fig. 10). During low tide (fig. 10*A*), the suspended-sediment concentration measured on the reef flat ranged from <5 to >70 mg/L, generally decreasing with distance off-

Figure 9. Photographs taken from same camera as in figure 7 show the difference in suspended-sediment concentration on the Moloka‘i reef flat at low tide under calm-wind conditions (*A*) and at high tide under trade-wind conditions (*B*). At low tide, turbidity of water is low, and the reef-flat surface is visible, whereas at high tide, wave-current interaction causes sediment to be suspended from the seabed, and turbidity of water is high.

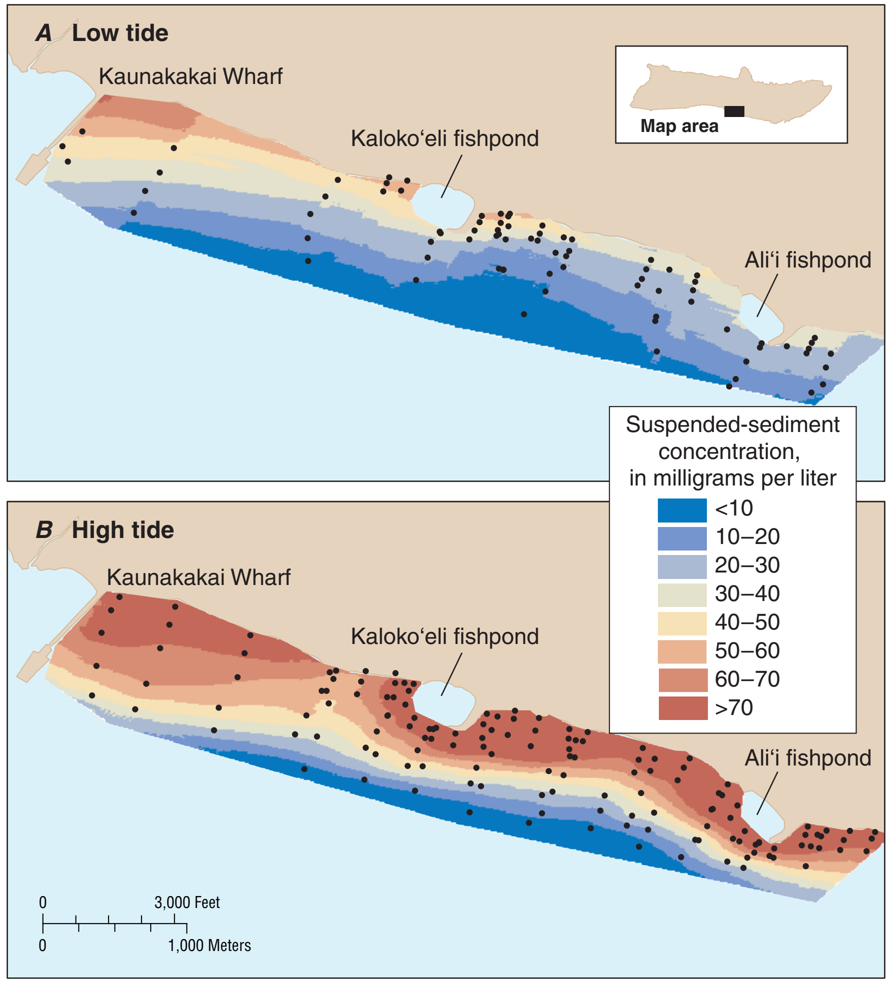

Figure 10. Amount of sediment resuspended under trade-winds environmental condition depends on location on the Moloka‘i reef flat and tidal stage, as shown by the spatial measurements at low tide during the period May 11–16, 2002 (*A*), and at high tide during the period August 18–22, 2002 (*B*). Peak suspended-sediment concentrations (>70 mg/L at low tide and >80 mg/L at high tide) observed at 20 cm (7.9 in) above seabed are shown in a nearshore band that widens around fishponds and to the east of Kaunakakai Wharf. Suspended-sediment concentration is relatively uniform throughout water column and rapidly decreases with distance offshore, indicating that most resuspendable fine sediment is contained on the inner reef flat. All measurements were taken in <2-m (<6.6 ft) water depth.

shore. The highest suspended-sediment concentrations were measured near shore and to the east (upwind) of Kaunakakai Wharf.

During high tide and under the trade-winds environmental condition (fig. 9*B*), the suspended-sediment concentration ranged from <5 mg/L offshore to >130 mg/L near shore and to the east (upwind) of the fishponds and wharf (fig. 10*B*). Higher suspended-sediment concentrations during high tide are due to greater water depths over the reef flat that allow deep-water waves to propagate over the reef crest, trade-wind-driven waves to be generated on the reef flat, and trade-wind-driven currents to speed up over the reef flat. Most suspended sediment is confined between the coastline and the mid reef flat (~600 m or 2,000 ft from shore), owing to the shallow, broad, low-relief morphology of the reef flat and the alongshore wind-driven currents. Suspended-sediment concentrations decreased to <10 mg/L near the reef crest, indicating that only small amounts of sediment were in suspension and possibly being transported to the fore reef during the study period. The only area on the reef flat where suspended-sediment concentrations >20 mg/L extended farther offshore was just to the east (upwind) of the wharf.

Sediment Flux: Where is the Sediment Going?

We evaluated the sediment flux (or sediment-transport rate) along and across the Moloka‘i reef flat by multiplying the current and suspended-sediment concentration together over a specific period. These two factors must be correlated over time to contribute to the sediment flux (for example, suspended-sediment concentration may be high, but if there is no water movement, the sediment flux is zero). Hourly records of sediment flux were calculated, then summed over the year-long data record, to get the net sediment flux for the year.

The data on net sediment flux were classified according to the four environmental conditions for the period May 2001–May 2002 (fig. 11). The trade-winds environmental condition is prevalent for most of the year (fig. 4), and the ability of trade winds to suspend moderate amounts of sediment, drive strong wind-driven currents, and persist over the study period resulted in their dominant contribution to the total sediment flux. The trade-winds environmental condition was subdivided into two parts: normal trade winds with no new sediment added, and trade winds following storms that introduce significant amounts of sediment onto the reef flat. Although the sediment flux on the Moloka‘i reef flat during the November 2001 Kona storm was small, under the trade-winds environmental condition in the subsequent days (and with subsequent sediment-input events), large amounts of sediment were transported westward, owing to the high sustained suspended-sediment concentrations (>50 mg/L) and strong currents (Field and others, this vol., chap. 21), illustrating the effect of readily available fine sediment on the sediment flux.

Environmental conditions other than trade winds contribute less to the total sediment flux on the Moloka‘i reef flat. The sediment flux associated with the storms environmental condition (to the west and offshore) was relatively small during the study period, owing to its infrequent occurrence, and although windspeeds were high, wind directions shifted over the event, causing current directions to vary during periods of high suspended-sediment concentrations and resulting in little net sediment flux. During the swell environmental condition, the net sediment flux was relatively low, owing to weak, varying tidal currents and resulting in net sediment flux to the east, moving sediment opposite to the prevailing trade-wind direction. The infrequent occurrence of this environmental condition on the reef flat (fig. 4), in combination with minimal sediment flux, leads to a low contribution to the

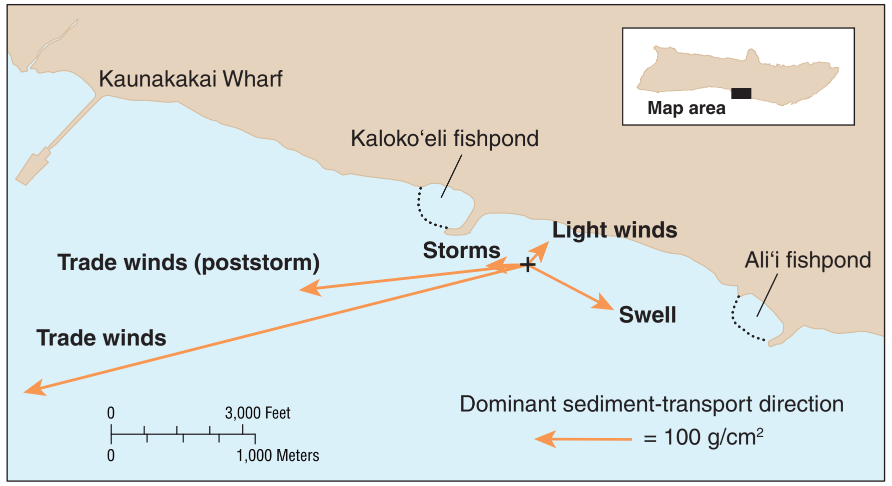

Figure 11. Dominant sediment-transport direction on the Moloka‘i reef flat is southwestward under trade-winds environmental condition at the ReefProbe site, consistent with mainly along-reef transport shown by Backpack measurements. Lengths of vectors, shown for various environmental conditions, are scaled to sediment flux through a square centimeter of water column summed over the time period of the condition from the May 2001–May 2002 dataset. Trade-wind sediment flux was further divided to show sediment flux following a large Kona storm (Field and others, this vol., chap. 21). Although swell and light-winds environmental conditions contributed only a minor amount to total sediment flux, they are important in that they can move sediment in directions opposite to trade winds.

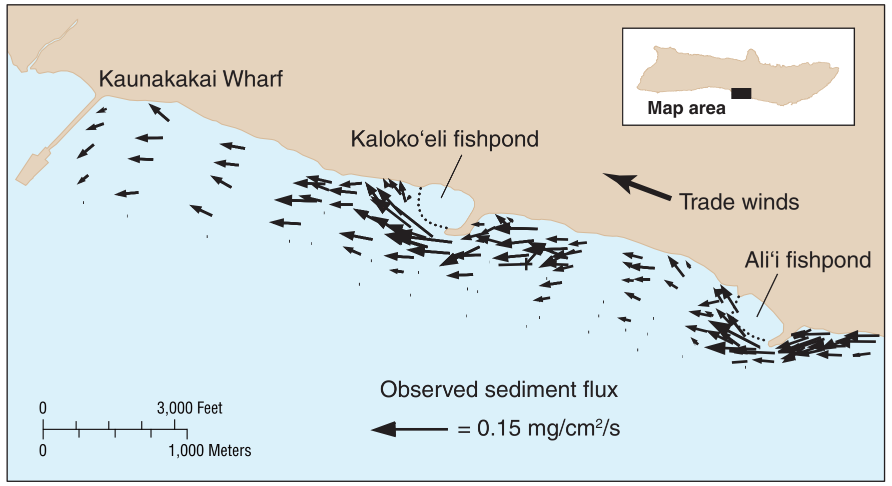

Figure 12. Observed sediment flux on the Moloka‘i reef flat under trade-winds environmental condition is dominantly within an inner-reef band, as indicated by measurements made at high tide. Sediment flux is calculated from current and suspended-sediment concentration at each survey point on the reef flat. Dominant direction of sediment flux is alongshore to the west for most survey points. Peak sediment fluxes were calculated for areas just seaward of fishponds, where current velocities are high, as well as for areas on the inner reef flat to the east and west of fishponds, where suspended-sediment concentrations are high.

total annual sediment flux. The south-central part of the Moloka‘i reef flat is generally blocked from deep-water ocean waves, minimizing the effect of offshore waves relative to many other reefs in Hawai‘i. The light-winds environmental condition, though frequent on the reef flat, resulted in minimal sediment flux, owing to low suspended-sediment concentrations and weak nearbed currents (generally due only to tidal ebb and flood). Thus, over the study period, trade-wind-driven processes were the dominant control on reef-flat sediment transport.

Distribution of Sediment Flux on the Reef

Backpack measurements of sediment flux under the trade-winds environmental condition indicate that much of the terrigenous sediment resuspended on the Moloka‘i reef flat is transported predominantly alongshore and is confined to the inner to middle reef flat (fig. 12), mainly owing to the higher suspended-sediment concentrations on the inner reef flat and the relatively constant windspeeds across the mid reef flat. Little crossreef mixing of water and sediment by the dominantly alongshore wind-driven currents occurs under the trade-winds environmental condition, as evidenced by the marked cross-shore gradients in suspended-sediment concentration and composition. In areas where flow is impeded by obstacles (east of the fishponds and wharf, fig. 1), currents are very slow, resulting in trapping of water and sediment there.

Sediment-Deposition Rate Over a Tidal Day

During the trade-wind season, sediment-suspension events occur on the Moloka‘i reef flat on a daily basis. Most of the sediment in the water column settles out of suspension when the winds and wind-driven waves subside, generally in the late afternoon. A sediment-deposition rate can be estimated over a 24-hour period to simulate the amount of sediment that would settle out of suspension and be deposited on the reef flat (fig. 13). Using an average daily suspended-sediment concentration of 20 mg/L on the mid reef flat, the mean daily sediment-deposition rate on the reef flat is estimated at 2 mg/cm^2 per day. Using the maximum measured suspended-sediment concentration of 100 mg/L, the sediment-deposition rate during these times is estimated at 10 mg/cm^2 per day, approaching the limit of acceptable rates for coral growth, as suggested by Rogers (1990).

An important point is that the sediment deposited in one day at the above rates may get resuspended the next day—it cannot be viewed as a long-term accumulation that results in burial of individual corals. Fine sediment has been shown to be trapped temporarily by macroalgae (Stamski and Field, 2006), and presumably, some of the sediment deposited on the reef flat gets trapped in selected areas, resulting in net accumulation over time. This analysis also highlights the difficulty in interpreting sediment-trapping data as a net flux (Bothner and others, 2006).

