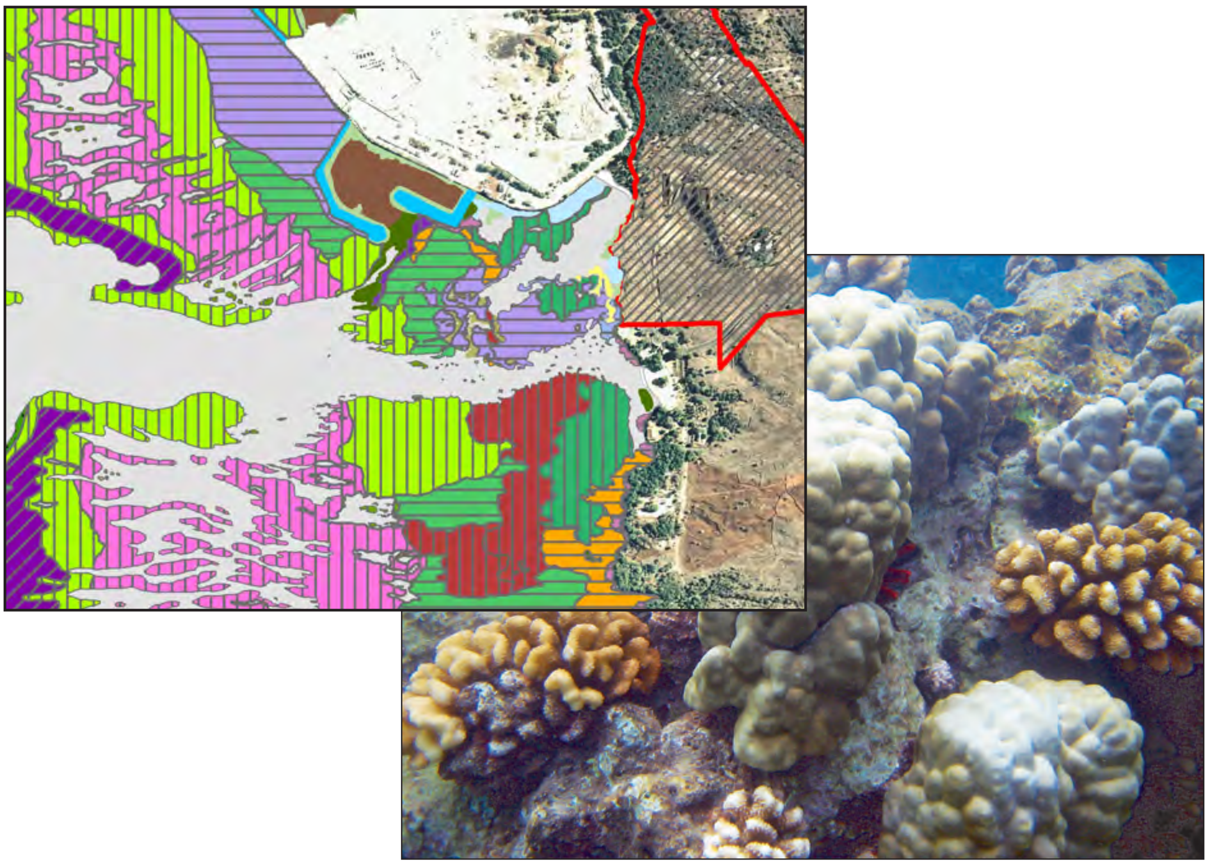
Prepared in cooperation with the U.S. National Park Service

Geologic Resource Evaluation of Pu`ukoholā Heiau National Historic Site, Hawai`i

Part II: Benthic Habitat Mapping



Scientific Investigations Report 2006-5254

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

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By Susan A. Cochran, Ann E. Gibbs, and Joshua B. Logan

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DIRK KEMPTHORNE, Secretary

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U.S. Geological Survey, Reston, Virginia: 2007

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Manuscript approved for publication, September 28, 2006
Text edited by Peter H. Stauffer
Layout by David R. Jones

Suggested citation:
Cochran, S.A., Gibbs, A.E., and Logan, J.B., 2007, Geologic resource evaluation of Pu`ukoholā Heiau National Historic Site, Hawai`i; Part II, Benthic habitat mapping: U.S. Geological Survey Scientific Investigations Report 2006-5254, 20 p.

Cover: Left, enlarged portion of benthic habitat map showing Pelekane Bay and Pu`ukoholā Heiau National Historic Site shoreline. Right, underwater photograph shows example of coral reef habitat on the Kona coast of Hawai`i.

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Geologic Resource Evaluation of Pu`ukoholā Heiau National Historic Site, Hawai`i

Part II: Benthic Habitat Mapping

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Introduction

In cooperation with the U.S. National Park Service (NPS), the U.S. Geological Survey (USGS) has mapped the underwater environment in and adjacent to three parks along the Kona coast on the island of Hawai`i (fig. 1). This report is the second of two produced for the NPS on the geologic resource evaluation of Pu`ukoholā Heiau National Historic Site (PUHE) and presents benthic habitat mapping of the waters of Kawaihae Bay offshore of PUHE. See Part I (Richmond and others, 2008) for an overview of the regional geology, local volcanics, and a detailed description of coastal landforms in the park.

PUHE boundaries do not officially extend into the marine environment; however, impacts downslope of any activity in the park are of concern to management. The area of Kawaihae Bay mapped for this report extends from the north edge of the U.S. Coast Guard Reservation north of Kawaihae Harbor approximately 3.5 km south to the north edge of the Mauna Kea Golf Course and Beach Resort at Waikoloa and from the shoreline to depths of approximately 40 m (130 ft), where the fore reef drops off to the sandy shelf (fig. 2). The waters of smaller Pelekane Bay directly offshore of the park, while not formally under NPS jurisdiction, are managed by the park under an agreement with the State. This embayment is described in greater detail because of its special resource status.

PUHE lies within the Kawaihae watershed, which contributes ~75 percent of the drainage in the northern portion of the study area; the Waikoloa/Waiulaula watershed contributes ~25 percent in the southern portion of the study area. Drainages from these watersheds into the study area include Makahuna, Makeāhua, Pohaukole, Kukui, and Waikoloa/Waiulaula Gulches. The Waikoloa/Waiulaula Gulch is the only perennial

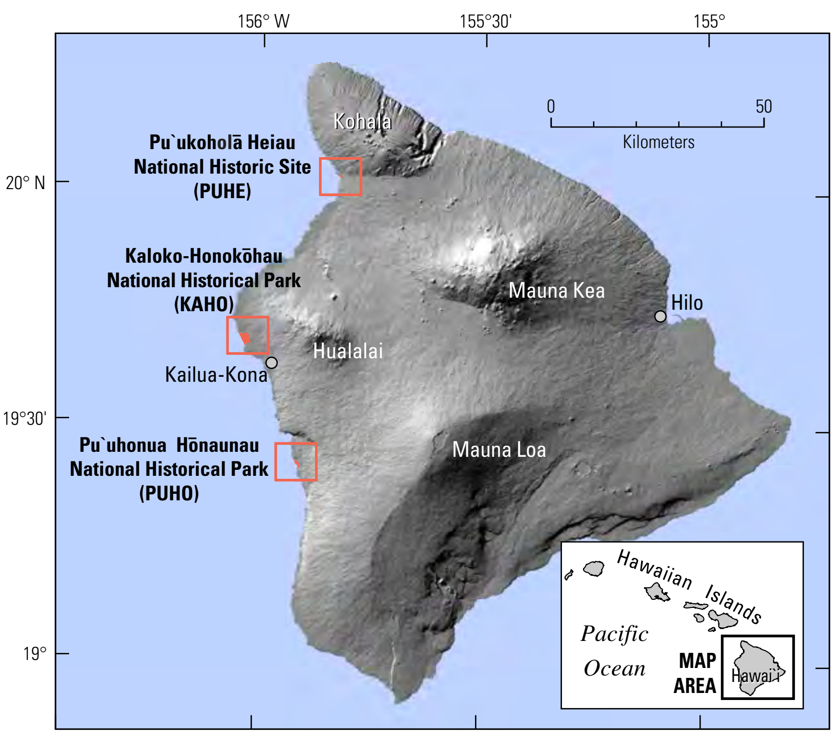

Figure 1. Index map of the Island of Hawai`i showing the location of the three National Parks along the Kona coast. Volcano names are shown in white.

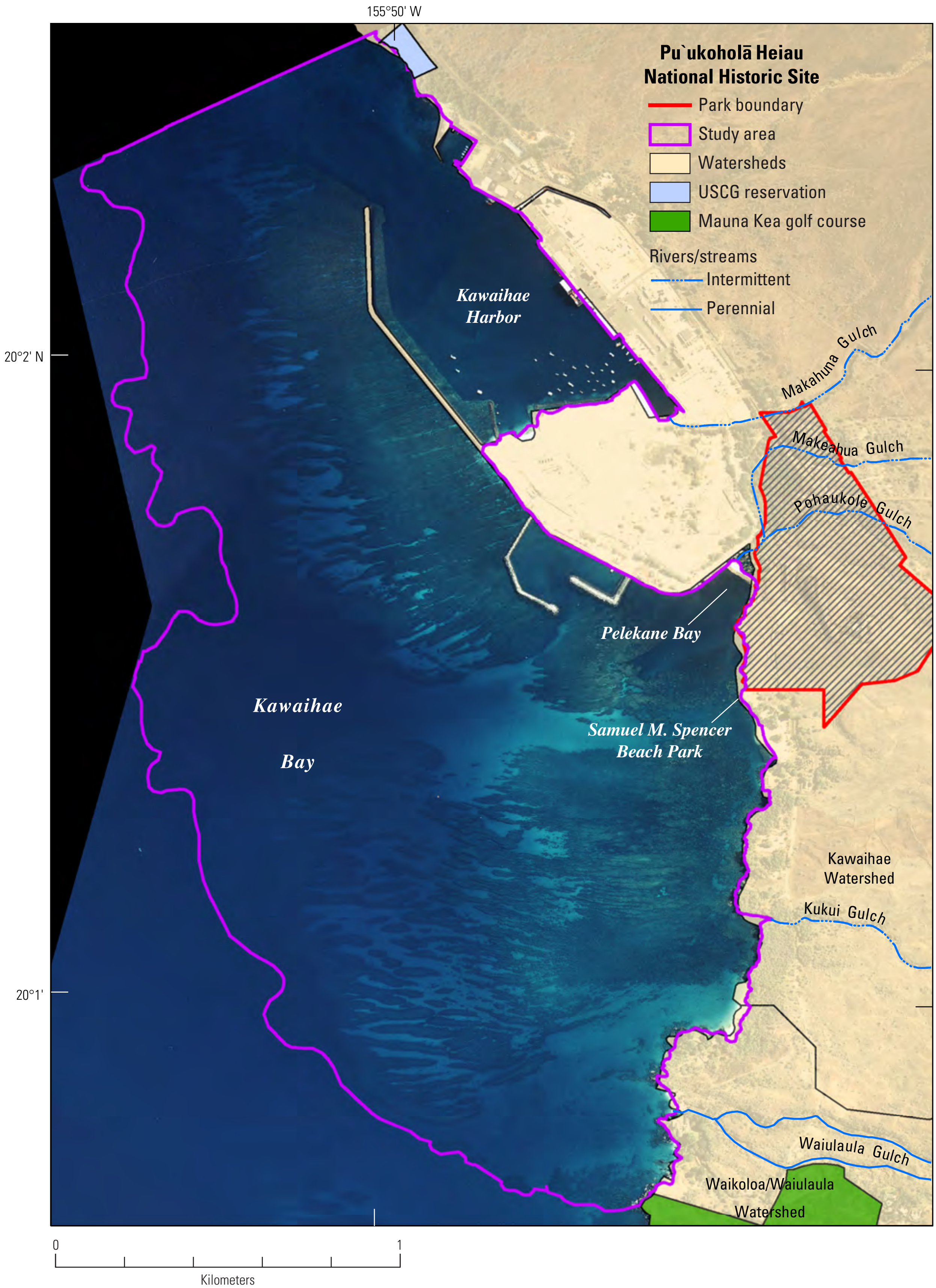

Figure 2. Aerial photomosaic showing PUHE park boundary, study area, watersheds, streams, and place names discussed in text.

stream with a year-round water flow. Only during periods of extreme rainfall will water flow in the Makeāhua and Pohaukole gulches, merge together in the park, and empty directly into Pelekane Bay.

