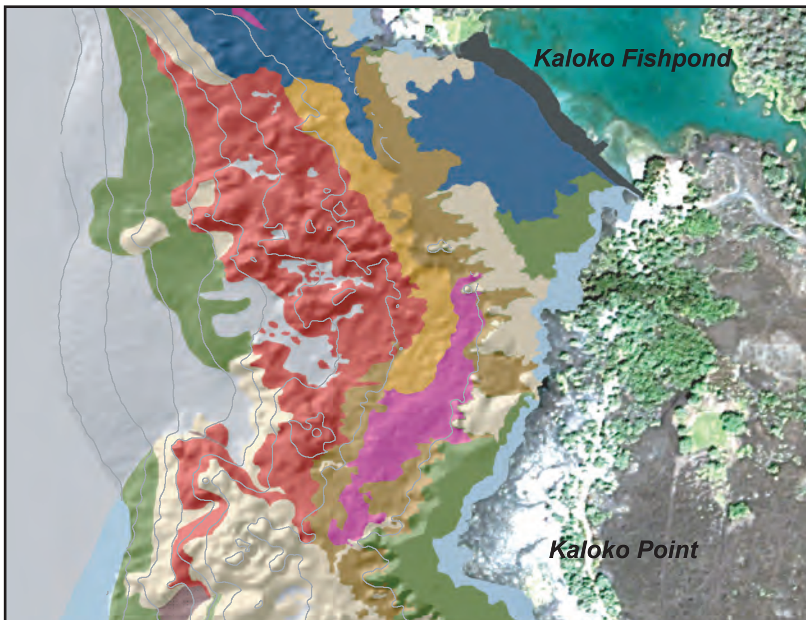
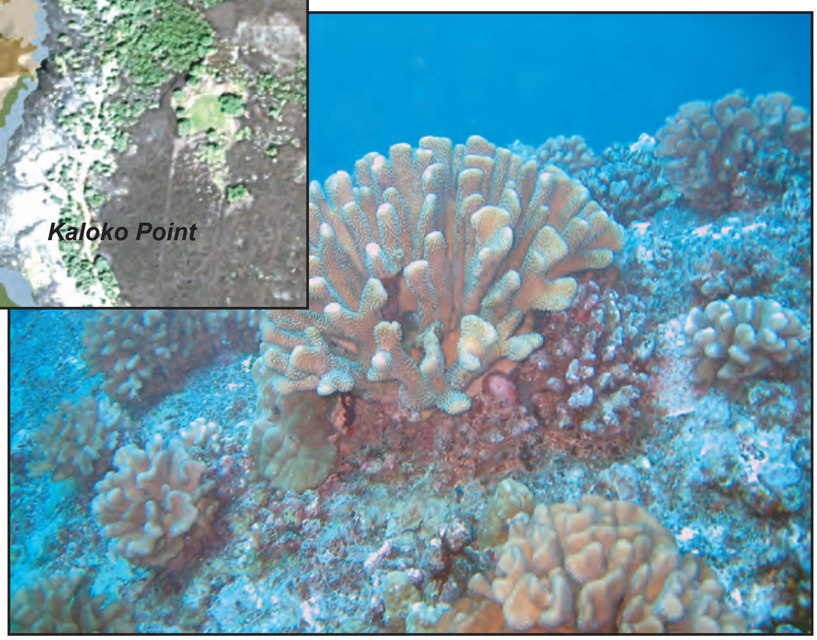
Prepared in cooperation with the U.S. National Park Service

Benthic Habitats and Offshore Geological Resources of Kaloko-Honokōhau National Historical Park, Hawai`i





Scientific Investigations Report 2006-5256

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

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

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Cover: Left, enlarged portion of benthic habitat map showing Kaloko-Honokōhau National Historical Park shoreline. Right, underwater photograph shows example of coral reef habitat on the Kona coast of Hawai`i.

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Benthic Habitats and Offshore Geological Resources of Kaloko-Honokōhau National Historical Park, Hawai`i

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Executive Summary

Kaloko-Honokōhau National Historical Park (KAHO) is one of three National Park lands located along the western coast of the Island of Hawai`i and the only one to include submerged lands and marine resources within its official boundaries. The park was established in 1978 and is 1,160 acres in size, including 596 acres of marine area. The submerged lands are currently managed by the State of Hawai`i, Department of Land and Natural Resources, Division of Aquatic Resources (DLNR-DAR). KAHO is located adjacent to a moderately well developed area of the Kona coast. The park is bordered on the south by the Honokōhau small-boat harbor and on the north by a luxury residential/resort and golf course development currently (2006) under construction. A county landfill and wastewater treatment facility that discharges treated effluent are located within a mile upslope of the harbor and the park. Across the highway from the east boundary are a rock quarry and a light industrial and business district. Future development slated for lands adjacent to the south boundary of the park include a 300-percent expansion of the small-boat harbor, along with construction of hotels, condominiums, and a light industrial park.

Marine resources located within KAHO include coral reef and habitat for many marine animals, including the green sea turtle and a variety of fish and invertebrates. In addition, many archeological, cultural, and recreational resources are located within the marine realm of the park. Potential threats and stressors to the modern marine environment include ground-water and surface-water contamination, invasive plants and algae, fishing pressure and use of monofilament gill nets (which can ensnare marine life or become tangled on reefs and be left behind as fishing debris), and visitor use impacts, such as scuba diving and snorkeling. Illegal dumping, oil releases, boat groundings, and other physical damage to reef resources are potential threats from users of the nearby harbor. Special issues of concern for the park include establishing baseline conditions of the offshore resources before the development of adjacent coastal lands.

Until this study, only a general knowledge of the distribution of benthic habitats and the characteristics of the offshore region of Kaloko-Honokōhau National Historical Park was available. In 2003, a collaborative project between the U.S. Geological Survey (USGS) Coastal and Marine Geology Program and the National Park Service (NPS) was initiated to develop detailed benthic-habitat classification maps for the marine lands within and adjacent to the park. The intent of this project is to provide baseline maps and a Geographic Information System (GIS) database and description of the biological and geological resources of these marine lands in order to facilitate the management, interpretation, and understanding of park resources.

A benthic-habitat classification map was created for the park using existing color aerial photography, Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) bathymetric data, georeferenced underwater video, and still photography. Individual habitat polygons were classified using five basic attributes: (1) major structure or substrate, (2) dominant structure, (3) major biologic cover on the substrate, (4) percentage of major biological cover, and (5) geographic zone. Additional information regarding geology, morphology, and coral species were also noted.

Geologic Framework

The offshore region of KAHO consists of multiple, coalescing volcanic flows that form distinct morphological regions and support diverse benthic habitats. The offshore geology is predominantly composed of smooth to undulating pahoehoe-type basalt flows that form flat to gently sloping benches, cliffs, and steep shelf escarpments. In some locations the basalt surface is irregular and mounded into ridges, pinnacles, and arches. Large rounded boulders and smaller scattered rocks are common throughout the park. In only a few locations does coral cover or accreted carbonate reef obscure the underlying volcanic surface.

The upland area of the park is composed of three Holocene basalt flows that originated from Hualālai Volcano and range in age from 10 ka (thousand years) to 1.5 ka. The geologic history and ages of the submerged flows, however, are poorly constrained. In general, the surface of the submerged volcanic substrate shows textures commonly seen on subaerial flows (ropey pahoehoe, pinnacles, and tubes), suggesting that little erosion has occurred in these locations. However, the presence of the shallow and deep cliffs and the abundant, well-rounded boulders that cover much of the study area indicates that extensive erosion has been modifying the shape of the sea floor over an extended period of time. No features or morphology that would indicate primary deposition underwater (for example, lava pillows) were observed, suggesting that the flows we observe today were originally deposited subaerially and have subsided to their present position below sea level.

Benthic Species

The reefs at KAHO are primarily *Porites* reefs, comprising mainly *P. compressa* and *P. lobata*; overall, four individual *Porites* species were identified. A total of thirteen species of coral from nine genera were observed within the park. KAHO has a high abundance of the endemic octocoral, *Anthelia edmonsoni*. This species is common at many other locations on the west coast of the Island of Hawai`i, although relatively rare at most other sites within the State. Seven species of invertebrates were observed within the park, most commonly the collector urchin, *Tripneustes gratilla*, and the rock-boring urchin, *Echinometra mathaei.* The Crown of Thorns sea star, *Acanthaster planci,* was also observed at numerous locations within the park.

Benthic Habitat

Benthic habitat varies greatly throughout the study area. Nearly 73 percent of the study area consists of a hardbottom structure that is potentially available for coral habitation; the remaining 27 percent includes unconsolidated sediment and artificial and artificial/historical features. Coral cover is predominantly low, with 68 percent of the total hardbottom area covered with 10 to <50 percent coral. Significant areas of moderately high (50 to <90 percent; 12 percent total hardbottom) and high (90 to 100 percent; 2 percent total hardbottom) coral coverage are also mapped within the study area. Generally, coral cover increases with depth, with the maximum at depths between about 10 and 20 m of water.

Coral Distribution

The coral cover in the park is low overall, except for areas that are relatively protected from high wave energy—in the most deeply embayed reaches off the harbor mouth and off Kaloko Fishpond. In both of those areas, the coral communities are diverse, healthy, and thriving. The embayments are locally protected from south swell and Kona storms by Noio Point and from all but the most westerly north Pacific swell by Wawahiwa`a Point. Between the two, the deep bench and central bench/escarpment regions provide additional protection from larger waves that shoal across the relatively exposed platforms.

Status of the Habitat

Overall, the park's offshore region supports a healthy and relatively diverse coral habitat. Little evidence of invasive macroalgae and no diseased coral were observed. However, a few limited occurrences of macroalgae were noted. Several specimens of the potentially destructive sea star *Acanthaster planci* were observed, although limited evidence for widespread destruction of coral suggests that these predators may be balanced within the ecosystem.

The only anomalous habitat area appears to be off the harbor mouth, where an area of low coral cover was mapped between some of the most abundant and diverse coral communities within the study area. The causes of this apparent degradation are unclear.

Low sedimentation rates, along with the dearth of invasive or native macroalgae and the presence of thriving, healthy reefs in protected locations, suggest that the coral habitat in KAHO is primarily controlled by natural wave-induced stresses, with little evidence of anthropogenic stresses. Areas of high visitor use, such as near the shoreline or around mooring buoys, were not specifically evaluated for impacts of the users.

Special Considerations and Recommendations

As results of the study reported in this work, the following observations and recommendations are given:

- The areas of highest coral cover within the park are located adjacent to the most highly developed (developing) areas of adjacent coast—offshore Honokōhau Harbor and Kaloko Fishpond. We recommend that the NPS establish long-term monitoring stations near these locations to evaluate any changes in environmental conditions (sedimentation, water quality, direct impact) that may adversely affect the habitats in the future.
- Establish coral and water-quality monitoring and current-measurement transects near the poorly colonized area off the harbor mouth and control area(s) in order to determine whether potential changes in sedimentation, water quality, or bottom currents are affecting coral colonization off the harbor mouth.
- Define boundaries of the degraded area off the harbor mouth to evaluate its stability, the processes affecting it, and/or to determine if the adjacent areas of thriving coral habitat are expanding, contracting, or susceptible to these same processes.
- Evaluate freshwater conduits and establish water-quality and benthic-habitat monitoring locations along the north boundary of the park, off Kohanaiki, near areas of recent and future development of housing and golf courses.
- Carry out additional scuba transects to better quantify spatial variations in the percent cover, health of P. compressa, and structure of the shelf-escarpment habitat.
- Establish long-term coral and fish monitoring sites to monitor coral health and ecosystem health throughout the park.
- Collect airborne infrared or hyperspectral imagery to isolate spectrally unique bio-indicators to improve delineation of intertidal habitats.

Introduction

This study is the result of a collaborative effort between the Coral Reef Project of the U.S. Geological Survey (USGS) Coastal and Marine Geology Program and Kaloko-Honokōhau National Historical Park (KAHO), the only national park along the west coast of the Island of Hawai`i to include a marine region within its official boundaries. The purpose of the study was to develop benthic-habitat classification maps for the marine lands within and adjacent to KAHO. Baseline maps and a Geographic Information System (GIS) database of biological and geological resources of these marine lands are provided in order to facilitate the management, interpretation, and understanding of park resources.

Using a combination of aerial photography, bathymetry, video, and still imagery, a total area of 2,479 km^2 was mapped between Noio Point and Wawahiwa`a Point from the shoreline out to the west boundary of the park. The total area also includes two areas north and south of the park that were mapped from the shoreline to 40-m water depth (fig. 1). The interpreted geological and benthic-habitat classification maps and GIS database produced by this collaborative effort are included in conjunction with this report.

Marine resources located within KAHO include coral and coral reef habitat for many marine animals, including the green sea turtle and a variety of fish and invertebrates. In addition, many archeological, cultural, and recreational resources are located within the marine realm of the park. Special issues of concern for the park include establishing baseline conditions of the offshore resources before the planned harbor expansion near the south end of the park and a golf course/resort/residential development near the north boundary.

Study Area

General Setting

Kaloko-Honokōhau National Historical Park (KAHO) is one of three National Park lands located along the west coast of the Island of Hawai`i. The park was established by an act of Congress (Public Law 95-625) in 1978. The legislated boundary of the park encloses approximately 1,160 acres, including nearly 600 acres of submerged marine resources. To date, only a portion of the park has been acquired by the NPS, with the remaining acreage held privately or by the state of Hawai`i. The submerged lands are currently managed by the State of Hawai`i, Department of Land and Natural Resources, Division of Aquatic Resources (DLNR-DAR). KAHO is one of only three National Park lands in Hawai`i to include marine resources within its official boundaries.

KAHO is located adjacent to a moderately well developed area of the Kona coast. The park is bordered on the south by the Honokōhau small-boat harbor, which is the primary fueling, maintenance, and berthing facility on the central Kona coast. The harbor was quarried out of basalt rock from the shoreline landward more than 0.5 km. The first phase of construction was completed in 1970, and secondary expansion was completed in 1979. A county landfill and wastewater-treatment facility that discharges treated effluent are located less than 2 km upslope of the harbor and the park. Across the highway from the east boundary are a rock quarry and light industrial and business district. Construction of a golf course and a resort/residential development with 500 single-family housing units, The Shores of Kohanaiki, began in 2005 on lands along the north boundary of the park within the Kohanaiki ahupua`a (a traditional Hawaiian land division extending from the upper ridgeline slopes to the sea). Development slated (circa 2006) for the lands adjacent to the park in the south include a 300-percent expansion of the small-boat harbor along with construction of hotels, condominiums, and a light industrial park (fig. 2).

The upland area of the park is composed of three Holocene basalt flows that originated from Hualālai Volcano. Flat to gently rolling pahoehoe and rough jagged a`a types of basalt flows are both found within the park and range in age from 10 ka (thousand years) to 1.5 ka (Wolfe and Morris 1996; fig. 3). Together they form a gentle seaward-sloping surface that meets the shoreline along a mostly flat-lying, narrow intertidal zone, except south of the harbor, where the shoreline is marked by a cliff 2-3 m high. A geological resources evaluation, including an overview of the regional geology, local volcanic deposits, and a detailed description of coastal landforms in the upland portion of the park can be found in a companion paper by Richmond and others (2007).

The offshore region of KAHO is characterized by multiple coalescing basalt flows, as discussed in detail below. The geologic mapping of Wolfe and Morris (1996) ends at the shoreline, and thus the geologic ages of the submerged flows are unknown and the relative relations to the emergent flows poorly constrained.

The mean tidal range at Kailua-Kona, which is a subordinate tidal station adjusted to the primary station at Hilo, is 1.4 feet (0.43 m) with a spring range of 2.1 feet (0.64 m) and a mean tide level of 0.9 feet (0.27 m) relative to mean lower low water (mllw) (National Oceanic and Atmospheric Administration National Ocean Service, 2005).

The numerous cultural and natural resources within the park include archeological sites, petroglyphs, native species, anchialine pools (inland depressions connected to the ocean by subterranean conduits), and three ancient manmade fishponds (Kaloko, `Aimakapā, and `Ai`ōpio fishtrap). In addition to these historical and natural resources within the upland part of the park, the offshore component of KAHO hosts a rich coral-reef community, habitat for many diverse marine species, as well as submerged archeological sites and popular recreational resources.

Potential threats and stressors to the modern marine environment include ground-water and surface-water contamination, invasive plants and algae, fishing pressure and

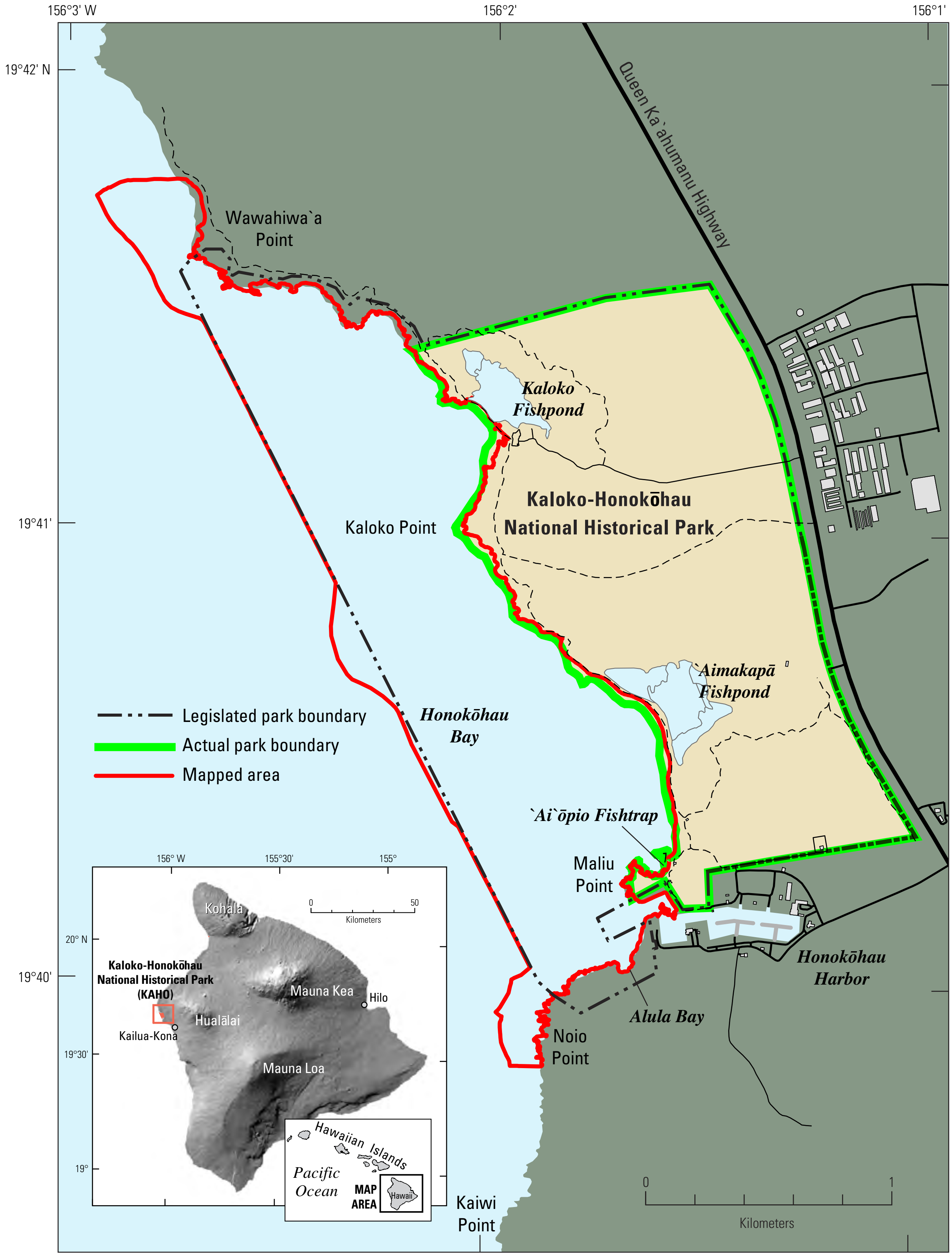


Figure 1. Location map showing the boundaries of Kaloko-Honokōhau National Historical Park, the mapped area, and the geographic locations described in this report. The "legislated boundary" was established by the U.S. Congress in 1978. The "actual boundary" includes only lands actually acquired by the National Park Service.

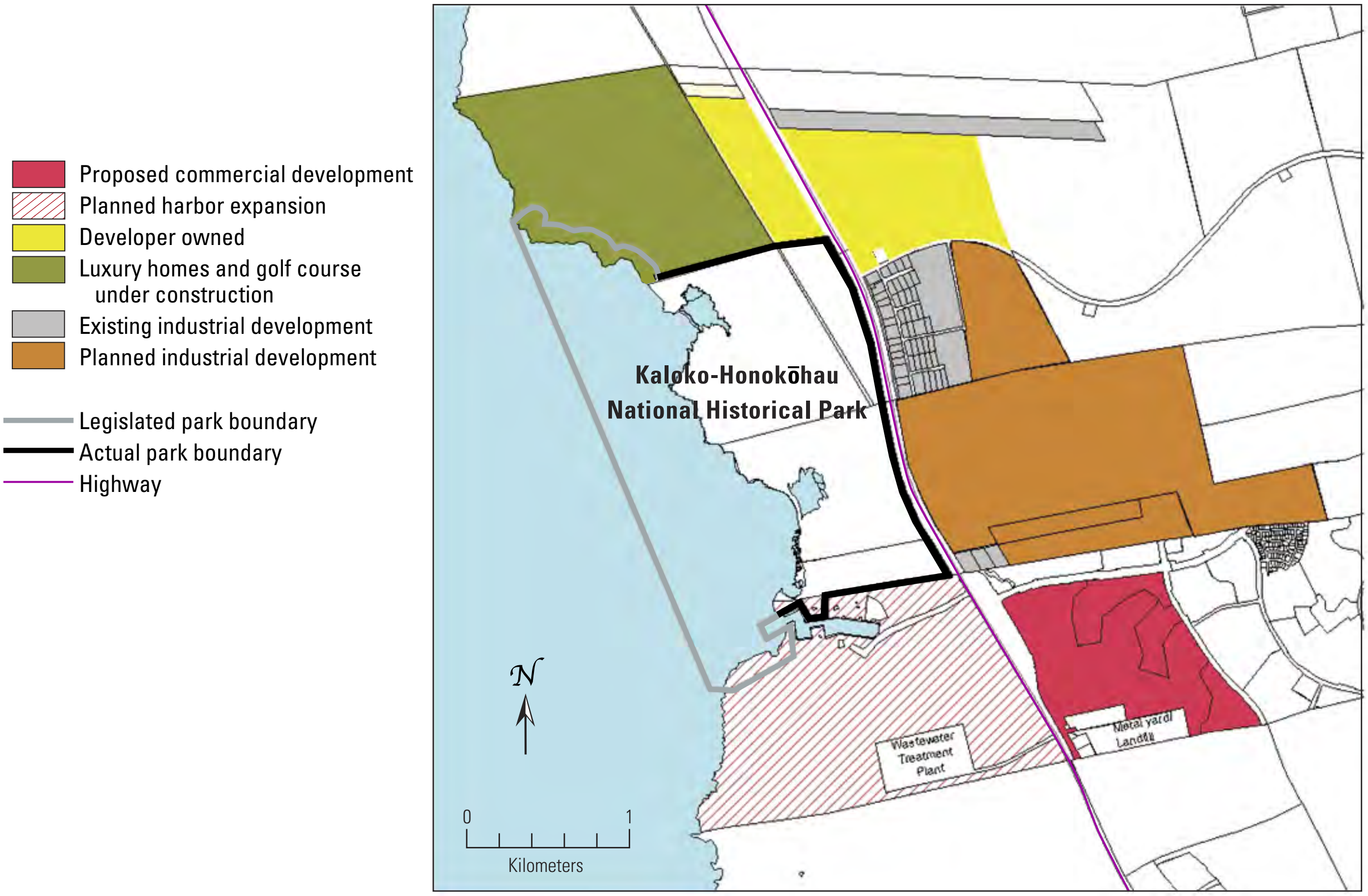


Figure 2. Map showing land use around Kaloko-Honokōhau NHP circa 2006 (from unpublished National Park Service data; Sallie Beavers, written commun., 2006).

use of monofilament gill nets (which can ensnare marine life or become tangled on reefs and then be left behind as fishing debris), and visitor use impacts, such as scuba diving and snorkeling. Illegal dumping, oil releases, boat groundings, and other physical damage to reef resources are potential threats from users of the nearby harbor. The proximity of coastal developments and their effects on water quality and aquatic ecosystems are also important considerations (DeVerse, 2006; Hoover and Gold, 2005).

Wave Climate

Although typically considered a low wave-energy coast, the Kona coast can experience large wave events associated with seasonally varying wave sources. Moberly and Chamberlain (1964) describe four primary wave patterns that influence the main eight Hawaiian Islands, including the following:

North Pacific swell.—This generates some of the largest waves in the Hawaiian Islands. It is produced by storms in the Aleutians and mid-latitude lows and approaches from the NW to NE. The largest waves are from October to May, and have heights of 8–14 ft (2–5 m) and periods of 10–15 s.

Northeast trade waves.—The second most powerful or influential waves on the islands are generated by trade winds that blow across the open ocean. These approach from the N to SE. The largest waves are from April to November, and have heights of 4–12 ft (1–4 m) and periods of 5–8 s.

Kona storm waves.—These waves are very erratic and infrequent. They are generated by local fronts or extratropical lows and are associated with the weakening of the trade winds. They approach from SE to SW. The largest waves are from SW, usually in the winter time (December-March), and have heights of 10–15 ft (3–5 m) and periods of 8–10 s.

Southern swell.—These waves are generated by winter storms in the Southern Ocean. The largest waves are from April to October. They are more common than Kona storms

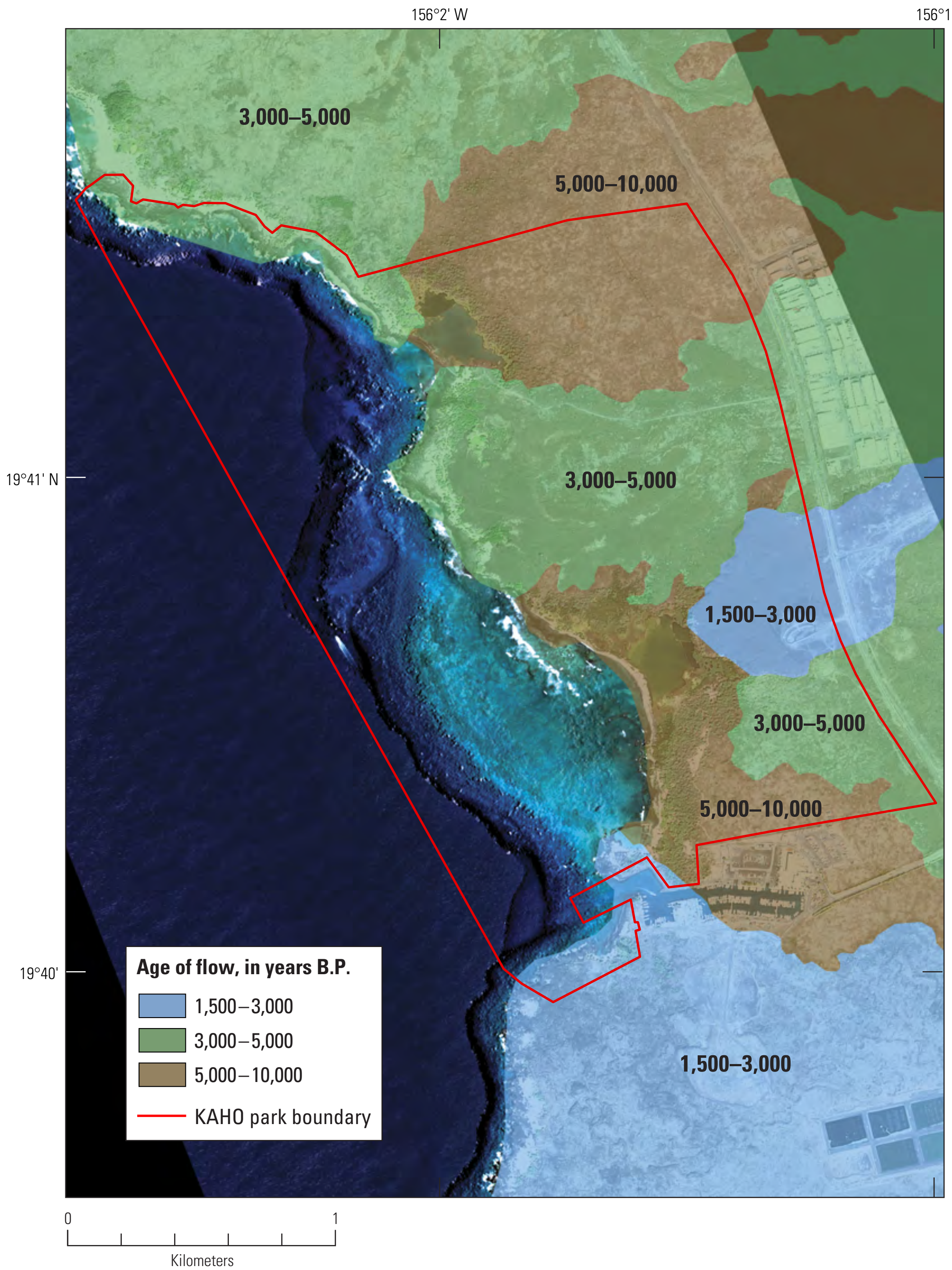


Figure 3. Aerial photomosaic showing volcanic flows within Kaloko-Honokōhau NHP. Three distinct flows, aged between 1,500 and 10,000 years, all originated from the Hualalai Volcano (Wolfe and Morris, 1996). The offshore part of the figure is Quickbird satellite imagery draped over bathymetry.