Sediment Recharge to the Reef Flat

If sediment were constantly being resuspended and transported along the Moloka‘i reef flat without new sediment being injected, over time the reef flat would clear out and become a dominantly carbonate system, with sediment originating only from the offshore reef system. Terrestrial sediment however, is recharged into the system, and local sinks store sediment on the reef flat (for example, near shoreline structures). Although only a few storms occurred during the study period, the runoff from these storms transported significant amounts of sediment from the land to the reef flat (Field and others, this vol., chap. 21). Thus, as the upland sources discharge sediment at point sites onto the inner reef under the storms environmental condition, the subsequent trade winds act over longer periods to redistribute the sediment westward in a thin band constrained relatively near shore. The sediment on the reef flat, though resuspended and transported on a daily basis, is replenished by episodic storms.

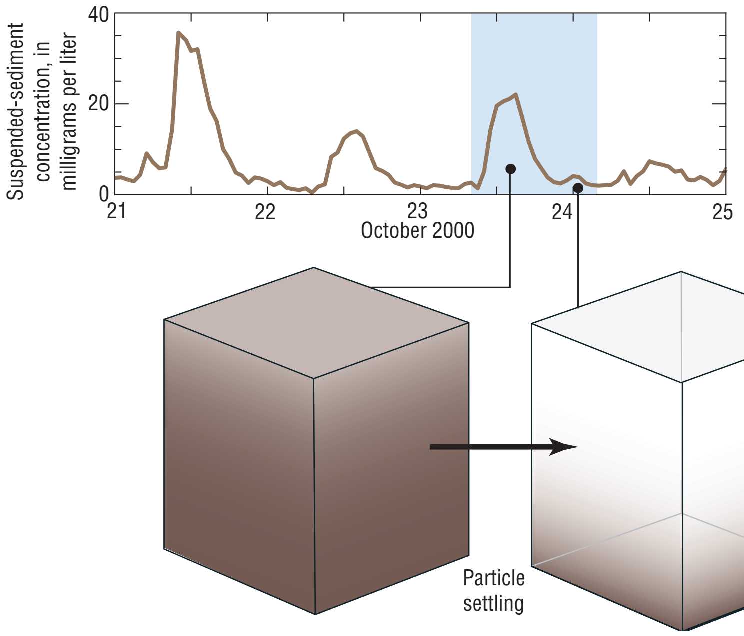

Figure 13. In each daily tidal cycle on the Moloka‘i reef flat, sediment is suspended in the water column and redeposited back onto the seabed, as illustrated by the variation in suspended-sediment concentration over a single day (for example, one day highlighted in blue). For a typical suspended-sediment concentration in the water column and a typical water depth of 1 m (3.3 ft), an average of ~20 mg/L of sediment settles out of suspension, and the short-term sediment-deposition rate is 2 mg/cm^2 per day. For higher suspended-sediment concentrations, a maximum of ~100 mg/L of sediment settles out of suspension and the sediment-deposition rate increases to 10 mg/cm^2 per day. Note that sediment deposited in a daily cycle will likely be resuspended in the following daily cycle.

Implications for Reef Flat Management

Rogers (1983, 1990) demonstrated that variations in suspended-sediment concentration affect coral growth and health. Our study adds to that understanding by documenting that suspended-sediment concentration varies across a reef flat and that a single measurement in both space and time is inadequate to describe conditions on a reef flat where, on a daily basis, seasonally varying winds and waves resuspend sediment. Thus, the effect of a discharge of even minor amounts of sediment onto the reef flat may be significant because this sediment can be resuspended many times before finally leaving the reef-flat environment.

CHAPTER 21

The Effects of a Kona Storm on the Moloka‘i Reef: November and December 2001

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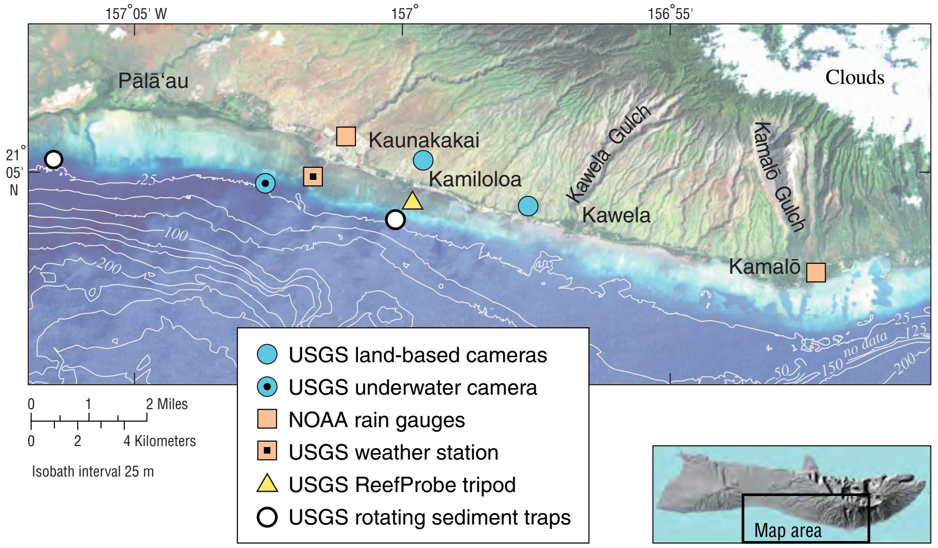
On the average, heavy rains affect the southern slopes of Moloka‘i once or twice each winter, usually as part of a Kona storm, a seasonal, tropical storm with winds coming from the “kona” (or leeward) side of the islands. In November 2001, such a storm occurred, the first in a four-year period. Runoff of sediment was heavier than normal, as evidenced by road closures. Large quantities of plant debris and soil that had accumulated on the hillsides through normal weathering processes were washed down through gulches to the coast. Culverts carrying water and debris beneath Highway 450 (King Kamehameha V Highway) quickly became clogged, as often occurs during a Kona storm, and gravel, sand, and mud washed onto the road. Muddy sediment poured over the coastal terrace, into the water, and onto the reef. The U.S. Geological Survey (USGS) had a set of instruments on the reef, as well as two cameras on land to photograph changes in ocean turbidity (fig. 1). The USGS conducted follow-up high-resolution aerial surveys on November 29 and acquired satellite images (Landsat TM) from that same day. What follows is our analysis of the storm and its short-term effect on the reef and some speculation about how such storms affect the reef over longer time periods.



- ● USGS land-based cameras
- ◉ USGS underwater camera
- ☐ NOAA rain gauges
- ▣ USGS weather station
- △ USGS ReefProbe tripod
- ○ USGS rotating sediment traps

Figure 1. Aerial photograph of central south Moloka‘i and the adjacent reef, showing the locations of the U.S. Geological Survey instruments and cameras and the National Oceanic and Atmospheric Administration rain gauges that recorded information during the November 27, 2001, Kona storm. Much of the sediment delivered to the coast in the storm was discharged from Kawela and Kamalō Gulches and other drainages.

The Storm of November 27, 2001

Rain began falling on Moloka‘i late on November 26, 2001, reaching a maximum rate of more than 2 cm/hr (0.8 in/hr) between 4 and 5 a.m. on November 27 and tapering off that afternoon (fig. 2). Total rainfall for the storm was nearly 10 cm (4 in) at Kaunakakai (National Weather Service Hydronet System, http://www.prh.noaa.gov/hnl/hydro/hydronet/hydronet-data.php, last accessed April 29, 2008). The rain gauge at Kamalō was not functioning during the storm, but by comparison with other storms (fig. 3), rainfall there was likely twice as high as at Kaunakakai, probably reaching levels near 20 cm (8 in). The previous three years had been relatively dry with little rainfall (fig. 3), and the high rainfall rate in the November 2001 storm overwhelmed possible infiltration rates and resulted in rapid transport of gravel, sand, and mud in large quantities down the steep slopes of south-central Moloka‘i. Overland flow and massive deposition on Highway 450 resulted in road closures and direct flow of muddy water onto the central Moloka‘i reef flat (fig. 4).

Long-term rainfall records at both Kaunakakai and Kamalō show that these areas typically experience one or two months of heavy rainfall each winter, usually from Kona storms such as the one on November 27, 2001 (fig. 3). The previous wet winter was 1996–97, although the Kaunakakai gauge also recorded more than 15 cm (6 in) of rain in the summer of 1998.

Wind and Waves During the Following Month

USGS instruments recorded wind speed and direction, as well as wave heights and periods (calculated as wave stress) on south Moloka‘i throughout the fall and winter of 2001; these values are shown in figure 5. The winds show a pattern that is typical for the period during and following a Kona storm (fig. 5*A*). Before and during the storm, winds blew towards the north

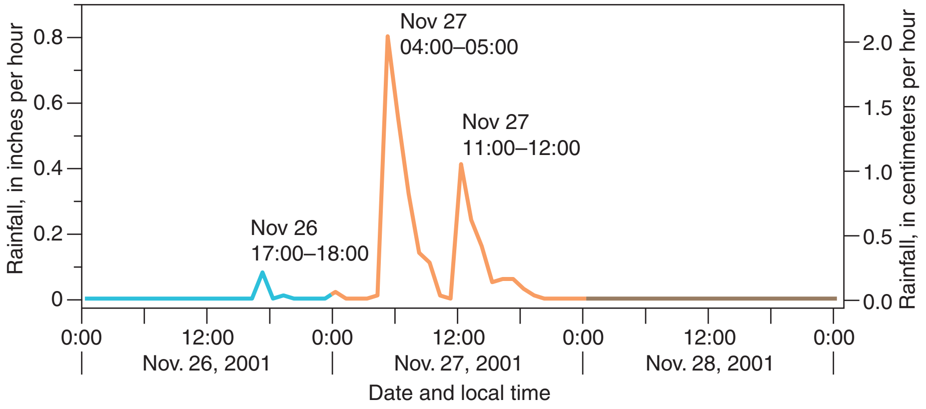


Figure 2. Rainfall amounts recorded hourly during the November 2001 storm by the rain gauge at Kaunakakai, Moloka‘i (source: National Weather Service Hydronet System, http://www.prh.noaa.gov/hnl/hydro/hydronet/hydronet-data.php, last accessed April 29, 2008).

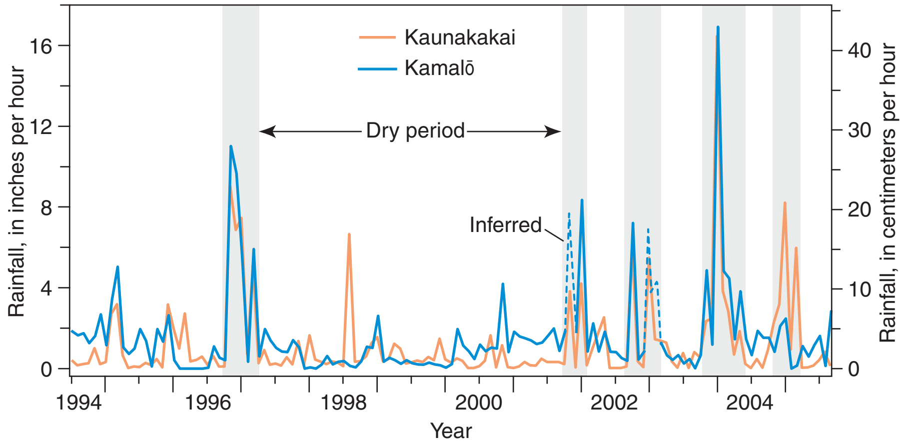


Figure 3. Monthly rainfall amounts for Moloka‘i between July 1994 and September 2005 as recorded by the rain gauges at Kaunakakai and Kamalō (source: National Weather Service Hydronet System, http://www.prh.noaa.gov/hnl/hydro/hydronet/hydronet-data.php, last accessed April 29, 2008). The rain gauge at Kamalō stopped working at times, including during the November 2001 storm. As in the December 2001 storms, rainfall at Kamalō is inferred to be nearly twice that at Kaunakakai. Note that, on average, each winter has a period of heavy rainfall (shown by gray bars), except for the four winters preceding the November 2001 storm. The lack of heavy rain for four years may have led to a heavier-than-normal soil buildup, and consequently to heavier-than-normal sediment runoff.

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and northwest at speeds greater than 10 m/s (22.4 mph). Immediately after the storm, on November 28, the winds decreased in speed and shifted to a typical trade-wind pattern, with winds blowing dominantly toward the west. In the days that followed, from November 28 to about December 1, trade winds were variable in intensity. From about December 1 through December 15, trade winds were consistently strong, as is typical during the trade-wind season, attaining speeds of 10 m/s (22.4 mph) to 15 m/s (33.6 mph) during the day and relaxing at night. This pattern of wind speeds and directions is important to the fate of sediment on the reef.

Wave stresses for November and December 2001 (fig. 5*B*) were calculated from wave heights as recorded by a wave gauge deployed at 10-m (33 ft) water depth on the fore reef off Kamiloloa (see Storlazzi and others, this vol., chap. 11). The measurements show high stresses starting before November 27, peaking that day, and steadily decreasing for the following two days. Short bursts of high stress occurred sporadically throughout December, but never to the same level as recorded on November 27 and 28. This, too, is important to the fate of sediment on the reef.