In the late 1950s the reef off of PUHE was dredged to construct Kawaihae Harbor. Coral rubble was used in the construction of causeways and a revetment wall surrounding the commercial harbor. In the late 1960s the reef near Pelekane was blasted to create a small-boat harbor adjacent to the larger commercial harbor. Damage from these activities, in addition to a change in circulation patterns, has led to problems of high turbidity in Pelekane Bay (Tissot, 1998).

Data and Methods

A standard for characterization of coral-reef environments was first implemented by the National Oceanic and Atmospheric Administration (NOAA) for mapping the Florida Keys (Rohman and Monaco, 2005) and Puerto Rico and the Virgin Islands (Kendall and others, 2001). This standard for mapping coral reefs in the United States and its territories describes benthic habitats on the basis of their sea-floor geomorphology, geographic zonation, and biological cover.

In this study, the benthic-habitat classification maps were created using the standards established by NOAA but at a finer scale (minimum mapping unit of 100 m versus 1 acre) and with additional data sources, including existing color aerial photography, Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) bathymetric data, georeferenced underwater video, and still photography. The maps were generated using both ArcView and ArcMap Geographic Information System (GIS) software by ESRI (http://www.esri.com), and a statistical analysis of accuracy of the resultant maps was performed. The flowchart in figure 3 illustrates the complete methodology.

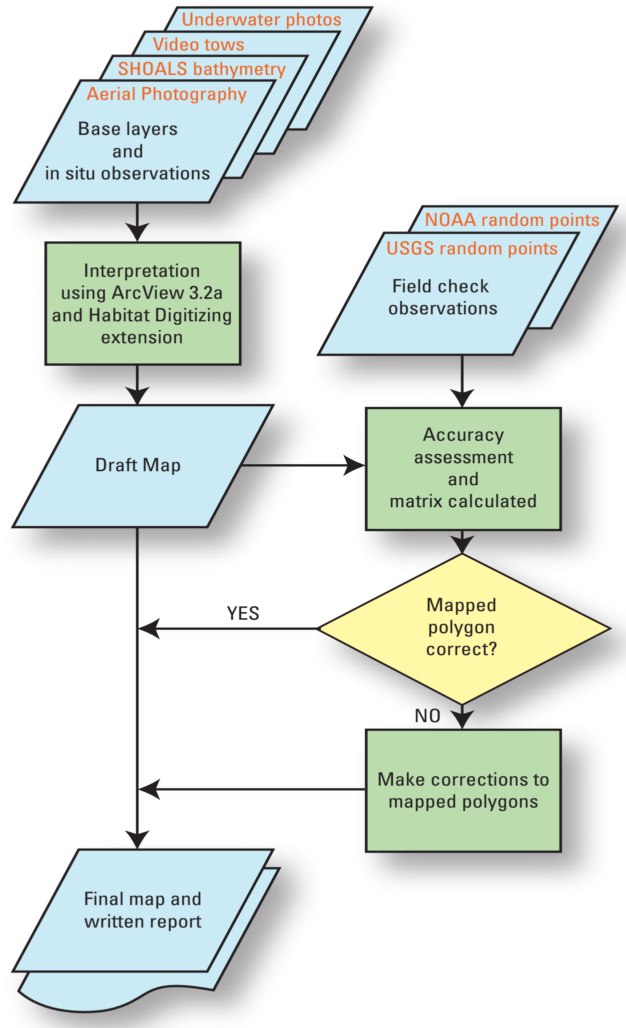

Figure 3. Flowchart illustrating methodology used to create Acquired Data habitat map. See text for complete description.

Background Data

SHOALS Bathymetry

High-resolution SHOALS bathymetry point data collected in 2000 by the U.S. Army Corps of Engineers (USACE) were obtained and converted to a raster surface using ESRI's 'GRID' function. The bathymetric data have an average horizontal point spacing of 4 m ± ~3 m and a vertical resolution of ± 0.15 m, with a maximum water penetration of about 42 m (138 ft) in the study area. However, there are data gaps in the harbor and nearshore in Pelekane Bay, probably from lack of signal penetration due to poor water clarity (fig. 4). Contour lines, hillshades, and slope maps were derived from this dataset using standard ArcMap functions. For further details regarding SHOALS data, see http://shoals.sam.usace.army.mil.

Aerial Photography

True-color aerial photographs for Kawaihae Bay were collected in June 2000 by NOAA. For further details on NOAA aerial photography for Hawai`i see http://ccma.nos.noaa.gov/products/biogeography/hawaii_cd/htm/flightln.htm. These images were post-processed and mosaicked by the USGS, resulting in a digital mosaic with a resolution of 1 meter per pixel (fig. 5). A two-step process was used to georectify, or geometrically correct, the aerial mosaic to real-world coordinates, using previously georegistered black and white USGS digital orthophoto quads (DOQs) of the area as an intermediate reference between the SHOALS data and the unregistered aerial photography. In the first step, a shaded-relief image generated using the SHOALS lidar bathymetry data was digitally merged with the DOQs. In the second step,

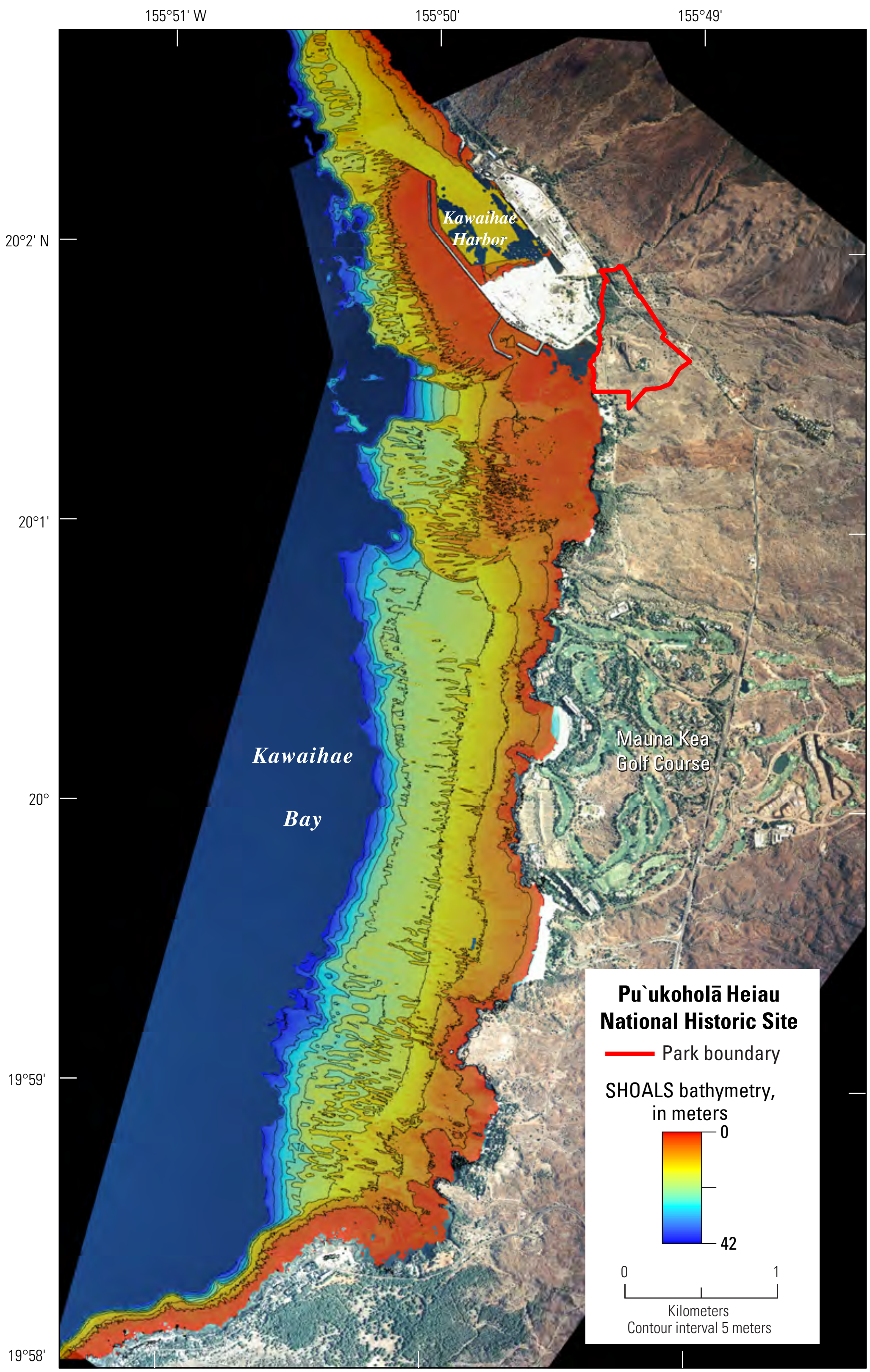

Figure 4. Aerial photomosaic of Kawaihae Bay overlaid with SHOALS bathymetry coverage.