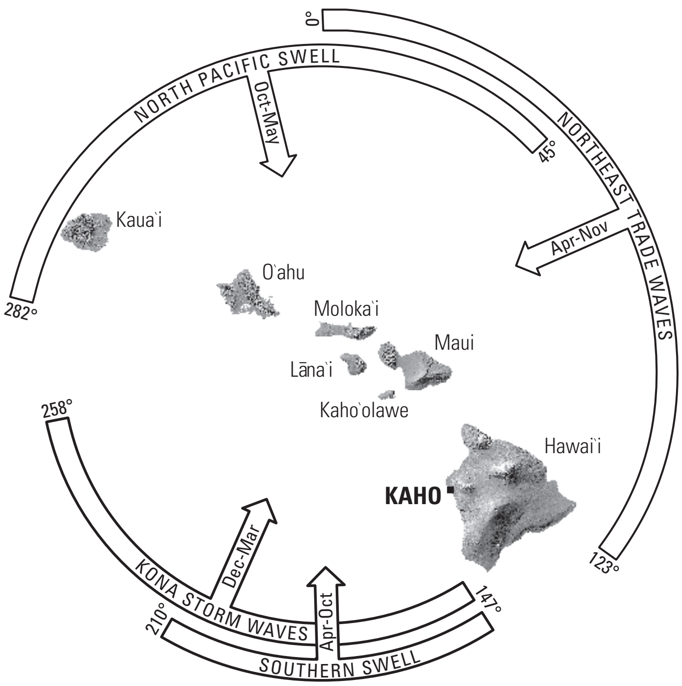


Figure 4. Diagram illustrating primary wave patterns for the main Hawaiian Islands (after Moberly and Chamberlain, 1964).

waves, but smaller, having heights of 1–4 ft (0.3 to 1.3 m) and periods of 14–22 s.

The Kona coast is protected from the effects of northeast trade waves by its location along the west coast of the island. It is also semiprotected by the islands of Maui, Moloka`i, and Lāna`i from all but the most westerly of north Pacific swell. Hence, primary wave energies that affect the Kona coast and KAHO in particular are from westerly north Pacific swell, southern swell, Kona storm waves, waves associated with the passage of low-pressure systems and typhoons (hurricanes), and locally generated wind waves (fig. 4).

Previous Efforts

Previous efforts to document or evaluate the underwater habitat and geological resources in Kaloko-Honokōhau NHP are limited. Recently, Hoover and Gold (2005) presented an extensive assessment of coastal water resources and watershed conditions in the park, which includes an overview of offshore resources and discussion of previous studies. Parrish and others (1990) provide a comprehensive description of the physical characteristics and biological communities of the intertidal and subtidal environments. Shoreline habitat, intertidal habitat, and nine major subtidal habitats are differentiated, including shallow sand, shallow pavement, shore cliff, shallow cliff, deep cliff, boulder and deep pavement, pinnacles and canyons, deep coral slope, and deep sand zones. Coral, fish, and invertebrate communities specifically associated with each of the habitat zones are also described in detail by Parrish and others (1990).

The U.S. Army Corps of Engineers compiled and summarized the results of oceanographic, water-quality, and biological investigations conducted between 1971 and 1982 after the initial construction and expansion of the Honokōhau Harbor (U.S. Army Corps of Engineers, 1983). These studies included surveys of water quality and circulation and of the status and population of plankton, coral, invertebrates, and fish. In that compilation, Maragos (1983) describes the patterns of coral colonization within and outside of the harbor and entrance channel over the 11-year period (1971–1982). Direct physical impact to existing corals was limited to the area just seaward of where the entrance channel was quarried and dredged from the existing shoreline. Surveys within the harbor and entrance channel showed relatively rapid coral colonization in the 11 years following harbor construction. Observations also showed increased coral mortality and a decrease in individual species abundance following the harbor expansion in 1979, although there was little evidence linking the decline to harbor construction (Maragos, 1983). Surveys conducted outside of the harbor entrance showed no substantial changes between 1971 and 1982, and flourishing coral communities in water depths less than 5 m appeared unaffected by the blasting and dredging of the entrance channel.

A benthic habitat map for the KAHO area was produced in 2002 by National Oceanic and Atmospheric Administration (NOAA) Biogeography Team as part of a larger effort to map the distribution of coral reefs and other benthic habitats throughout the main Hawaiian Islands (fig. 5). Using aerial photography collected in 2000, coral reefs and other benthic habitats were mapped using a minimum mapping unit of 1 acre and the classification scheme established by Coyne and others (2003). For more information see: http://ccma.nos.noaa.gov/products/biogeography/hawaii_cd/.

Data and Methods

A standard for characterization of coral-reef environments was first implemented by 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^2 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

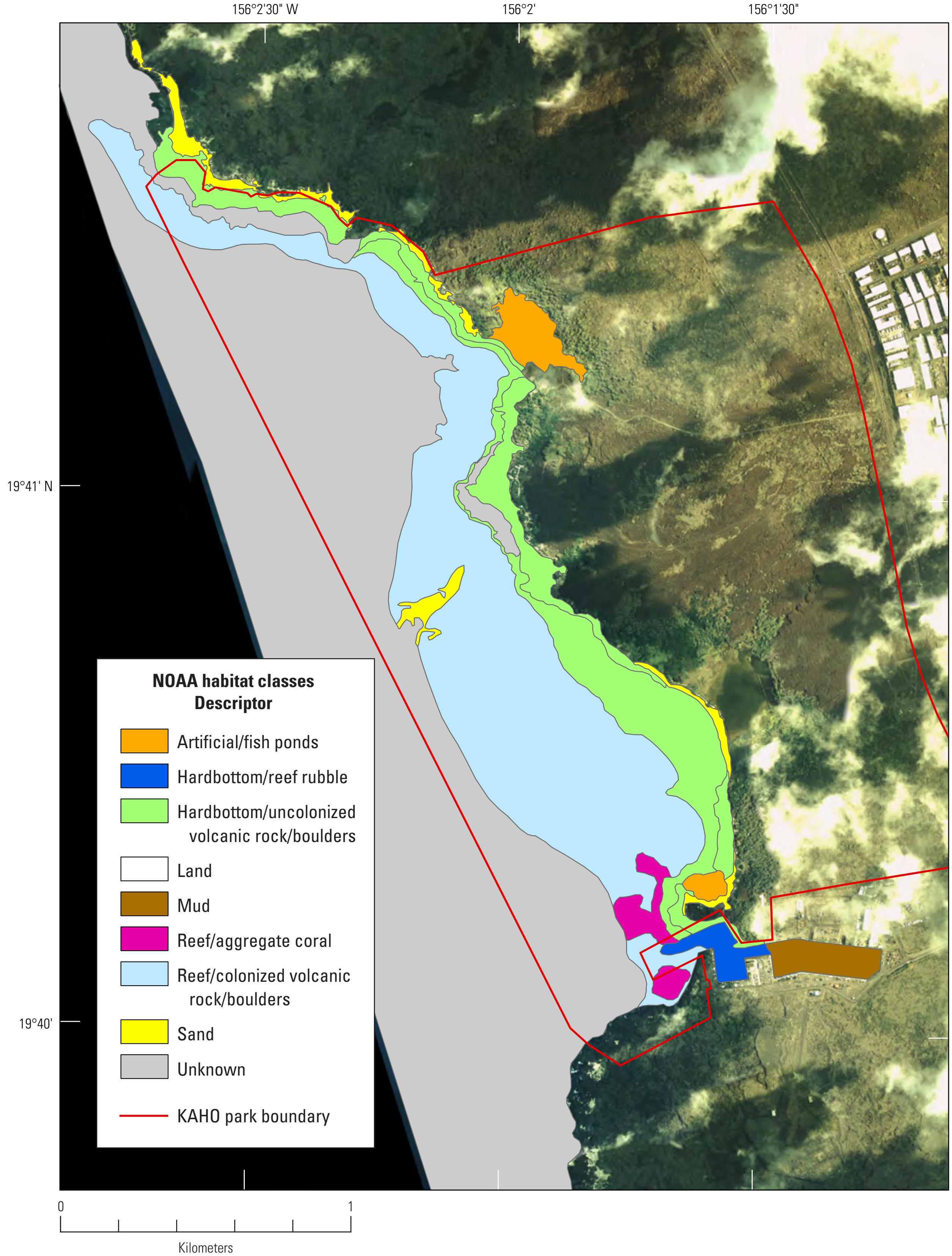


Figure 5. Example from the KAHO area of the photography and benthic habitat maps produced and used by the National Oceanic and Atmospheric Administration's (NOAA) Biogeography Program for the main eight Hawaiian Islands. Data from: http://ccma.nos.noaa.gov/products/biogeography/hawaii_cd/

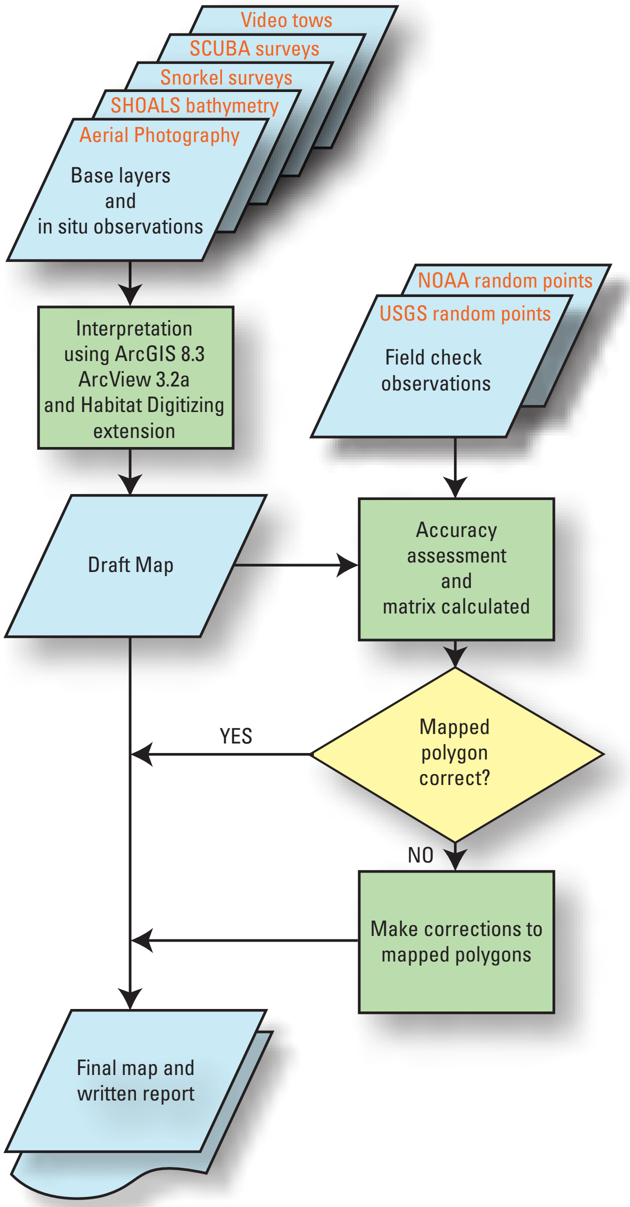


Figure 6. Flowchart illustrating methodology used to create the habitat map. See text for complete description.

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 6 illustrates the complete methodology.

Background Data

Aerial Photography

The National Park Service (NPS) provided the aerial imagery used as a base layer in this mapping effort. True-color and infrared aerial photographs were collected in August and October 2002, respectively. The images were orthorectified, mosaicked, and geometrically registered to true map coordinates by the NPS, resulting in a digital mosaic with a resolution of 0.16 m per pixel (fig. 7). Metadata included with the data states that the horizontal accuracy of this photography is "better than 2 m." In places, adjacent frames of imagery overlap and sea-floor features are obscured. Overall, the photography is quite good, with most features being recognizable to a water depth of 15 to 25 m.

Pan-sharpened (an image processing method in which a higher resolution panchromatic image is merged with a lower-resolution color or multispectral image, resulting in a higher resolution image with as much of the spectral information as possible), multispectral Quickbird satellite imagery is used as a background image for many figures in this report because of its superior visual quality and larger coverage area (fig. 8). Quickbird imagery was not used for interpretive purposes because of its lower spatial resolution of 0.6 m.

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 (fig. 9). The bathymetric data have an average horizontal point spacing of 4 m (± ~3 m) and a vertical resolution of ± 15 cm, with a maximum water penetration of about 42 m in the study area. The vertical datum is mean lower low water (mllw). The SHOALS technology determines water depth by comparing the time difference between a pulse of laser energy reflected off the surface of the water and one reflected off the sea floor. This time difference is difficult to resolve in shallow water (< ~1 m) or where waves are breaking. The maximum depth the system is able to sense is related to the complex interaction of reflectance of bottom material, incident sun angle and intensity, and the type and quantity of particles in the water column. As a rule of thumb, the SHOALS system should be capable of sensing bottom to depths equal to two or three times the Secchi depth—the depth to which an 8-inch (20 cm) disk with alternating black and white quadrants can be seen from the surface. For further details regarding SHOALS data, see http://shoals.sam.usace.army.mil.

For the most part, continuous bathymetric data were obtained for the entire park area, except in the shallow coastal waters of Honokōhau and Kaloko Bays and a swath of missing data in the central part of Honokōhau Bay (fig. 9). Bathymetry in the central part of Honokōhau Bay was filled using the few data points available from the historical National Ocean Service (NOS) survey H09336, collected in 1968. A triangulated irregular network (TIN) of the point data was generated, from which one- and four-meter grids were created. One-meter grids were used for visualization purposes only, but the four-meter grids were used for all analytical calculations and interpretations. Isobaths, hillshades, and slope maps were

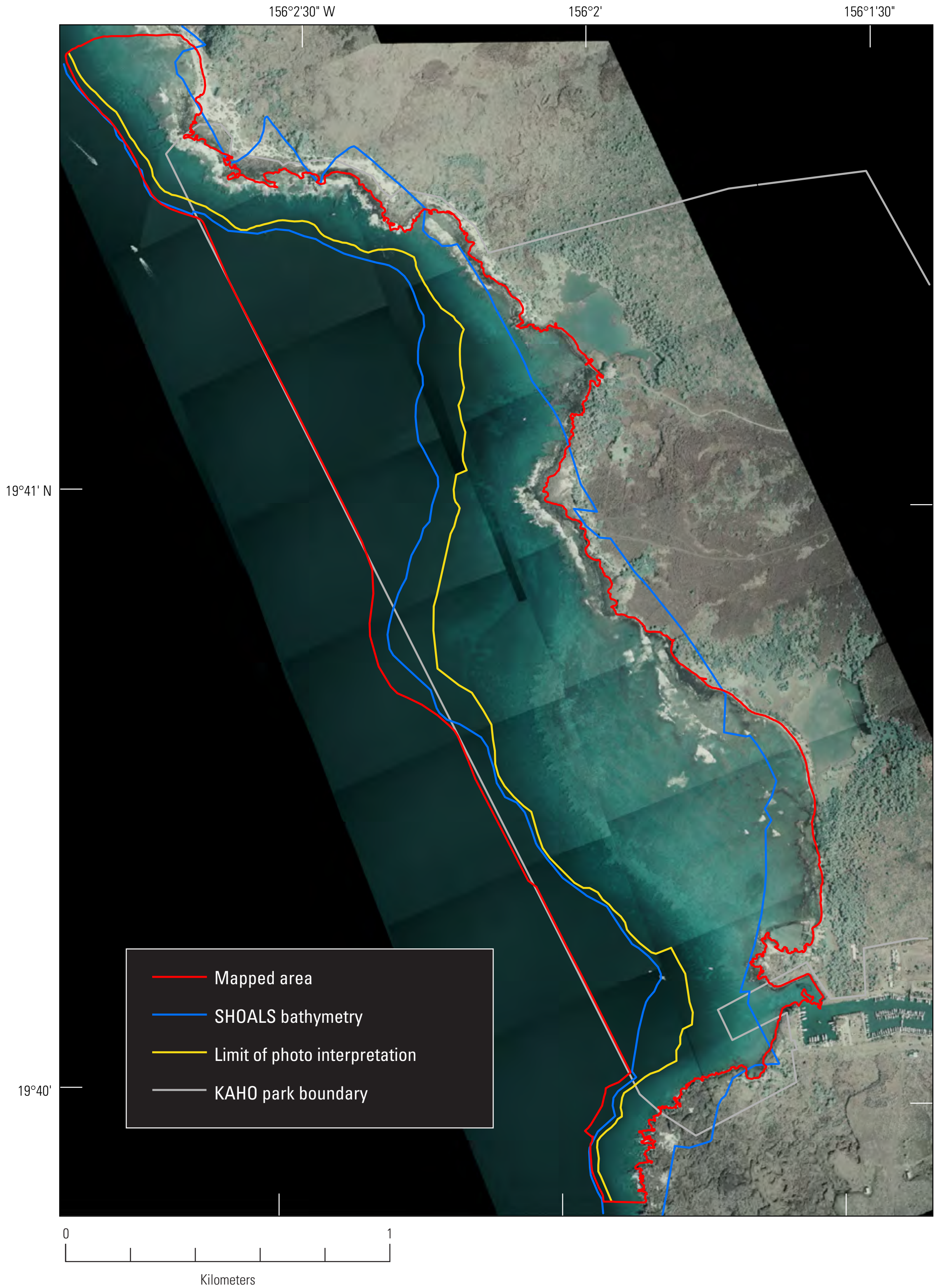


Figure 7. Aerial photomosaic showing the mapped area, the coverage area of SHOALS bathymetry, the offshore limit of interpretable aerial photography, and the KAHO park boundary.

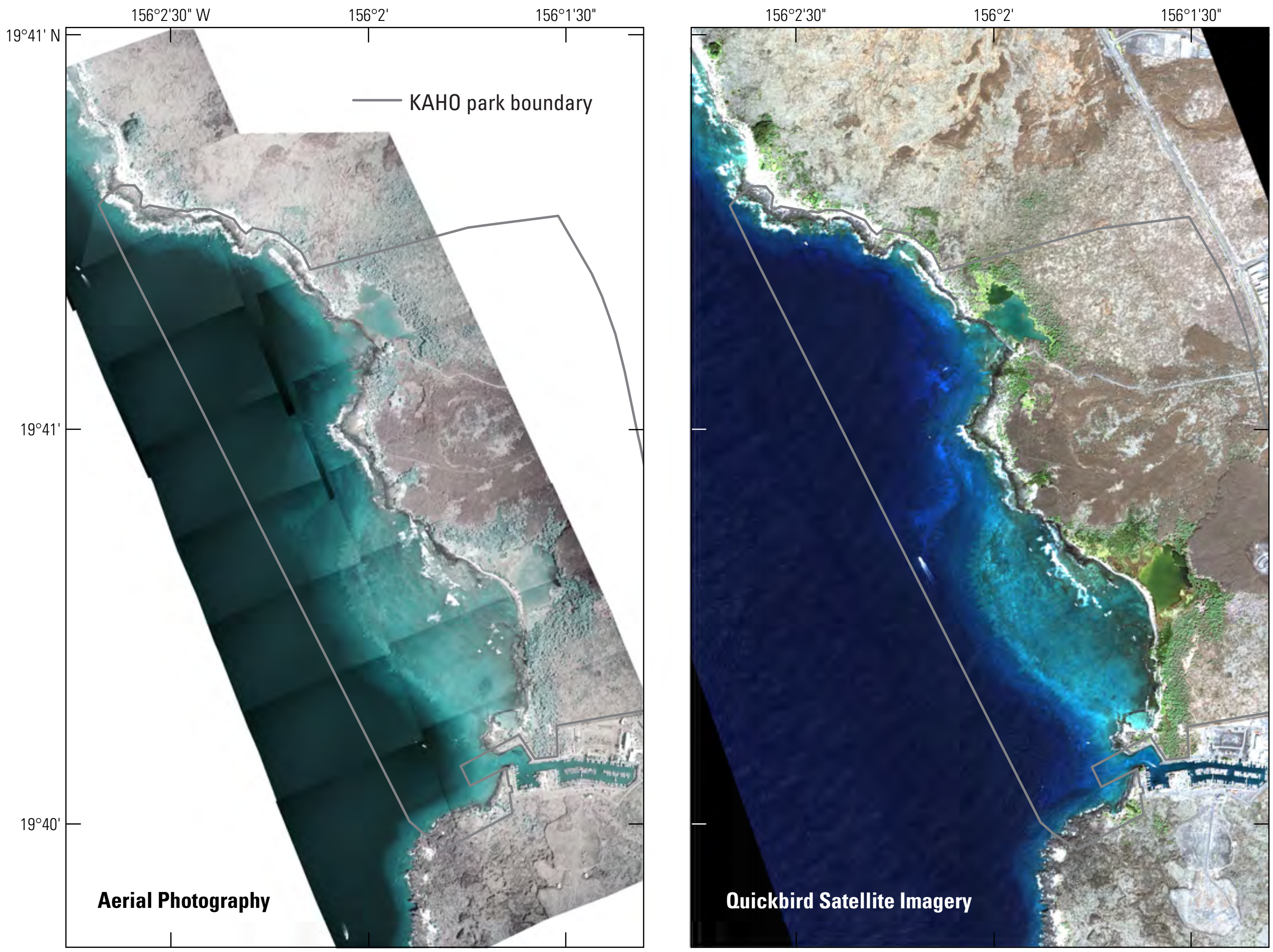


Figure 8. Comparison of aerial photomosaic (left) and Quickbird satellite imagery (right) of the KAHO park area.

derived from these grids using standard ArcMap functions and then used to assist in the interpretation.

Additional reconnaissance-type bathymetry data were collected using a ship-mounted Lowrance fathometer to obtain general information on water depth and sea-floor morphology beyond the limit of the lidar data. No corrections for variations in water temperature or salinity with depth were applied to the data. Because of this, comparisons between the lidar and fathometer-derived depths for the same area show greater offsets with increasing water depth. Geographic positioning was obtained using a Garmin GPS76 receiver enabled with a Wide Area Augmentation System (WAAS). The stated horizontal accuracy of the Garmin GSP76 is better than 3 m when receiving WAAS corrections. The fathometer's transducer was located approximately 5 m aft of the GPS antenna. This offset was applied when comparing the data sets.

Acquired Data

Underwater Video and Still Photography

Nearly 48 trackline kilometers (22 hours) of underwater video footage and more than 500 still images (89 towed lines, 124 on-station drop/drift sites, 5 SCUBA, transects and 3 snorkle transects), were collected during three field surveys between December 2003 and August 2004 (fig. 10). Navigation and other information regarding these surveys are available online at:

http://walrus.wr.usgs.gov/infobank/a/a803hw/html/a-8-03-hw.nav.html

http://walrus.wr.usgs.gov/infobank/a/a204hw/html/a-2-04-hw.nav.html

http://walrus.wr.usgs.gov/infobank/a/a604hw/html/a-6-04-hw.nav.html

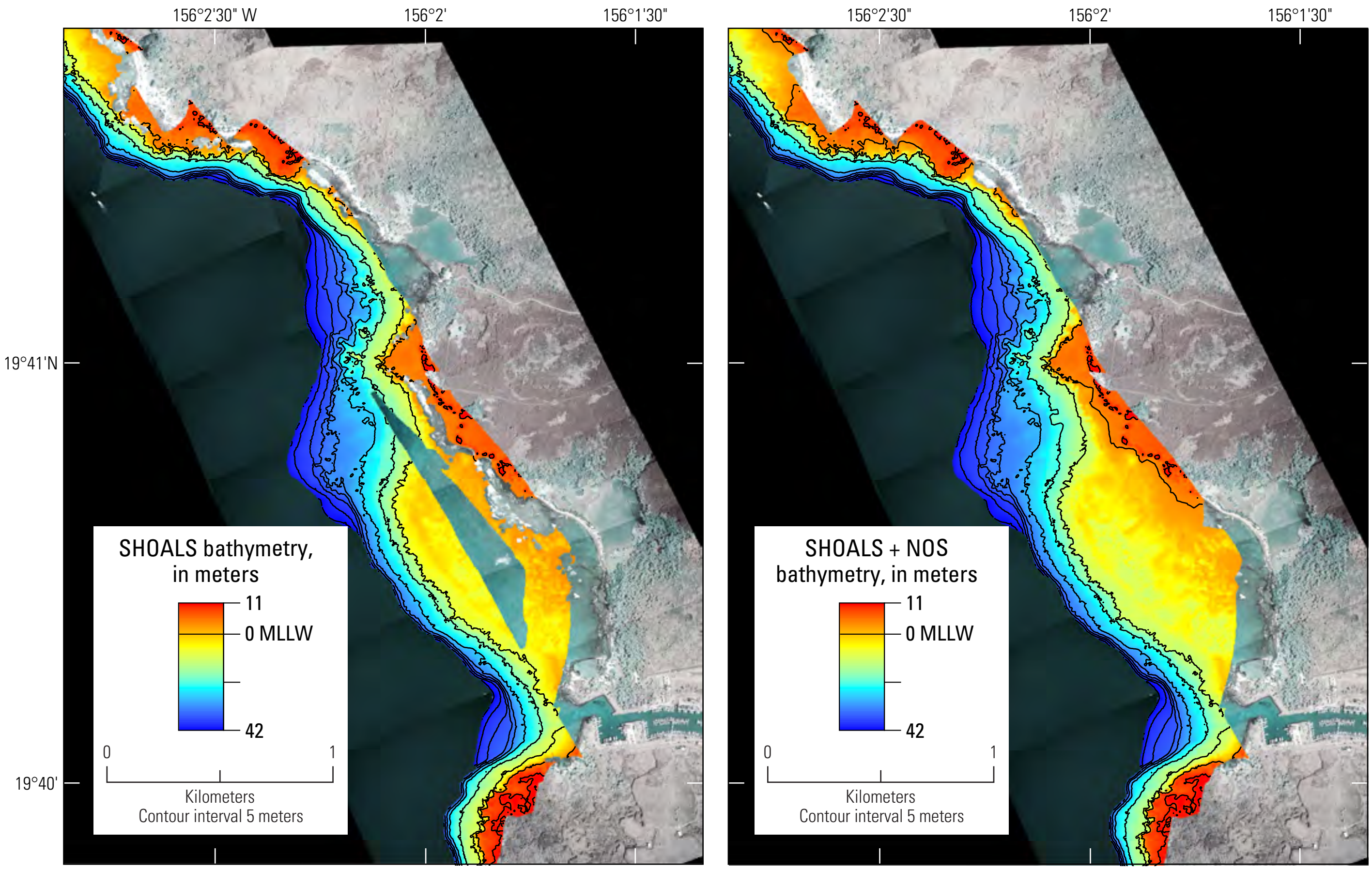


Figure 9. Aerial photomosaics of the KAHO park area overlain with bathymetry data. Left image: Gridded data set showing original SHOALS survey coverage. Right image: Gridded data set with the gaps filled using soundings from an historical National Ocean Service (NOS) bathymetric survey.