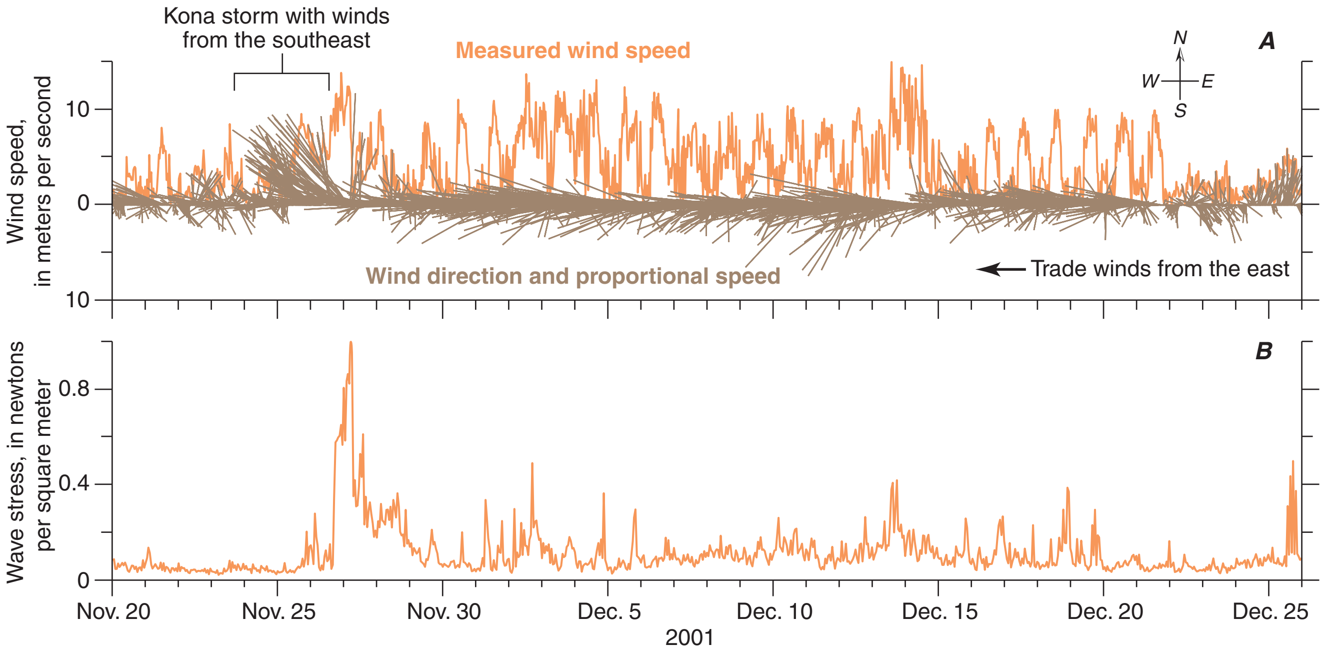


Figure 5. Physical forcing during the November and December 2001 storms on Moloka‘i. *A*, Wind speed and direction for the months of November and December 2001, as recorded by the U.S. Geological Survey weather station on the Kaunakakai Wharf. The brown lines point in the direction that the wind was blowing, and their lengths gives the proportional wind speed. Measured wind speed is shown in orange. Note the Kona wind pattern (blowing strongly north and northwest) on November 26 and 27, followed by trade winds blowing to the west that increase in strength after the storm. *B*, Wave stress (a measure of force per unit area) as recorded by the wave gauge at 10-m (33 ft) depth offshore Kamiloloa. Note that waves are strong (high stress values) during the storm on November 27 and subside significantly following the storm's passage.

Lyndon Dela Cruz

Figure 4. Sediment transport and deposition resulting from the November 2001 storm on Moloka‘i. *A*, Highway 450 near mile marker 7, showing sediment deposits on roadbed. Closures such as this are common along this stretch of road and typically occur about once a winter. *B*, Overland flow of sediment across Highway 450 and onto the reef flat near mile marker 6.

Sediment Plumes on the Reef Flat

Critical information about the timing and extent of sediment plumes on the reef flat was provided by comparing satellite images (fig. 6), turbidity measurements (fig. 7), land-based photographs (fig. 8), and aerial photographs for the days before, during, and following the storm. The ReefProbe (see Ogston and others, this vol., chap. 20, for a description of this oceanographic instrument) was positioned on the reef flat about 5 km (3 mi) west of Kawela Gulch, one of the major sources of flood sediment to the coast. Salinity measurements at the ReefProbe show a large decrease in salinity on November 27 (fig. 7), immediately after the storm, as fresh water flowed across the reef flat and downwind to the west. Interestingly, the fresh-water pulse was not accompanied by a maximum in turbidity levels. Previous studies by Ogston and others (2004), detailed in chapter 20 of this volume, found a strong correspondence between tide stage and turbidity. During high tides, water on the reef flat becomes deep enough for waves to form there and to resuspend fine-grained sediment; thus there exists a strong diurnal signal to the values of suspended sediment on the reef flat. During the five days following the heavy rains of November 27, turbidity rose sporadically, or spiked, several times because of the coincidence of large offshore wave energy and high tide. Turbidity values (fig. 7) during those five days were equal to or slightly higher than values that typically occur on the reef flat during normal (nonstorm) periods of high tides and moderate trade winds (Ogston and others, 2004; Storlazzi and others, 2004; Presto and others, 2006). This indicates that much of the sediment discharged in the 2-day storm was deposited near the discharge points at Kamalō and Kawela to form deposits of terrigenous (land-derived) sediment along the shoreline and on the inner reef flat.

Following the Kona winds (blowing towards the northwest and north) that accompanied the rain on November 27, 2001, the winds gradually returned to a trade-wind-dominated pattern on November 28, 29, and 30 (fig. 5*A*). Satellite imagery, instrument data, and cameras mounted on a water tower on land captured this pattern convincingly (figs. 6, 7, and 8). Photographs taken from November 27 through 30 show that at the ReefProbe site at Kamiloloa the turbidity levels were apparently low (relative to the Kawela site) and that winds were also variable, as evidenced by the palm tree fronds hanging

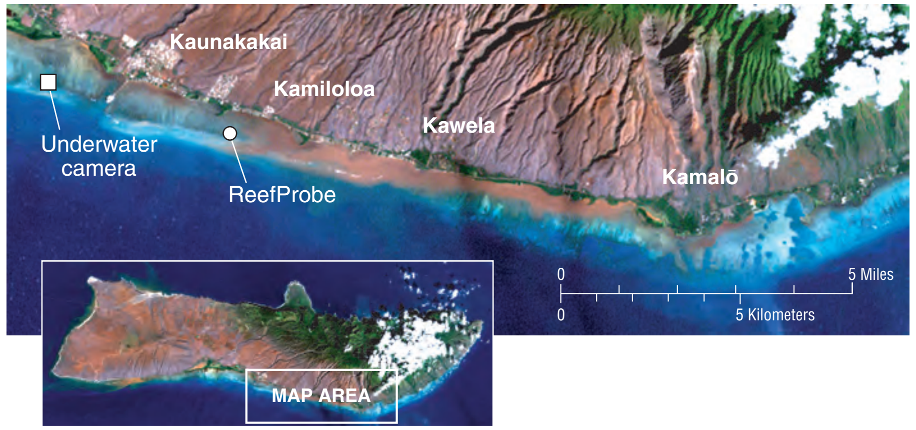


Figure 6. The Landsat satellite passed over Moloka‘i on November 29, two days after the heavy rainfall, and provided this image of highly turbid waters on the fringing reefs of south Moloka‘i. Note that at this time the muddy waters were concentrated on the reef flat from Kamalō to Kawela and farther west but had not yet reached the ReefProbe instrument site at Kamiloloa.

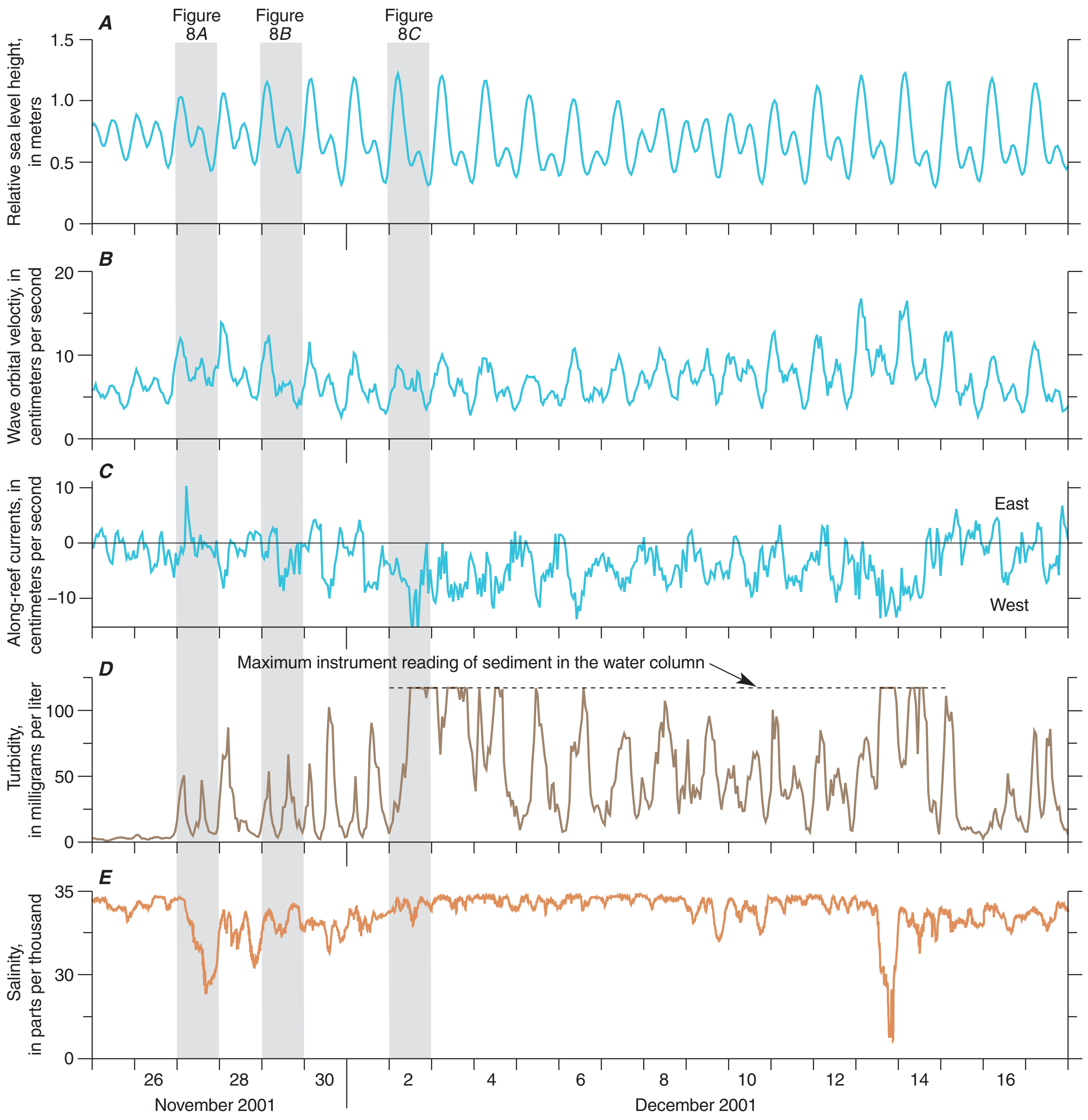


Figure 7. Tides, waves, currents, turbidity, and salinity for the period of November 25 to December 18, 2001, as recorded at the ReefProbe on the reef flat off Kamiloloa, south Moloka‘i. Note the marked drop in salinity that occurred shortly after the rainfall on November 27, and again on December 13. Of particular interest is the lag in turbidity after the November storm. Typical daily values of turbidity were seen in the 4 days following the flood event until about December 2; at that time strong along-reef currents appear to have transported large quantities of sediment in the water column, resulting in maximum values of turbidity. Note that on December 14 there is another rain period, marked by the low salinity, yet trade winds were strong and there was no lag in turbidity. Photographs representing the time periods marked by the gray bars can be seen in figure 8. *A*, Sea surface height, or tidal stage. *B*, Wave orbital velocities. *C*, Along-reef (parallel to shore) currents (negative values show flow to the west.) Currents were measured at 0.2 m above the bed. *D*, Turbidity. *E*, Salinity.