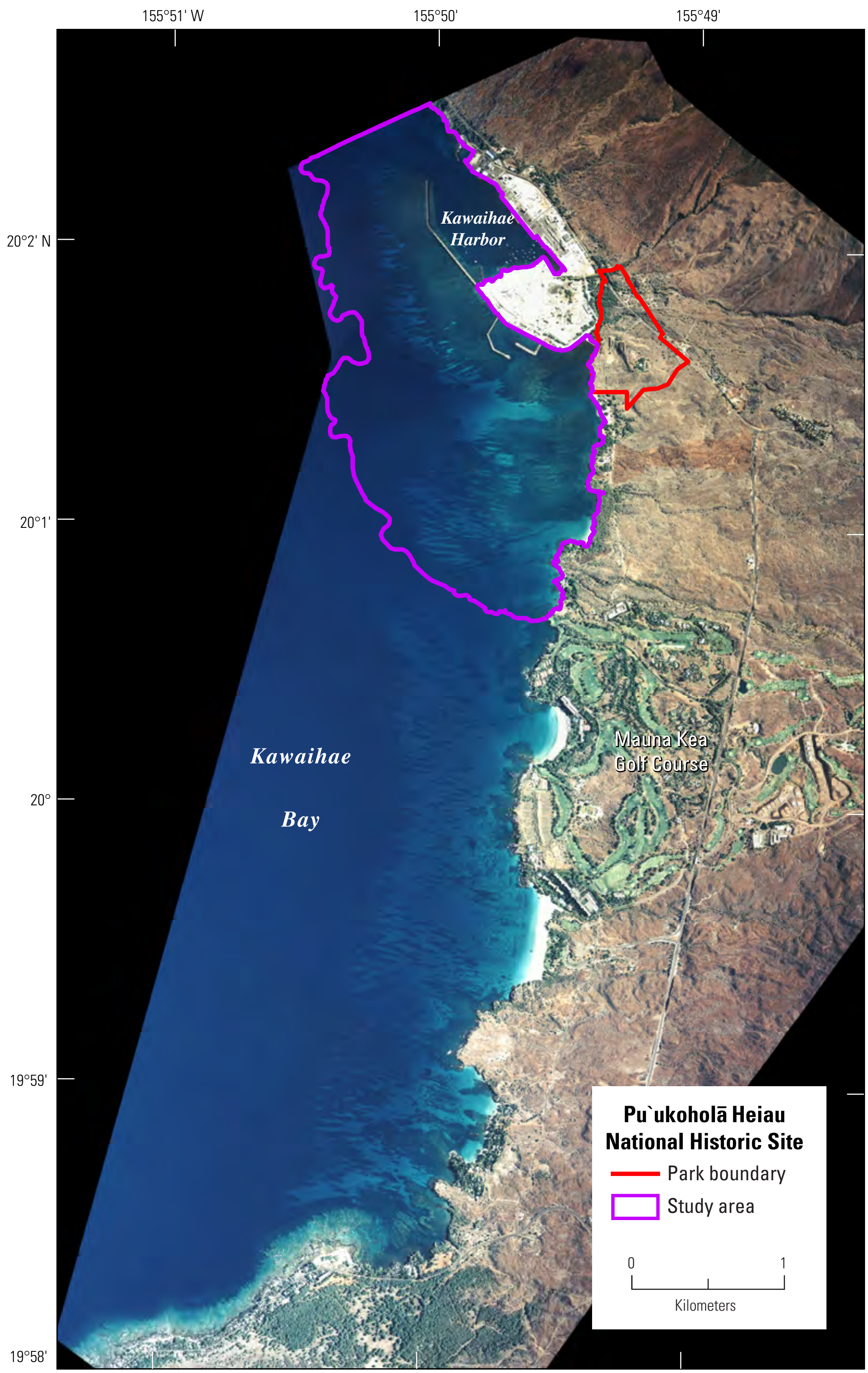

Figure 5. Aerial photomosaic of Kawaihae Bay area showing PUHE park boundary and study area.

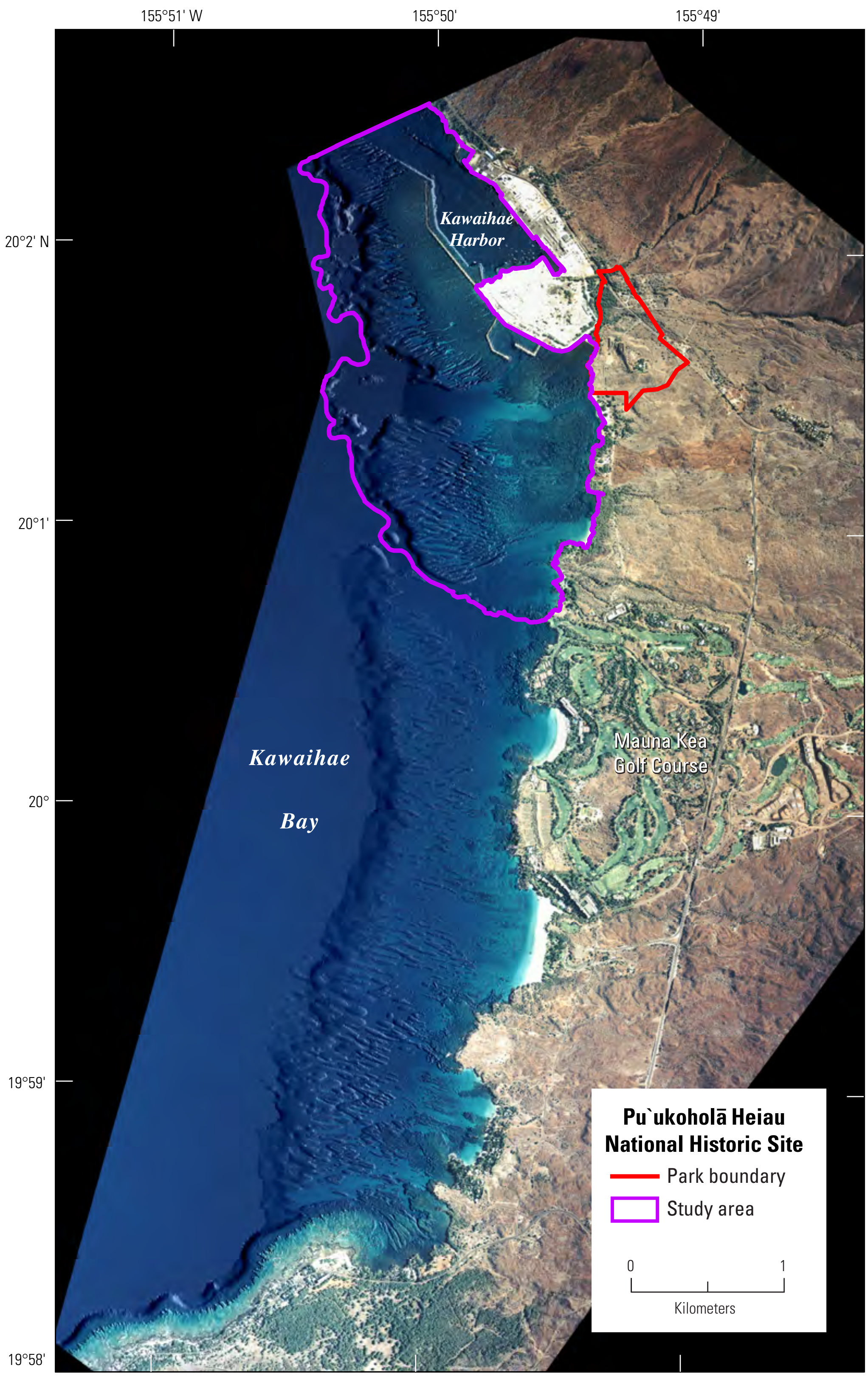

Figure 6. Aerial photomosaic of Kawaihae Bay merged with shaded relief from SHOALS bathymetry. The combination of color and shaded relief assists with interpretation of benthic habitats.

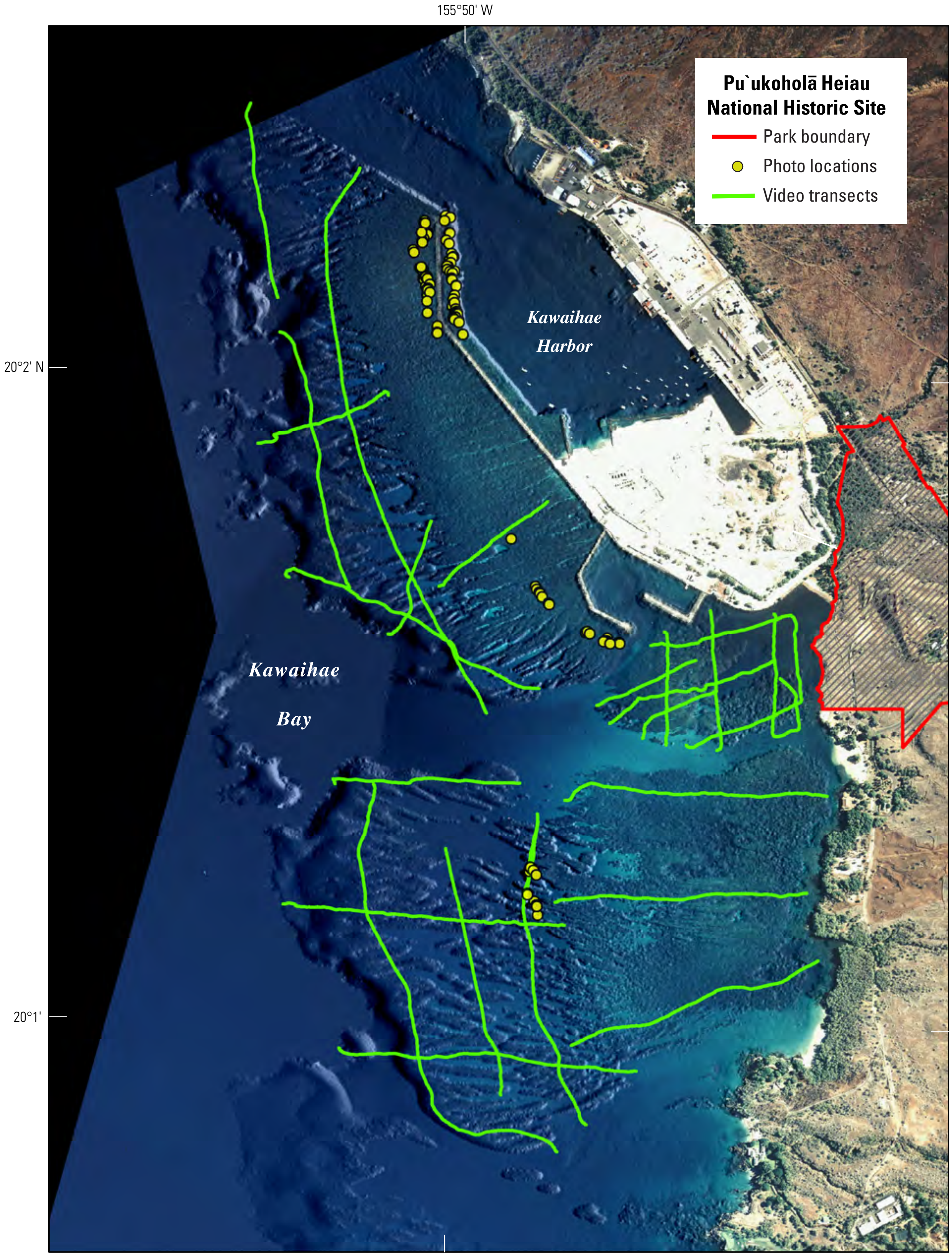

Figure 7. Aerial photomosaic of northern Kawaihae Bay showing shaded relief, overlaid with locations of video transects and still photos.

the digital SHOALS/DOQ merge became the "geometric master" to which the aerial photography mosaic was matched.