Several types of camera systems and collection methods were used. During diving and snorkeling, video was collected with a hand-held SONY TRV-900 video recorder and still images were obtained using a hand-held digital camera (Olympus C-4000, Sony DCS-P5, or Canon PowerShot S-400).

Video imagery was primarily obtained by either towing a camera behind a vessel while underway or dropping it over the side while remaining on a fixed station or drifting slowly. Two vessels were used during the study, the *Alyce C*, a 32-ft vessel operated by Captain Joe Reich of Moloka`i (fig. 11) and a 13-ft Boston Whaler owned by the NPS. The camera system used was a watertight video camera illuminated with a light-emitting diode (LED) light ring designed by SeaViewer Underwater Video Systems (http://www.seaviewer.com). When rigged for towing, the camera was mounted in a small aluminum hand-held frame with a rear-mounted plastic fin (fig. 12*A*). When rigged for on-station dropping, the SeaViewer camera and light were integrated with two battery-powered lasers and a Seabird CTD instrument in a steel frame (fig. 12*B*). Live video from both systems was viewed in a shipboard laboratory on a standard CRT monitor and recorded directly to miniDV tape (fig. 13). Time, date, location, and ship speed were overlaid on the video using Sea-Trak Global Positioning System (GPS) Video Overlay, 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. Location data were recorded using a hand-held, WAAS-enabled, Garmin GPS76 receiver. 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) software packages. Video could be interactively queried and geographically referenced feature annotations added to the database.

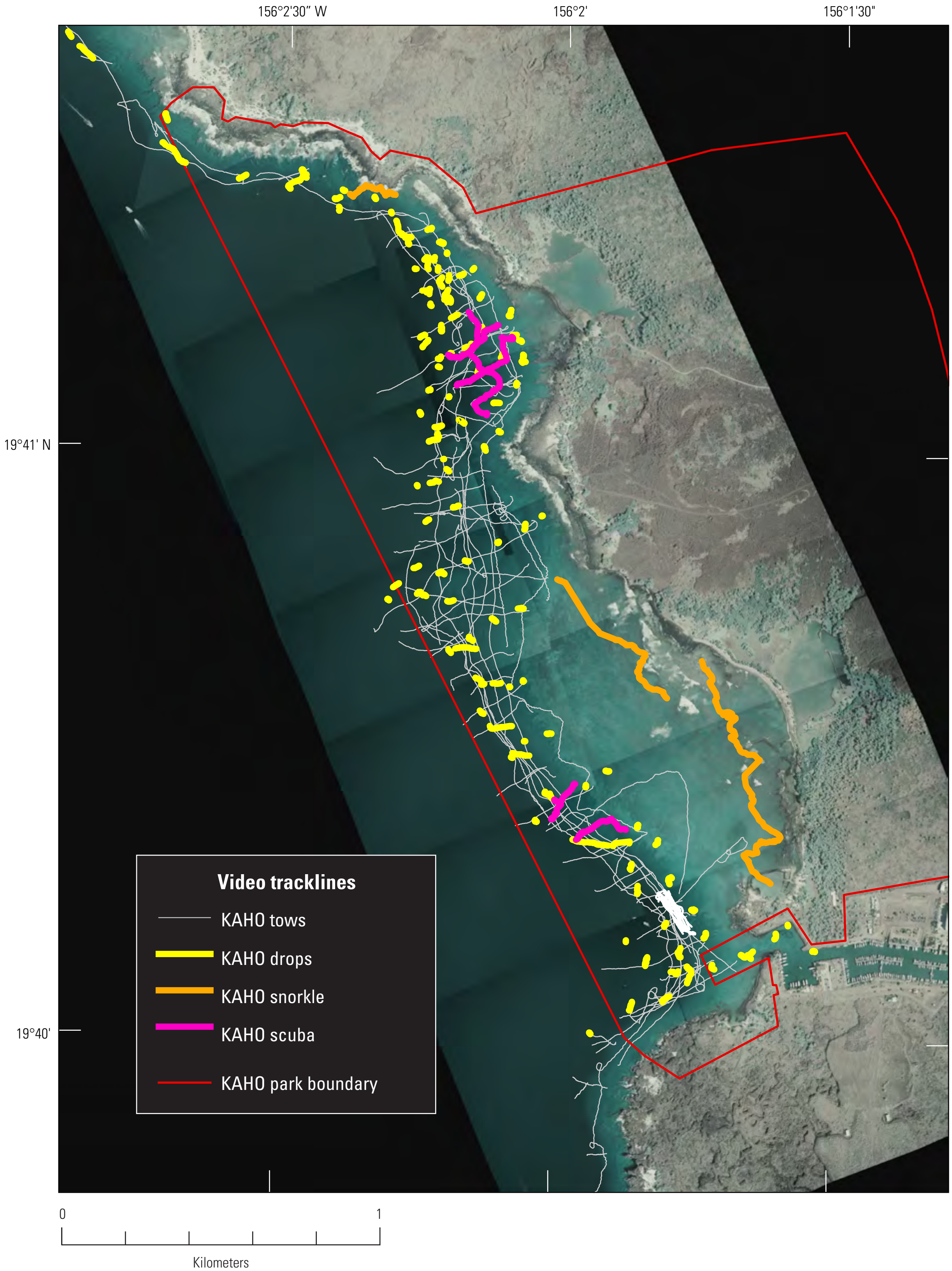


Figure 10. Aerial photomosaic of the KAHO park area overlain with video trackline locations.

Figure 11. Photograph of the *Alyce C* of Moloka`i heading out of Mā`alaea Harbor, Maui.

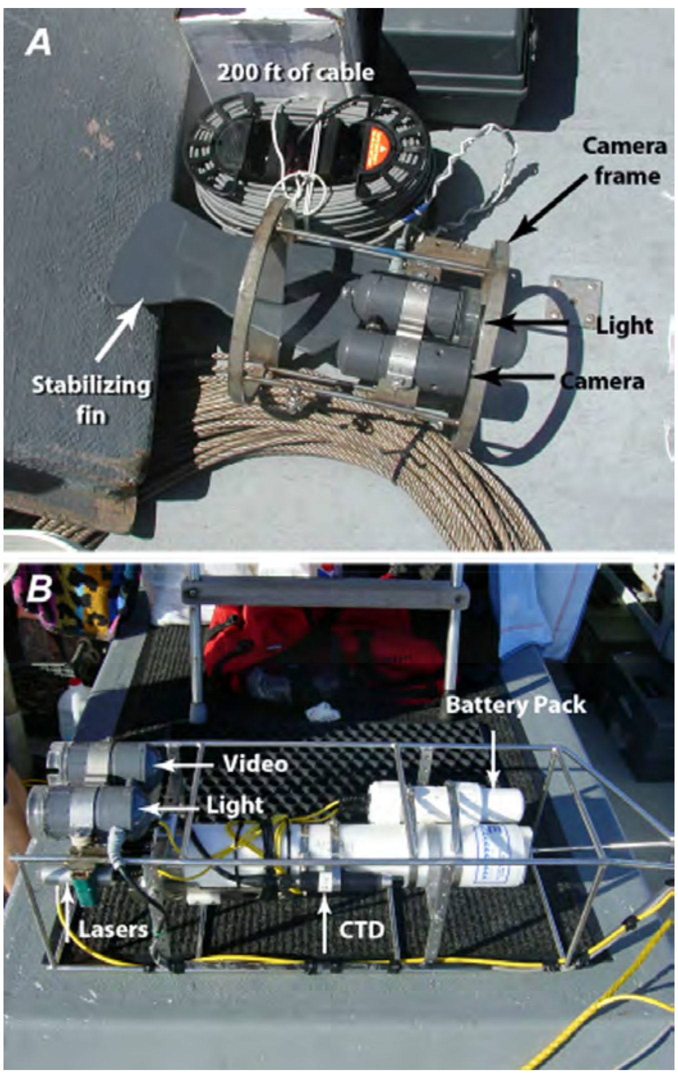


Figure 12. Photograph of the SEAVIEWER camera system (*A*) rigged to collect towed video, and (*B*) with SeaBird CTD acquisition system rigged to collect drop video and CTD information.

Video Mosaics

Recent advances in software development have allowed digital video to be converted to georeferenced image strips that can be imported into a GIS. Researchers at the University of New Hampshire (UNH) are developing software tools for pattern recognition from one video frame to the next, which results in a continuous image mosaic made from overlapping video frames. Collaborators from the USGS (Pete Dartnell) and UNH (Yuri Rzhanov) used sea-floor video acquired during this study to make 38 mosaics of the study area. Original video on miniDV tape was converted into Audio Video Interleave (AVI) format using commercial software and divided into 2-minute sections in order to limit file size and to minimize propagation errors. Using the suite of UNH's software, the video was then de-sampled, keeping every 15^{th} to 20^{th} frame (depending on camera sled speed), and the outer edges of the AVI were cropped to remove the navigation and time stamps (Sea-Trak) superimposed on the video. With the clean AVI, both automatic and manual pattern recognition were performed, calculating the X-Y shift and rotation from one frame to the next. An image mosaic was generated using the video frames and the offset information. Finally, the image mosaics were rectified using GIS techniques and the navigation information on the original video, as well as true-color aerial photography where shallow portions of the reef were visible. Once the imagery was properly georeferenced, it was imported into a GIS for direct comparison and ground-truthing of the benthic habitats (fig. 14).

Benthic Habitat Mapping Using GIS

Digital benthic habitat maps were created using ESRI's ArcMap 8.3 and ArcView 3.2 software with a habitat digitizing extension created by NOAA (to download the extension see: http://ccma.nos.noaa.gov/products/biogeography/digitizer/.

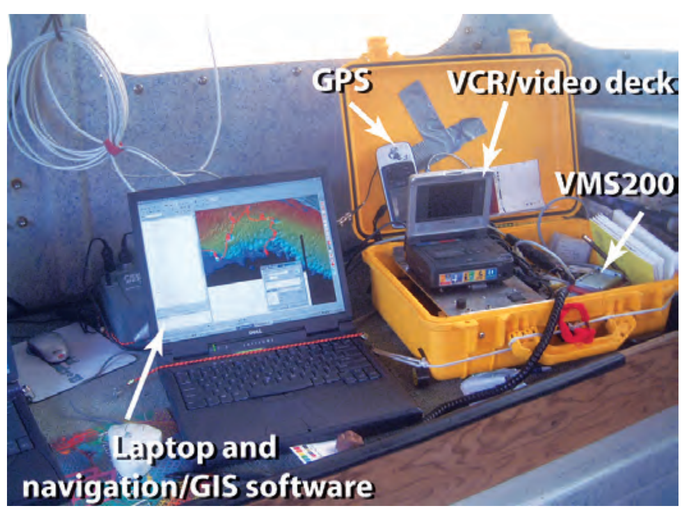


Figure 13. Photograph of shipboard laboratory set-up for navigation, recording of ship's position, and feature annotation.

Figure 14. Example from KAHO park of an underwater video mosaic overlaid on aerial photography.

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 and classified 1,185 polygons, covering more than 2,479 km^2. 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).

Features were primarily interpreted and digitized using aerial photography. In areas where sea-floor features were too deep to be resolved in the aerial photograph (about 25 m or greater water depth), the morphological characteristics of the sea floor observed in the bathymetry, combined with underwater imagery, were used to define and classify the habitat polygons.

Classification Scheme

The classification scheme used was based on a scheme established by NOAA's biogeography 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. We used the NOAA definition of benthic habitats and classification scheme as a starting point to provide continuity with other habitat maps. We made modifications to the classification scheme where necessary to improve identification of benthic habitats and geologic substrates within Kaloko-Honokōhau NHP.

The identification of coralline and turf algae from towed video was nearly impossible, and no attempt was made to map these cover classes for this study. However, turf and/or calcareous coralline algae, readily identifiable when diving and snorkeling, are likely the dominant cover classes in areas classified as "uncolonized" (Rodgers and others, 2004).

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.

The four major structure (substrate) 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

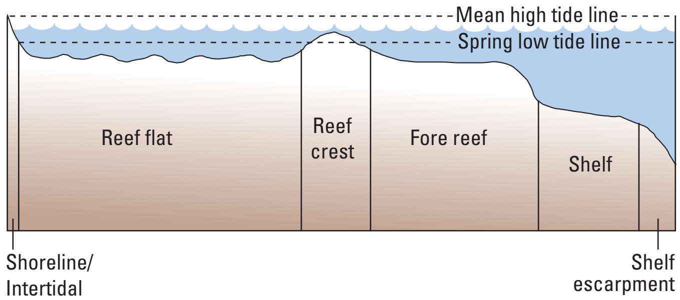


Figure 15. Schematic diagram showing the generalized cross-shelf coral reef zonation. Not shown: land, channel, dredged, or vertical wall (modified from Kendall and others, 2004). Detailed descriptions of the zones are given in the appendix.

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%

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

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

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).

For this study, 187 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. 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 (http://walrus.wr.usgs.gov/infobank/), and the other will reside at the National Park Service, Kaloko-Honokōhau NHP Headquarters. This report and project shapefiles are also available online at http://pubs.usgs.gov/sir/2006/5256.

Results

Benthic Species

Colleagues from the University of Hawai`i Coral Reef Assessment and Monitoring Program (CRAMP) conducted a Rapid Assessment Transect (RAT) survey to quantify and evaluate the distribution of coral, invertebrates, algae, and fish within the park (Rodgers and others, 2004). Seventeen random sites were visited, and detailed biological characteristics, including percent coral cover, species richness and diversity, algal functional groups (macroalgae, coralline, and turf), substrate cover, and topographic relief (rugosity) were quantified along a 10-m transect at each site. Invertebrate and fish populations were quantified at the same sites along 25-m transects. Their analysis shows that the substrate in the park is dominated by turf algae and calcareous coralline algae. Very low amounts of macroalgae and sand were identified. A total of nine species of coral from five genera were quantified along the transect lines (fig. 16). Absolute coral cover ranged from less than 3 percent to more than 50 percent and mean coral cover was 23 percent, similar to the statewide average of 22 percent. The reefs at KAHO are primarily *Porites* reefs, comprising mainly *P. compressa* and *P. lobata*; overall, four individual *Porites* species were identified. KAHO also has a high abundance of the endemic octocoral, *Anthelia edmonsoni*, with extremely high cover on some transects. This species is common at many other locations on the west coast of the Island of Hawai`i, although relatively rare at most other sites within the State. Seven species of invertebrates were observed within the park, most commonly the collector urchin *Tripneustes gratilla* and the rock-boring urchin *Echinometra mathaei*. The Crown of Thorns sea star, *Acanthaster planci*, was also observed at numerous locations within the park (table 5).

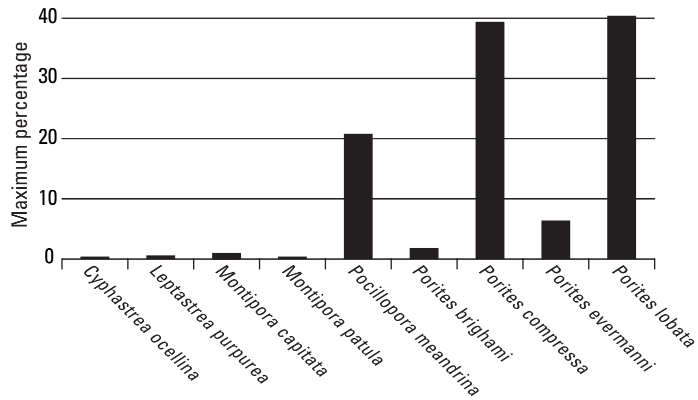


Figure 16. The maximum percentage of the nine coral species quantified from all Rapid Assessment Transect (RAT) surveys (data from Rodgers and others, 2004).

Table 5. Species observed at Kaloko-Honokōhau National Historical Park (KAHO) during Rapid Assessment Transect (RAT) surveys (Rodgers and others, 2004).

Coral	Invertebrates	Algae
Anthelia edmonsoni[1]	*Acanthaster planci*	*Asparagopsis taxiformis*
Cycloceris spp.[2]	*Culcita novaeguinea*	*Malamansia glomerata*
Cyphastrea ocelina	*Diadema spp.*	*Neomeris annulata*
Leptastrea purpurea	*Echinothrix spp.*	
Montipora capitata	*Echinometra mathaei*	
Montipora patula	*Heterocentrotus mammilatus*	
Palythoa turberculosa[1]	*Tripneustes gratilla*	
Pavona varians[2]		
Pocillopora edouxii[2]		
Pocillopora meandrina		
Porites brighami		
Porites compressa		
Porites evermanni		
Porites lichen[2]		
Porites lobata		

[1]Soft corals; [2]Species observed in the area, but not quantified along the transect line.

Benthic Habitats

Benthic habitat varies greatly throughout the study area (figs. 17, 18). Nearly 1.8 km^2 (73 percent) of the study area consists of a hardbottom structure that is potentially available for coral habitation; the remaining 27 percent includes unconsolidated sediment and artificial and artificial/historical features. Of the available hardbottom, 1.3 km^2 (76 percent) is covered with a minimum of 10 percent coral. Coral cover is predominantly low, with 84 percent of the total hardbottom area covered with 10 to <50 percent coral. Significant areas of moderately high (50 to <90 percent; 14 percent total hardbottom) and high (90 to 100 percent; 2 percent total hardbottom) coral coverage are also mapped within the study area (fig. 19). Generally, coral cover increases with depth, and reaches maximum values between about 10 and 20 m of water (fig. 20).

Geologic Framework and Habitat Zones

The region offshore KAHO consists of multiple, coalescing volcanic flows that form distinct morphological regions and support diverse benthic habitats. The offshore geology is predominantly composed of smooth to undulating pahoehoe-type basalt flows that form flat to gently sloping benches, cliffs, and steep shelf escarpments (fig. 21). In some locations the basalt surface is irregular and mounded into ridges, pinnacles, and arches. Large rounded boulders and smaller scattered rocks are common throughout the marine portions of the park. In only a few locations does coral cover or accreted carbonate reef obscure the underlying volcanic surface.

The underlying geologic framework and morphology of the submerged volcanic flows within Kaloko-Honokōhau NHP provide the primary control on benthic habitats within the park. Twelve unique habitat zones, based primarily on water depth, sea-floor slope, and seafloor structure describe the offshore morphology and typical coral communities found within the park. The habitat zones include shoreline/intertidal, dredged, shallow cliff, shallow bench (narrow and broad), intermediate bench, deep bench, shelf break, shelf escarpment, pinnacles/ridges, deep cliff, and deep slope (fig 22; table 6).

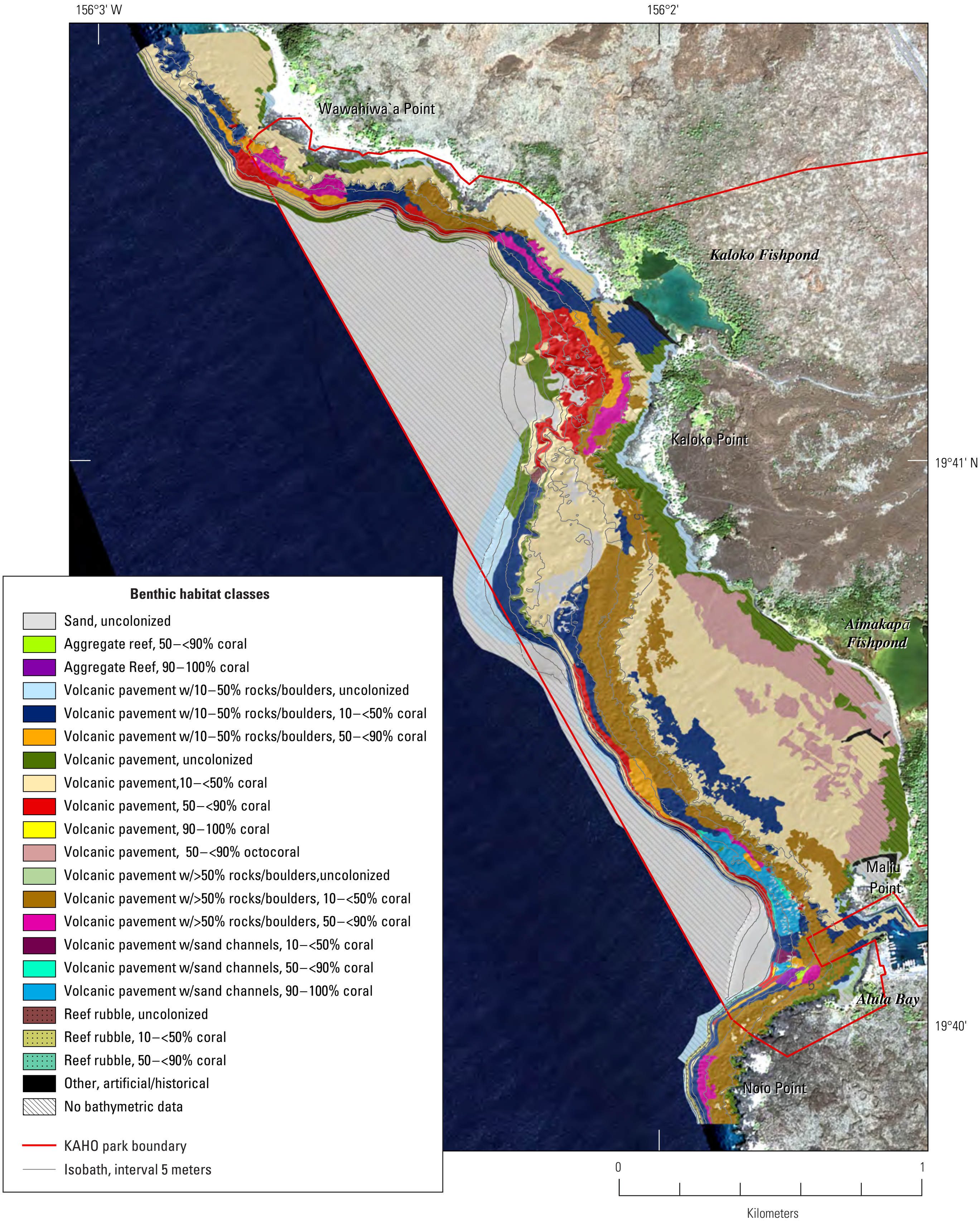


Figure 17. Benthic habitat map of Kaloko-Honokōhau area draped on shaded relief bathymetry. Hatched lines indicate areas lacking bathymetric data. Background image is Quickbird satellite imagery.

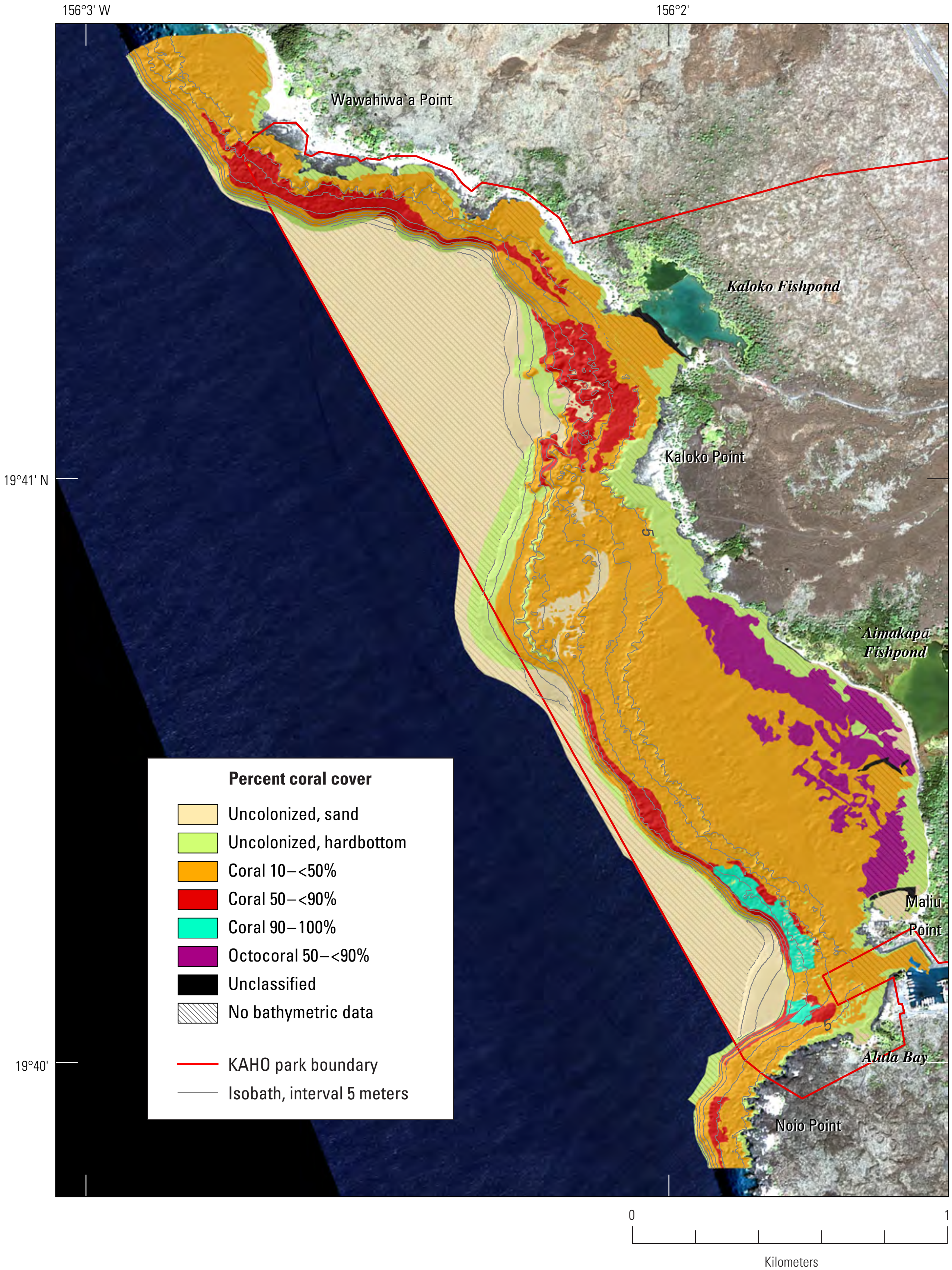


Figure 18. Map showing the distribution of percent coral-cover classes in the KAHO area draped on shaded relief bathymetry. Hatched lines indicate areas lacking bathymetric data. Background image is Quickbird satellite imagery.