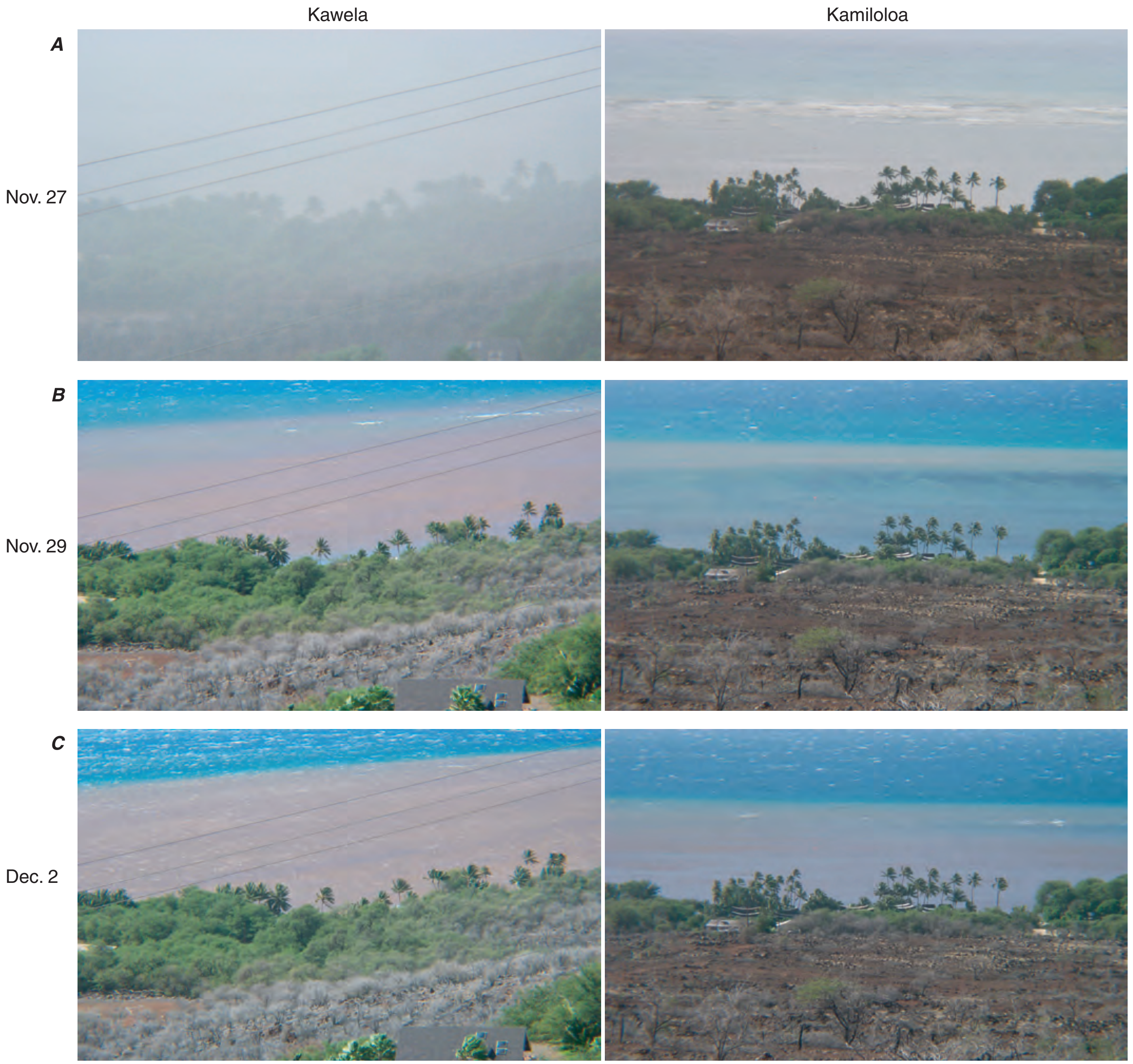


Figure 8. Photographs looking south taken from cameras mounted on water towers on the south coast of Moloka‘i show the westward movement of sediment-laden water under the influence of strong trade winds. A pair of photographs is shown, one from Kawela and one farther to the west at Kamiloloa, for each of the three mornings of November 27 (*A*, the day of the rain), November 29 (*B*), and December 2 (*C*), 2001. The reddish-brown mud is present in the water at Kawela on November 29 and finally at Kamiloloa on December 2 after several days of strong westward-blowing trade winds.

straight. Trade-wind strength gradually increased from November 29 through December 1 and reached maximum speeds on the afternoon of December 2. The steady and strong winds that started at the very end of November likely resulted in erosion of flood sediment that had been deposited near the shoreline at Kawela and other source areas farther east. The trade-wind-induced waves and currents then resuspended and transported the muddy flood sediment westward toward Kaunakakai. The pulse of muddy sediment moving westward along the reef flat is clearly shown by the maximum turbidity levels that were recorded at the ReefProbe site starting December 2 and by the land-camera images at Kamiloloa (fig. 8).

Satellite images (Landsat Thematic Mapper, or TM) with 30-m resolution and aerial images with 0.6-m resolution were collected on November 29, 2001, to detect and map the distribution, concentration, and total amount of suspended sediment over the south Moloka‘i reef. Two large suspended-sediment plumes were evident on November 29 (fig. 6), one on the west end of the south coast and a much larger one along the south-central coast, and their suspended-sediment concentrations (SSC), determined from water samples collected from the upper 0.5 m, ranged from 30 to 410 mg/L. These values were used to develop a model relating digital values from the satellite images to SSC, and the amount of suspended sediment in the upper 0.5 meter of water was then computed. Calculations using the TM images show that the total amount of suspended sediment in the upper 0.5 m of water on November 29, 2001, was approximately 1,500 tons (Chavez and others, 2004).

The significance of this series of events to the health of the reef is twofold. First, it is now evident that even a moderate amount of rain results in substantial transport of mud, sand, gravel, and associated debris directly from land to the reef flat. Second, the mud component is not moved entirely or even mostly in a plume across the reef flat and into deeper water. Rather, most of the mud is stored along the shore and inner reef flat near its on-land source. There it becomes a long-lasting source of turbidity as trade-wind waves resuspend the deposits nearly every day and slowly move the particles westward by means of trade-wind-driven currents.

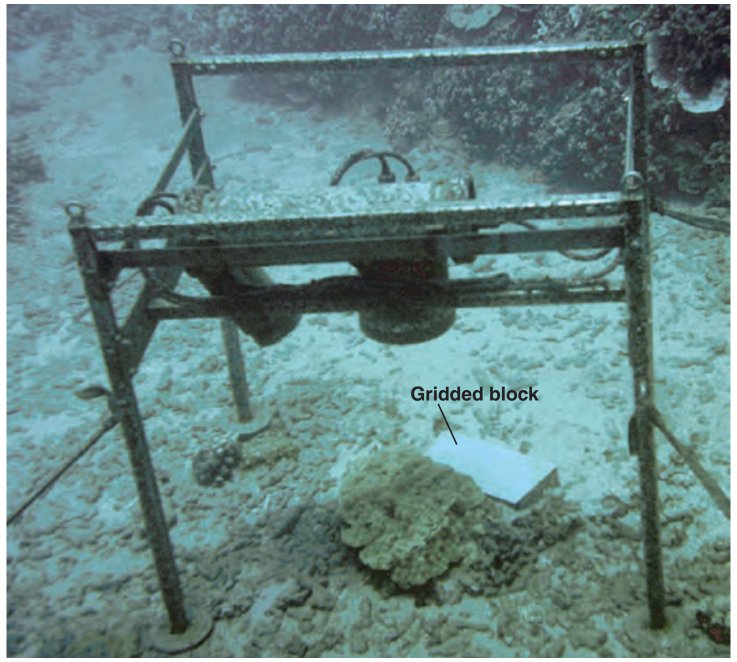


Figure 9. Bottom-mounted underwater camera on the fore reef west of Kaunakakai Harbor, Moloka‘i. The camera was located at a water depth of 12 m in a groove between two coral spurs (one visible in background). The camera took an image every four hours of the colony of *Porites lobata* (lobe coral) and a gridded concrete block, both beneath the frame. Scale is indicated by the size of the block (20.3 × 40.6 cm; 8 × 16 in).

Was the Fore Reef Affected by the Sediment Discharge?

The fore reef off south Moloka‘i is a magnificent reef with luxuriant coral cover hundreds to thousands of acres in extent (see chapters 5 and 9 of this volume for a discussion of the coral and benthic habitats, respectively, found along the south Moloka‘i reef). An important question is how much of the high load of sediment that washes onto the Moloka‘i reef flat is transported across the reef crest and onto the fore reef. Again, the storm of November 27, 2001, provided us an opportunity to learn more about that process during a large Kona storm, the typical kind of event that causes heavy rains on south Moloka‘i. Before the storm, instruments had been placed on the fore reef, as well as on the reef flat. The instruments on the fore reef included a rotating sediment collector with a wave gauge attached (see Bothner and others, this vol., chap. 19, for details about the instrument) and an underwater camera station (fig. 9) that recorded images of sediment collecting on a flat surface and the seabed six times daily. The data from these two systems show that sediment deposition on the fore reef is a complicated process and is not simply the result of plume fallout after heavy rainfall onshore.

Using a time series of photographs of the sea floor on the fore reef just west of the Kaunakakai Wharf, it was possible to document the timing of high-turbidity events and thus relate them to the events that were occurring along the coast. The pictures in figure 10 show that, starting on November 27 at 4 a.m. and continuing for the next 24 to 36 hours, the amount of suspended sediment was so high that visibility was greatly reduced in water that is normally quite clear, probably because of local sediment resuspension. Importantly, the water began to clear late on November 28. The satellite image obtained on November 29 shows that even by that date sediment plumes had not moved a significant distance along the reef flat, let alone onto the fore reef. Thus the high level of turbidity here was related to waves and not to plume fallout. However, at other locations along the reef, closer to discharge points, plume fallout may have generated turbid water.

If sediment plumes had not reached the fore reef by November 27 and 28, then what caused the distinctive high levels of turbidity observed by the underwater camera? One possible, and likely, source is wave action. On November 26 through 28, large waves hit the south Moloka‘i coast. Bottom shear stresses from waves such as occurred on those dates are capable of resuspending sand and mud particles that lie in areas normally too deep or protected from wave disturbance. Thus it is likely that the large southerly swell arriving at south Moloka‘i on November 26 was responsible for resuspending large volumes of sediment and causing high levels of water turbidity before the products of the on-land rainfall could be dispersed to the fore reef.

Additional evidence supporting such a scenario was provided by sediment collected in traps that had been placed on the reef flat and the fore reef before the storm. In addition to the rotating sediment trap described above, single 0.5-m tube traps (10-cm diameter) were placed at various locations on the reef for a three-month period (November 15, 2001, to February 14, 2002). Single tube traps from both ends of the island (Hale O Lono and Pūko‘o) were completely filled during this three month fall-winter period, but analysis of the sediment in the traps indicates that its source was chiefly from local reef areas, with only a small (~10 percent) amount contributed from land (Bothner and others, 2006). The evidence for this is that the material filling the traps is about 90 percent calcium carbonate, which can only be derived from the reef, and is coarse (nearly 80 percent sand).

The time-series trap sample number 3 at Pālā‘au (fig. 11) was collected during the storm period and was full of sediment. Because the sampling period was 4.5 days, and because the runoff and large waves occurred at nearly the same time within this period, which process was most responsible for the high sample volume is difficult to determine. That is, how much of the sediment collected was contributed by wave-induced resuspension of sediment on the fore reef, and how much was contributed by direct settling from sediment plumes emanating from the coast?

The nature of the sediment filling the tubes provides some answers. Trap sample number 3, which included the storm period, had about the same (or lower) amount of terrigenous sediment as prestorm samples (about 24 percent). At Kamiloloa, another rotating sediment trap showed that the terrigenous sediment there increased from approximately 34 percent in prestorm samples to 39 percent in poststorm samples during periods with similar wave conditions. This increase is relatively small and does not indicate massive sedimentation from plume fallout. The sediment tube trap on the fore reef off Kamiloloa had a distinctive layer corresponding to the storm, but even that layer is unlikely to result solely from plume fallout. It is composed of only 27 percent terrigenous sediment, and therefore more than two-thirds of it was derived from the reef itself. Furthermore, 60 percent of the sediment in that layer is sand, which is not easily transported by surface currents. The composition of sediment caught in these tube traps is persuasive evidence that wave resuspension, not sediment discharge from streams, is the key factor causing turbidity on the reef. Recent work (Bothner and others, 2006) shows a strong relation between sediment collection and wave stresses, even in periods of no runoff.

How Kona Storms Generate Turbidity on the Moloka‘i Reef

Our study of the November 27, 2001, Kona storm on south Moloka‘i has demonstrated that such events contribute sediment and turbidity to the reef flat and fore reef, but they do it in a complex manner. The waves that accompany the weather fronts are a major factor in resuspending both terrigenous and reef-based sediment and transporting it on the reef, where it deposits on corals and other benthic organisms and inhibits photosynthesis. Heavy rains produce floods in intermittent streams and gullies as well as overland flow at the coast. In the November 2001 storm, large amounts of terrigenous sediment were deposited along the coast and on the reef flat, where they became available as a source for later resuspension. These events and resulting conditions are summarized in figure 12.

The sequence of natural processes that occurred before, during, and following the November 27, 2001, Kona storm provide a solid basis for understanding the natural cycle of ridge-to-reef sedimentation in this environment. These processes are neither unusual nor extreme, and they most likely represent events that happen one or more times annually. The conditions that led to high sediment mobility and high turbidity on the reef in November and December 2001 were as follows:

- On land: A high rate of rainfall (10 cm, or 4 in, within 24 hours) led to high water and sediment runoff onto the reef. The high

Figure 10. This series of bottom photographs (taken with the underwater camera near Kaunakakai Harbor, see figure 9) shows the timing of periods of turbidity on the fore reef that can be compared with the land-camera images of the reef flat shown in figure 8. The images show clear water and a sediment–free block surface at the time of deployment in mid-November 2001. Black lines on the concrete block are 2 cm apart. Before the rain event in late November, the block had become covered by sediment. The water became very turbid beginning at 4 a.m. on November 27, as rains just began onshore, and remained turbid for approximately the next 24 hours. This interval coincides with the period of large waves that accompanied the storm. By November 29, the water is relatively clear again, there is less sediment on the block surface, and what sediment is present appears coarser than before the storm.

sediment runoff was likely exacerbated by land-use practices and a preceding dry period (~3 years). The sediment reached the coast and inner reef by means of gullies and overland flow, and much of it was deposited near the discharge points at the coast.

- On the reef: Waves were high before and during the heavy rainfall, then dropped back to normal levels. During the storm, large storm waves caused resuspension of previously deposited sediment, leading to turbidity on the fore reef. Winds were onshore; trade winds were mild to nonexistent and only slowly became reestablished in the days following the storm. The return to trade-wind conditions following the storm caused renewed resuspension and along-reef transport of flood sediment.