A merge of the aerial photography and SHOALS bathymetry data shows shaded relief as well as color differences and was used for the interpretation of PUHE benthic habitats (fig. 6).

Acquired Data

Underwater Video and Still Photography

Nearly 17 trackline kilometers of underwater video footage (24 lines) and more than 150 still images were collected during two field surveys between April 2004 and August 2004 to assist in interpretation of the aerial photography and lidar bathymetry (fig. 7). Navigation and other information regarding these surveys are available online at http://walrus.wr.usgs.gov/infobank/a/a204hw/html/a-2-04-hw.meta.html, and http://walrus.wr.usgs.gov/infobank/a/a604hw/html/a-6-04-hw.meta.html. Several types of camera systems were used, depending on water depth and collection methods. During diving and snorkeling, still images were collected using a hand-held digital camera (Sony DCS-P5 or Canon Elph S-400).

Video imagery was obtained by towing a camera off the *Alyce C*, a 32-ft vessel operated by Capt. Joe Reich of Moloka`i (fig. 8), and a 13-ft motorboat owned by the NPS. The camera system used was a watertight video camera illuminated with a light-emitting diode (LED) ring designed by SeaViewer Underwater Video Systems (http://www.seaviewer.com). The camera was mounted in a small aluminum hand-held frame with a rear-mounted plastic fin (fig. 9). Live video was viewed in a shipboard laboratory on a standard CRT monitor and recorded directly to miniDV tape. Time, date, location, and ship speed were overlaid on the video using the Sea-Trak global positioning system (GPS) method, also developed by the SeaViewer company.

Simultaneous navigation, recording of ship position, and feature annotation were conducted in real time using Red Hen Systems' (http://www.redhensystems.com) VMS200 hardware and MediaMapper software on a PC laptop (fig. 10). Location data were recorded using a hand-held, WAAS-enabled, Garmin (http://www.garmin.com) GPS76 receiver. The stated horizontal accuracy of the Garmin GPS76 is better than 3 m when receiving WAAS corrections. The VMS200 transmitted NMEA-formatted GPS data at two-second intervals to the first audio channel of the video tape. A database was simultaneously created by MediaMapper to cross-reference the GPS locations and video time codes. This technique allowed for navigation and video to be viewed in real time and the location of features of interest and comments (for example, start/end of lines, substrate types) to be added to the database during data collection. Back in the lab, this technique allowed rapid random access to the original video by selecting locations along the navigation trackline within MediaMapper and GeoVideo (an extension developed by Red Hen Systems for integration with the ESRI ArcMap platform)

Figure 8. Photograph of the *Alyce C* of Moloka`i heading out of Mā`alaea Harbor, Maui.

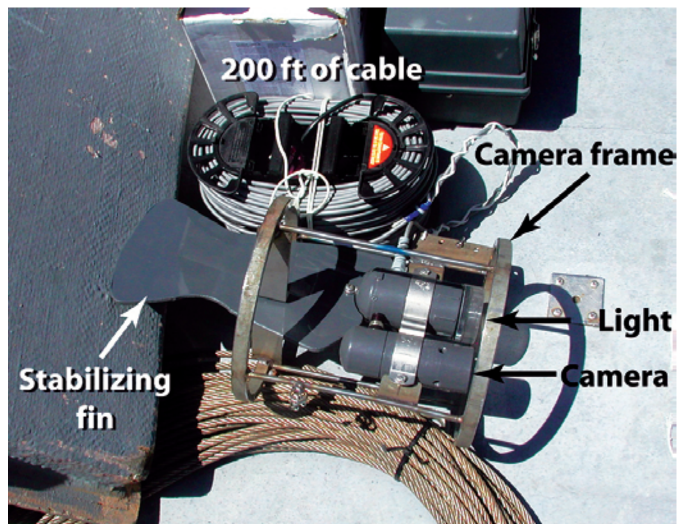

Figure 9. Photograph of SEAVIEWER camera system rigged to collect towed video.

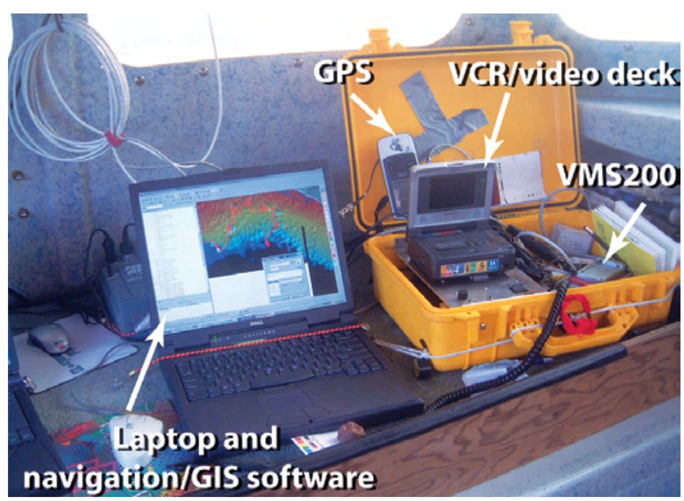

Figure 10. Photograph of shipboard system for navigation, recording of ship's position, and feature annotation.

software packages. Video could be interactively queried and geographically referenced feature annotations added to the database.

Benthic Habitat Mapping using GIS

Digital benthic habitat maps were created using ESRI's ArcViewGIS v.3.2 software with a habitat digitizing extension created by NOAA (to download the extension see http://ccma.nos.noaa.gov/products/biogeography/hawaii_cd/htm/digitize.htm). The habitat digitizing extension allows users to delineate habitat areas and assign attributes to the habitat polygons based on a predetermined classification scheme using a point-and-click menu system.

We digitally delineated more than 300 polygons, covering more than 4 km^2, by interpreting features seen in both the aerial photographs and SHOALS bathymetry layers, with additional input from other data. A minimum mapping unit (MMU) of 100 m^2 was used; however, 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).

Classification Scheme

The classification scheme is based on a scheme established by NOAA's biogeography benthic habitat mapping program in 2002 (Coyne and others, 2003) for the main eight Hawaiian islands, and subsequently revised in 2004 (National Oceanic and Atmospheric Administration National Centers for Coastal Ocean Science, 2005). Developed with input from coral reef scientists, managers, local experts, and others, the hierarchal scheme allows users to expand or collapse the level of thematic detail as necessary. As stated above, we are using NOAA's definition of benthic habitats and their classification scheme as a starting point to provide continuity to the coral reef scientific community. However, we have made additional modifications to the classification scheme to better reflect the benthic habitats and geologic substrates found along the Kona coast.

The classification scheme uses five basic attributes to describe each polygon on the benthic habitat map: (1) the major structure or underlying substrate, (2) the dominant structure, (3) the major biologic cover found on the substrate, (4) the percentage of major biological cover, and (5) the geographic zone indicating the location of the habitat. The structure combination with the overlying biologic cover is referred to as a "habitat." Majority rules—if a polygon includes two or more substrate or coverage types, the polygon is identified with the dominant one.

Four major structure types are further subdivided into fifteen dominant structures (table 1). Ten major biologic cover types are also modified by the percent of coverage (tables 2 and 3). The classification scheme allows for any biologic cover to be found on any structure/substrate, although many combinations are unlikely (for example, coral on sand, or emergent vegetation on spur-and-groove). Less than 10 percent cover of any type is equivalent to 90–100 percent uncolonized; therefore 0–10 percent cover is not used. Each polygon is coded with a 4-digit UNIQUEID attribute that reflects the combination of the individual habitat components (major structure, dominant structure, major biologic cover, and percent cover).

Table 1. Major structure (substrate) types with dominant structure subdivisions.

[Numbers represent UNIQUEID identifier.]

Major Structure	Dominant Structure
1 Unconsolidated Sediment	**1** Mud **2** Sand
2 Reef and Hardbottom	**1** Aggregate Reef **2** Spur-and-Groove **3** Individual Patch Reef **4** Aggregated Patch Reef **5** Volcanic Pavement with 10–50% Rocks/Boulders **6** Volcanic Pavement **7** Volcanic Pavement with >50% Rocks/Boulders **8** Volcanic Pavement with Sand Channels **9** Reef Rubble
3 Other	**0** Unknown **1** Land **2** Artificial **3** Artificial/Historical
9 Unknown	**0** Unknown

Table 2. Major biologic cover classes.

[Numbers represent UNIQUEID identifier.]

Major Biological Cover
0 Unknown
1 Uncolonized
2 Macroalgae
3 Seagrass
4 Coralline Algae
5 Coral
6 Turf
7 Emergent Vegetation
8 Mangrove
9 Octocoral

Table 3. Percent cover classes.

[Numbers represent UNIQUEID identifier.]

Percent Cover
0 Unknown
2 10–<50%
3 50–<90%
4 90–100%

The fifth attribute, zone, refers only to a habitat community's location within the coral reef ecosystem and does not indicate the substrate or biological cover type (fig. 11). Eleven zones correspond to typical reef geomorphology found in current literature (table 4). An additional dredged zone has been added to include those areas where anthropogenic change has occurred (for example, harbors and manmade channels).

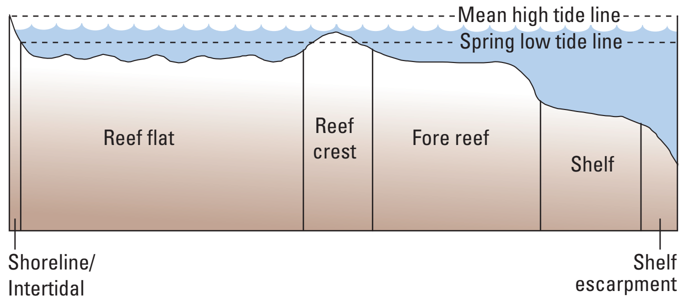

Figure 11. Schematic diagram showing the generalized cross-shelf coral reef zonation. Not shown: land, channel, dredged, or vertical wall (modified from Kendall and others, 2004). Detailed descriptions of the zones are given in the appendix.

Detailed descriptions of habitats and zones, including example photographs, may be found in the appendix.

Table 4. Geomorphic zones of coral reef ecosystems.

Zone
Land
Shoreline/Intertidal
Vertical Wall
Lagoon
Back Reef (with Lagoon)
Reef Flat (without Lagoon)
Reef Crest
Fore Reef
Bank/Shelf
Bank/Shelf Escarpment
Channel
Dredged

Accuracy Assessment

The validity, or usefulness, of any classification or interpretation may be determined with an accuracy assessment, which compares the interpretation with what is actually found in the field. In this project, the benthic habitat map's overall accuracy and its accuracy from both the user and producer points of view were determined.

Overall accuracy indicates which points on the map are classified correctly according to a field check (Lillesand and Keifer, 1994). Producer accuracy indicates how well the map producer classified the different cover types (that is, the number of points on the map labeled correctly). User accuracy indicates the probability that a point in a given class is actually represented by that class in the field (that is, which mapped areas are actually what the map says they are).