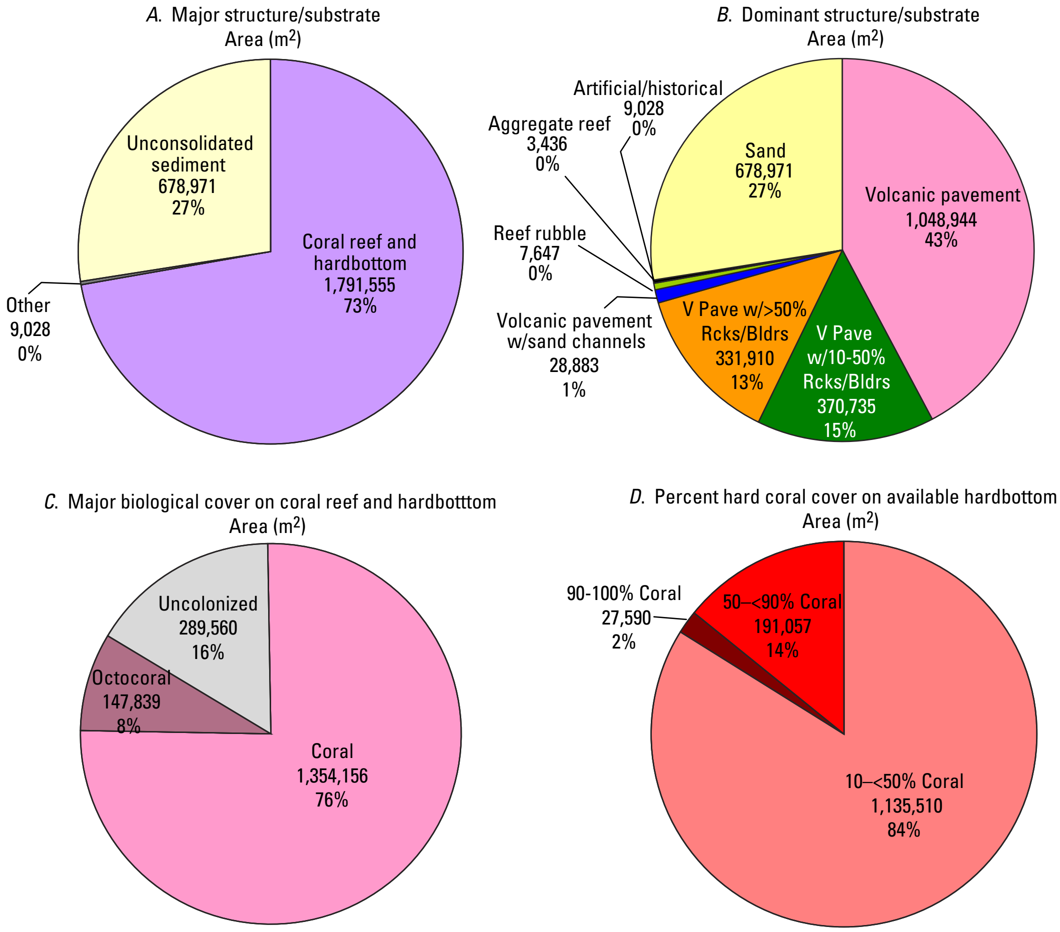
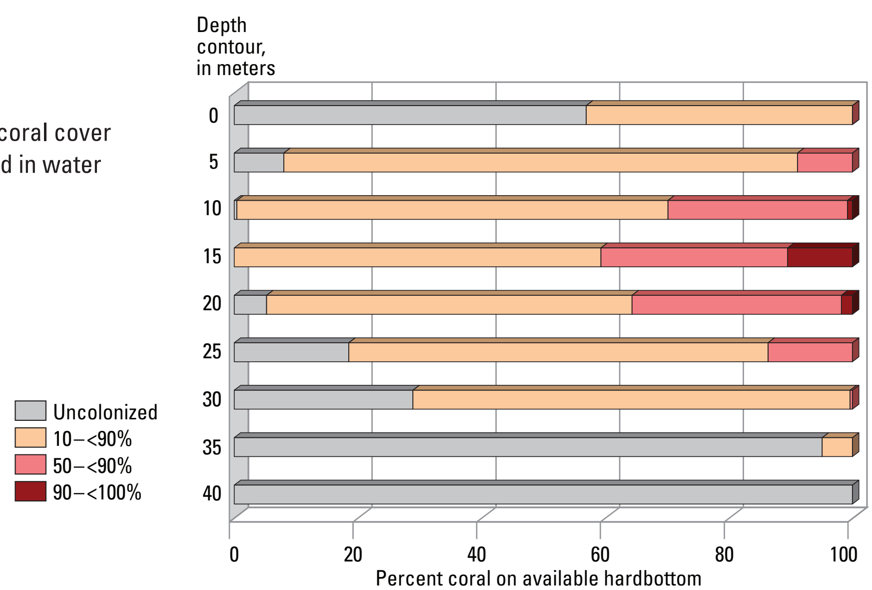


Figure 19. Relative abundance of (*A*) major and (*B*) dominant substrate structures, (*C*) major biological coverage on coral reef and hardbottom, and (*D*) percent hard coral cover on available hardbottom in the KAHO study area. All unconsolidated sediment (27 percent of the study area) is sand (*A*, *B*). The remaining 73 percent of the study area is reef and hardbottom available for coral habitat (*C*). Of this available hardbottom, 76 percent is covered with a minimum of 10 percent coral (*C*, *D*). The majority of the study area is colonized with less than 50 percent live coral. Octocoral is considered separately from hard scleractinian coral. V pave = volcanic pavement; Rcks/Bldrs = rocks and boulders; Chnls = channels.

Figure 20. Bar graph showing the percent coral cover by depth. The highest coral cover is located in water depths between 10 and 20 m (33 and 66 ft).



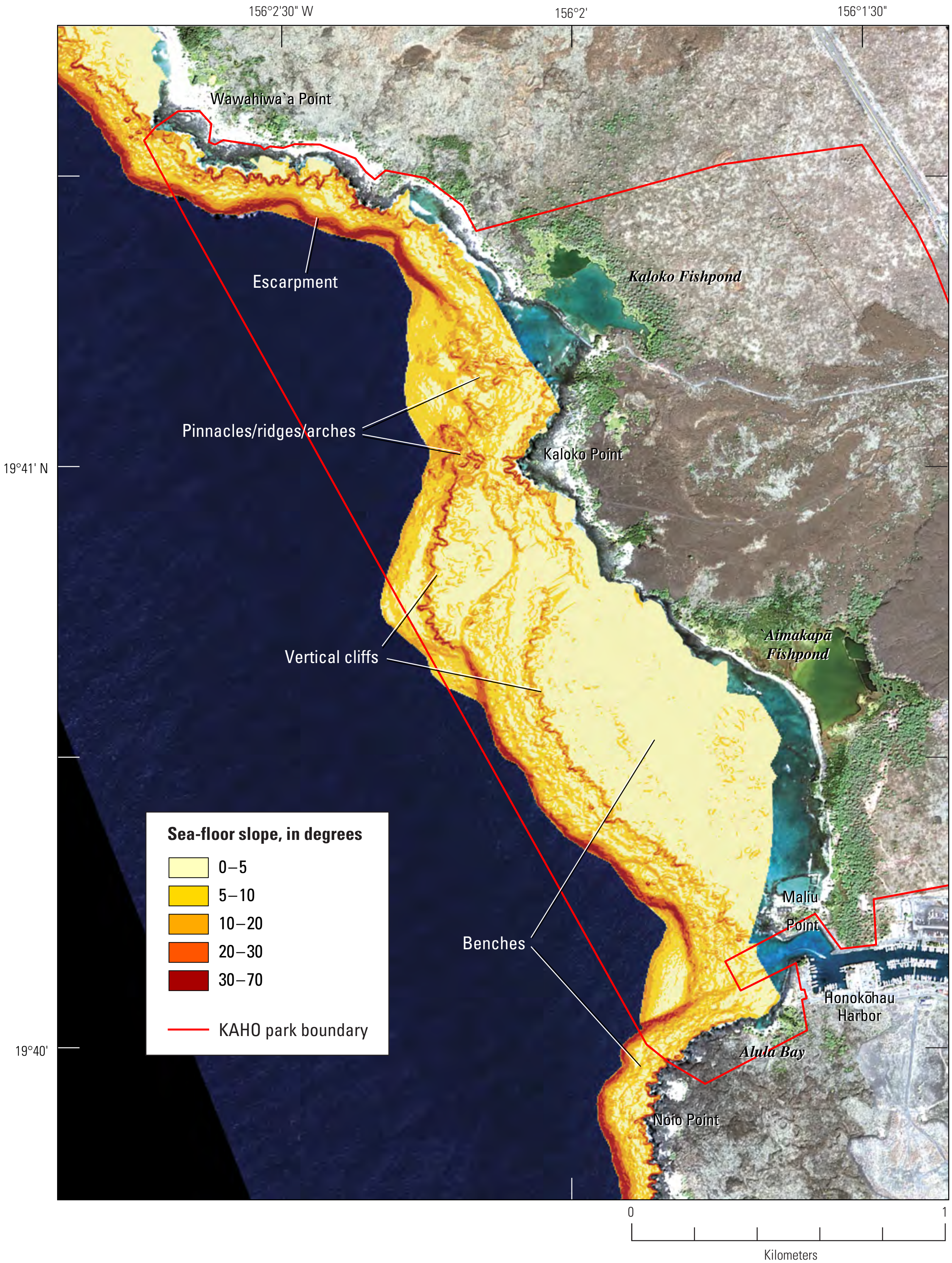


Figure 21. Sea-floor slope map illustrating the complexity of the sea-floor surface and the variety of sea-floor structures within KAHO.

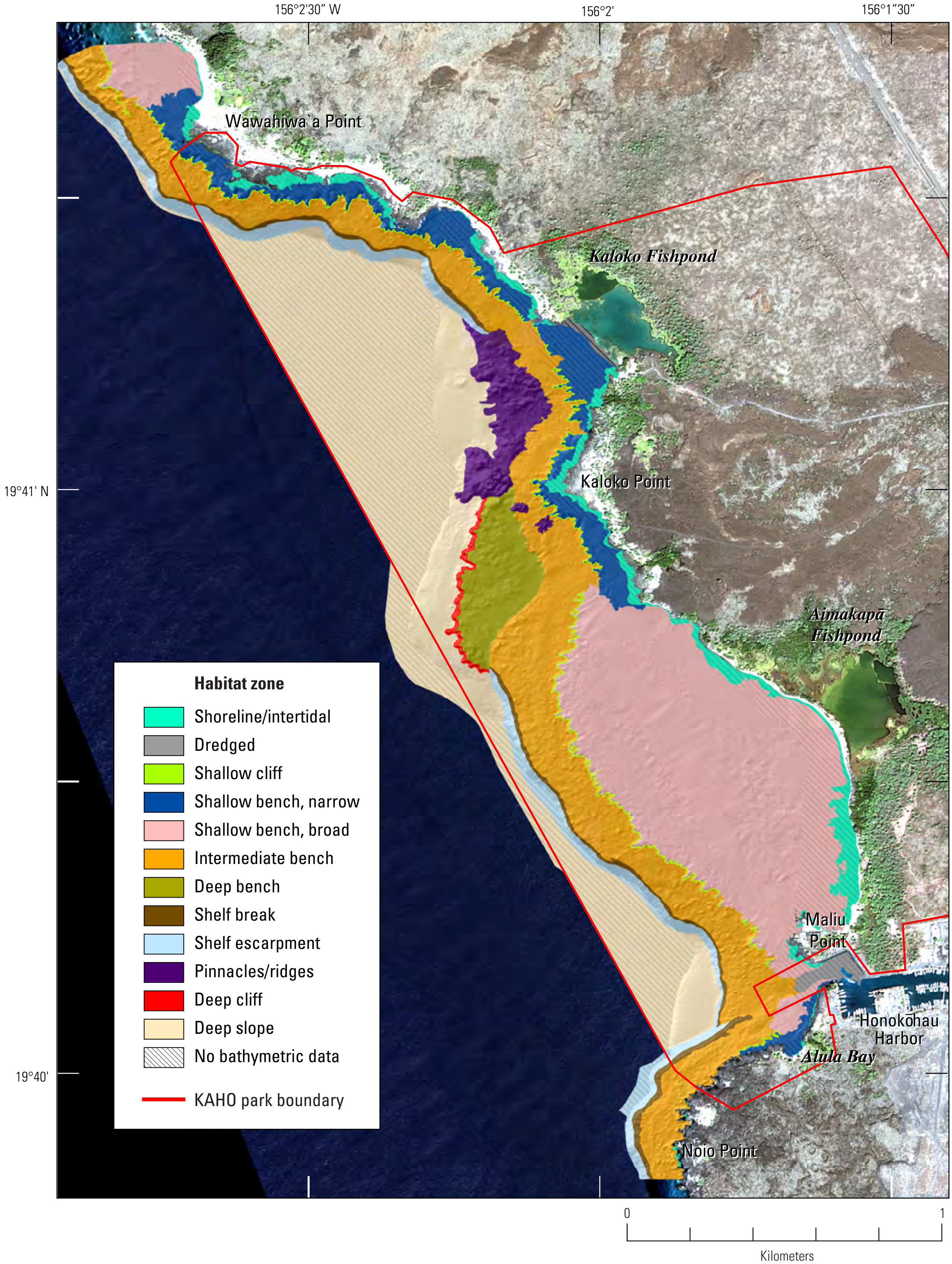


Figure 22. Delineation of the twelve habitat zones described in the text, overlaid on shaded relief bathymetry. Hatched lines indicate areas lacking bathymetric data.

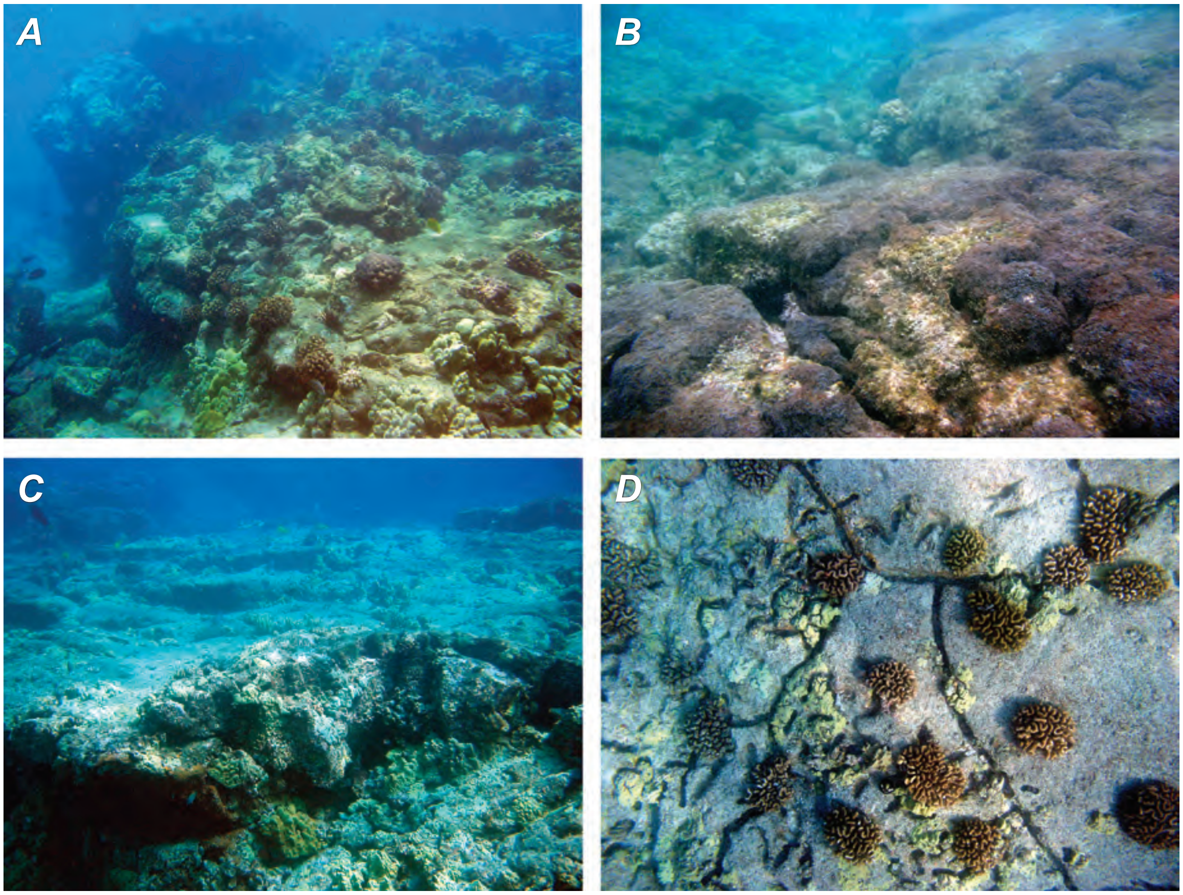


Figure 23. Representative photos of the shallow bench habitat zone. *A*, Seaward edge of narrow bench characterized by scattered *Pocillopora meandrina* and *Porites lobata* on a volcanic pavement. *B*, A blanket of the lavender-colored octocoral *Anthelia edmonsoni* colonizing volcanic pavement in the shallowest regions of the broad bench. *C*, Low-lying ridges on the broad platform. *D*, *P. meandrina* and encrusting *Porites* species on smooth volcanic pavement that has been bored by urchins.

Table 6. Total area and relative percentage of total area of the twelve habitat zones.

Habitat zone	Area (m^2)	Total area (%)
Shallow cliff	7,047	0.3
Deep cliff	7,456	0.3
Dredged	11,144	0.4
Shelf break	37,134	1.5
Pinnacles/Ridges	78,109	3.1
Shoreline/Intertidal	78,431	3.2
Deep bench	83,365	3.4
Shelf escarpment	115,106	4.6
Shallow bench - narrow	157,640	6.4
Intermediate bench	512,431	20.7
Shallow bench - broad	635,722	25.7
Deep slope	751,290	30.4
Total	2,474,875	

Shoreline/Intertidal

The shoreline/intertidal habitat zone is present throughout most of the study area but was difficult to differentiate from aerial photography alone. It was constrained by water depth (between about -1 and +1 m mllw), a wet/dry line, or deeper black color of the wet rocks as seen on the aerial photograph. This habitat is typically uncolonized pavement, scattered volcanic rocks (< ~ 0.5-m diameter), or sand. The pavement surface is commonly covered by a carpet of undifferentiated algae species. South of the harbor and west of Alula Bay the shoreline is delineated by a shear cliff that drops 2-3 m to the sea floor, and no significant intertidal habitat zone is present.

Dredged

The dredged habitat zone includes a small area off the mouth of the Honokōhau Harbor. Benthic cover includes poorly colonized pavement, rocks, boulders, and uncolonized sand. Coral cover is limited to isolated heads of *P. meandrina* and individual colonies of *P. lobata*. Some areas of higher coral cover were observed on the southern edge of the channel.

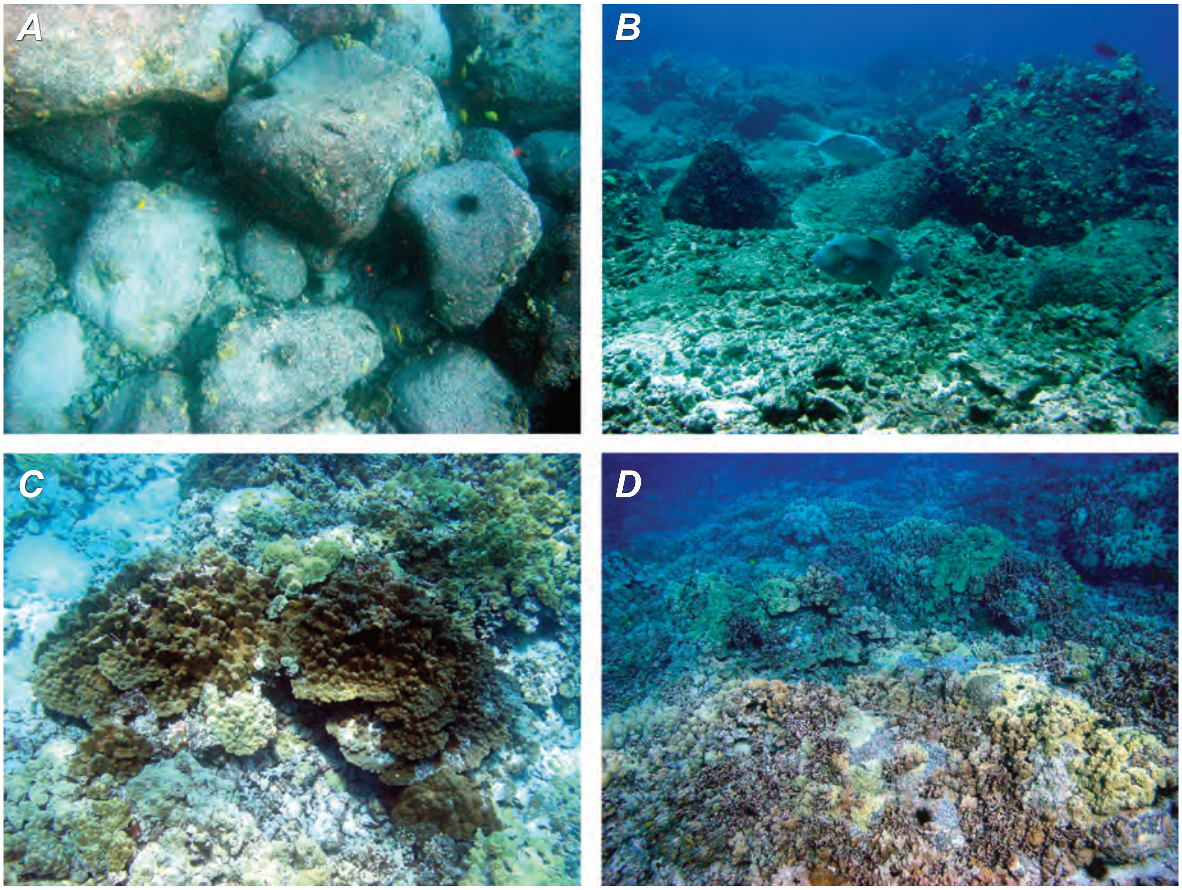


Figure 24. Representative photos of the intermediate bench habitat zone. *A*, Poorly colonized, boulder-covered pavement at the base of the shallow cliff. *B*, Poorly colonized volcanic pavement with scattered rocks and rubble near the center of the study area. *C*, Porites species colonizing boulders south of Kaloko Fishpond. *D*, Moderately high coral cover on volcanic pavement offshore of Honokōhau Harbor.

Shallow Bench (Narrow, Broad)

A nearly flat, shallow bench habitat zone, extending seaward from the shoreline to water depths of at most ~6 m, exists throughout the study area. This habitat zone has been subdivided into two categories—narrow shallow bench and broad shallow bench. The narrow bench is typically less than 50 m wide and commonly wave washed, whereas the broad bench extends several hundreds of meters offshore.

The narrow shallow bench extends along the coast from Wawahiwa`a Point southward to about 400 m south of Kaloko Point and a ~400 m stretch south of Honokōhau Harbor. It is widest offshore of Kaloko Fishpond (~140 m), but in general is approximately 50 m wide. It is typically flat (slope < ~4°) and less than 5 m below sea level. It is commonly wave washed and fronted by a low cliff, 1-3 m high, along most of its reach. Substrate type and cover vary from uncolonized pavement and sand to poorly colonized pavement and boulders. Where present, coral cover is predominantly *P. meandrina*, with secondary *P. lobata* and low-lying encrusting coral species (fig. 23*A*).

The broad shallow bench is the 2nd largest habitat zone in the study area. It begins about 325 m south of Kaloko Point and continues southward to just south of the Honokōhau Harbor. A small area of this zone is also present north of Wawahiwa`a Point. At its widest point, offshore of `Aimakapa Fishpond, the bench is nearly 700 m wide. It is a shallow (< ~ 6 m), low-lying (avg slope < 3°) bench of pahoehoe-type volcanic pavement with many low ridges and troughs (< 1 m high). Large waves commonly shoal and break across this shallow platform, especially over the northern section off `Aimakapā Fishpond. The breaking waves hindered validation of the benthic cover over the shallower portions of this habitat. Benthic cover includes uncolonized pavement near the shoreline and carpets of the lavender-colored octocoral *Anthelia edmonsoni* in water depths less than about 2 m (fig. 23*B*). Coral cover generally increases seaward. The flat volcanic pavement is poorly colonized, with scattered small colonies of primarily *P. lobata* (10 to <50 percent), although higher percentages of coral cover are found locally on the lee side of low-lying ridges and filling cracks in the volcanic surface (fig. 23*C*). Toward the seaward edge of the shallow platform, the volcanic surface is covered with scattered rocks (< 0.5 m diameter) and colonization increases slightly (still <50 percent), with larger colonies of *P. lobata* and *P. meandrina*.

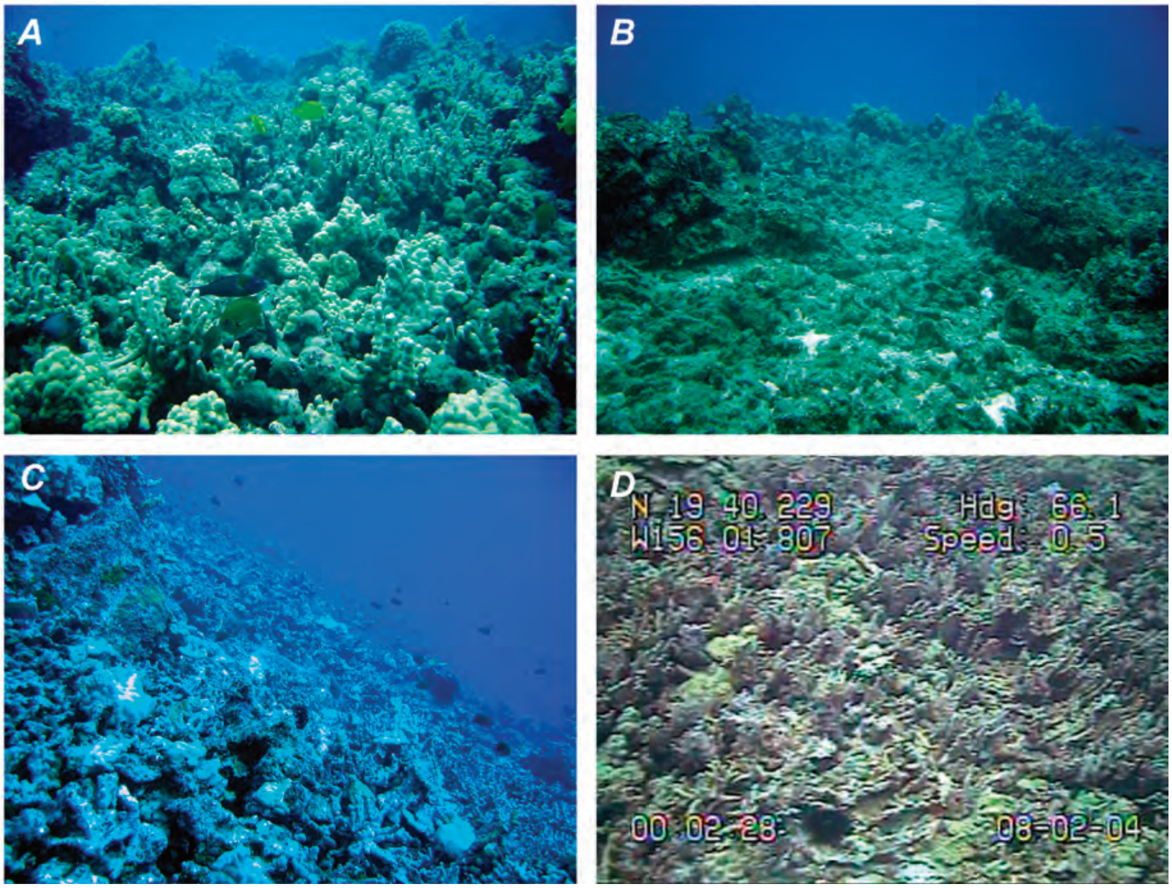


Figure 25. Representative photos of the shelf break and shelf escarpment habitat zones. *A*, Moderately high coral cover on shelf break. *B*, Poor coral cover on shelf break. *C*, Scattered coral and rubble on shelf escarpment. *D*, High coral cover and diversity on shelf escarpment.

The volcanic pavement in this area is also commonly bored by urchins (*Echinometra mathaei*; fig. 23*D*). The broad shallow bench is fronted by a shallow cliff 2-3 m high along its entire stretch, except south of the harbor and at several locations north of the harbor where no cliff is distinguishable from photography or bathymetry.