These conditions led to a decoupling of sedimentation on the reef flat and on the fore reef off central Moloka‘i. The reef flat was characterized by initial high levels of deposition at coastal deltas and adjacent areas. Following the storm, trade winds became reestablished, leading to daily resuspension and high turbidity. Macro algae and silt increased markedly for at least six months after the storm (Stamski and Field, 2006).

On the fore reef, the storm was characterized by high wave stresses and onshore winds, resulting in temporary high turbidity and temporary deposition. Because periodic high wave stresses subsequently resuspended and transported the sediment, there was apparently no significant long-term storage of fine-grained terrestrial sediment on the fore reef.

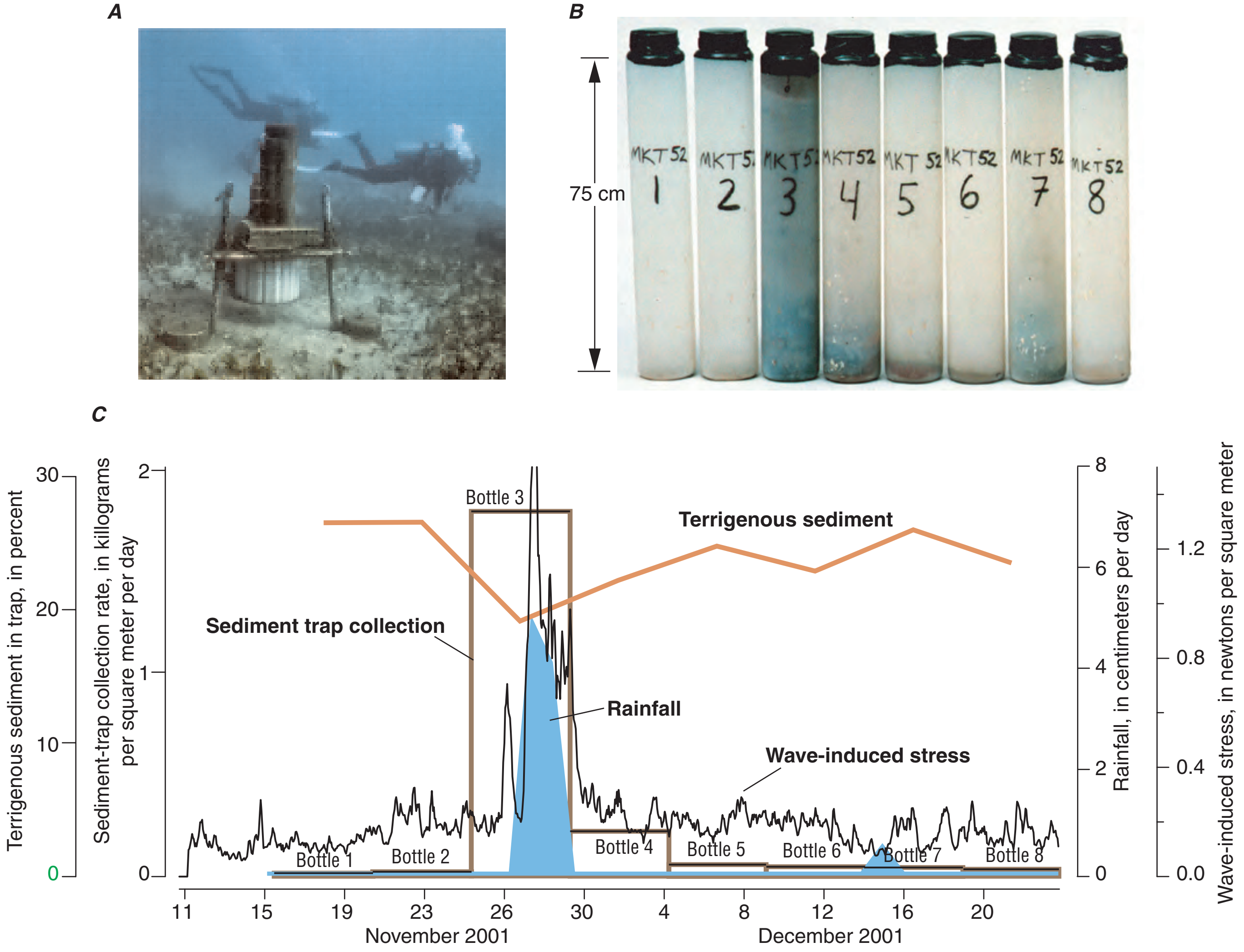


Figure 11. Sediment-collection data from the rotary sediment trap at Pālā‘au, Moloka‘i. Each tube from the rotating sediment trap on the fore reef represents 4.5 days of sediment collection (see Bothner and others, this vol., chap. 19). *A*, The sediment trap in place on the sea floor (photograph taken on the fore reef off Kamiloloa). *B*, The Pālā‘au sediment-collection tubes aligned in chronological order. Tube number 3 represents the time period of the Kona storm. *C*, Sediment-collection rate for each tube plotted against rainfall (blue), wave stresses (black), and percent noncarbonate in the collected sediment (orange). Although the high rate of sediment collection (as shown by the filled tube number 3) corresponds with the heavy rainfall, it also correlates with the period of high wave stress. The lack of significant change in the amount of terrestrial sediment (noncarbonate) in the tubes indicates that wave resuspension was the significant factor in filling the tubes, not fallout from flood plumes.

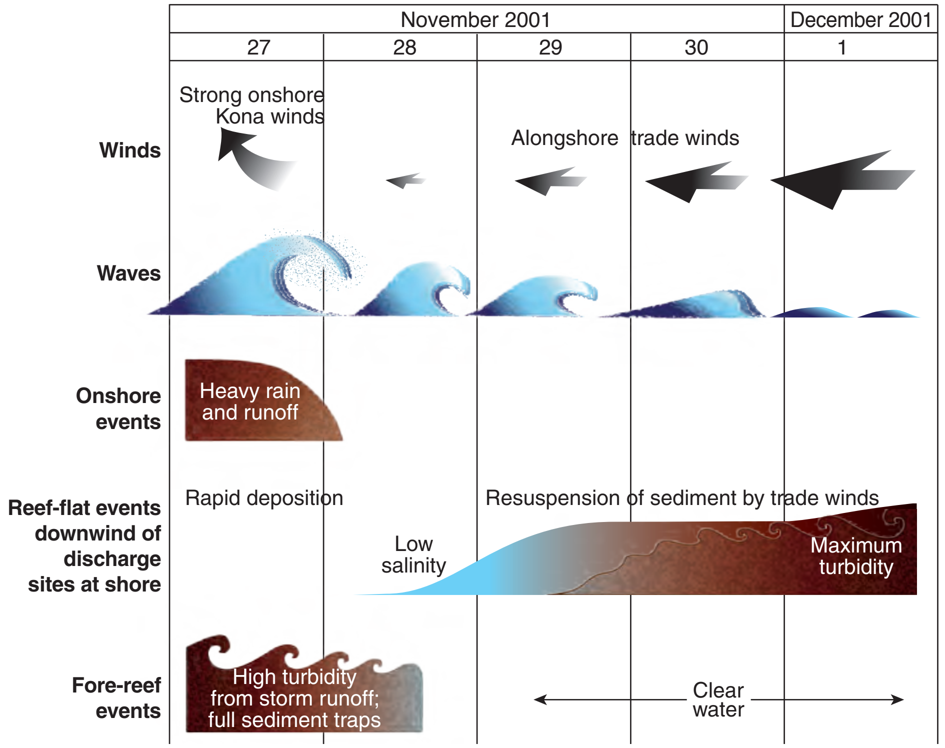
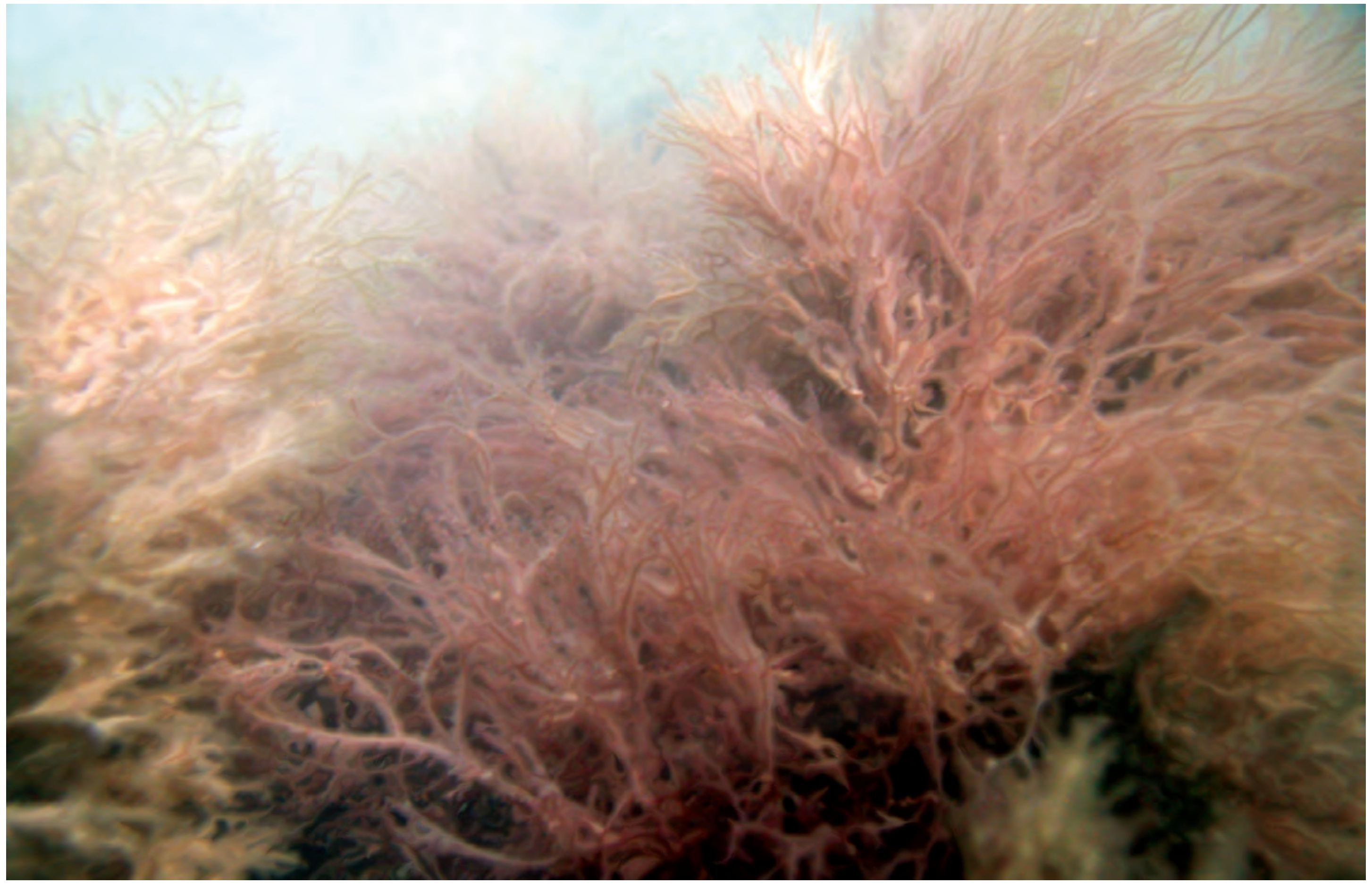


Figure 12. Schematic diagram summarizing the series of events in late November 2001 that influenced turbidity and sediment transport on the south Moloka‘i reef off Kamiloloa. The timing of observations of turbidity on the reef flat and the adjacent fore reef are important, as they document that the two settings are somewhat independent, or decoupled, in the short term. Rainfall and wave stress were both at maximum values on November 27. Although it took several days for terrestrial sediment to have an impact on the reef flat, wave-induced turbidity was immediate on both the reef flat and the deeper fore reef. On the reef flat, sedimentation and maximum turbidity came later than on the fore reef, as terrigenous flood deposits were gradually and increasingly resuspended by trade-wind waves, transporting sediment west along the reef flat by means of trade-wind currents.

Summary

Sunset from south Moloka‘i, with a rain cloud over the island of Lanai.



Spyridia filamentosa red algae on the Moloka‘i reef flat.

SUMMARY

The Moloka‘i Coral Reef Today, and Alternatives for the Future

Michael E. Field[1], Susan A. Cochran[1], Joshua B. Logan[1], and Curt D. Storlazzi[1]

From the contributions collected in this publication have emerged two important observations that have significance locally, nationally, and internationally. First, the fringing coral reef along the south coast of Moloka‘i is one of the most extensive and luxuriant reefs in the eight main Hawaiian Islands. It is longer and more continuous and has denser coral cover than reefs at any of the other islands—this alone makes it a state and national treasure worthy of study and protection. The second observation is more sobering: sections of the south Moloka‘i reef have been damaged in the past by sedimentation ultimately caused by human activities in adjacent watersheds. Although some of those activities are no longer taking place, their lingering effects are still being felt in the form of excess sediment runoff. We here review the basis for each of these observations, discuss how sedimentation affects the reef, and summarize the choices that are faced by the people of Moloka‘i and the State of Hawai‘i with regard to the reef’s future.