This mapping project was performed concurrently with similar projects at two other National Parks along the Kona coast, Kaloko-Honokōhau National Historical Park (KAHO) and Pu`uhonua O Hōnaunau National Historical Park (PUHO). A combination of field check data from all three parks was used to measure the accuracy of the PUHE benthic habitat map. Nearly 190 randomly generated sample points were visited by third-party coral reef research biologists from the University of Hawai`i who are highly familiar with the classification scheme. In addition, more than 50 sampling points from the NOAA database (http://ccma.nos.noaa.gov/products/biogeography/hawaii_cd/htm/aap.htm) were used in the accuracy assessment.

Once the accuracy assessment calculations were completed, any misinterpreted polygons identified were corrected, thus increasing the percent accuracy of the final map.

Data Archive

Underwater video footage, photographs, and associated shapefiles have been transferred to DVD. One complete set will be held in the USGS archives (see http://walrus.wr.usgs.gov/infobank/a/a204hw/html/a-2-04-hw.meta.html and http://walrus.wr.usgs.gov/infobank/a/a604hw/html/a-6-04-hw.meta.html to view list of analog holdings), and the other will be presented to the National Park Service to accompany this report. This report and project shapefiles are also available online (http://pubs.usgs.gov/sir/2006/5254).

Results

Kawaihae Bay

The reef system off PUHE in Kawaihae Bay is much different from those of the other two National Parks on the Kona Coast. As at KAHO and PUHO, the PUHE reef lacks the back reef, lagoon, and reef crest zones, and instead the shelf platform begins at the shoreline and slopes away to the deeper ocean. However, unlike the other two parks, PUHE also has a complex fore reef structure vertically accreting on top of the shelf, beginning approximately 0.25 km from shore (fig. 12). The coral reef systems offshore from KAHO and PUHO have very little, if any, vertical accretion.

The PUHE fore reef consists of a nearshore coralline algae-covered reef platform, transitioning into a distinct series of shore-normal spur and grooves, which then merge near the seaward edge and form an extensive aggregate reef. In between the shoreline and the fore reef, the shelf slope is covered with individual and aggregated patch reefs, the northernmost of which were dredged in the creation of Kawaihae Harbor (fig. 13). The roughly 4.15 km^2 study area is bisected by a broad expanse of sand-covered bottom with a gentle ~3° slope seaward, possibly formed by an old offshore stream extension during a sea-level lowstand (fig. 14).

More than 2 km^2 (51 percent) of the study area consists of live accreting coral structures, including aggregate reef (1.41 km^2) and spur and groove formations (0.64 km^2) (fig. 15). The

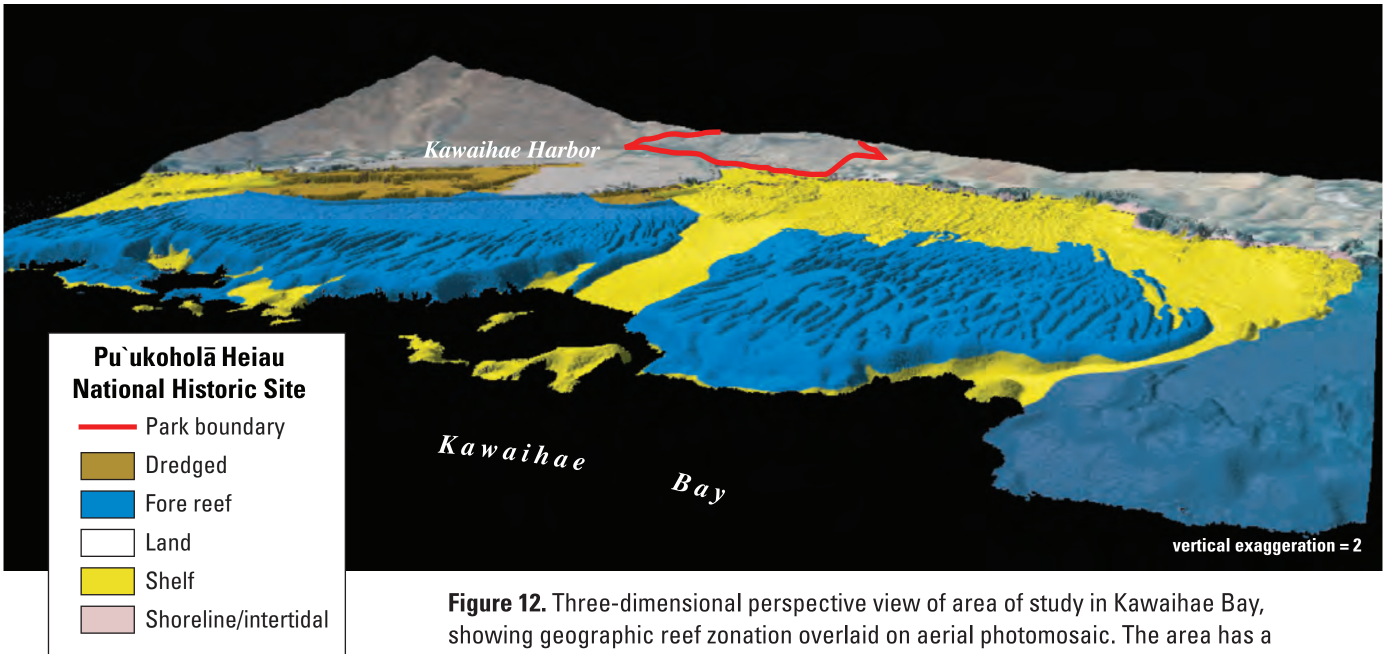

Figure 12. Three-dimensional perspective view of area of study in Kawaihae Bay, showing geographic reef zonation overlaid on aerial photomosaic. The area has a complex fore-reef structure on top of the underlying shelf. View is to the northeast. Approximate distance along the bottom of the figure is 2.5 km.

spur and groove structures dominate between –5 and –15 m (–15 and –50 ft). Below –15 m the aggregate reef dominates the fore reef (fig. 16), which then drops off sharply (~30–40°) into a sand-covered sea floor around –40 m (–130 ft). Nearly 2 km^2 (46 percent) of the study area has at least 10 percent live coral cover (fig. 17). The highest densities of live coral are found on the buttresses (spurs) and on the aggregate reef at the seaward edge of the fore reef. In these places the live coral ranges from 50 to 100 percent cover and is predominantly *Porites compressa*. Along the shoreward edge of the fore reef, backed up along the main harbor breakwater and in the transition zone to patch reefs, the aggregate reef platform is covered with mostly coralline algae. The live coral growth found here is restricted to small juvenile colonies, predominantly *Porites lobata*, which is able to withstand high wave environments. A highly diverse live coral environment is found directly behind the main harbor breakwater, where it is sheltered from extreme wave conditions.

Pelekane Bay

County-owned Samuel M. Spencer Beach Park borders the PUHE shoreline to the south, and the Kawaihae Harbor fill revetment abuts the north boundary. The waters just offshore from the Pu`ukohola and Mailekini Heiaus are known as Pelekane Bay. In 1998 the State of Hawai`i designated Pelekane Bay as a Category 1 impaired water resource, not meeting, or in imminent danger of not meeting, clean water guidelines (State of Hawai`i, 1998). Although not officially part of PUHE, the 6 acres (0.024 km^2) of Pelekane Bay are managed by the Park through an understanding with the State. After heavy rainfall, Makeāhua and Pohaukole streams merge and breach a coastal sand berm, draining into Pelekane Bay near the edge of Kawaihae Harbor's revetment wall and carrying silt and mud from upland erosion of the Kawaihae watershed. Kawaihae Harbor limits the natural flushing in this small bay, thus exacerbating siltation problems (Tissot, 1998). In this shallow murky water lies Hale o Kapuni Heiau, dedicated to the Hawaiian shark gods. Hale o Kapuni is now completely submerged, and the remains have been covered over with silt and dredge spoils.

A belt of broken coral and rocks from dredge spoils scattered on volcanic pavement is found running along the Kawaihae Harbor revetment wall to approximately 40 m into Pelekane Bay (fig. 18). Classified as uncolonized, this is an area of high siltation and limited turf algal growth. The lack of algae in this area may be due to light limitations from turbidity (Ball, 1977). A thin ribbon (~3 to 5 m) of aggregated patch reefs covered with turf algae and sediment lies between this belt and the sand channel in the middle of the bay. The ancient Hawaiian royal courtyard at Pelekane Beach is found on the southwest-facing shore of Pelekane Bay. On the PUHE side of the small bay, uncolonized volcanic rocks and boulders line the shore's edge.

Aggregated patch reefs are found from the southern point of the harbor revetment wall, stretching across the mouth of Pelekane Bay and south along the coast from Samuel M. Spencer Beach Park to the mouth of Kukui Gulch, only broken by the broad sand plain offshore from the beach park. The live coral found on the patch reefs is limited and consists mostly of small colonies of *Pocillopora damicornis* and *Porites lobata*. The patch reefs nearest to shore are being overtaken by turf