Shallow Cliff

The shallow cliff habitat zone fronts both the narrow and broad shallow benches. The cliff is a near-vertical wall, typically between 1 and 3 m high, although in places multiple steps separate the shallow bench from the intermediate bench below. The ~4-m point spacing of the lidar data is too coarse to accurately define the edges and morphology of the shallow cliff. In order to distinguish this near-vertical feature on a planar map, it was arbitrarily given a width of about 1 m in plan view. Where multiple steps could be identified, the seaward-most edge was mapped. This resulted in an overestimation of the relative surface area included in this habitat zone, although the total is still less than 1 percent of the total habitat mapped. The habitat was classified as uncolonized volcanic pavement, although limited areas of coral, both *P. lobata* and *P. meandrina*, were observed on the cliff faces and typically covered less than 10 percent of the substrate.

Intermediate Bench

The intermediate bench habitat zone is the 3rd largest within the study area. Where the shallow cliff is present, the intermediate bench begins at its base and slopes gently (<12°) seaward to depths of around 20 m. South of the harbor, the zone directly abuts the 2-3-m-high cliff that marks the shoreline. The width of the bench varies between about 25 and 250 m but is typically about 75 m. It is narrowest in the northern part of the study area and widest off the harbor mouth. The seaward boundary of the habitat zone is generally the shelf break habitat zone, except in the northern part of Honokōhau Bay, where it abuts the pinnacles/ridges and deep bench habitat zones.

The intermediate bench habitat zone claims the highest variety of dominant substrate structure, percent coral cover, and overall coral diversity among all the habitat zones within the park. The habitat zone includes all the habitat classes mapped except for uncolonized rocks and boulders, rubble, and octocoral on volcanic pavement. The majority of this habitat zone is characterized by poorly (10 to <50 percent) to moderately (50 to <90 percent) colonized rocks and boulders on volcanic pavement (fig. 24*A*-*C*). However, the highest coral cover, highest diversity, and the only area of vertically accreted carbonate reef in the study area are also located within this intermediate bench habitat in the southern part of Honokōhau Bay, just off the harbor mouth (fig. 24*D*). Off Kaloko Point, the normally smooth and flat-lying volcanic pavement characteristic of this habitat is more irregular, fractured, and undulating.

Shelf Break

The shelf break habitat zone marks the seaward boundary of the intermediate bench habitat zone and extends the length of the study area, except adjacent to the pinnacles/ridges and deep cliff habitat zones. The shelf break zone lies at depths of 9 to 31 m and marks the transition between the gently sloping intermediate bench and the steep shelf escarpment below. Over most of the study area it is typically between 15 and 20 m deep; south of the harbor it is somewhat shallower, commonly between 12 and 15 m deep. Average slope values within this habitat zone are between 12° and 20°.

In general, the shelf break marks a dramatic transition in benthic habitat between the habitat zones above and below it. For example, fewer boulders and rocks exist on the shelf break compared to the intermediate bench, and coral cover is distinctly higher, and of higher diversity, compared to the shelf escarpment. A wide range of habitat classifications are included within this habitat zone (fig. 25*A*, *B*).

Shelf Escarpment

The shelf escarpment habitat zone extends the length of the study area except near the pinnacles/ridges and deep cliff habitat zones. The inner boundary of the shelf escarpment habitat zone is the seaward edge of the shelf break habitat zone in water depths of between about 15 and 20 m, and it continues to depths exceeding the limit of the lidar bathymetry data (>40 m). Limited fathometer transects show that the offshore slope flattens in water depths between 60 and 75 m, marking the end of the shelf escarpment zone and the beginning of the deep slope (fig. 26). Slopes on the shelf escarpment typically range between about 20° and 45°.

The shelf escarpment is a habitat characterized by uncolonized to poorly (10 to <50 percent) colonized volcanic pavement that is essentially monotypic, patchy thickets of live and skeletal *P. compressa* and rubble (fig. 25*C*). The extreme slope causes this habitat to be highly unstable and vulnerable to damage from boulders, rocks, and larger coral heads tumbling down the slope, as well as damage from higher wave energy conditions associated with severe, but episodic, storms. Small rocks and rubble are common within this habitat, while large boulders are rare. In only a few areas does coral cover exceed 50 percent (fig. 25*D*). Near the shelf break and in areas where the slope is somewhat lower, *P. lobata* and *P. meandrina* also colonize this habitat.

It was often difficult to distinguish live and dead coral percentages on *P. compressa* thickets using the towed video technique, especially in deeper water where natural light is diminished (fig. 27*A*). Commonly the habitat appeared to be continuous and in place rather than scattered rubble and broken fingers, although much appeared to be skeletal and not living. Drop-video and scuba transects often showed recent regrowth on the ends of the skeletal *P. compressa* fingers (fig. 27*B*). The soft octocoral *Anthelia edmonsoni* was also commonly observed with the *P. compressa* framework. Our estimates from the video data are on the conservative side, resulting in a classification of low overall percentage of coral cover. Additional deep-water studies in this habitat are necessary to more definitively determine the health and vitality of this *P. compressa* habitat.

Depth transitions were also difficult to determine because of the steep slope; a small distance over the surface of the water could correspond to a difference of several meters in water depth. Because of this, the depth of the transition from colonized to uncolonized coral is approximate. Where no other depth information was available, an arbitrary depth of 27 to 30 m was used to delineate the transition from colonized to uncolonized pavement or rubble, based primarily on scuba transects and general studies of corals in the Hawaiian Islands (Grigg and Epp, 1989; Grossman and Fletcher, 2004).

Deep Bench

The deep bench habitat zone is located offshore of Kaloko Point. It extends as much as 250 m across the shelf between the intermediate bench habitat zone on the east and the deep cliff habitat zone on the west. It is bounded on the north by the pinnacles/ridges habitat zone and on the south by the intermediate bench and the shelf escarpment habitat zones.

The deep bench habitat is a mostly smooth, pahoehoe-type volcanic pavement with large areas of rubble and sand. It is slightly (1-3 m), but distinctly, lower than the adjacent intermediate bench and slopes gently seaward (~2°) across the shelf between about 12 and 22 m of water depth. It ends along the crenulated edge of the ~3-7-m-high, near-vertical deep cliff in ~18-22 m of water. The habitat supports a mostly low (10 to <50 percent) but variable coral cover of primarily small colonies of lobate *P. lobata* and *P. meandrina*, and includes patches of uncolonized pavement, sand, and rubble. Locally there are areas of higher coral cover with larger heads of *P. lobata*. A relatively large sand sheet abuts the intermediate bench along the south boundary of this habitat zone.

Deep Cliff

The deep cliff habitat zone bounds the deep bench habitat zone along the seaward edge. It abuts the shelf escarpment habitat zone in the south and the seaward edge of the pinnacle/ridges habitat zone in the north. The cliff is typically 3-7 m high, and its upper edge varies in water depth from about

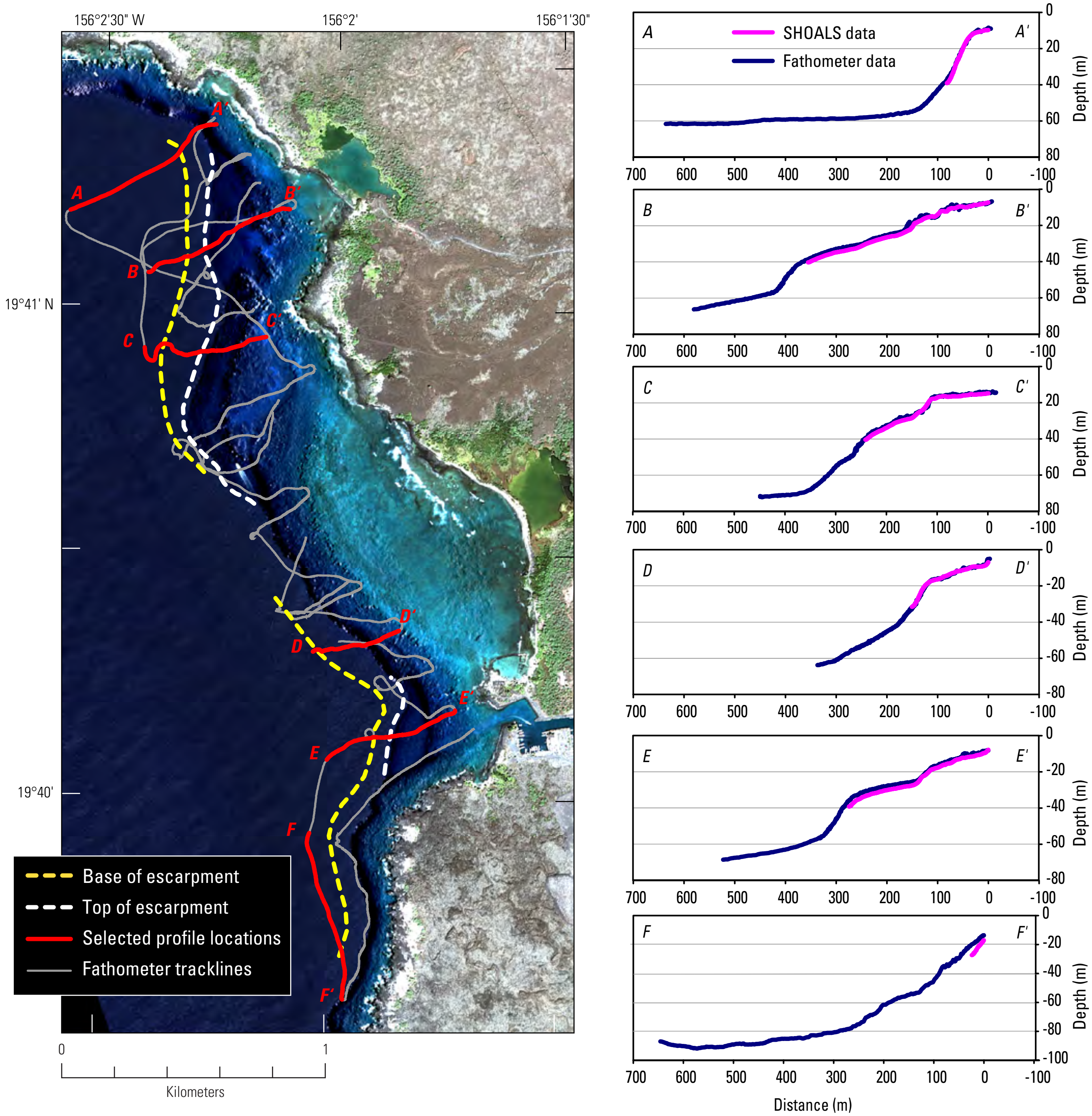


Figure 26. Map of fathometer tracklines and selected profiles in the KAHO area showing variation in offshore morphology. Profiles show bathymetry measured using lidar data in pink and fathometer data in blue. Fathometer data show that the profile morphology in general flattens in water depths of about 60 to 75 m, although multiple benches and shelves may exist offshore. In many places, the maximum depth of the lidar bathymetric data is near the top of the shelf escarpment. White and yellow dashed lines show the top and base, respectively, of the shallowest shelf escarpment as inferred from the fathometer data.

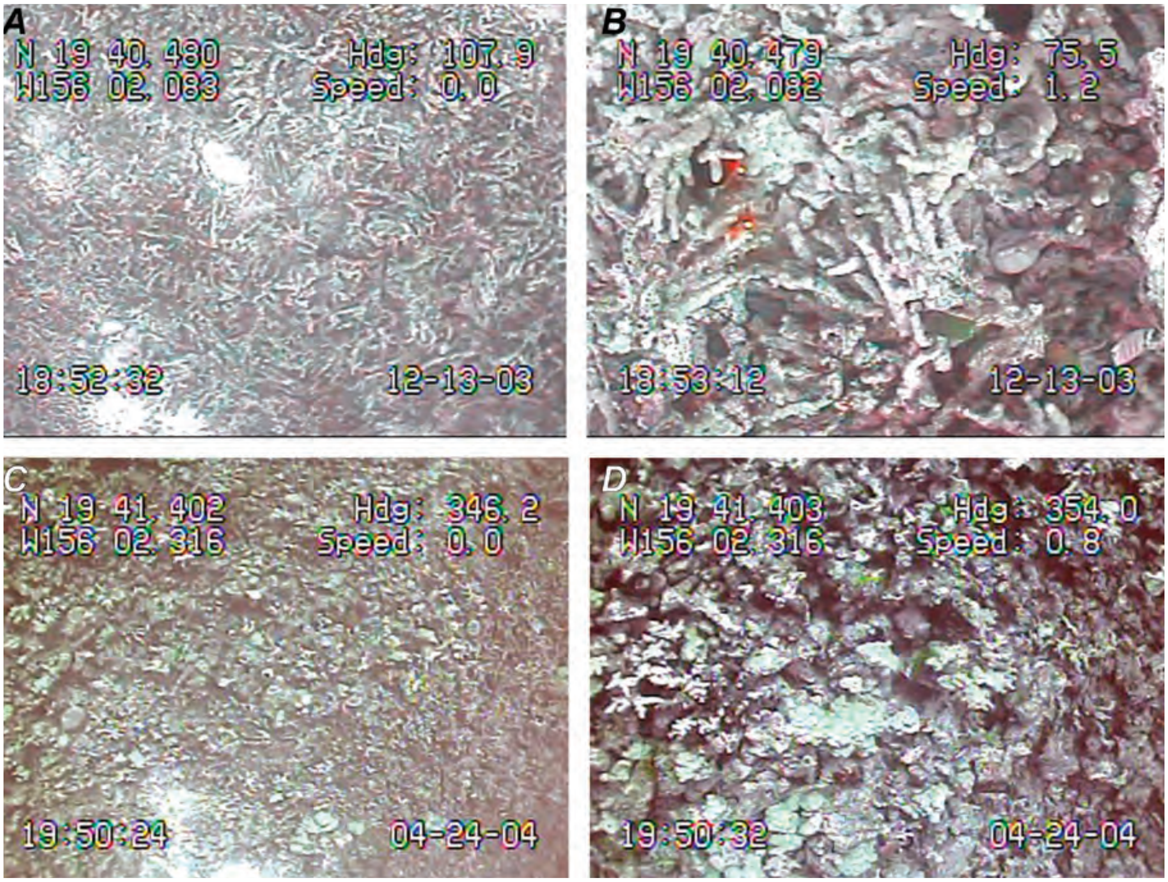


Figure 27. Representative photos of the shelf break and shelf escarpment habitat zones. *A*, Moderately high coral cover on shelf break. *B*, Closeup of A showing skeletal *P. compressa* framework with some regrowth at the tips; the two red laser points are 10 cm apart. *C*, Scattered coral and rubble on shelf escarpment. *D*, Closeup of *C* showing greater coral diversity and a more massive coral/rubble framework.

18 m in the north to near 22 m in the south. The entire habitat is located in water depths between 15 and 30 m and is entirely classified as uncolonized volcanic pavement.

Pinnacles/Ridges

The pinnacles/ridges habitat zone is dominated by a region of pinnacles, ridges, and arches in depths of about 9 to 25 m of water in the northern part of Honokōhau Bay, between Kaloko Fishpond and Kaloko Point. The habitat zone extends ~50-150 m across the shelf before transitioning, as an irregular, steep escarpment, to the deep sloping shelf habitat below. Two noncontiguous, but structurally similar pinnacles are also located south of Kaloko Point, surrounded by the irregular intermediate bench habitat.

The pinnacles/ridges habitat marks a well-defined transition from the generally smooth, gently sloping surface of the intermediate bench habitat to an irregular, undulating, and mounded surface, where the pinnacles rise more than 5 m from the adjacent sea floor to within 5 m of the surface. The ridges and intervening channels are typically oriented in a shore-normal direction. The geological origin of these structures is unclear, although we speculate they represent a more viscous composition of the lava during deposition, which would have resulted in significant heaving and fracturing as the flow was deposited and cooled.

The intricate structure and vertical relief in this area results in a wide range of coral cover and diversity—with some of the highest percentages of coral cover in the park being observed in this region (fig. 28). Relative topographic highs have low (10 to <50 percent) to moderately high (50 to <90 percent) coral cover of predominantly *P. meandrina* and *Porites sp.*, while the intervening lows are typically uncolonized pavement with a thin cover of sand and rubble. Where tops of the ridges and pinnacles reach close to the water surface, coral cover is typically low to moderate and predominantly *P. meandrina* and small and encrusting *P. lobata*. Along the edges and walls of these shallower features, and in general as water depth increases, percent coral cover and diversity increases. Some evidence of onshore/offshore flow transport, such as ripple patterns in sand channels, suggests that the intervening lows between the pinnacles and ridges are the primary transport pathways for water moving on and off the shelf during tidal changes and storm conditions.

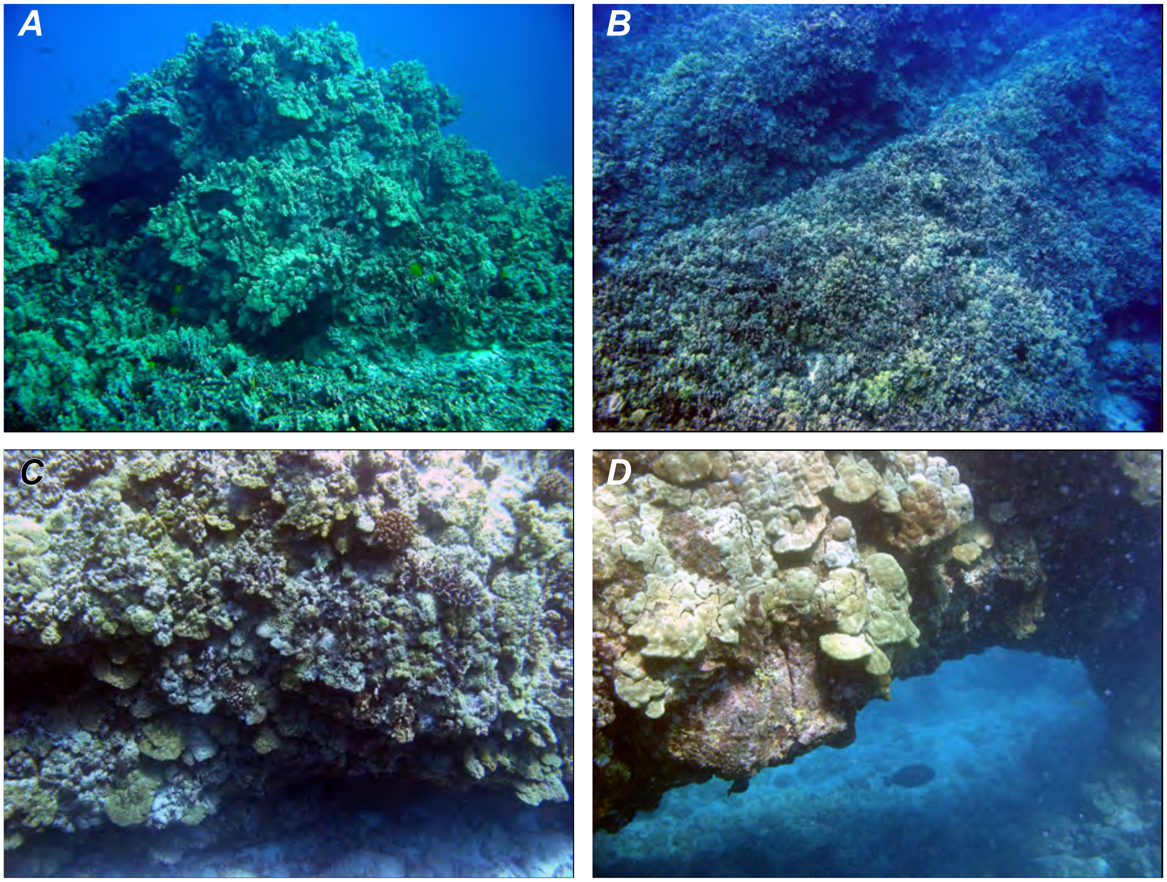


Figure 28. Representative photos of the pinnacles/ridges habitat zone. *A*, Pinnacle off Kaloko Point. *B*, Moderately high coral cover on shore-normal ridges. *C*, Moderately high coral cover and platey corals on vertical edge of a ridge. *D*, One of the numerous arches/bridges near Kaloko Fishpond.

Deep Slope

The deep slope habitat zone is the largest habitat zone mapped within the study area. The deep slope fronts the entire study area and is predominantly a gently sloping, uncolonized sand sheet. In places, coral rubble, scattered rocks, and large angular and rounded boulders are present. The habitat begins at the base of the shelf escarpment, deep cliff, and the pinnacles/ridges habitats, where there is a distinct transition from rubble and rock-covered or exposed volcanic pavement to predominantly sand. Where fronting the shelf escarpment habitat, the transition to sand is clearly imaged in the video but is beyond the limit of the lidar bathymetry; thus, the absolute depth of the transition is poorly known. Limited fathometer data indicates that the base of the shelf escarpment is between about 60 and 80 m of water. It is at this change in slope to a mostly low-lying or gently sloping surface where we interpret the start of the deep slope habitat zone (fig. 26). This habitat is mostly uncolonized; however, small colonies of lobate *P. lobata* were observed in small percentages on some of the boulders (fig. 29). Sea cucumbers and garden eels were also observed to inhabit this habitat zone.

Regional Patterns of Coral Cover

The habitat zones discussed above describe the structure of the volcanic flows that form the substrate of the park, the nature of that substrate, and the benthic habitats typically found there. It is the combination of the geological complexity of this substrate, including variations in shelf width, orientation, bathymetry, and corresponding exposure to incident wave energy, that results in regional patterns of coral cover within the park. These patterns are described in detail for six regions that are unique in their morphology and physiography: north bench/escarpment, pinnacles, west bench, central bench/escarpment, harbor embayment, and south bench/escarpment. Representative cross sections illustrating the differences in shelf width and sea-floor structure between regions are shown in figure 30. A detailed description of each region's geographic extent, morphology, and benthic cover follows.

North Bench/Escarpment

The north bench/escarpment region begins just north of Kaloko Fishpond and continues northwest along the coast to

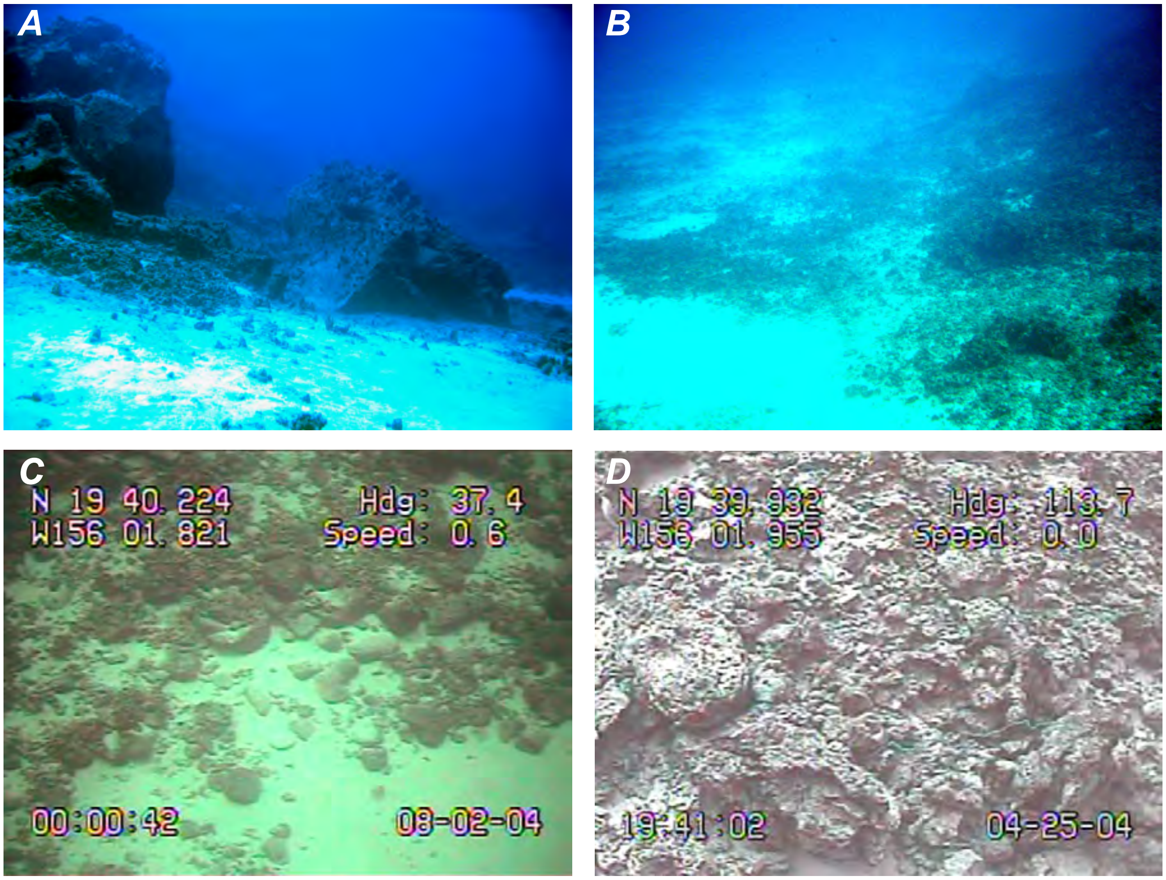


Figure 29. Representative photos of the deep slope habitat zone. *A*, Angular boulders at base of shelf escarpment. *B*, Uncolonized rubble and sand at base of shelf escarpment. *C*, Rocks and sand at base of shelf escarpment. *D*, Rubble and possibly accreted carbonate reef.

Wawahiwa`a Point and the north boundary of the study area. South of Wawahiwa`a Point, the coast is a low-lying volcanic platform formed by the 5-3 ka volcanic flow from Hualalai Volcano as mapped by Wolfe and Morris (1996). The shore platform slopes gently seaward and is, in places, covered with small (<0.5 m diameter) rocks. A narrow intertidal zone occupies much of the shore platform along this stretch and is continuous with the subtidal shallow bench below. No shoreline cliff is present. The shallow bench is narrow (<150 m; ~50 m avg) and typically wave washed. North of Wawahiwa`a Point, the shoreline/intertidal zone is sandy and the shallow bench broadens to nearly 300 m. The entire reach is fronted by the submerged shallow cliff, ~1 to 5 m high. The face of this cliff is riddled with caves, arches, and other volcanic features that attract many scuba divers to the area, as indicated by the numerous mooring buoys located nearby (fig. 26). Below this cliff, the intermediate bench is relatively narrow (<100 m) and slopes gently (<12°) seaward to the shelf break in water depths between about 12 and 18 m. Sea-floor slope increases dramatically beyond the break on the steep shelf escarpment, where slopes reach 45° and water depths exceed the limit of the lidar data (~ 40 m) (fig. 31).

Benthic habitats in this area are largely controlled by sea-floor slope and exposure to wave energy. On the shallow, flat, wave-washed bench, coral cover is typically low (10 to <50 percent) and almost entirely limited to isolated heads of *P. meandrina* on volcanic pavement. Between the base of the cliff and shelf break, the sea floor is mostly covered with large volcanic boulders (1-2 m in diameter) or scattered rocks on volcanic pavement. Coral colonization is predominantly low (10 to <50 percent), except around Wawahiwa`a Point, where moderate (50 to <90 percent) coverages were observed. The coral community is almost entirely composed of *P. meandrina*, a species that is well suited for shallow, high wave energy environments. Secondary amounts of encrusting and small colonies of *P. lobata* also inhabit this zone. Larger heads of *P. lobata* were infrequently observed between and in the lee of large boulders (figs. 32-34).