The Magnificent Coral Reef of South Moloka‘i

The early chapters of this book describe the expansiveness, diversity, and beauty of the fringing reef off south Moloka‘i. Except for Moloka‘i locals, infrequent scuba divers, and occasional visiting marine scientists, few people have understood the nature and importance of the reef. As a result of recent studies, we now know a great deal more about the reef—from lidar bathymetric surveys, aerial photographs, diver inventories, and instrument measurements. The south Moloka‘i reef is a living, growing structure stretching along most of the island’s south coast, from Hale O Lono on the west to Kamalō on the east, a distance of 40 km (25 mi). This stretch of coast is sheltered from the North Pacific swell by the island itself. Observations and mapping presented in this publication (see in particular Jokiel and others, this vol., chap. 5, and Cochran, this vol., chap. 9) document that much of the reef is an exceedingly rich and diverse marine benthic habitat, as exemplified by figure 1. Nearly all of the coral species known from the Hawaiian Islands, as well as several soft corals and an octocoral, are present on the Moloka‘i reef.

The Moloka‘i reef is a classic fringing coral reef with a wide, shallow reef flat; a well-developed reef crest at the seaward edge of the reef flat; and a biologically rich fore reef reaching to depths of 27 to 32 m (90 to 105 ft). As noted by Jokiel and others (this vol., chap. 5), the Moloka‘i coral reef hosts a rich and diverse marine benthic community dominated by five reef-forming corals: *Montipora capitata*, *Montipora patula*, *Porites compressa, Porites lobata*, and *Pocillopora meandrina*. The fore reef consists of coral ridges, or “spurs,” separated by sand channels, or “grooves,” In areas of dense coral coverage, the tops of the spurs are dominated by a *Porites compressa* (finger coral) community and the steep sides are dominated by a *Montipora* spp. community. Live coral is abundant on the fore reef, and the highest percentages, commonly in excess of 70 percent, are found at depths between 5 and 15 m (16 to 50 ft) along the entire reef and locally at depths between 20 and 25 m (66 to 82 ft).

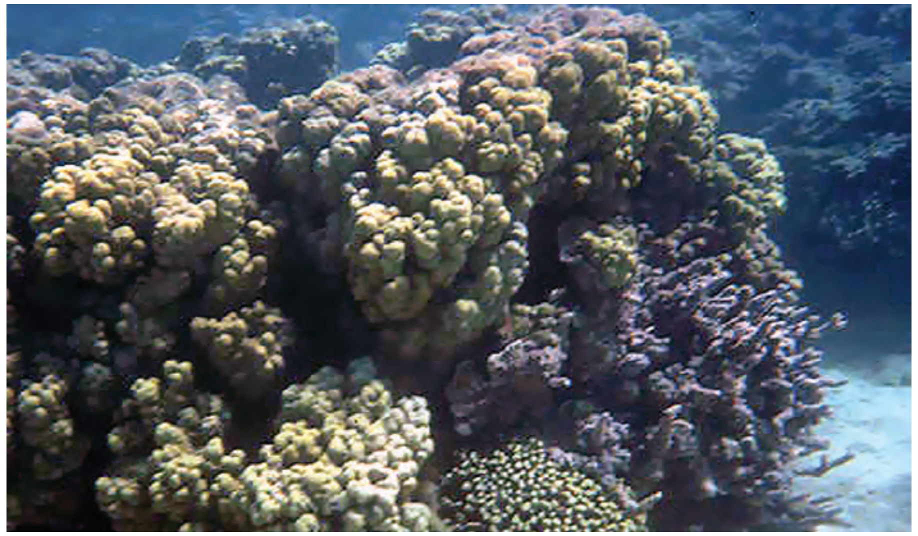


Figure 1. Underwater photograph taken off Kamalō, south Moloka‘i, showing a healthy fore reef. The coral colonies are multicolored (a sign that they are alive), and algae and fine sediment are noticeably absent.

The “blue holes” that characterize the Moloka‘i reef east of Kamalō appear to be unique within the main Hawaiian Islands. Some of these blue holes are open on one side toward the deep ocean, and others occur in the middle of the reef and thus are isolated from direct oceanic flow. Many blue holes, which are rimmed at the surface by *Porites compressa*, extend from near the water surface to depths of 25 m (83 ft) or more. The steep walls that form the perimeter of the blue holes are commonly covered by a lush coral growth and a vertically zoned habitat unique to these formations.

Many fishes observed in residence on Hawaiian reefs are important to the overall health of the coral reefs and ultimately of the islands. As Friedlander and Rodgers (this vol., chap. 7) point out, “fish provide food, cultural identity, and commerce to a broad majority of the local population of Moloka‘i and are an integral component of the marine environment.” Both the herbivorous fish that feed on algae and the predatory fish that feed on other fishes are critical to the overall health of the Moloka‘i coral reef. The herbivores help in the prevention of algal overgrowth on corals and the spread of alien and harmful algae. Predators play an important role in maintaining turnover rates and overall productivity. Finally, a comment by Friedlander and Rodgers (this vol., chap. 7) is particularly relevant to the present state of the reef:

> The broad reef fringing the south shore of Moloka‘i is probably the most productive reef flat in the main Hawaiian Islands for the harvest of reef fishes and invertebrates. The fish assemblage represents a diverse fauna that is healthier than those in more heavily exploited urban areas around the state, but it has shown signs of decline in overall health and quality over time.

There are many factors that can cause fish declines on coral reefs. For the Moloka‘i reef, one such factor may be the decline in the overall condition of the reef because of sedimentation.

Sediment as a Primary Threat to the Reef

As with most coral reefs around the world, the long-term health of the reef off south Moloka‘i faces numerous threats, most of which are induced by humans. On many Pacific and Caribbean coral reefs, rising sea-surface temperatures cause bleaching and enhance disease, overfishing alters the food web and allows competing algae to thrive and smother coral, and nutrification from runoff and from sewage-contaminated ground water also supports algal growth at the expense of coral growth (see, for example, Rogers, 1990; Hughes and others, 2003; Pandolfi and others, 2003; Richmond and others, 2007).

Degradation of coral reefs, as pointed out by Pollnac (2007), Pandolfi and others (2003), and other authors, is often related directly to human habitation (fig. 2). Progressive degradation has occurred throughout reefs in the Pacific Ocean, Red Sea, and Caribbean Sea as nearby societies have shifted from subsistence agriculture to colonial development to modern development. In the analysis by Pandolfi and others (2003), reefs of the eight main Hawaiian Islands are identified as being nearly 60 percent degraded (fig. 3).

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[1] U.S. Geological Survey Pacific Science Center, 400 Natural Bridges Dr., Santa Cruz, CA 95060

Figure 2. This graphic diagrammatically portrays the interplay between human civilization and coral reefs through time. As societies have grown and spread throughout tropical regions, there has been a corresponding decline in reef health, including depletion of larger fish stock from overfishing, and degradation from runoff of sediment and other anthropogenic pollutants has occurred. The path to recovery is uncertain. Few truly pristine coral reefs remain in the world today, some of which reside in the Northwestern Hawaiian Islands (from Pandolfi and others, 2005; image credit Mary Parrish).

At Molokaʻi, the damage from sediment-laden runoff from the land ranks as a first-order cause of reef degradation. By blocking light needed for photosynthesis, covering sites of potential coral growth, providing nutrients for harmful algae, and directly smothering coral polyps, sediment inhibits or prevents coral growth. However, even on this reef, where turbid red-brown water along the central coast of south Molokaʻi is considered the norm by locals and visitors alike, the linkage to declining coral health on the fore reef is not easily established. On the reef flat, though, the linkage is better defined.

Monitoring on the fore reef at depths of 3 m (10 ft) and 10 m (33 ft) for the past five years has produced confusing results. Monitoring sites on the reef along the Molokaʻi south shore have both some of the highest and some of the lowest levels of coral cover found in Hawaiʻi. Brown and others (this vol., chap. 6) and Jokiel and others (2004) document that sections of the reef around Kamalō contain some of the most densely packed coral communities in Hawaiʻi. However, they also point out that the Molokaʻi reef, judging from the sites that were surveyed, may not be faring as well as other sites in the State. The six Coral Reef Assessment and Monitoring Program (CRAMP) stations at Molokaʻi experienced the largest decline in coral cover (by island) between 2000 and 2002, compared to the other 54 CRAMP stations on Kauaʻi, Oʻahu, Kahoʻolawe, Maui, and Hawaiʻi (Brown and others, this vol., chap. 6; Jokiel and others, 2004). Declines on other Hawaiian Islands can be roughly correlated with rising human population, but on Molokaʻi the population is relatively low and stable. Here, the impacts to watersheds from farming, ranching, feral grazers, and other causes of soil loss (Roberts and Field, this vol., chap. 15) are a strong indication that sediment yield is a cause of coral decline at selected locations on the fore reef.

Visual surveys of the reef condition and estimates of coral cover were made along the fore reef by Jokiel and others (this vol., chap. 5) and are reproduced here in figure 4 because of the importance of this survey to understanding the condition of the reef. Previous work has determined that in most places on the Molokaʻi reef, coral growth is continuous from the base of the reef at depths of about 27 m (90 ft) up to shallow depths near the reef crest. Between the Kaunakakai Wharf and One Aliʻi, however, the pattern is distinctly different: coral was severely degraded or absent at all water depths in a 1-km swath off the wharf; and for the entire distance from the wharf to One Aliʻi, coral cover was absent or nearly absent on the upper fore reef at depths of 5 to 10 m (16 to 33 ft) (fig. 4*A*). Recent observations in 2007 (fig. 4*B*) established that at even shallower depths (< 5 m) coral was very sparse or absent, the bottom consisted of bare rock, reef rubble, and sand, and the water was chronically turbid. Observations west of the Kaunakakai Wharf and east of One Aliʻi show that coral is relatively abundant and the water clear at those same depths. The coral-poor area between the Kaunakakai Wharf and One Aliʻi coincides with the movement of chronically turbid waters westward and off the reef flat (Ogston and others, this vol., chap 20; Ogston and others 2004; Presto and others, 2006).

The link between coral health and sedimentation is more evident on the expansive reef flat bordering south Molokaʻi. The entire reef flat between Pālāʻau and Kamalō bears evidence of damage from sedimentation. West of Pālāʻau, the reef flat has healthy coral growth within 50 m of the shoreline and, on the very west end of the island, the limiting factors appear to be wave stresses and abrasion from the Southern swell and North Pacific swell. East of Kamalō, the coast and reef are more exposed to waves, and the less extensive coral cover appears to be a consequence of waves breaking on the reef flat. (Storlazzi and others, this vol., chap.11).

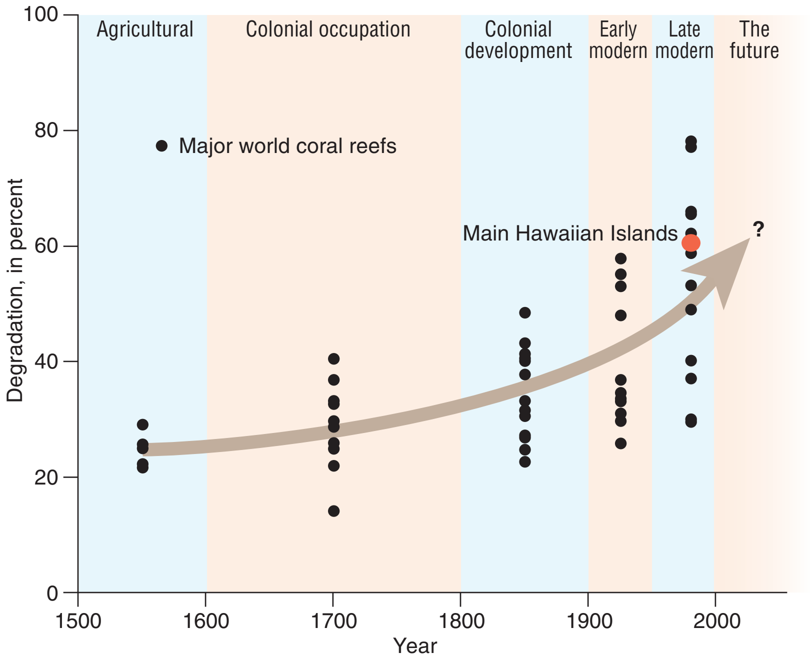

Figure 3. Trends in ecosystem conditions over the past five centuries for coral reefs in the Pacific Ocean, Caribbean Sea, and Red Sea (modified from Pandolfi and others, 2005). The arrow shows the general trend, from 20 to 30 percent degraded in the 16th century to 30 to 70 percent degraded at present. Note that the main Hawaiian Islands are now summarized as being nearly 60 percent degraded.

The evidence for sediment damage on the central Molokaʻi reef flat between Pālāʻau and Kamalō is both circumstantial and direct. The circumstantial evidence consists of observations of relatively thick deposits of muddy sand along the inner reef flat, photographs and measurements of turbid water, and an apparent lack of coral. The connection between these characteristics seems clear, but without direct documentation of poor coral condition caused by excess sediment, it remains circumstantial. The direct evidence comes from measurements of those factors, specifically coral cover and suspended sediment concentrations, made in April 2005 between the Kaunakakai Wharf and Kamalō (fig. 5*A*,*B*). Within 300 m of the shoreline, sediment concentrations greatly exceeded 10 mg/L, a number commonly used as the upper limit for turbidity for maintaining healthy corals (Rogers, 1990). Concentrations at many of the inshore sites exceed 20 mg/L, a level found to be lethal at other reefs (Hodgson, 1997; Hodgson and Dixon, 1992). Another factor is time—even low concentrations of suspended sediment over extended time periods can cause coral death (Hubbard, 1997). Virtually no coral is present within 300 m of the shoreline between the Kaunakakai Wharf and Kamalō. The first measurable coral cover, about 2 percent, appears about 400 m from shore, and coral cover gradually increases to about 10 percent (still a low level) on the central to outer reef flat 600 m from shore (Rodgers and others, 2005).