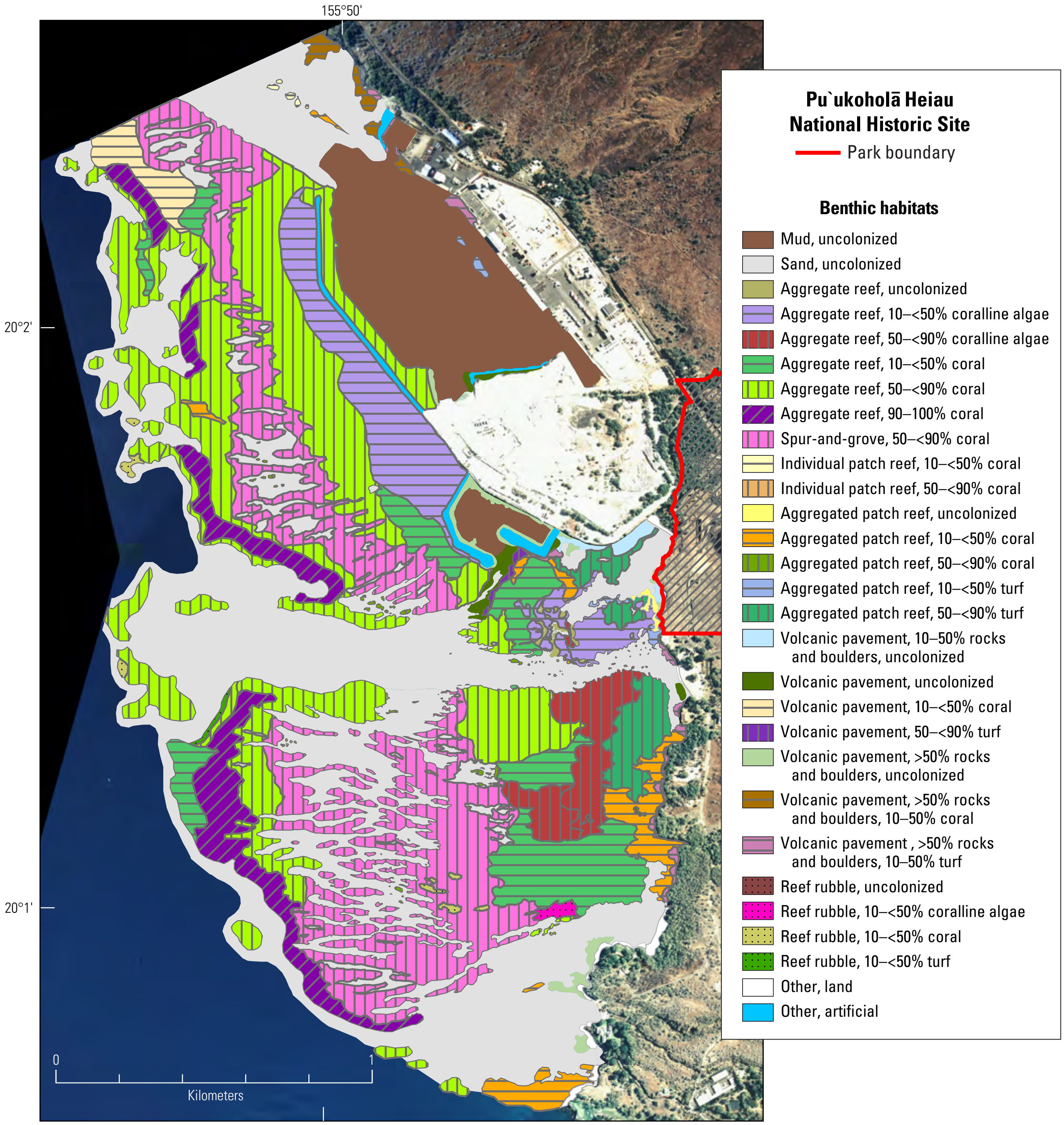

Figure 13. Aerial photomosaic of Pu`ukoholā Heiau National Historic Site, overlaid with benthic habitat map.

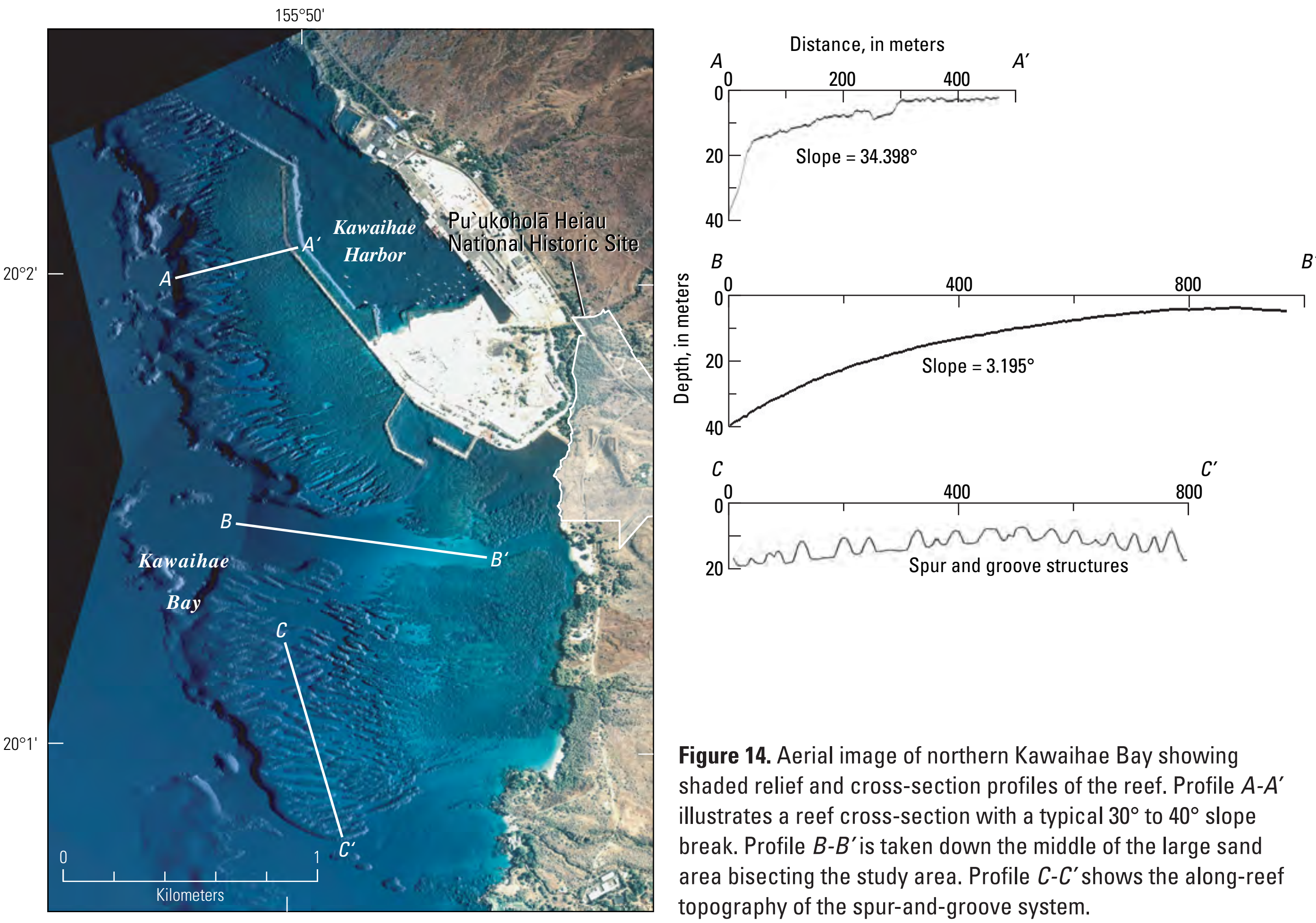

Figure 14. Aerial image of northern Kawaihae Bay showing shaded relief and cross-section profiles of the reef. Profile *A-A′* illustrates a reef cross-section with a typical 30° to 40° slope break. Profile *B-B′* is taken down the middle of the large sand area bisecting the study area. Profile *C-C′* shows the along-reef topography of the spur-and-groove system.

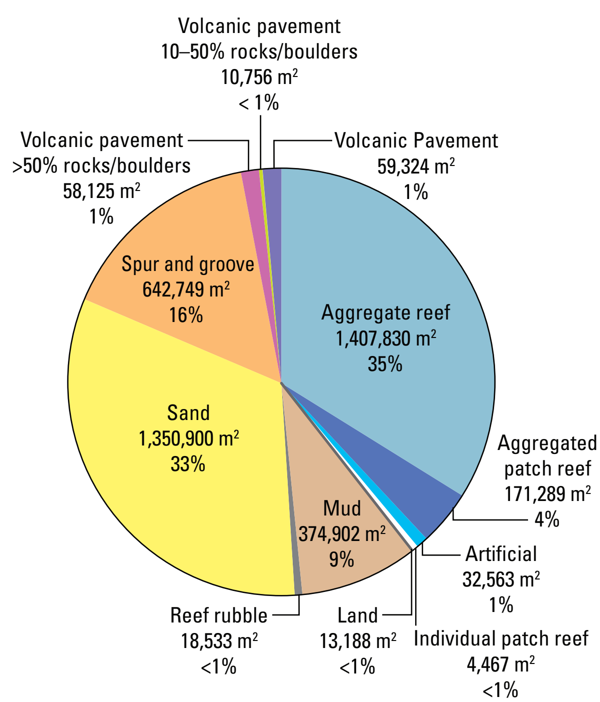

Figure 15. Pie chart showing the breakdown of dominant reef structures of the PUHE study area. Aggregate reef makes up more than 1.4 km^2; spur and groove encompasses nearly 0.65 km^2.

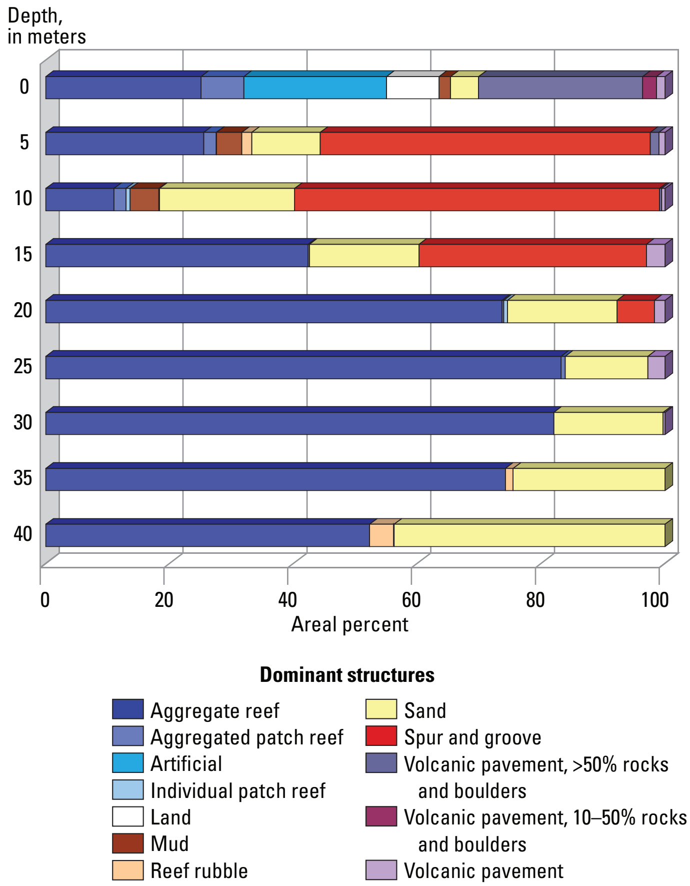

Figure 16. Graph showing proportions of dominant structures with depth at PUHE. Spur and groove structures dominate at depths between 5 and 15 m. Below 15-m depth, the study area is dominated by aggregate reef.

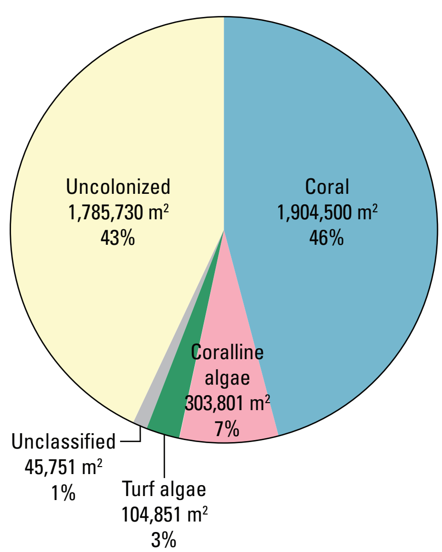

Figure 17. Pie chart showing the breakdown of major biologic coverage in the PUHE study area. Nearly 2 km (46 percent) of the study area is covered with a minimum of 10 percent coral. Coralline algae cover 7 percent of the reef, mostly on the fore reef just offshore of the harbor breakwater and on the nearshore patch reefs.

algae and sediment, whereas coralline algae dominate the reef approximately 200 m offshore.