The shelf break habitat in this region is typically colonized volcanic pavement with low to moderately high percentages of coral. North of Wawahiwa`a Point, coral cover is typically low (10 to <50 percent) and a combination of both *P. meandrina* and *P. lobata*. Areas of locally higher percentages of coral (50 to <90 percent) associated with scattered boulders and rocks are found off Wawahiwa`a Point. South of the Point,

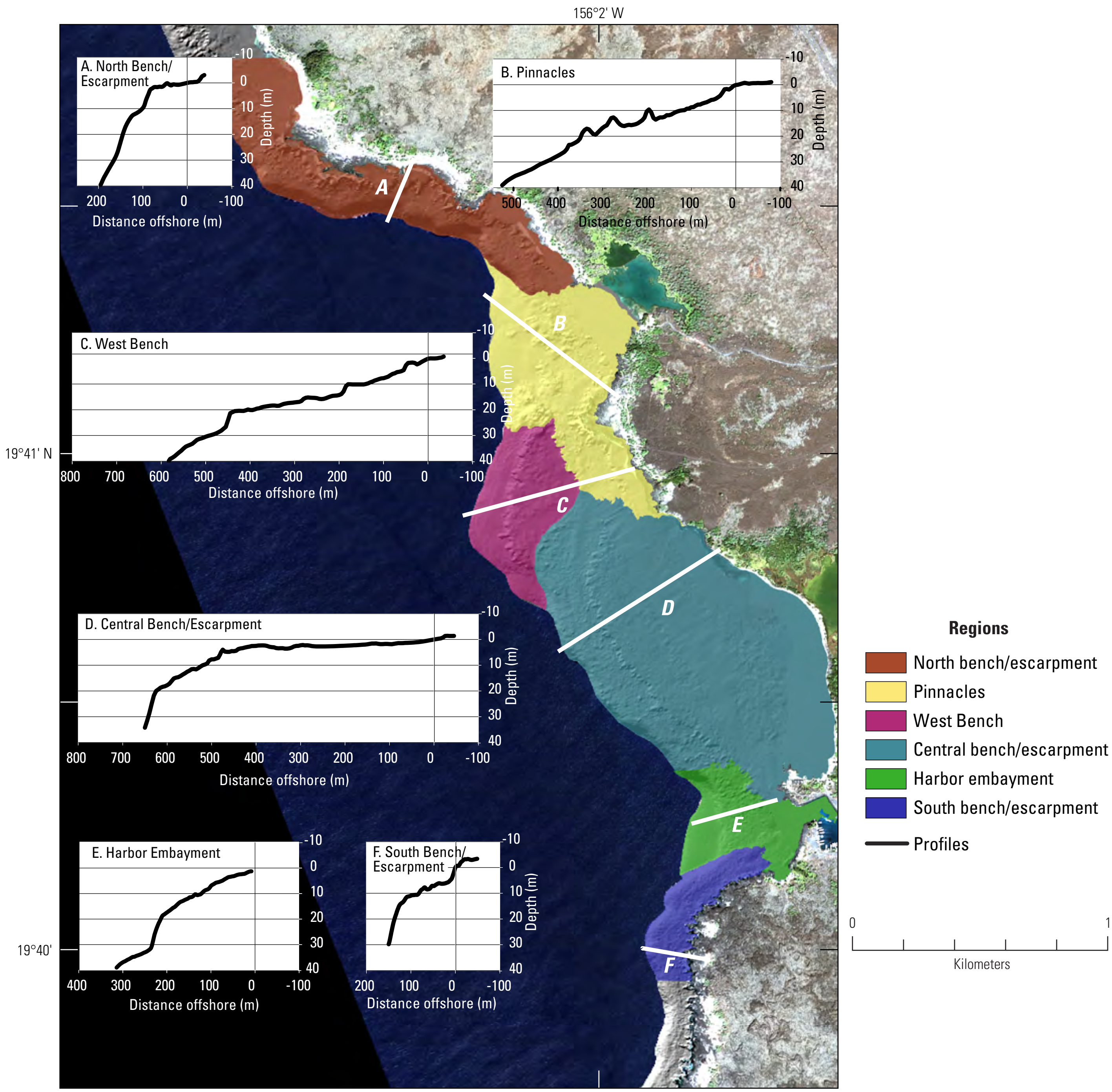


Figure 30. Cross-shelf profiles of the six regions described in the report, illustrating how the shelf width, offshore slope, and sea-floor character vary within the KAHO park area. The vertical and horizontal scales are the same for each section, and the maximum depth is limited by lidar penetration. Vertical exaggeration for all profiles is x6.

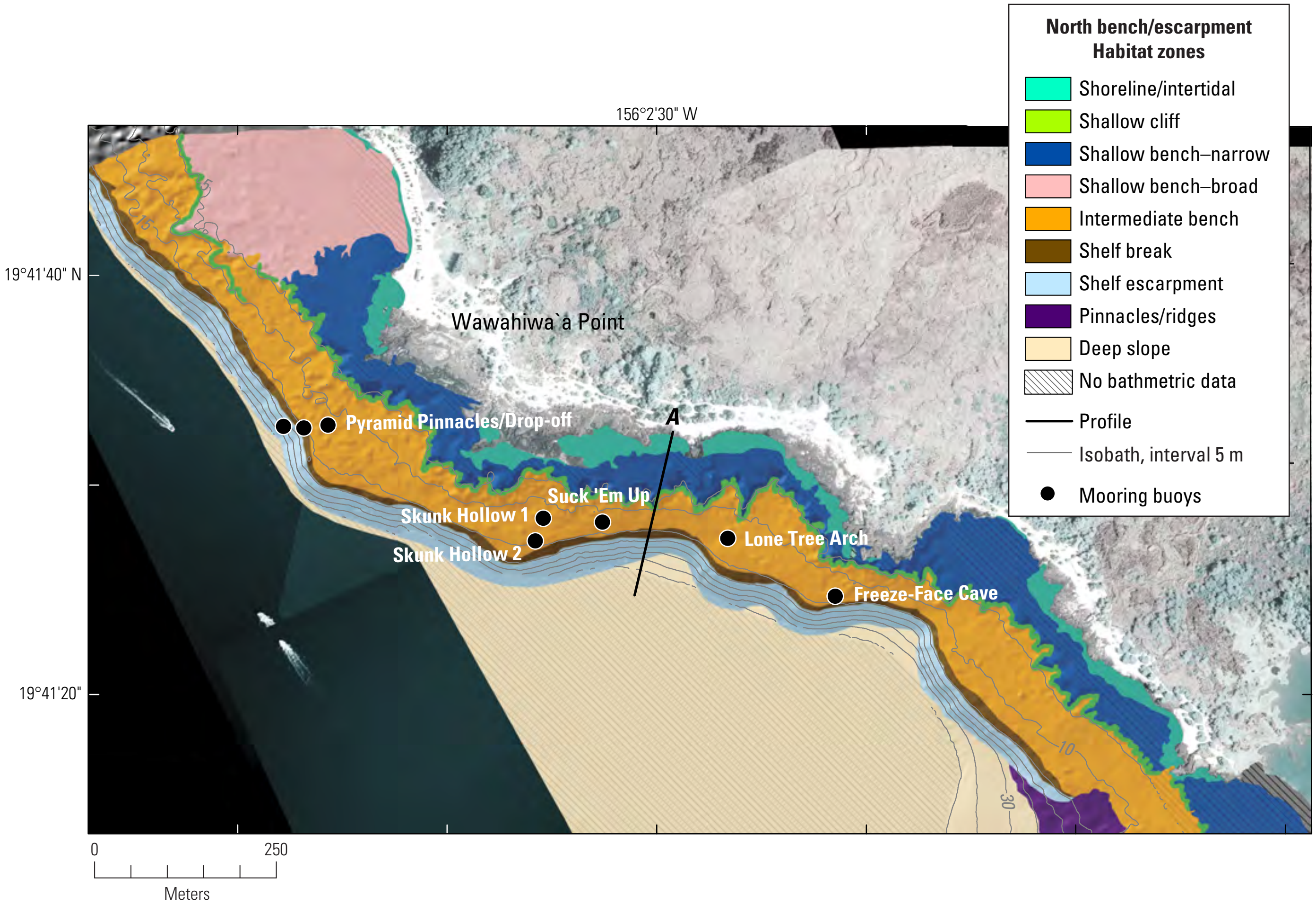


Figure 31. Habitat zones of the north bench/escarpment region of KAHO overlaid on shaded relief bathymetry. Hatched lines indicate areas lacking bathymetric data. Line A shows the location of the cross-shelf profile shown in figure 33.

coral cover and the relative percentage of *P. lobata* generally increase. An east-west-trending band of moderately high coral cover (50 to <90 percent) found off the relatively protected south-facing shoreline in this region contains the highest percentage and diversity of coral, dominated by *P. lobata* with lesser amounts of *P. meandrina* and *P. compressa* on volcanic pavement.

The shelf escarpment in this region is characterized by thin, patchy assemblages of primarily *P. compressa* (10 to <50 percent). Along nearly this entire stretch, the coral habitat is characterized by thin, rubbly *P. compressa* framework. The relatively high concentrations of *P. compressa* framework suggest that the reef may have thrived in the past, but at present is mostly dead and shows sign of stress and wave damage. Thicker accumulations with higher percentages of live coral are found on relatively less steep portions of the escarpment and where the habitat is more protected from incident wave energy, such as within the embayment off Lone Tree Arch mooring buoy. Overall, live coral cover decreases with increasing water depth, with mostly <10 percent live coral cover on rubble and volcanic pavement in water deeper than about 30 m. Uncolonized rubble, scattered rocks, and boulders mark the transition to an uncolonized sand sheet at the (inferred) base of the escarpment. The actual depth and reason for this transition to sand are unknown, as it is beyond the depth limit of the lidar data.

In general, the relative percentage of *P. meandrina* decreases seaward and the relative percentages of both *P. lobata* and *P. compressa* increases seaward in the north bench/escarpment region. The highest overall coral cover is found in the intermediate bench and shelf break habitat zones, between Wawahiwa`a Point and the Lone Tree Arch mooring buoy, where the shelf break is relatively wider and semiprotected from the incident north Pacific swell.

Pinnacles

The pinnacles region abuts the north bench/escarpment region in the north and both the west bench and central bench/

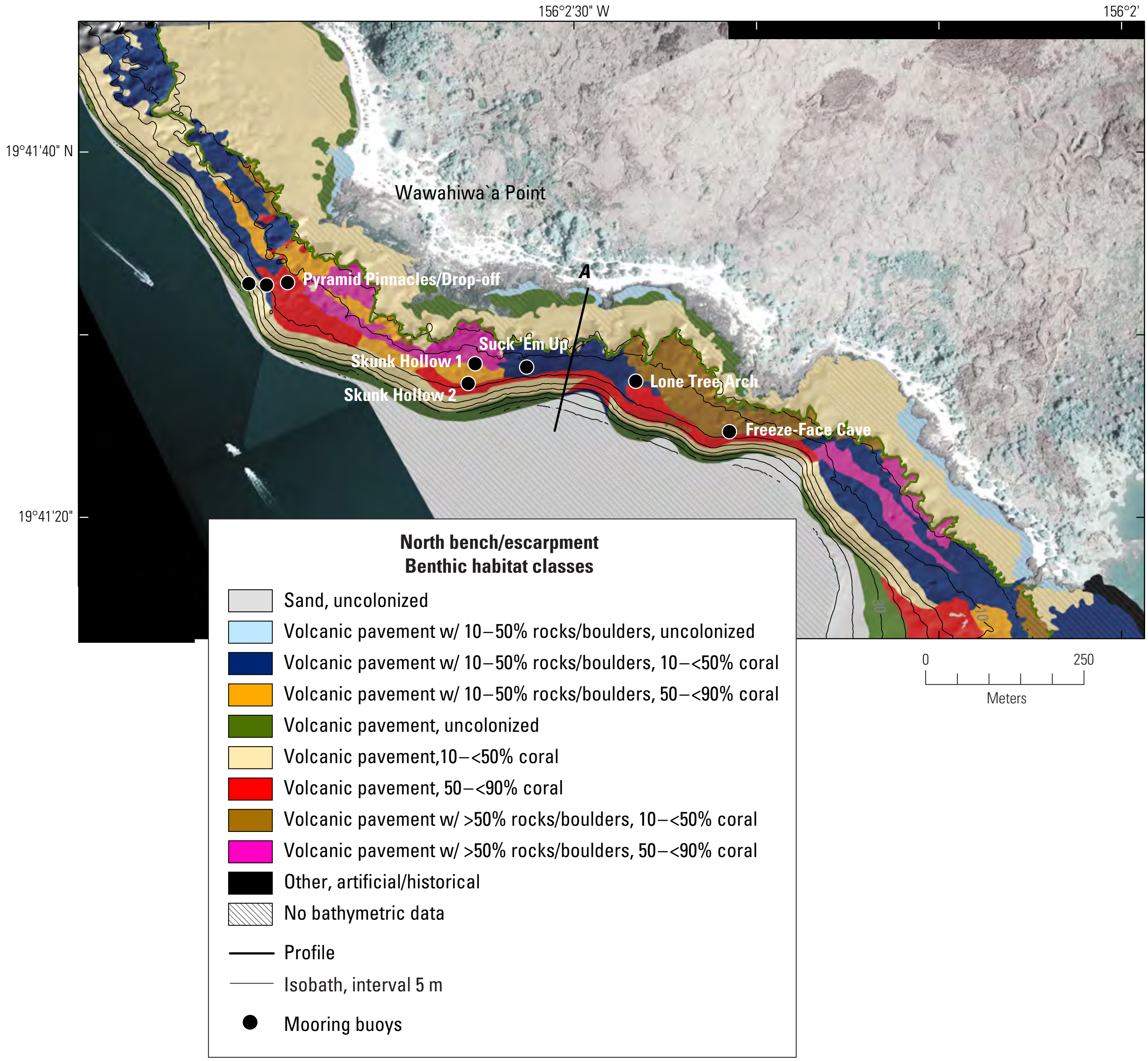


Figure 32. Benthic habitat classifications of the north bench/escarpment region of KAHO overlaid on shaded relief bathymetry. Hatched lines indicate areas lacking bathymetric data. Line A shows the location of the cross-shelf profile shown in figure 33.

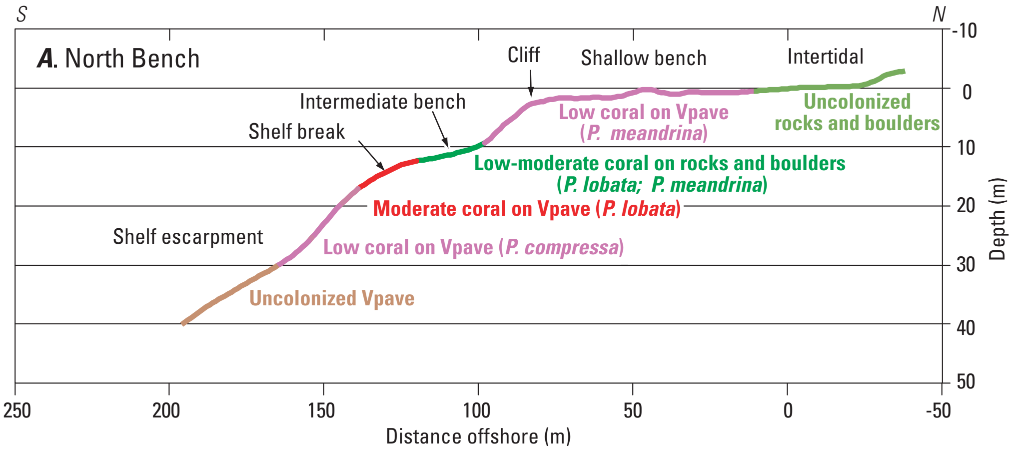


Figure 33. Cross-shelf profile (A) and typical benthic habitat transitions of the north bench/escarpment region of KAHO. Vpave = volcanic pavement. Vertical exaggeration is x2.

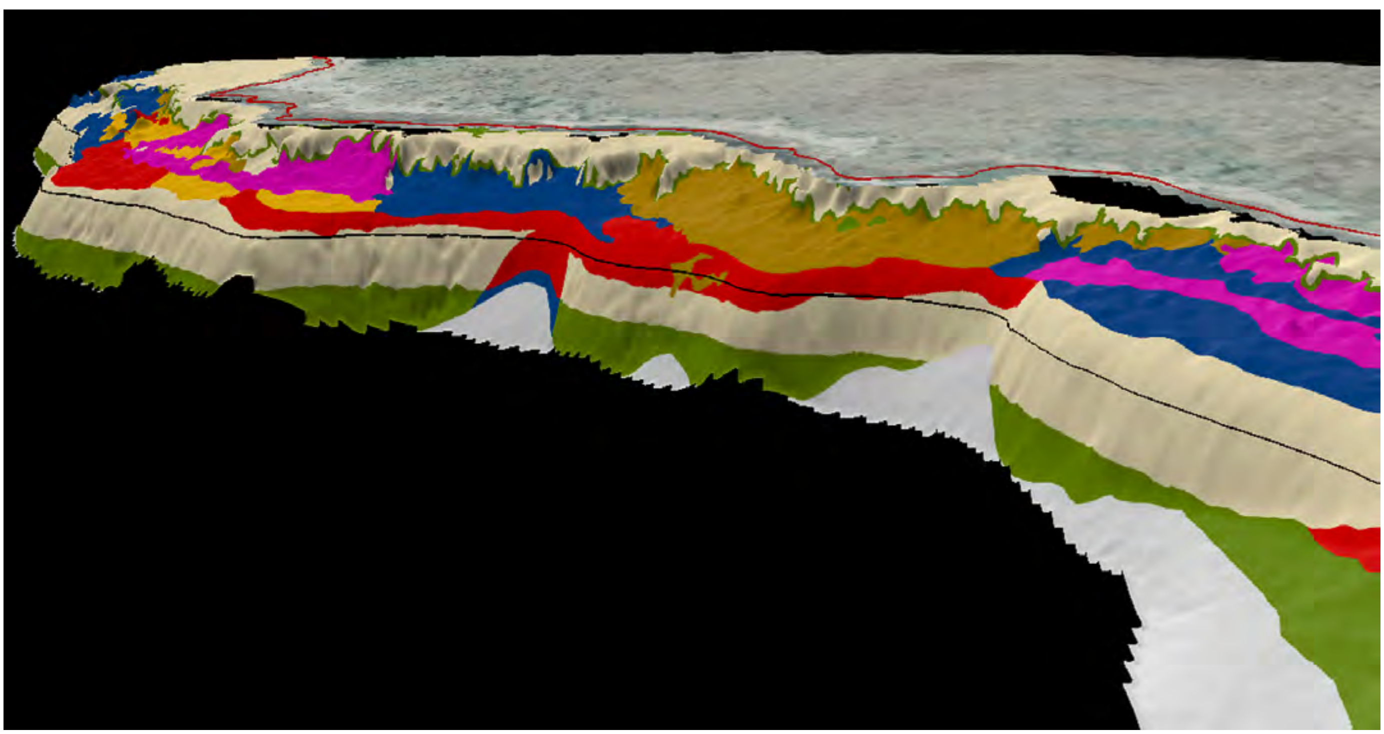


Figure 34. Three-dimensional perspective view of the north bench/escarpment region of KAHO, showing benthic habitat classifications draped on lidar bathymetry. The colors are the same as in figure 32. The red line is the shoreline, and the black line is the 20-m isobath. Habitat classifications are displayed only where lidar data exist. Vertical exaggeration is x3. View is toward the northeast. Approximate distance along the bottom of the figure is 1 km.

escarpment regions in the south (fig. 35). The shoreward boundary of this region is marked by the wall fronting Kaloko Fishpond and the generally low-lying volcanic platform of the 5-3 ka volcanic flow as mapped by Wolfe and Morris (1996). As with the north bench/escarpment, a narrow intertidal zone fronts the shoreline south of the fishpond and is continuous with the shallow bench habitat. The shallow bench fronts the entire shoreline in this region. Directly west of Kaloko Fishpond it is broader (as much as ~150 m) and shallower (< ~3 m) than to the north and south (where it is < 5 m deep and ~50 m wide). In all areas it is a flat, pahoehoe-type volcanic pavement, with scattered rocks and boulders only off Kaloko Fishpond and along the shoreline and intertidal reaches.

Low amounts of coral (10 to <50 percent), primarily isolated heads of *P. meandrina* with lesser amounts of small lobate and encrusting colonies of *P. lobata*, colonize the subtidal portions of the shallow bench north of Kaloko Point (figs. 36-38). To the south, higher incident wave energy focusing around the Point causes the bench to be wave washed. Because of this, we classify the shallow bench in this area as uncolonized (< 10 percent) volcanic pavement. A low cliff (~1-2 m high) separates the shallow bench from the deeper intermediate bench below. The cliff is mostly continuous throughout this area, except for a ~45-m stretch off the central part of Kaloko Fishpond.

The intermediate bench habitat extends from the base of the cliff across the shelf to about 10-m depth, a distance of between about 30 and 120 m (~80 m avg). North of Kaloko Point, the surface slopes gently seaward and consists of smooth pahoehoe-type volcanic pavement covered with boulders and scattered rocks. Larger and more densely packed boulders exist closer to shore. Coral cover and diversity in this habitat increases from low (10 to <50 percent) near the base of the cliff to moderately high (50 to <90 percent) as water depth and distance from the cliff increase. Some boulders are nearly entirely obscured by coral growth, and large mushroom-shaped colonies of *Porites evermanni* are characteristic of this area of the park. West and south of Kaloko Point, the character of the volcanic pavement on the bench becomes undulating and irregular, the bench is covered with boulders and rocks in places, and coral cover is typically low (10 to <50 percent).

Beginning at a depth of about 10 m of water and continuing across the shelf into 18 to 25 m of water, the pinnacles/ridges habitat dominates the sea floor between Kaloko Fishpond and Kaloko Point. Small pinnacle areas associated

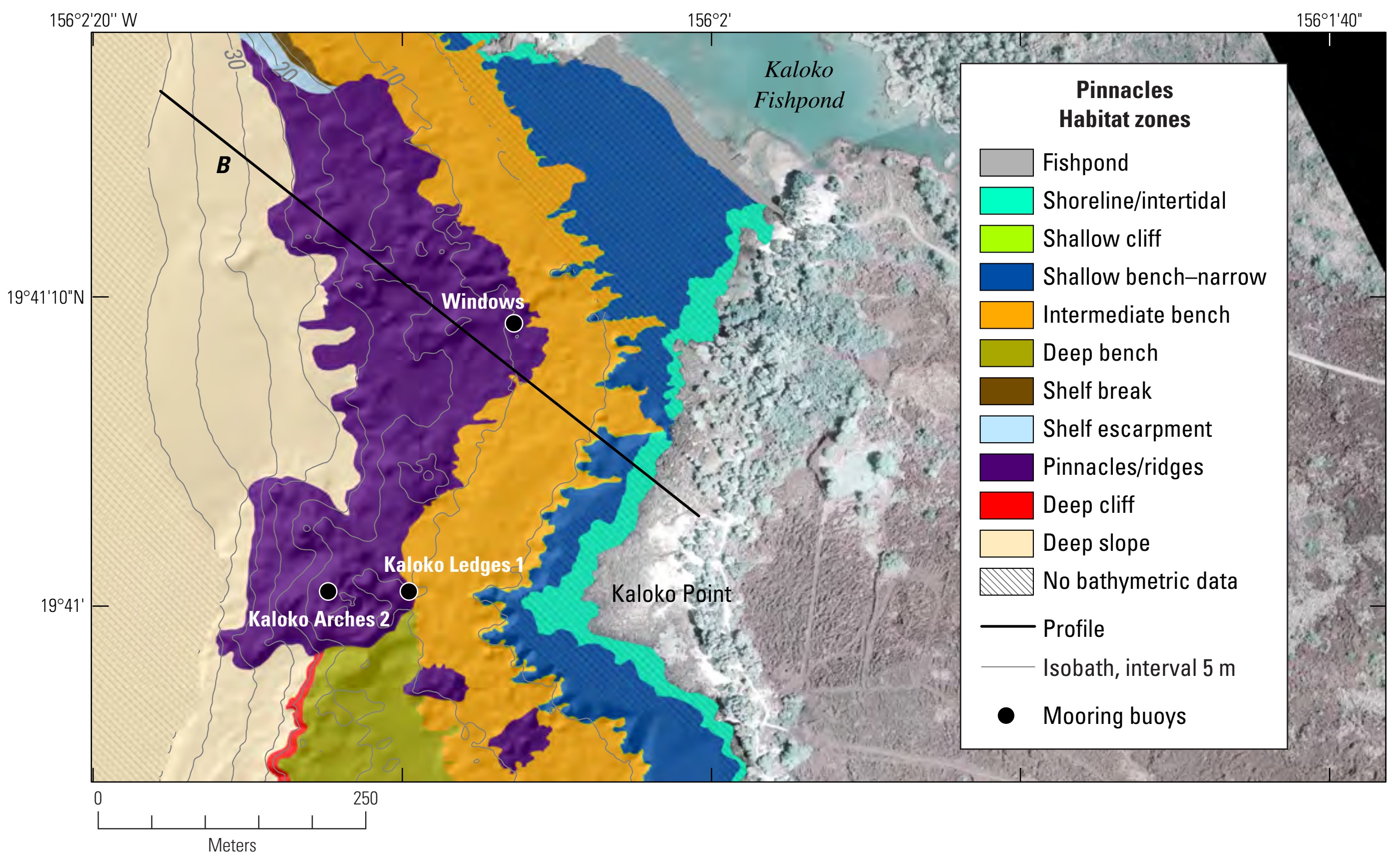


Figure 35. Habitat zones of the pinnacles region of KAHO overlaid on shaded relief bathymetry. Hatched lines indicate areas lacking bathymetric data. Line B shows the location of the cross-shelf profile shown in figure 37.

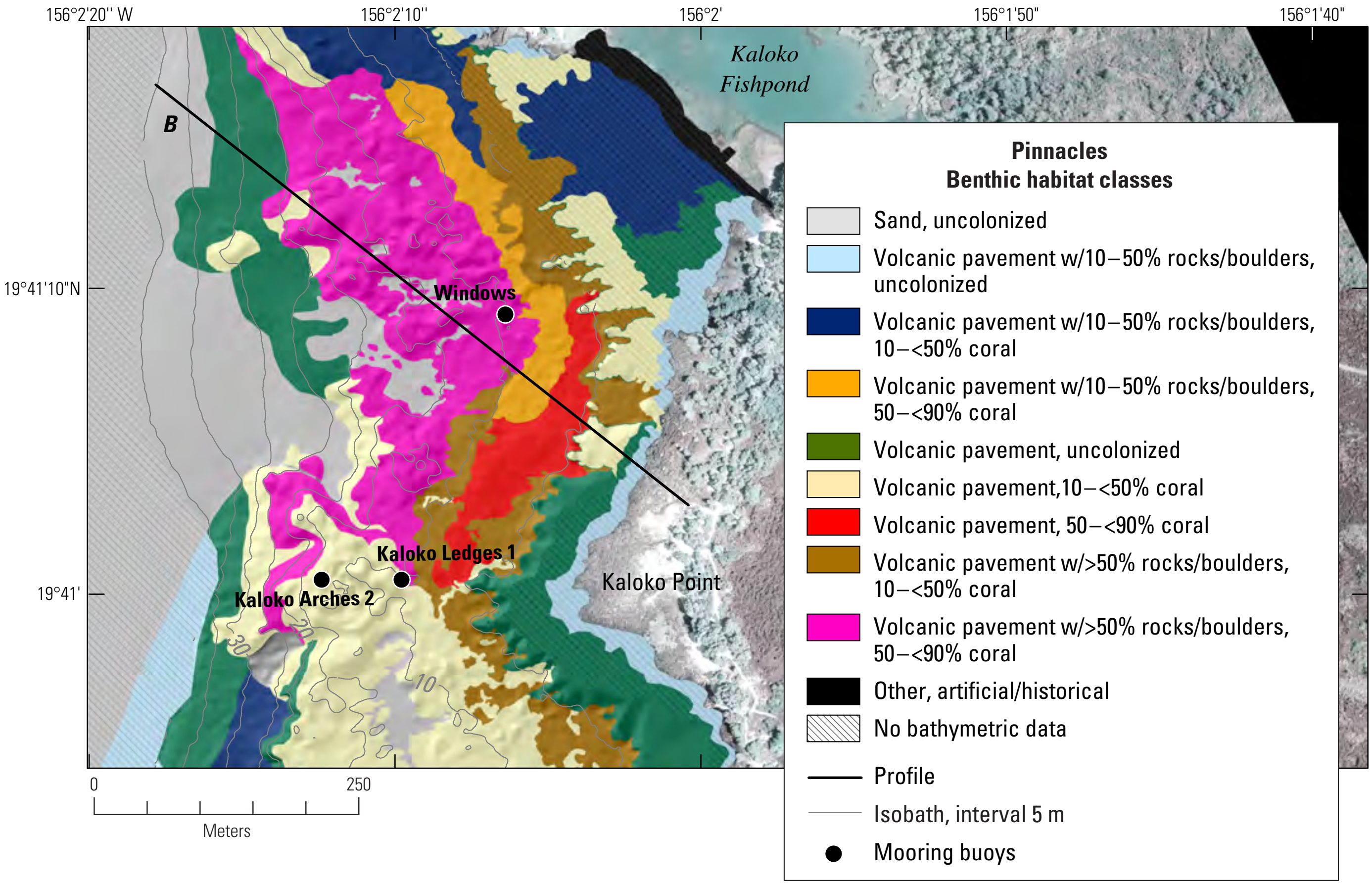


Figure 36. Benthic habitat classifications of the pinnacles region of KAHO overlaid on shaded relief bathymetry. Hatched lines indicate areas lacking bathymetric data. Line B shows the location of the cross-shelf profile shown in figure 37.