The low to absent coral on the inner reef flat between the Kaunakakai Wharf and Kamalō is striking. Evidence presented in earlier chapters on the abundance of algae and the low abundance of fish, when combined with the information on low coral cover and chronic high levels of sedimentation, makes it clear that this magnificent reef has been degraded and faces ongoing threats to its well-being as an ecosystem.

Why the Well-Being of the Reef Matters

Our comments above have sought to recognize that the Molokaʻi coral reef has major significance in terms of its intrinsic beauty, biodiversity, cultural importance, and as a local food resource. We have also endeavored to summarize findings that we and our colleagues interpret as evidence that parts of the reef are impacted by sediment, and that other parts (conceivably the entire reef) are threatened by sediment runoff from the land. Degradation of coral reefs is not limited to Molokaʻi, nor is it limited to Hawaiʻi— it is occurring on a global scale (Brown, 1997; Hughes and others, 2003a). Sediment runoff is one of the major causes of global reef decline (Pandolfi and others, 2003; Bellwood and others, 2004; Fabricius, 2005; Richmond and others, 2007). Our comments here are intended to place the potential loss of the Molokaʻi reef in perspective, for loss of the living reef would forever alter Molokaʻi. Coral constructs a complex reef that hosts a diverse biota, protects the shoreline from erosive waves, and provides food for locals. When coral dies in significant quantities, the food web shrinks, erosion of the old reef reduces its effectiveness as a barrier, and what once was a thriving complex ecosystem becomes a surface dominated by alga and sediment.

Although no one would argue that the survival of people on Molokaʻi is dependent upon actions taken in the watershed and on the reef, the situation

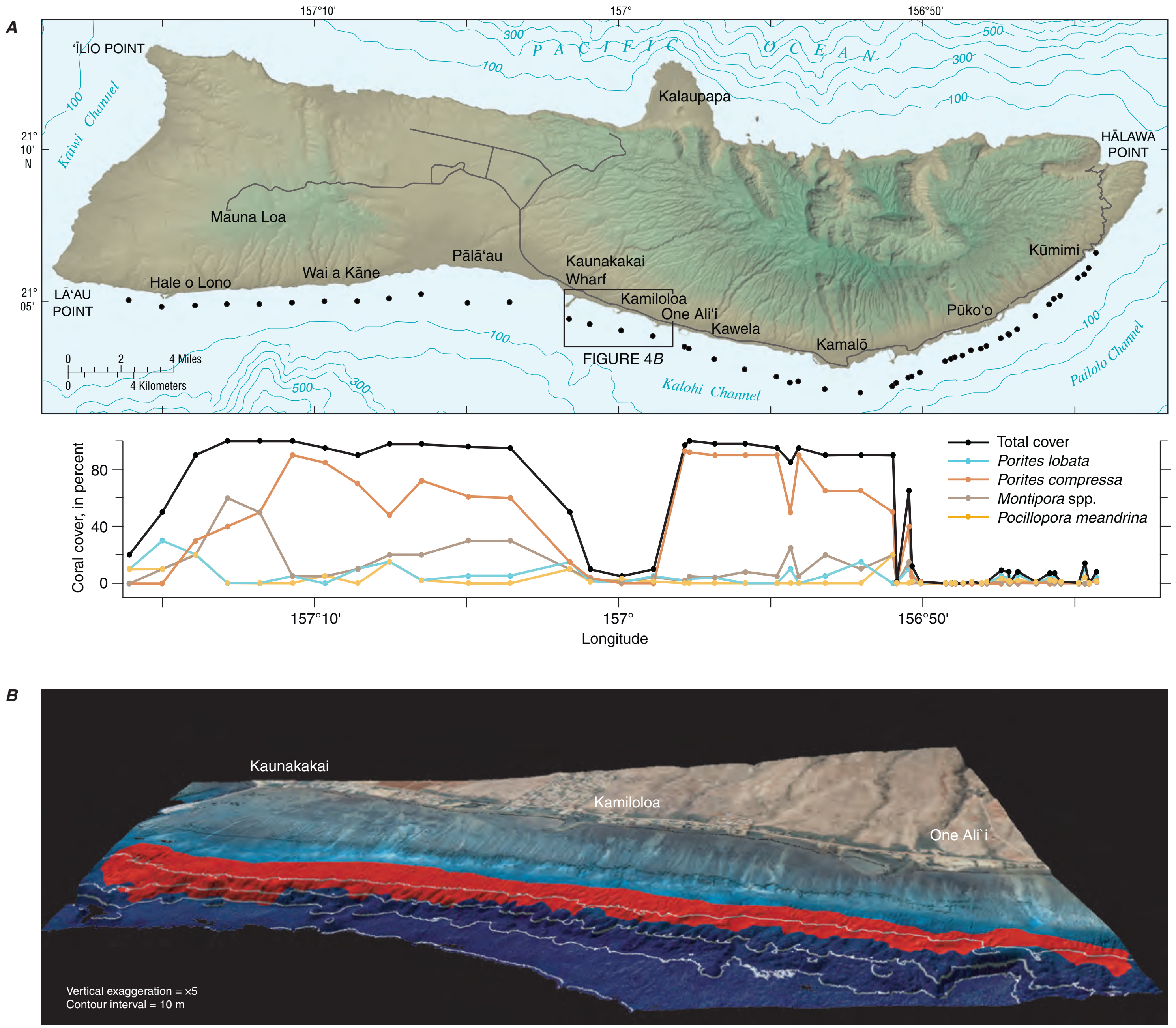

Figure 4. Variation of coral abundance along the south Moloka‘i reef. *A*, Coral abundance on the fore reef along the south shore of Moloka‘i in 2001, based on single point observations (dots in upper panel) in about 10 m (33 ft) of water every 2 km (1.24 mi) along the length of the reef (Jokiel and others, this vol., chap. 5). Note the very high total coral abundance from Hale O Lono on the west end of the island to east of Kamalō, with the pronounced drop in coral cover between the Kaunakakai Wharf and Kawela. *B*, An aerial photograph overlaid on shaded topography gives a 3D perspective view of the Moloka‘i reef between Kaunakakai and One Ali‘i and shows results of detailed follow-up surveys in 2002 and 2007. Observations made on scuba dives in the area of low coral cover from the 2001 survey showed that the entire upper fore reef at depths of 10 m (33 ft) in this area has low coral cover of ~15 percent (shown in red on the image). Coral cover in deeper water is high (>80 percent), except off the 3-km reef segment east of the wharf at Kaunakakai, where coral is degraded or absent. Distance along bottom of image is about 6.5 km (about 4 mi).

might be different if the island were isolated geographically, culturally, and economically from other human populations. Moloka‘i is part of the county of Maui, the State of Hawai‘i, and the United States. As such, even if the reef were to be totally destroyed, the Moloka‘i community would remain intact, at a reasonable standard of living. But the community of Moloka‘i and all of Hawai‘i would be far poorer—culturally and biologically—from the loss of this reef. The most intractable issue is the question of habitat damage and potential loss of a resource that has immeasurable intrinsic and cultural value.

In his seminal book, "Collapse: How Societies Choose to Fail or Succeed," Jared Diamond (2005) identifies four ways that societies fail to respond to ecological damage:

> First of all, a group may fail to anticipate a problem before that problem actually arrives. Second, when the problem does arrive, the group may fail to perceive it. Then, after they perceive it, they may fail even to try to solve it. Finally, they may even try to solve it but may not succeed. (p. 421)

How then do Diamond’s four categories apply to Moloka‘i? Gradual landscape change is difficult to detect, and it is likely that early Hawaiians did not anticipate or recognize changes in watershed processes and the downstream effects that resulted from cutting hardwood trees and cultivating crops. It may be that the problem was perceived during the last century, but that few actions were taken to remediate the effects from these activities (planting of mangroves at Pālā‘au was one such action). Finally, it may be that some actions were undertaken to offset soil erosion and loss, but that these actions largely failed because of the complex nature of the problem.

The key issue for avoiding environmental disasters is the recognition that change is occurring. Such recognition is often difficult—perceptions by residents of an area tend to be distorted by “shifting baselines” (Pauly and others, 1998) or “creeping normalcy” (Diamond, 2005), slow trends that are masked by large and irregular year-to-year variations. For example, a 75-year-old resident of Moloka‘i may recall reef waters off Kamiloloa as being clearer in his youth, but 45-year-old and 15-year-old residents will probably disagree with each other and with the older resident about what is “normal.” Over time and through generations, humans tend to develop “landscape amnesia” (Diamond, 2005), forgetting original environmental conditions because change is gradual. Thus the potential exists for people to accept the degraded coral, depleted fishery, abundant algae, and turbid water as normal.

It need not be so, and there is encouraging evidence that, with enough will and local support, the condition of the reef can improve. The introduction of mangroves at Moloka‘i in 1902—itself an action with its own environmental consequences—is direct evidence that successful actions can be taken to preserve and protect the reef. What future actions will be taken, and will they be successful?

What’s Next for the Moloka‘i Coral Reef?

Alternative scenarios are possible for the future of the reef, besides continued decline. The inhabitants of Moloka‘i, along with resource managers at the State and Federal levels, share responsibility for the protection and restoration of the reef. The sheltered setting of south Moloka‘i and the variety and abundance of bottom types—pinnacles, fore reef, channels, blue holes, reef flat—

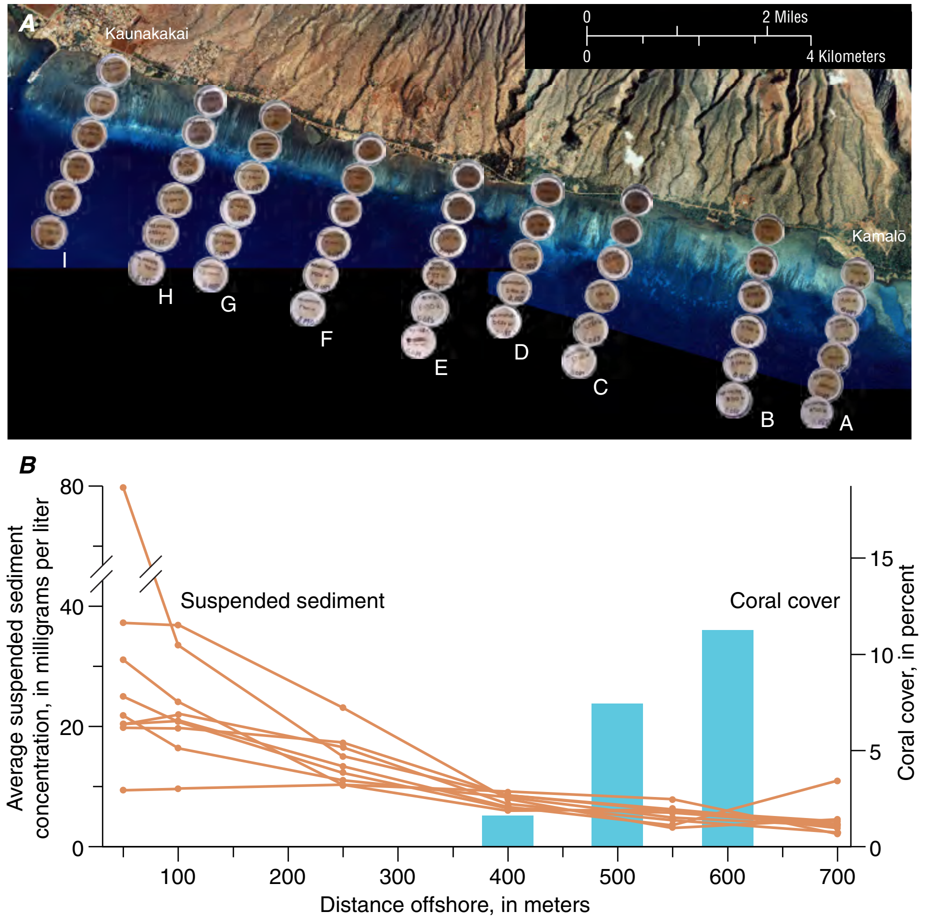

Figure 5. Turbidity of water on the south Moloka‘i reef flat and its relation to coral cover. *A*, Aerial mosaic of the central south Moloka‘i reef flat, between the Kaunakakai Wharf and Kamalō, with superimposed images of round filter papers containing the residue from filtering 1 to 2 liters (~1 to 2 quarts) of water. Samples were collected on April 7, 2005, at distances of 50, 100, 250, 400, 550, and 700 m from the shoreline. The filter papers are arranged on the image from nearshore to offshore along the sampling transects, but are shown non-overlapping for visual purposes. The darker brown color indicates that the nearshore waters contain relatively high levels of silt particles, which are derived from the island slopes (as confirmed by chemical tests). The highest concentrations of land-derived particles are on the inner reef flat. *B*, Concentrations of sediment in water on the Moloka‘i reef flat between the Kaunakakai Wharf and Kamalō, and their relation to coral cover, from field surveys and samples collected in April 2005. Suspended sediment concentrations are high near the shoreline (typically 20 to 70 mg/L) and decrease to 10 mg/L or less about 400 m from the shoreline. A concentration of 10 mg/L is considered the upper limit at which coral can grow successfully (Rogers, 1990). Also shown on this figure is the average coral cover on the reef flat, as mapped by Rodgers and others (2005). No appreciable coral exists within ~400 m of the shoreline, and at 400 m it is less than 5 percent. Coral cover gradually increases seaward to values of ~10 percent, which are still low compared with most other places on the reef.

have given rise to a rich coral setting. As Jokiel and others (this vol., chap 5) observe, diverse habitats in this area support rich coral reef communities.