Accuracy of Maps

An accuracy assessment was performed for the major biological covers (table 5). A total of 241 randomly selected points for all three National Parks (PUHO, KAHO, and PUHE) were checked in the field. The overall accuracy of 91.29 percent (with a 95-percent confidence interval of ± 1.1) indicates which points on the map were classified correctly according to the field check. Producer's accuracy is an indication of how well we correctly identified pixels for each different class (for example, coral = 96.39 percent, uncolonized = 75.00 percent). User's accuracy is the probability that, for a classified pixel on the map, the map user will actually find that class in the field (for example, coral = 94.67 percent, octocoral = 60.00 percent). A tau coefficient of 0.9005 was calculated as described by Ma and Redmond (1995), and indicates that 90.05 percent more points were classified correctly than would be expected by chance alone.

After accuracy assessment calculations were performed, any misinterpreted polygons identified on the Kona coast reef maps were corrected using the field check data, thus increasing the overall accuracy of the final maps to greater than 91.29 percent.

Resource Concerns

An important concern within the study area is water turbidity and siltation in Pelekane Bay. Sediment-laden runoff from the Makeāhua/Pohaukole Gulch during periods of high rains is trapped in the embayment because of the alteration of the coastline at Kawaihae Harbor. With the natural flushing reduced, sedimentation from high turbidity levels has resulted not only in the degradation of the nearshore ecosystem, but has also contributed to the burial of Hale o Kapuni Heiau. Remediation efforts, such as the installation of sediment traps upstream, can help stop the influx of mud and pollutants to the nearshore environment. Dredging can remove the current build-up of sediment, but care needs to be taken so that the submerged heiau is not damaged any further. Increasing the circulation in the embayment will help restore it to natural flushing conditions.

Acknowledgements

This project was funded by the USGS Coastal and Marine Program's Coral Reef Project, and by the U.S. National Park Service. The authors thank Pat Chavez and his group from the USGS in Flagstaff for coordinating our acquisition of the SHOALS bathymetric data and their work on processing the aerial photomosaics. Will Smith and colleagues from the University of Hawai`i Coral Reef Assessment and Monitoring Program (CRAMP) team performed the third-party field-check

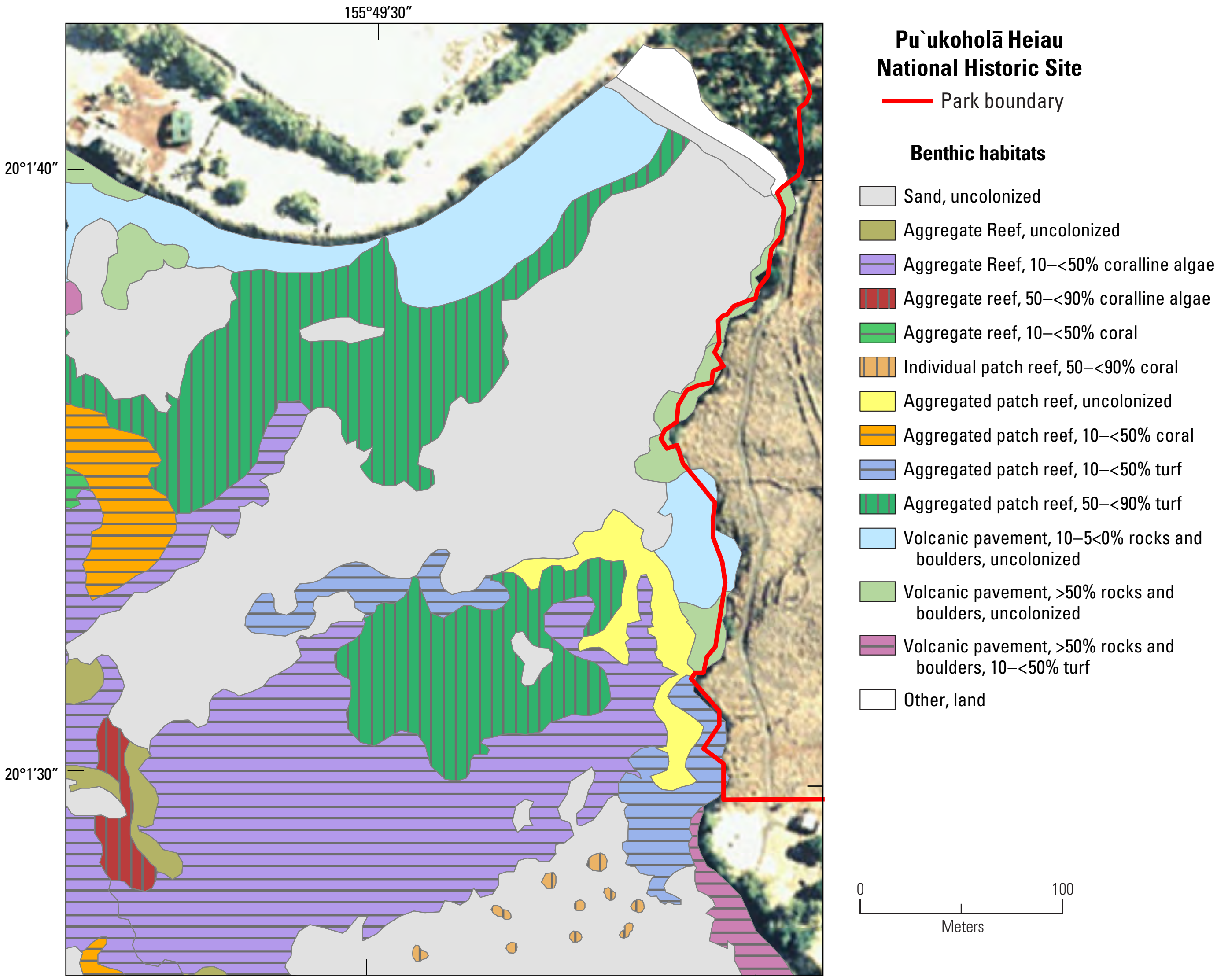

Figure 18. Enlarged portion of the benthic habitat map showing Pelekane Bay and PUHE shoreline.

Table 5. Matrix showing accuracy assessment for the major biological cover classes.

		Found to be in field							Total	User's Accuracy
		Coral	Coralline Algae	Macro-algae	Turf Algae	Octocoral	Emergent Vegetation	Uncolonized		
As mapped	Coral	160							169	94.67%
	Coralline Algae	0	15	0	0	0	0	1	16	93.75%
	Macroalgae	0	0	0	0	0	0	3	3	0.00%
	Turf Algae	0	0	0	0	0	0	0	0	
	Octocoral	0	0	1	0	3	0	1	5	60.00%
	Emergent Vegetation	0	0	0	0	0	0	0	0	
	Uncolonized	6	0	0	0	0	0	42	48	87.50%
Total		166	16	1	0	4	0	54		
Producer's Accuracy		96.39%	93.75%	0.00%		75.00%		77.78%	241	
										Diagonal Sum = 220
										Overall Accuracy = 91.29%

observations and provided the accuracy assessment calculations. Sallie Beavers from Kaloko-Honokōhau NHP supplied us with the smaller boats (motorboats and kayaks) and assisted with logistics while we were on island. This manuscript benefited from reviews by Brian Edwards and Mike Field. A special mahalo goes to Captain Joe Reich, owner of the *Alyce C* on Moloka`i, whose exceptional navigation and local expertise were critical to the success of this project.

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Appendix
Detailed Classification Scheme

The following describes the classification scheme used by the U.S. Geological Survey for benthic habitat mapping of National Parks on the Kona Coast of Hawai`i. Each of the habitats and zones is described in detail with some example photos. Many of the descriptions are from NOAA's classification scheme for the main eight Hawaiian Islands (Coyne and others, 2003), and subsequent revision (National Oceanic and Atmospheric Administration National Centers for Coastal Ocean Science, 2005).

Habitats

Major Structure—Unconsolidated Sediment

Mud Fine sediment often associated with stream discharge and buildup of organic material in areas sheltered from high-energy waves and currents (for example, harbors, fishponds).

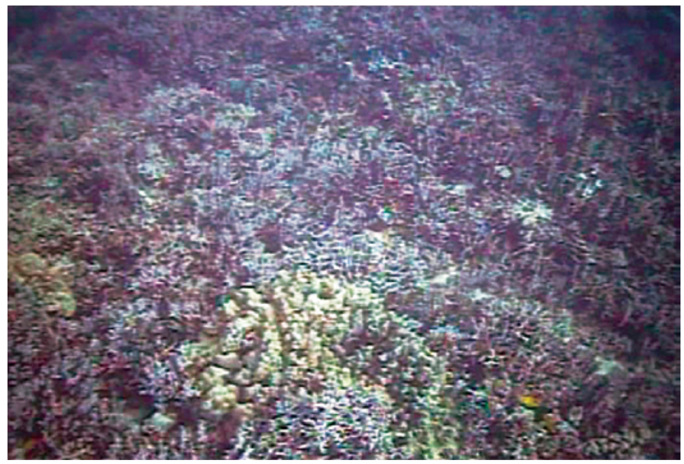
Example of muddy shallow area exposed at low tide. (Kawela, Moloka`i)

Sand Coarse sediment typically found in areas exposed to currents or high wave energy (reef-derived) or on beaches (land-derived or reef-derived).

Example of uncolonized sand. (Kaloko-Honōkohau, Hawai`i)

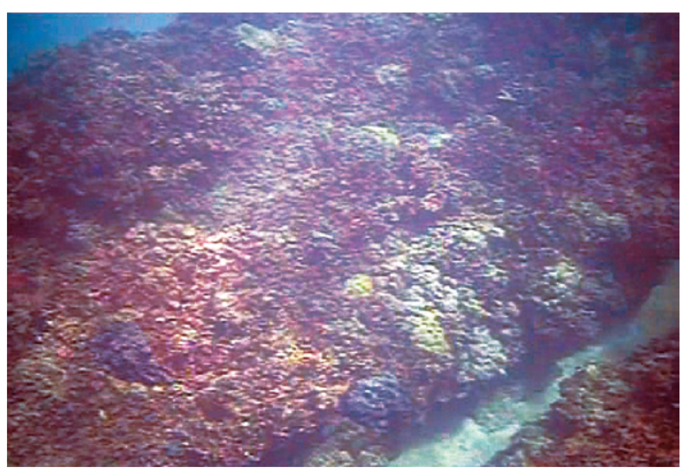
Major Structure—Reef and Hardbottom

Aggregate reef Formations with high relief and complexity, which form an extensive reef structure without sand channels (as found in spur-and-groove). Note that aggregate reef refers to the underlying hard structure and implies nothing about the nature of the biological cover, nor whether it is live or dead.