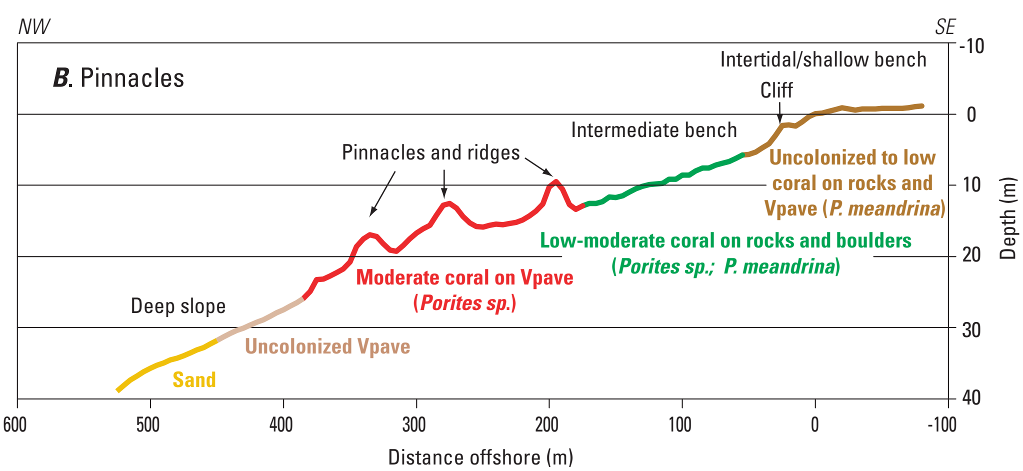


Figure 37. Cross-shelf profile (B) and typical benthic habitat transitions of the pinnacles region of KAHO. Vpave = Volcanic Pavement. Vertical exaggeration is x4.

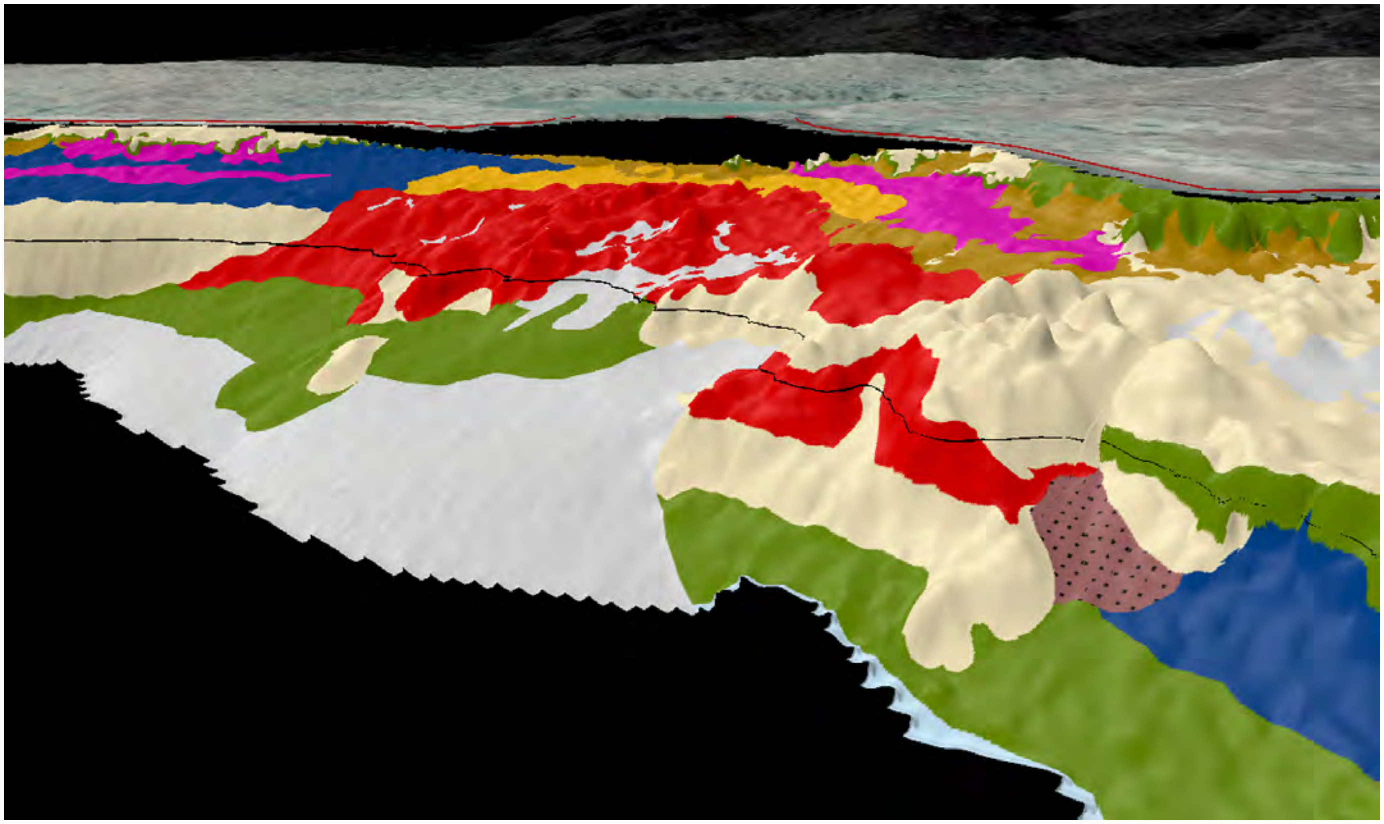


Figure 38. Three-dimensional perspective view of the pinnacles region of KAHO, showing benthic habitat classifications draped on lidar bathymetry. The colors are the same as in figure 36. The red line is the shoreline, and the black line is the 20-m isobath. Habitat classifications are displayed only where lidar data exist. Vertical exaggeration is x3. View is toward the east. Approximate distance along the bottom of the figure is 0.7 km.

with the irregular surface of the intermediate bench are present just south of Kaloko Point. West of Kaloko Fishpond, the pinnacles are colonized with a typically thin but moderately high (50 to <90 percent) cover of coral, with relatively high community diversity. The intervening bathymetric lows between the pinnacles are typically uncolonized volcanic pavement with some coral rubble and sand. A large sand sheet separates two areas of pinnacles off the southern end of Kaloko Fishpond. Shore-normal ridges in the northern part of the embayment support relatively higher percentages of coral (approaching 90 to 100 percent) and locally have vertically accreted carbonate reef. In places, the benthic habitat in this region is similar to and difficult to distinguish from the volcanic pavement with sand channels observed in the southern part of Honokōhau Bay.

West and south of the headland at Kaloko Point, the coral cover on the pinnacles and ridges drops to 10 to <50 percent in water depths less than about 16 m. On the escarpment fronting the pinnacles, in water depths between about 16 and 25 m, coral cover is moderately high (50 to <90 percent) and consists primarily of *P. compressa* and *P. lobata*. Locally, coral cover approaches 90 to 100 percent with possible aggregate reef accretion.

The pinnacles region ends along a well-defined edge in water depths of around 20 to 25 m, where the sea-floor structure transitions to a relatively smooth and moderately sloping, deep-water shelf. The deep shelf comprises a poorly colonized volcanic pavement and uncolonized sand with rubble and angular boulders. A few small colonies of lobate *P. lobata* were observed on the pavement and boulders in this environment.

The great bathymetric relief, relatively high and diverse coral cover, and interesting structural features in this area provide rich habitat for fish and make it an attractive area for recreational diving and snorkeling activities. Culturally, this area was heavily used by native Hawaiians (Greene, 1993; Hoover and Gold, 2005), and the pinnacles likely provided high-quality fishing opportunities. It is possible that submerged archeological sites and/or artifacts associated with these offshore fishing grounds may be found in the area.

West Bench

The west bench region is bounded by the pinnacles region to the north and central bench/escarpment region to the south and comprises the deep bench, deep cliff, and deep slope habitats (fig. 39). The west bench is slightly (1–3 m) but distinctly lower than the adjacent regions, and the landward extent is defined by a low cliff or step that marks the transition. Relative to other areas in the park, the benthic habitat in west bench region is the most poorly colonized and least diverse of all the regions. The bench is generally flat to gently rolling pahoehoe with mostly low coral cover of primarily small lobate *P. lobata* and *P. meandrina* and patches of uncolonized pavement, sand, and rubble. Locally there are areas of higher coral cover with larger heads of lobate *P. lobata*. A relatively large sand sheet abuts the intermediate bench of the central bench/escarpment region (figs. 40-42).

The deep cliff fronts and defines the west bench habitat. Below this cliff the sea floor is a sloping shelf covered with scattered rocks, large boulders, and rubble on a veneer of sand on volcanic pavement. Isolated colonies of small *P. lobata* colonize the boulders to a depth of about 33 m. A sharp and distinct contact between this rocky, rubbly pavement and uncolonized sand was observed in the video, although the absolute position and depth of this transition are unknown as it is beyond the limit of the lidar data. Fathometer data show that the sloping shelf continues to about 45-m water depth where at least one other cliff and bench are encountered before the base of the slope is reached and the shelf flattens, in about 70-m water depth. The base of this slope is likely the boundary of the uncolonized sand field (fig. 26).

Central Bench/Escarpment

The central bench/escarpment is the largest region within the study area. It extends about 1,300 m alongshore, from about 300 m south of Kaloko Point to Honokōhau Harbor, and from the shoreline to nearly 1 km offshore. It is dominated by the broad shallow bench habitat zone, but also includes the intertidal, intermediate bench, shelf break, shelf escarpment, and deep slope habitat zones (fig. 43).

The shoreline backing the majority of the central bench/escarpment is the 10-5 ka volcanic flow, except for a ~170-m stretch in the northern part of the region where the 5-3 ka flow

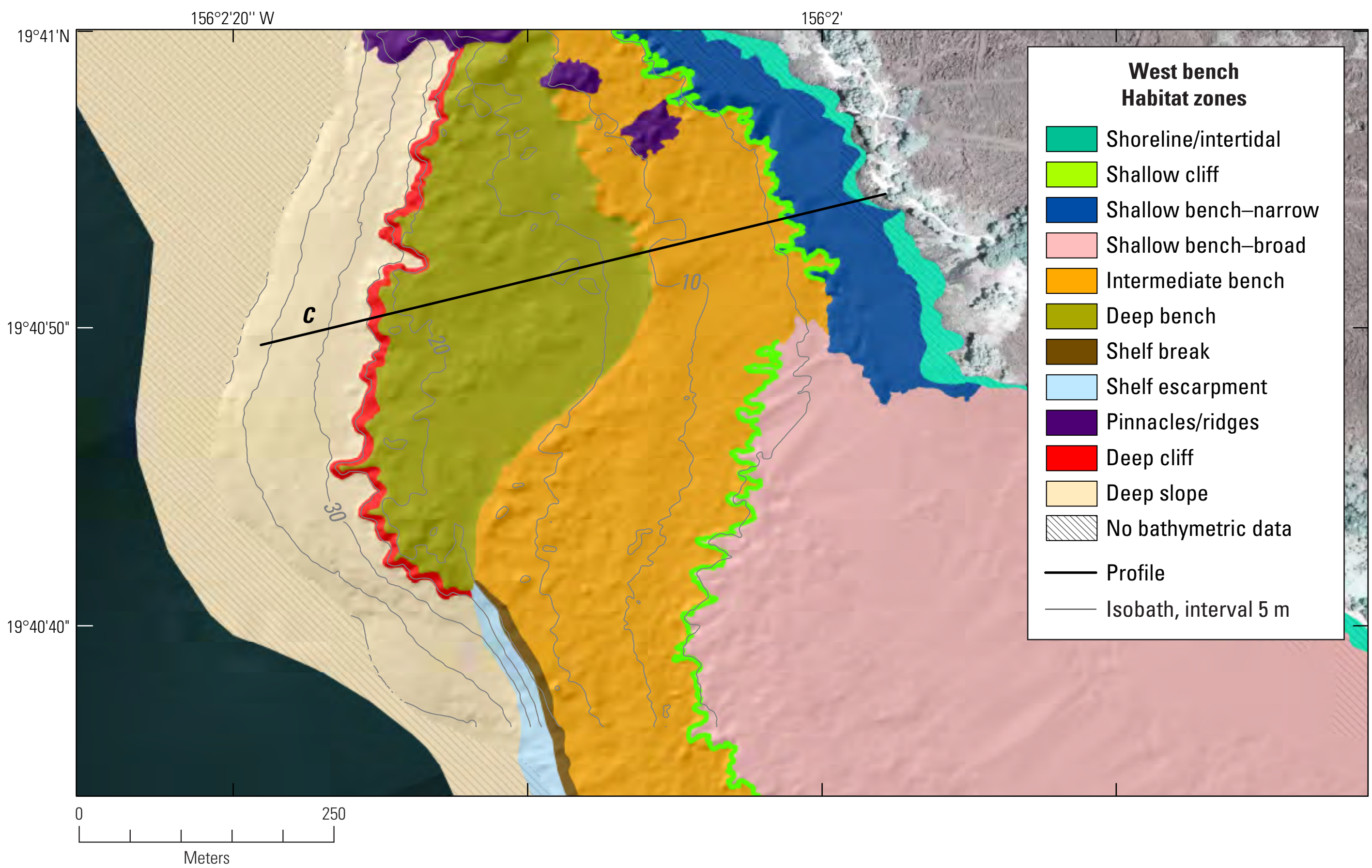


Figure 39. Habitat zones of the west bench region of KAHO overlaid on shaded relief bathymetry. Hatched lines indicate areas lacking bathymetric data. Line C shows the location of the cross-shelf profile shown in figure 41.

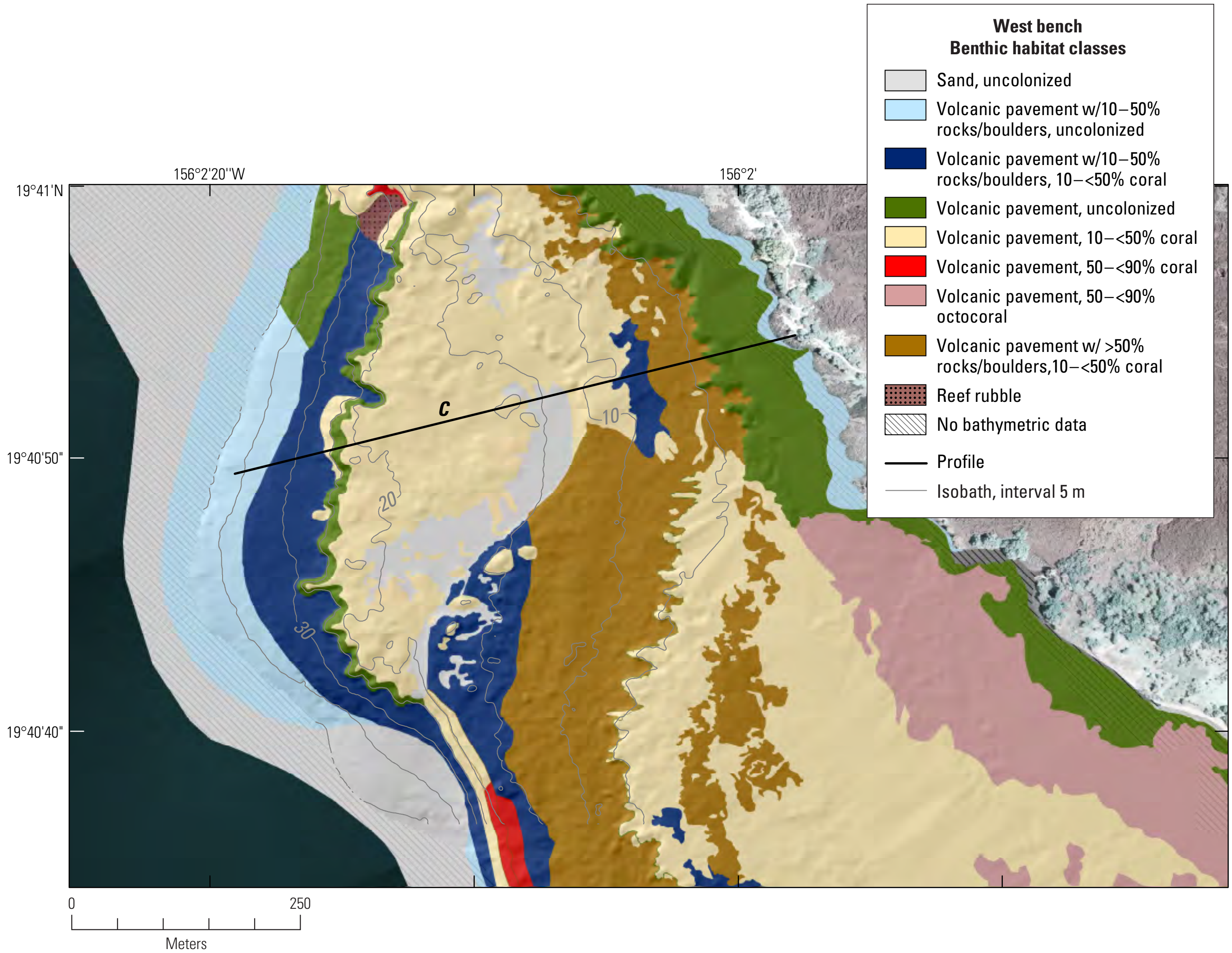


Figure 40. Benthic habitat classifications of the west bench region of KAHO overlaid on shaded relief bathymetry. Hatched lines indicate areas lacking bathymetric data. Line C shows the location of the cross-shelf profile shown in figure 41.

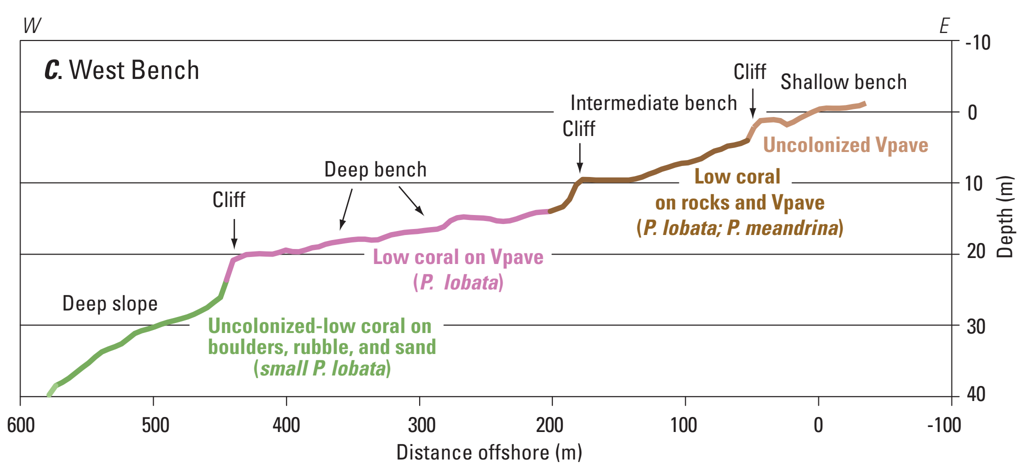


Figure 41. Cross-shelf profile (C) and typical benthic habitat transitions of the west bench region of KAHO. Vpave = Volcanic Pavement. Vertical exaggeration is x4.

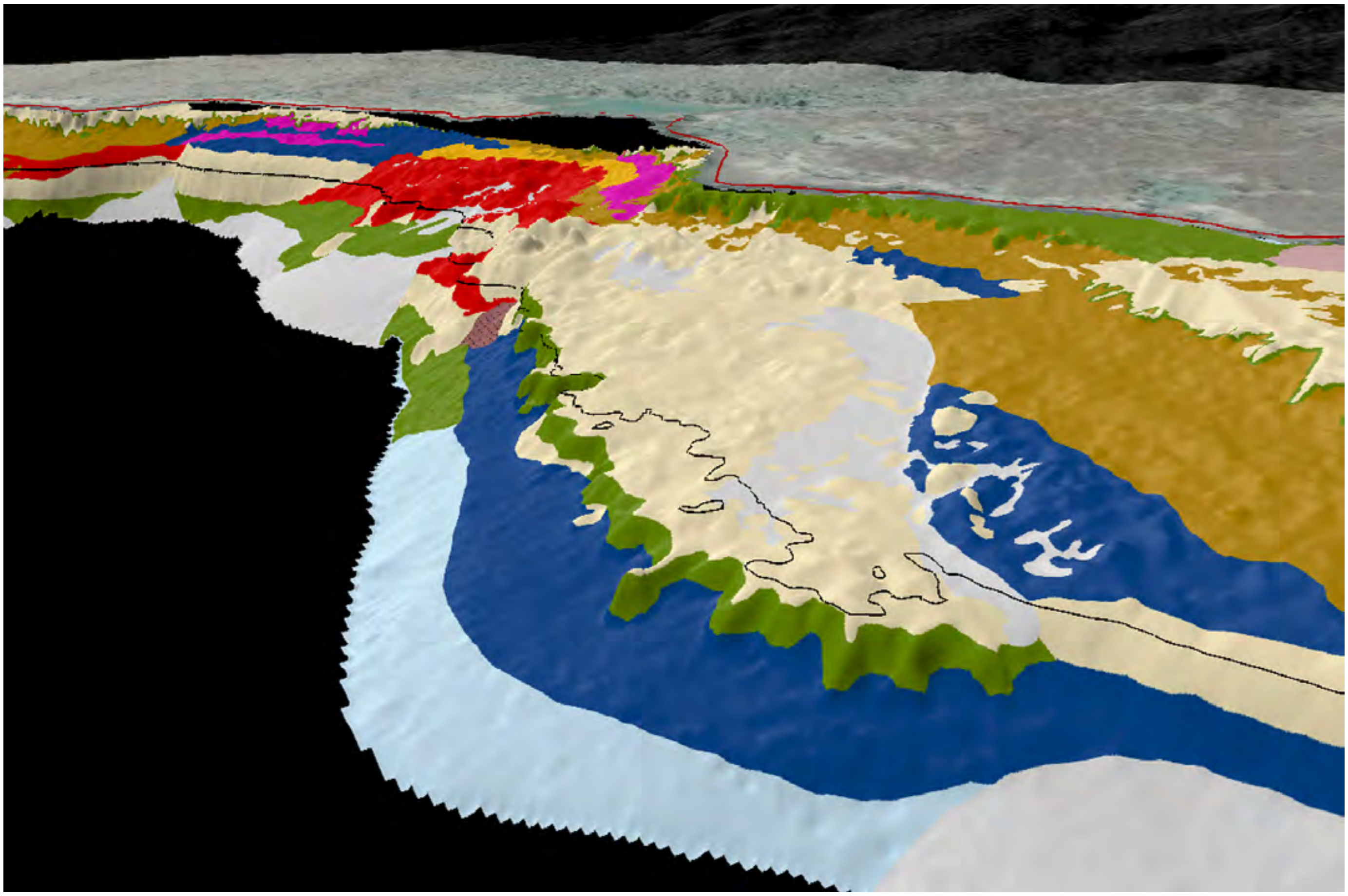


Figure 42. Three-dimensional perspective view of the west bench region of KAHO, showing benthic habitat classifications draped on lidar bathymetry. The colors are the same as in figure 40. The red line is the shoreline, and the black line is the 20-m isobath. Habitat classifications are only displayed where lidar data exist. Vertical exaggeration is x3. View is toward the northeast. Approximate distance along the bottom of the figure is 1.5 km.

reaches the coast (Wolfe and Morris, 1996). Intertidal habitat found along the entire stretch of this region is a combination of uncolonized rocks, sand, and flat volcanic pavement covered with undifferentiated algae. No shoreline cliff is present, and the intertidal zone transitions to the shallow bench habitat as water depth exceeds about 1 m.

The benthic habitat of the shallow bench in this region is relatively homogeneous (figs. 44-46). In water depths less than about 2 m, hard corals are rare, and the octocoral *Anthelia edmonsoni* covers the volcanic pavement like a carpet. In deeper water, low percentages (10 to <50 percent) of coral colonize mostly flat volcanic pavement or scattered rocks. Coral diversity is typically low and dominated by small lobate colonies of P. lobata and P. meandrina. Coral abundance generally increases as water depth and distance offshore increase. Near the seaward edge of the shallow bench, the sea floor is more fractured and heaved, forming ledges and crevices that support slightly higher, although still <50 percent, coral cover.

Near the 5-m isobath, the shallow cliff marks the end of the shallow bench and beginning of the intermediate bench habitat. The intermediate bench extends along the entire stretch of the central bench/escarpment region. From the base of the shallow cliff to about the 11-m isobath, a nearly continuous cover of large (1-2 m), rounded boulders sits on the volcanic pavement. The boulders are typically poorly colonized (10 to <50 percent) by small colonies of *P. lobata*. Between the boulders, rubble and smaller rocks are colonized with slightly higher percentages (still <50 percent) of coral, including larger colonies of *P. lobata* as well as some *P. compressa*. There are local areas of boulder-free pavement and higher coral cover.