The reef of south Moloka‘i has long served as a food, cultural, and recreational resource for the people of Moloka‘i, but its ability to do so in the future is not guaranteed. Many residents have noted that the nearshore waters are browner and the food resources reduced compared to earlier years. Friedlander and Rodgers (this vol., chap. 7) noted that fish resources are fewer and that management starting at the very local level was required:

> In addition, the men and women of the fishing community have expressed concern about the declining size and abundance of several important resource species such as kūmū and moana kale (blue goatfish, *Parupeneus cyclostomus*).

The coral reef off south Moloka‘i has been damaged—in some places severely—by excess sediment runoff from the land, particularly between the Kaunakakai Wharf and Kawela. Without protection of the reef from overuse and from excess sedimentation, its future is in jeopardy. Brown and others (this vol., chap. 6) point out that only 5 percent of Hawaiian reefs are in a threatened stage at this time but that portions of the Moloka‘i reef make up a significant part of the threatened group. Continued overuse of the reef for food sources, along with sediment influx from the land, will lead to continued degradation of the Moloka‘i coral reef ecosystem.

The fate of reefs receiving large quantities of sediment from adjacent landmasses is well studied. Woolfe and Larcombe (1998, 1999) discuss how reefs transform from healthy, accreting reefs to ones marked by declining health because of increased sediment input. The positions of the Moloka‘i reef flat and fore reef in such a scenario are well known at present, but the future pathway will depend on whether sedimentation continues unchecked or whether local actions are successful in significantly reducing the amount of land-derived sediment reaching the reef.

As long as large quantities of sediment are delivered annually onto the Moloka‘i reef flat, and as long as the reef is unprotected from overfishing, anchor damage, and other local stresses, it will be at risk. Climate change will likely place additional stresses on the coral communities through more acidic and warmer ocean waters (Hoegh-Guldberg and others, 2007), but that is a factor that cannot be controlled locally. The other stressors can be controlled locally, through strong sediment-management methods and establishment of large marine protected areas on the reef. As Hoegh-Guldberg and others (2007) point out, one important approach for offsetting the impacts of climate change on reefs is to reduce the influence of local stressors, such as suspended sediment in overlying waters.

Some steps are being taken locally to limit the impact of sediment on the reef. The Moloka‘i Watershed Advisory Group, The Nature Conservancy, the Hawai‘i Local Action Strategy of the U.S. Coral Reef Task Force, the U.S. Geological Survey, and other groups and agencies have all made concerted efforts to understand the factors that cause significant sediment runoff to the reef and to implement measures to limit the runoff. Eliminating feral goats, limiting wildfires, and guarding against harmful coastal and watershed construction activities all help to improve the situation, but these measures by themselves are not enough.

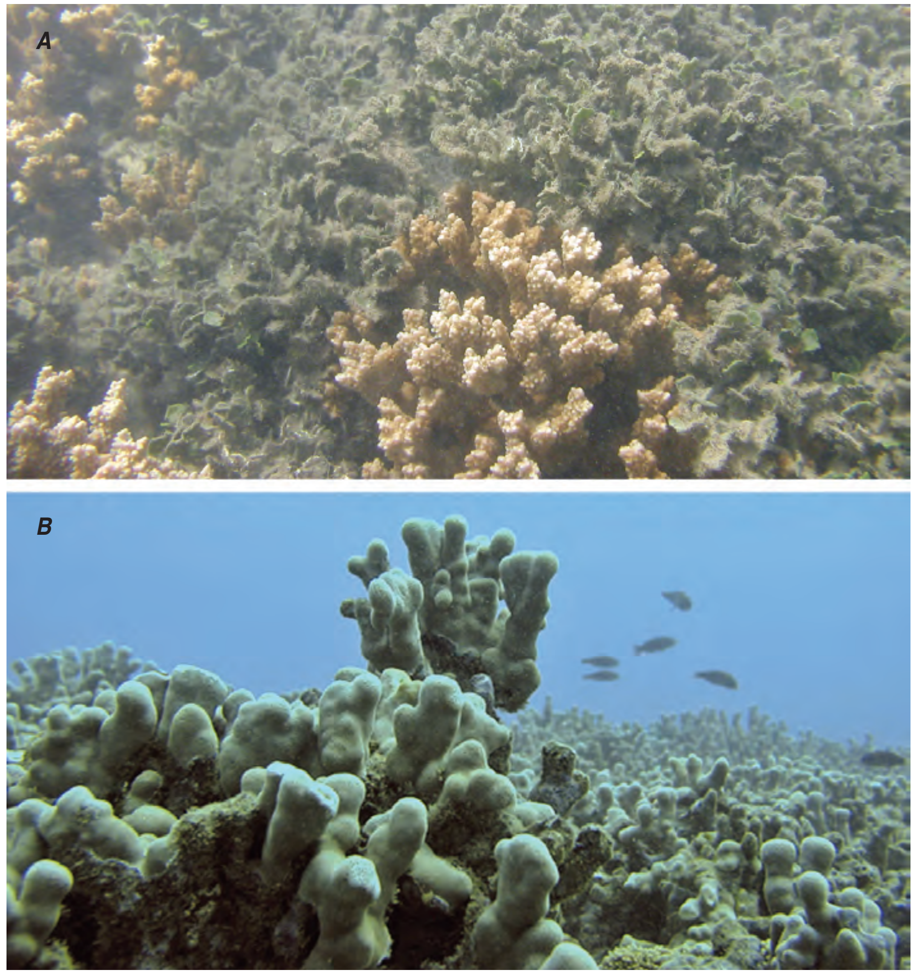

Figure 6. Two photographs of coral habitats that represent alternative pathways for the future of the Moloka‘i reef. *A*, Sediment and algae covering the surface have led to a decline in coral growth and its demise in places such as shown here, most notably on the reef flat and upper fore reef off central Moloka‘i. If land use and sediment runoff are not controlled, this may be the fate of large portions of the reef. *B*, Much of the Moloka‘i reef today remains healthy, as seen in this photograph. Reduction in sediment loads to the reef will help preserve this type of setting—and perhaps allow damaged areas to recover to a healthier state.

The ultimate fate of the coral reef off south Moloka‘i has not yet been determined (fig. 6). It is for the people of Moloka‘i, along with appropriate support at the county, State, and Federal levels, to take the necessary measures to safeguard this very special place—the reef of south Moloka‘i—for future generations. First steps could include support of efforts by nongovernmental and government groups to control fires, goats, and other factors that contribute to excess sediment runoff. Preserving the reef for generations of Moloka‘i and Hawai‘i residents can ultimately be best achieved by designating a large section of the reef as a marine protected area, one that is shielded from abuse by overfishing, sediment runoff, and other impacts.

Glossaries

Acronyms

ANOVA	analysis of variance (a statistical analysis procedure)
CCA	crustose coralline algae
CRAMP	Coral Reef Assessment and Monitoring Program
CRTF	United States Coral Reef Task Force
CTD	instrument that measures water conductivity (salinity), temperature, and depth
DAR	State of Hawai‘i Division of Aquatic Resources
DEM	digital elevation model
DLNR	State of Hawai‘i Department of Land and Natural Resources
DOC	dissolved organic carbon
DOI	United States Department of the Interior
ENSO	El Niño Southern Oscillation
ERM	effects range-median; a measurement of sediment toxicity
GIS	geographic information system
GLM	general linear model; a statistical analysis procedure
GPS	global positioning system
IRM	isothermal remanent magnetization; a technique to measure the magnetic properties of rock or sediment
LIDAR	light detection and ranging
MAB	meters above bottom
MMU	minimum mapping unit
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NPWMA	Nu‘upia Ponds Wildlife Management Area (O‘ahu)
PAR	photosynthetically active radiation
PSU	practical salinity units
SAG	spur-and-groove
SGD	submarine ground-water discharge
SHOALS	scanning hydrographic operational airborne lidar survey
SSC	suspended sediment concentration
SWAPS	spectral wave prediction system
TIN	total inorganic nitrogen
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey

Hawaiian Words

‘a‘ama	crab
āholehole	Hawaiian flagtail
ahupua'a	smaller subdivision of moku which define watersheds
aku	skipjack tuna
akule	bigeye scad
ali‘i	royalty
‘ama‘ama	mullet
enenue	chub
hā‘uke‘uke	shingle urchin
halalū	smaller sized akule
he‘e	octopus
hieau	sacred worship site or altar
hīnālea lauwili	saddle wrasse
hoo‘ilo	cooler and wetter weather season when winds are inconsistent
humuhumu hi‘u kole	pink durgeon
humuhumu lei lei	triggerfish
humuhumu nukunuku āpua‘a	reef triggerfish
humuhumu‘ele‘ele	black durgeon
kāhala	amberjack
kala	bluespine unicornfish
kapu	ancient Hawaiian system of laws and regulations; forbidden
kau	warmer and drier weather season when winds blow steadily
kawakawa	wavy-back tuna
kole	goldring surgeonfish
kūmū	whitesaddle goatfish
laenihi	razorfish
limu	seaweed
limu ‘ele ‘ele	a type of seaweed
limu kala	a type of seaweed
limu kohu	a type of seaweed
limu līpoa	a brown algae
limu manauea	a type of seaweed
limu pālahalaha	a type of green seaweed
limu waiwai‘ole	a green algae
loko i‘a	fishpond
loko kuapā	type of shoreline fishpond, fully enclosed except for a makaha
loko ‘ume iki	low-walled fishpond with walled lanes leading in and out
lū‘au	special occasion feast
lua wai	water holes
mā‘i‘i‘i	brown surgeonfish
mahimahi	dolphinfish
makaha	slotted gate in fishpond
makai	toward the sea
manauea	a type of seaweed
manini	convict tang
mauka	towards the mountains
moana kale	blue goatfish
moana ukali	a type of goatfish
moi	Pacific threadfin
moku	wedge-shaped parcels of land from mountain crest to shore
nabeta	razorfish
nui	large, big
‘oama	juvenile goatfishes
ō‘io	bonefish
ogo	a type of seaweed
onaga	long-tailed red snapper, also known as **‘ula‘ula koa‘e**
ono	wahoo, delicious
‘ōpakapaka	pink snapper
‘opihi	limpets
palani	eyestripe surgeonfish
pali	cliff
pāpio	juvenile jacks
pualu	yellowfin surgeonfish
puka	a depression, hole
roi	peacock grouper
ta‘ape	bluestripe snapper
taro	staple starchy plant
to‘au	blacktail snapper
uhu	parrotfish
uhu uliuli	spectacled parrotfish
uku	green jobfish
ula	spiny lobster
ula papa	slipper lobster
‘ula‘ula	red snapper
‘ula‘ula koa‘e	long-tailed red snapper, also known as **onaga**
ulua	jacks
uma-uma lei	orangespine unicornfish
‘ū‘ū	soldierfishes and squirrelfishes
weke	goatfish

Fieldwork Activities

Fieldwork activities for the research reported in this volume were assigned identification numbers, to which all data are tied. InfoBank (http://walrus.wr.usgs.gov/infobank/) is the U.S. Geological Survey Coastal and Marine Geology Team's online data catalog of these activities and more. Fieldwork activity IDs for USGS work on the Moloka'i reef and associated volume chapters are shown below.

Activity ID#	URL	Date (month/year)	Chapter(s)
S-22-00-HW	http://walrus.wr.usgs.gov/infobank/s/s2200hw/html/s-22-00-hw.meta.html	January 2000	9, 17, 19, 20
A-14-01-HW	http://walrus.wr.usgs.gov/infobank/a/a1401hw/html/a-14-01-hw.meta.html	January 2001	19, 20
A-2-01-MK	http://walrus.wr.usgs.gov/infobank/a/a201mk/html/a-2-01-mk.meta.html	April 2001	19, 20
A-1-01-HW	http://walrus.wr.usgs.gov/infobank/a/a101hw/html/a-1-01-hw.meta.html	July 2001	19, 20
W-1-01-HW	http://walrus.wr.usgs.gov/infobank/w/w101hw/html/w-1-01-hw.meta.html	September 2001	1
A-1-01-MK	http://walrus.wr.usgs.gov/infobank/a/a101mk/html/a-1-01-mk.meta.html	November 2001	19, 20
A-1-02-HW	http://walrus.wr.usgs.gov/infobank/a/a102hw/html/a-1-02-hw.meta.html	February 2002	19, 20
A-2-02-HW	http://walrus.wr.usgs.gov/infobank/a/a202hw/html/a-2-02-hw.meta.html	July 2002	9
A-L-02-HW	http://walrus.wr.usgs.gov/infobank/a/al02hw/html/a-l-02-hw.meta.html	August 2002	13, 20
A-1-03-HW	http://walrus.wr.usgs.gov/infobank/a/a103hw/html/a-1-03-hw.meta.html	February 2003	9
H-1-03-HW	http://walrus.wr.usgs.gov/infobank/h/h103hw/html/h-1-03-hw.meta.html	July 2003	9
A-5-03-HW	http://walrus.wr.usgs.gov/infobank/a/a503hw/html/a-5-03-hw.meta.html	July 2003	13
A-6-04-HW	http://walrus.wr.usgs.gov/infobank/a/a604hw/html/a-6-04-hw.meta.html	August 2004	13

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