Example of aggregate reef with 90–100 percent coral. (Kawaihae Bay, Hawai`i)

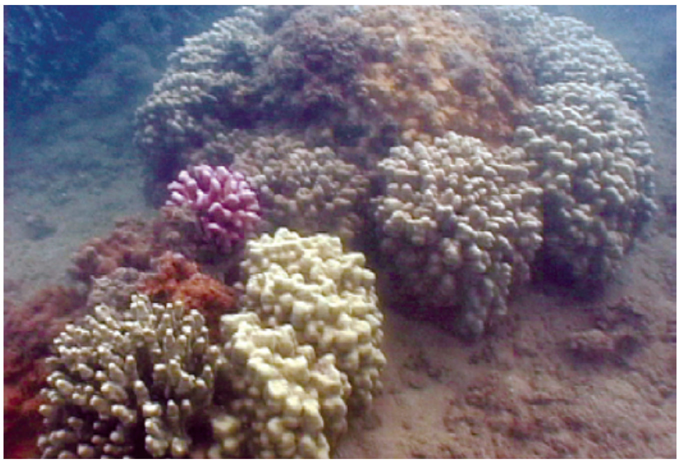
Spur-and-groove Elongate, alternating sand and coral formations that are oriented perpendicular to the shore or bank/shelf escarpment. The coral formations (spurs) of this feature typically have a high vertical relief relative to the pavement with the channels, and are separated from each other by 1–5 meters of sand or bare pavement (grooves).



Example of spur-and-groove reef system with 90–100 percent coral cover on the spurs. (Kawaihae Bay, Hawai`i)

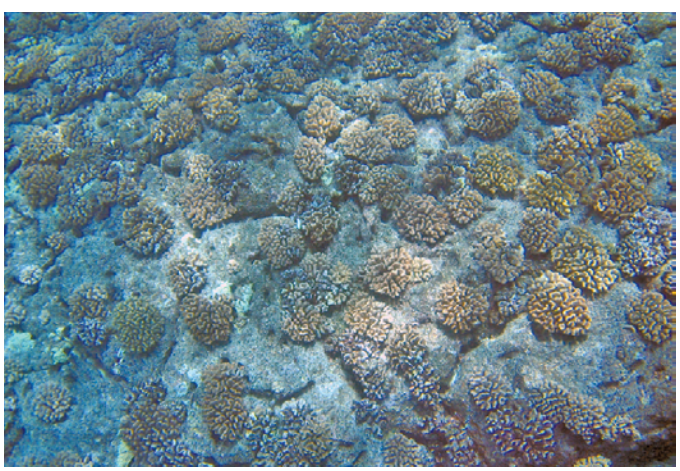
Individual patch reef Coral formations, larger than or equal to the MMU (100 m^2 in this study), that are isolated from other coral reef formations by sand, seagrass, or other habitats and that have no organized structural axis relative to the contours of the shore or shelf edge.

Aggregated patch reefs Clustered coral formations, smaller than the MMU (100 m^2 in this study) or too close together to be mapped separately, that are isolated from other coral reef formations by sand, seagrass, or other habitats and that have no organized structural axis relative to the contours of the shore or shelf edge.



Example of aggregated patch reefs covered with 50–<90 percent coral. These patch reefs are smaller than the minimum mapping unit and so could not be called individual patch reefs. They would be digitized together, along with the others shown in the background, as aggregated patch reefs. (Moloka`i)

Volcanic pavement Volcanic substrate with less than 10 percent loose rocks or boulders scattered on the surface. May be smooth or irregular, depending on the original lava flow and subsequent erosion patterns.

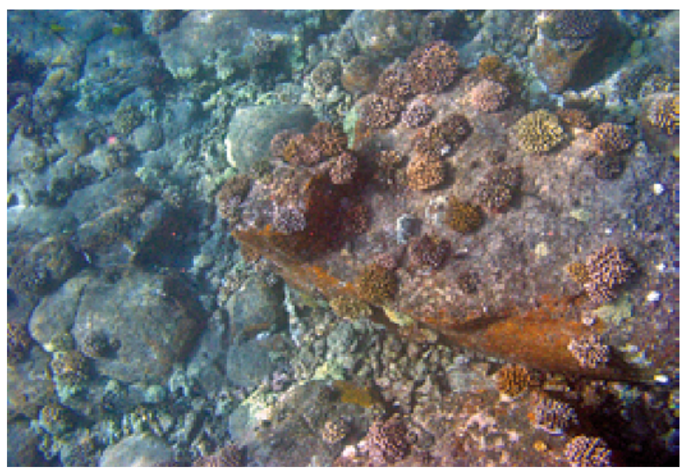


Example of volcanic pavement with 50–<90 percent coral cover. (Hōnaunau Bay)

Volcanic pavement with sand channels Having volcanic substrate alternating with sand channels that are oriented perpendicular to the shore or bank/shelf escarpment. The sand channels have low vertical relief relative to spur-and-groove formations.

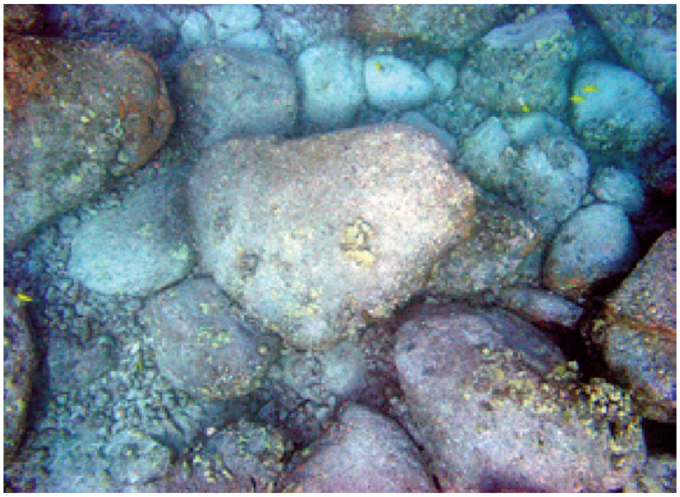
Example of volcanic pavement with sand channels, with 90–100 percent coral cover. (Kaloko-Honokōhau, Hawai`i)

Volcanic pavement with 10–50 percent rocks/boulders Volcanic substrate with 10–50 percent volcanic rocks and/or boulders scattered on the surface. The underlying substrate may be smooth or irregular, depending on the original lava flow and subsequent erosion patterns.



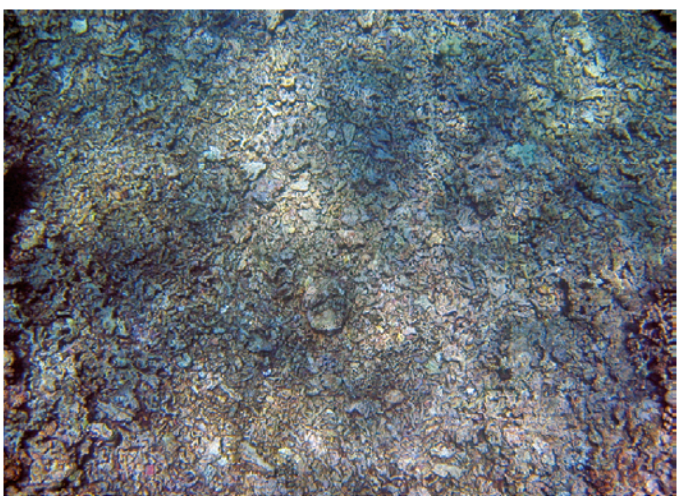
Example of volcanic pavement with 10–50 percent rocks/boulders, with 10–50 percent coral cover. (Hōnaunau Bay, Hawai`i)

Volcanic pavement with >50 percent rocks/boulders Volcanic substrate with >50 percent volcanic rock and/or boulders on the surface. The underlying substrate may be smooth or irregular, depending on the original lava flow and subsequent erosion patterns.



Example of volcanic pavement with >50 percent rocks/boulders with <10 percent cover, therefore 90–100 percent uncolonized. (Kaloko-Honokōhau, Hawai`i)

Reef rubble Dead, unstable coral rubble, often covered with coralline algae or filamentous or other macroalgae.



Example of reef rubble with <10 percent cover, therefore 90–100 percent uncolonized. (Kawaihae Bay, Hawai`i)

Major Structure — Other

Land Area shoreward of the mean high water line, or landward edge of emergent vegetation, when present.

Artificial Manmade habitats such as large piers, submerged parts of riprap jetties, and shoreline areas created from dredge spoil.

Artificial/historical Manmade features of historical significance, such as active and relict fishpond walls.

Zones

Land Area shoreward of the mean high water line, or landward edge of emergent vegetation, when present.

Shoreline/intertidal Area between the mean high water line (or landward edge of emergent vegetation) and lowest spring tide level. Typical habitats include mangrove and other emergent vegetation, sand, mud, and uncolonized rock.

Vertical wall Area with near-vertical slope along channels, from shelf to shelf escarpment, or between different inner-shelf platforms. This zone is typically narrow and may not be visible in remotely sensed imagery, but is included because it is recognized as a biologically important feature. Typical habitats include coral, algae, and uncolonized rock.

Lagoon The shallow area between the shoreline/intertidal zone and the back reef zone of a barrier reef system. If no reef crest is present, there is no lagoon zone. Typical habitats include individual patch reefs, sand, seagrass, algae, and pavement. (Not typically used for the Kona Coast.)

Back reef (with lagoon) Area between the seaward edge of a lagoon floor and the landward edge of a reef crest. This zone is only present when a reef crest and lagoon exist. Typical habitats include sand, coral rubble, seagrass, algae, and patch reefs. (Not typically used for the Kona Coast.)

Reef flat (without lagoon) Shallow, semiexposed area between the shoreline/intertidal zone and the reef crest of a fringing reef system. This zone is protected from the high-energy waves commonly experienced on the reef crest and fore reef. The reef flat is not present if there is a lagoon. Typical habitats include sand, rubble, pavement, algae, mud, and patch reefs.

Reef crest The flattened, emergent (especially during low tides) or nearly emergent segment of a reef, usually where the waves break. This zone lies between the back reef and fore reef zones of a barrier reef system, and between the reef flat and fore reef of a fringing system. Typical habitats include reef rubble, patch reefs, and aggregate reefs.

Fore reef Area from the seaward edge of the reef crest that slopes into deeper water to the landward edge of the bank/shelf platform. Also defined as fore reef are features not forming an emergent reef crest but still having a seaward-facing slope that is significantly greater than the slope of the bank/shelf. Typical habitats include aggregate coral reef and spur-and-groove.

Bank/shelf A deep-water platform extending offshore from the seaward edge of the fore reef to the beginning of the escarpment where the insular shelf drops off into deep, oceanic water. If no reef crest is present, the bank/shelf is the flattened platform between the shoreline/intertidal zone and deeper ocean offshore. Typical habitats include sand, patch reefs, algae, colonized and uncolonized pavement with and without sand channels, and other coral habitats.

Bank/shelf escarpment The edge of the bank/shelf where depth increases rapidly into deep, oceanic water. This zone begins at approximately 20 to 30 meters depth, near the depth limit of features visible in aerial images. This zone captures the transition from the shelf to deep oceanic waters. Typical habitats include sand, aggregate reef, and spur-and-groove.

Channel Naturally occurring channels that often cut across several other zones. Typical habitats include sand, mud, and uncolonized pavement.

Dredged Area in which natural geomorphology is disrupted by excavation or dredging (for example, harbors and manmade channels). Typical habitats include rubble, sand, and mud.

Unknown Zone uninterpretable because of turbidity, cloud cover, water depth, or other interference.