Near the 11-m isobath, the benthic habitat on the intermediate bench changes dramatically. South of about 19° 40’ 20” (2178000 N), shore-normal ridges of volcanic pavement separated by sand and rubble-filled channels become the dominant substrate structure. Nearly continuous, moderately high (50 to <90 percent) to high (90 to 100 percent) coral cover is distributed over the ridges. Some large boulders are also integrated with the coral growth. The coral community in this area appears to be thriving and very healthy. Diversity is relatively high, with a variety of species and forms comprising

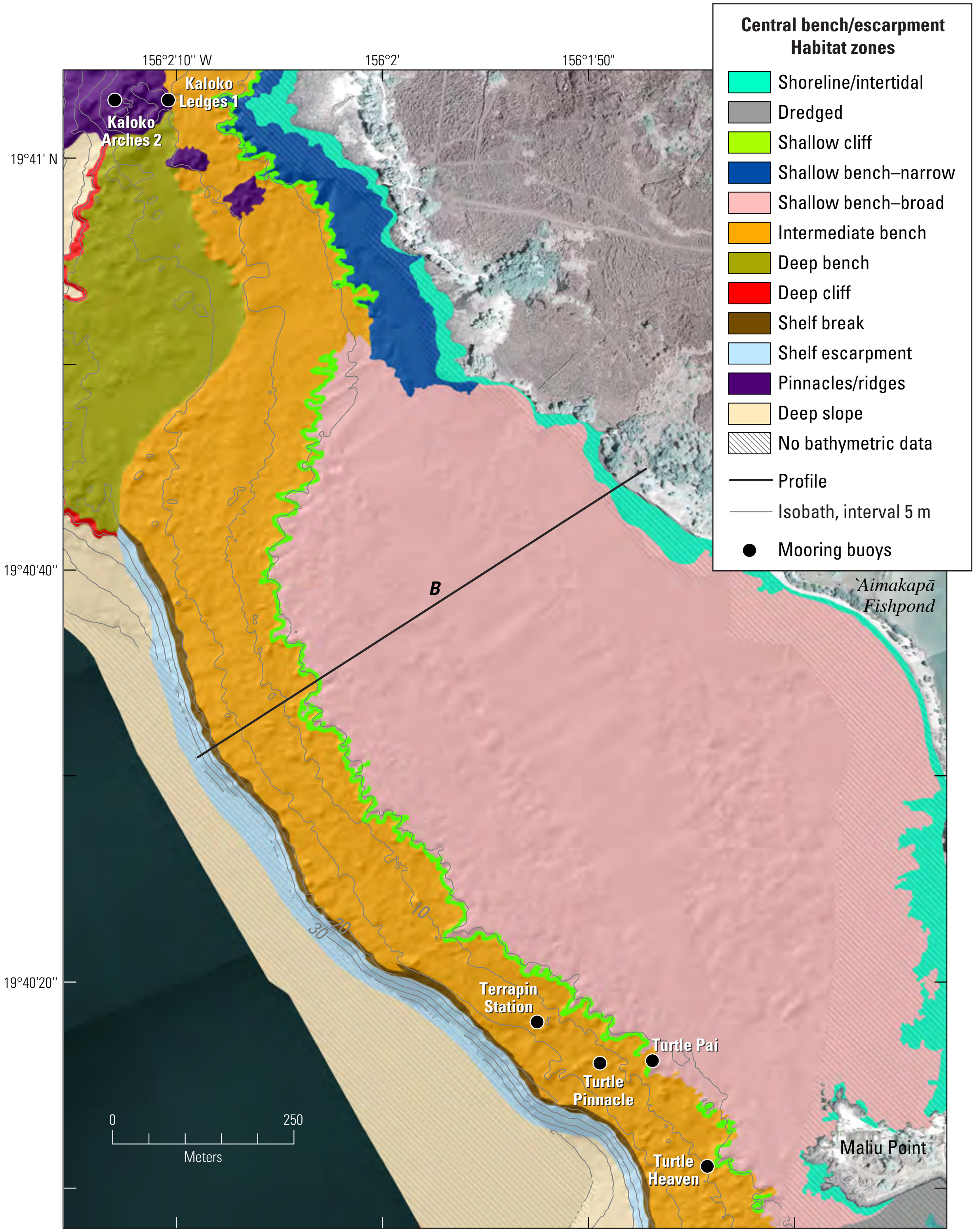


Figure 43. Habitat zones of the central bench/escarpment region of KAHO overlaid on shaded relief bathymetry. Hatched lines indicate areas lacking bathymetric data. Line D shows the location of the cross-shelf profile shown in figure 45.

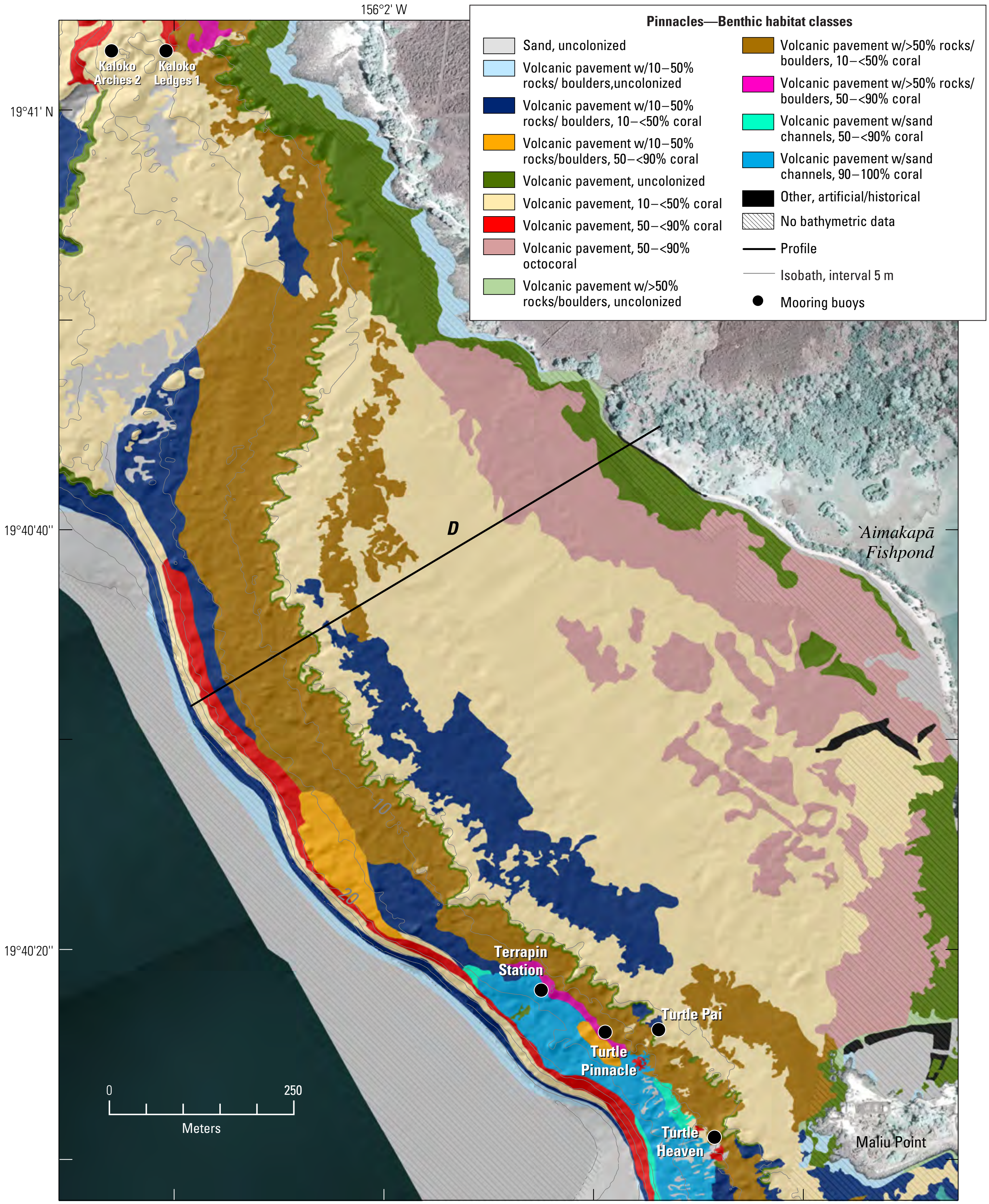


Figure 44. Benthic habitat classifications of the central bench/escarpment region of KAHO overlaid on shaded relief bathymetry. Hatched lines indicate areas lacking bathymetric data. Line D shows the location of the cross-shelf profile shown in figure 45.

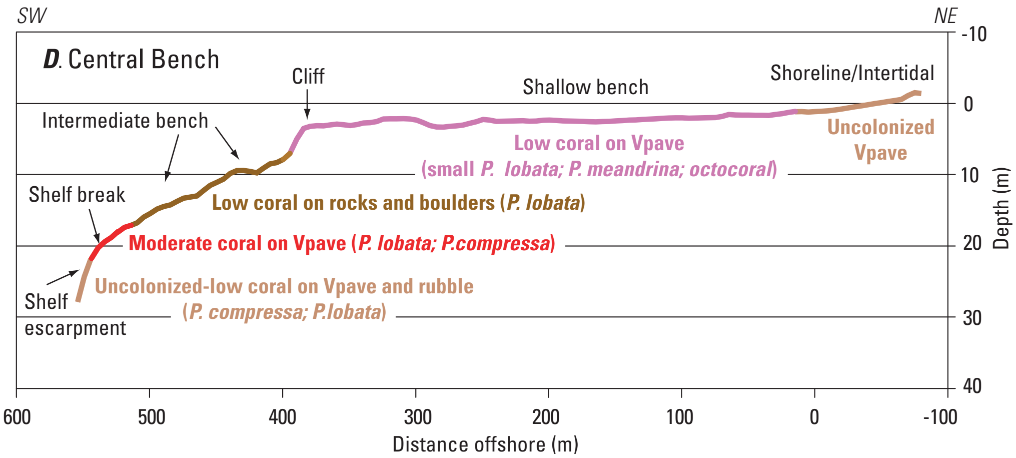


Figure 45. Cross-shelf profile (D) and typical benthic habitat transitions of the west bench region of KAHO. Vpave = Volcanic Pavement. Vertical exaggeration is x4.

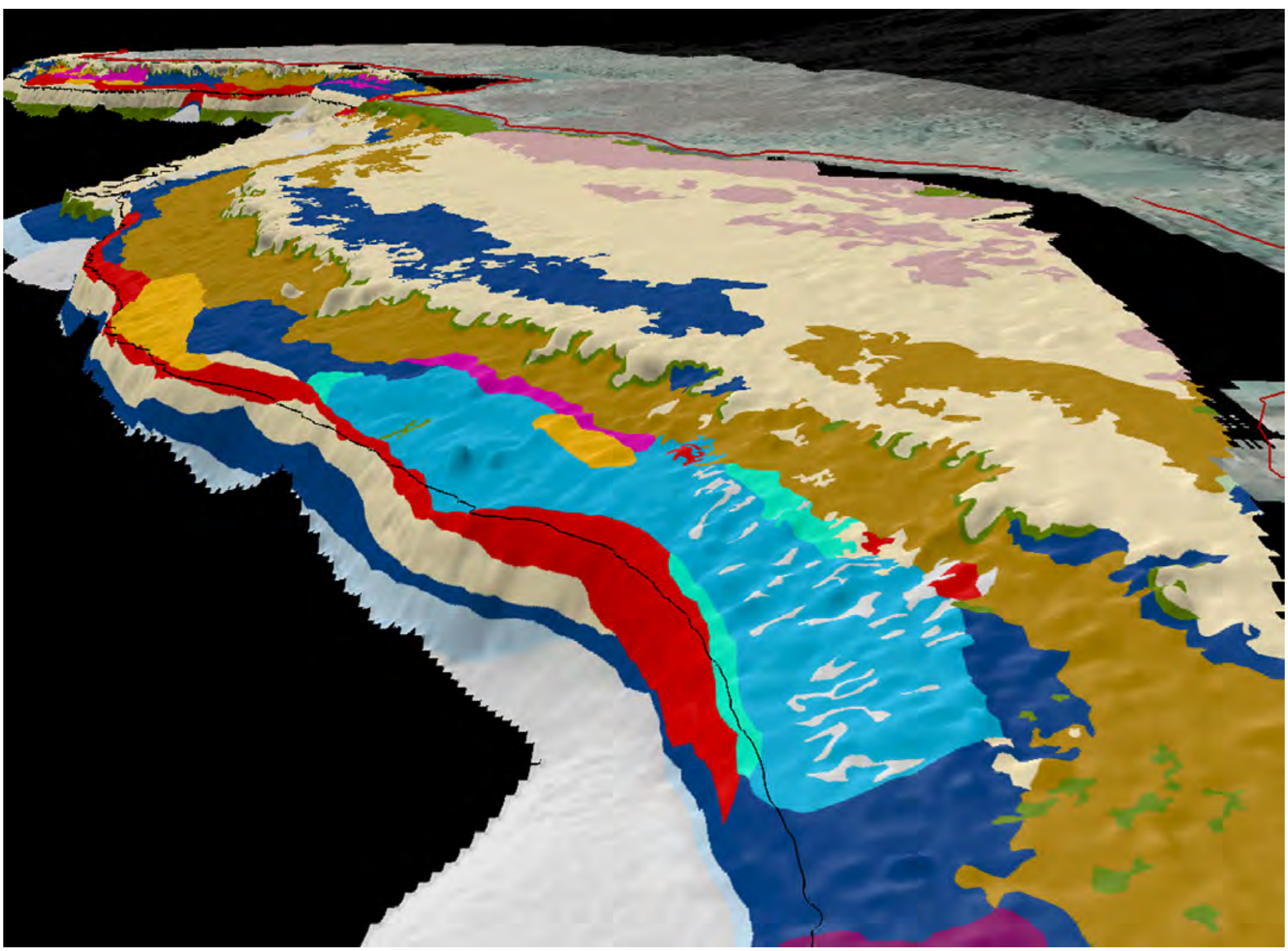


Figure 46. Three-dimensional perspective view of the central bench/escarpment region of KAHO, showing benthic habitat classifications draped on lidar bathymetry. The colors are the same as in figure 44. The red line is the shoreline, and the black line is the 20-m isobath. Habitat classifications are displayed only where lidar data exist. Vertical exaggeration is x3. View is toward the northeast. Approximate distance along the bottom of the figure is 0.5 km.

mostly *P. lobata* and *P. compressa*. In some places there may be aggregated reef or carbonate accumulation. Overall, however, the underlying volcanic pavement is still visible despite the high coral cover.

North of about 19° 40’ 20” (2178000 N), there is a relatively distinct transition from the volcanic pavement and sand channels to volcanic pavement covered with scattered rocks, boulders, and coral rubble. Coral cover is variable, with low (10 to <50 percent) to moderate (50 to <90 percent) coral cover of predominantly *P. lobata*. A band of colonized pavement on the seaward edge of the intermediate bench near the north boundary of the central region shows somewhat higher coral cover and community diversity, with moderately high (50 to <90 percent) cover of *P. lobata* and *P. compressa*. Overall, coral cover decreases toward the north and the adjoining west bench region.

The shelf break habitat fronting the central bench/escarpment region, between about 14 and 27 m water depth, is a fairly continuous stretch of volcanic pavement with moderately high (50 to <90 percent) coral cover of primarily *P. lobata* and *P. compressa*. Coral cover on the shelf break decreases to low (10 to <50 percent) percentages of mostly *P. lobata* in the northern part of the central region near the west bench region.

A well-defined shelf escarpment habitat fronts the central bench/escarpment region between the harbor embayment in the south and the deep cliff of the deep bench region in the north. The benthic habitat is characterized predominantly by thin, patchy *P. compressa*, skeletal *P. compressa* framework, and coral rubble on volcanic pavement. Where the offshore slope increases to ~>30°, little continuous *P. compressa* or framework exists and the slope is predominantly covered with scattered rocks and low amounts of live *P. compressa* and *P. lobata*. The habitat is mostly uncolonized below about 30-m depth. The mapped transitions in habitat in this region are approximate, because of the extreme offshore slope and water depth.

An uncolonized sand sheet fronts the entire stretch of the central bench/escarpment region. A sharp and distinct contact between the uncolonized rocks, rubble, and pavement of the shelf escarpment habitat and the sand was observed in video. The depth and location of this contact are poorly known. It is delineated from the few video transects that cross the transition, and the position is somewhat subjective. Limited fathometer data show a break in slope at a water depth of about 60 m, and we infer this to be the base of the shelf escarpment. If this base of the escarpment is coincident with the transition in habitats, the position is about 75 m farther offshore than delineated on our maps (fig. 26).

Overall, the central bench/escarpment region supports some of the most diverse and complex habitat observed within the park. The region includes all the habitat classes observed except aggregated reef and reef rubble. With the extensive shallow habitat, the high coral cover associated with the pavement and sand channels north of the harbor, and the easy access along much of the shoreline, the area is popular with scuba divers and snorkelers. Many fish were observed along the shallow cliff and boulder regions, as were sea turtles in the shallows.

Harbor Embayment

Some of the highest and lowest coral cover in the study area is located off the mouth of the Honokōhau Harbor. The boundary of this region is defined by the embayment fronting the harbor, and it overlaps some of the central bench/escarpment and south bench/escarpment regions (fig. 47). The orientation of the coast and sea floor changes dramatically here, from a mostly north-south orientation north of the embayment, to a northeast-southwest orientation to the south. The morphology of the sea floor is similar to elsewhere in the park, where a shallow bench drops to an intermediate bench and then over a steep escarpment to a deep slope below. Unique to this area, however, is the presence of a sand sheet at the base of the shelf escarpment, in about 25 m of water, and a dredged channel off the harbor mouth.

The 3.0 to 1.5 ka volcanic flow (Wolfe and Morris 1996), the youngest of the three present in the park, forms the coastline between Maliu Point and the south end of the study area. Between Maliu Point and Alula Bay, the coast is fairly low lying and nearly continuous with the offshore shallow bench habitat. A gap in the lidar data exists in this area, so elevation and depth information are limited to qualitative field observations. Intertidal and shallow bench habitats characterize the shoreline from Maliu Point south to about 130 m west of Alula Bay. The shallow bench was likely continuous across the mouth of the harbor before the dredging of the channel associated with harbor construction. The shallow bench comprises poorly colonized rocks, boulders, and volcanic pavement. Low-lying species such as encrusting *Porites* species and the octocoral *Anthelia edmonsoni* inhabit these shallow-water areas. Uncolonized sand and some boulders exist within Alula Bay. The easy access and shallow, protected waters in Alula Bay makes it a popular spot for visitors and snorkelers. The boundary between this region and the south bench/escarpment is somewhat subjective and is defined by the southward limit of the shallow bench habitat and the western boundary of Alula Bay (figs. 47–51).

In the dredged zone at the mouth of the harbor, the benthic habitat is predominantly poorly colonized pavement and rocks. Scattered *P. meandrina* and *P. lobata* are the common species. Numerous tires and other debris were observed in this region, along with areas of higher (still <50 percent) coral cover near the south wall of the dredged channel.

The majority of the harbor embayment region is the intermediate bench habitat. In water depths less than about 10 m, the habitat is characterized by a near-continuous cover of large (1-2 m diameter) rounded boulders, colonized with 10 to <50 percent of primarily lobate and encrusting *P. lobata* and scattered heads of *P. meandrina*. In some areas coral cover on the boulders exceeds 50 percent. Near the 10-m isobath, the sea-floor structure and coral cover change dramatically,

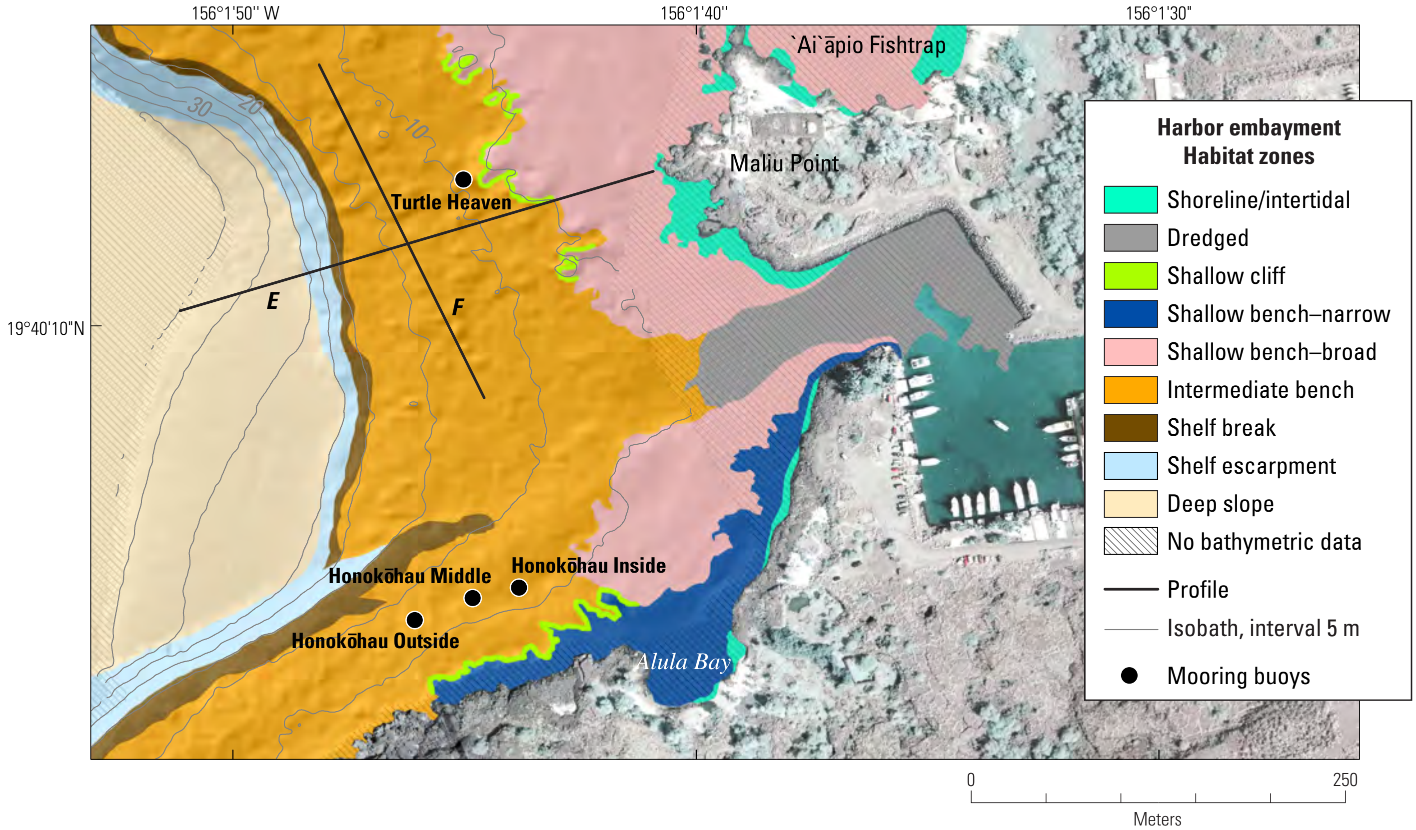


Figure 47. Habitat zones of the harbor embayment region of KAHO overlaid on shaded relief bathymetry. Hatched lines indicate areas lacking bathymetric data. Lines E and F show the locations of the cross-shelf profiles shown in figures 49 and 50.

from the boulder-covered pavement to predominantly shore-normal ridges of volcanic pavement and intervening sand and channels. The ridges are generally less than 2 m high (fig. 50) and are almost completely colonized with coral. The coral community structure is relatively diverse compared to other areas of the park, but still dominated by *P. lobata*, with lesser amounts of other *Porites* species, including *P. compressa* and *P. evermanni*. These features are differentiated from the spur-and-groove structure by their diminutive size, lack of continuity, and little vertical accretion of coral.

Adjacent to this area of thriving coral communities west of the harbor mouth is a zone of poorly colonized scattered rocks, volcanic pavement, and sand channels (fig. 48). The absolute boundaries of this degraded area are poorly known; limited survey transects crossed this area, and no obvious differences in bottom character are evident in the aerial photography. However, relatively sharp transitions from moderately high and high to low coral cover are observed at both the north and south boundaries of this zone. The bottom structure across this boundary is apparently similar to the shore-normal ridges characteristic of the highly colonized area to the north, but with distinctly lower coral cover.

The shelf break and shelf escarpment are located just seaward of the intermediate bench in water deeper than about 19 m. The benthic habitat of the shelf break is similar to that observed on the adjacent intermediate bench, but with somewhat less coral cover (50 to <90 percent) on the volcanic pavement. The shelf escarpment fronting the harbor embayment region is not as steep as to the north and south, particularly fronting the relatively degraded area, where the offshore slope is typically less than 20°. A sharp contact with an uncolonized sheet of sand extends seaward from the base of the escarpment in about 25 m of water. Elsewhere in the study area the base of the shelf escarpment is in water depths greater than 40 m.

South Bench/Escarpment

Like the north bench/escarpment region, the south bench/escarpment region is characterized by a relatively narrow intermediate bench that slopes gently seaward from the coast before dropping steeply over the shelf escarpment. In contrast to the north, however, where the emergent coast is low lying and a rocky intertidal zone transitions to a shallow wave-washed bench, no shallow bench and little intertidal habitat exists in the south. This can be attributed to the younger

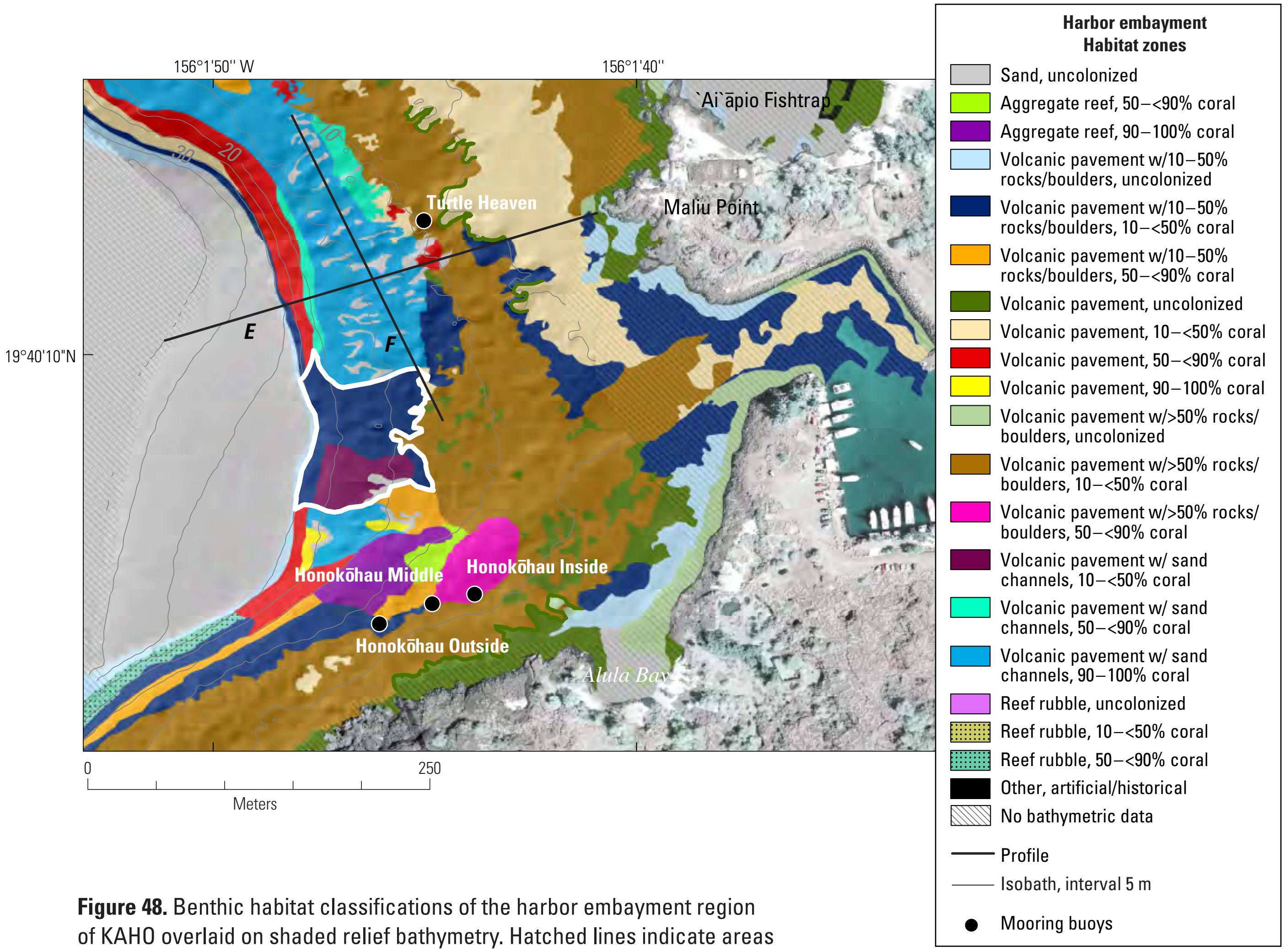


Figure 48. Benthic habitat classifications of the harbor embayment region of KAHO overlaid on shaded relief bathymetry. Hatched lines indicate areas lacking bathymetric data. Lines E and F show the locations of the cross-shelf profiles shown in figure 49 and 50. The white line delineates the approximate boundary of the degraded area discussed in the text.

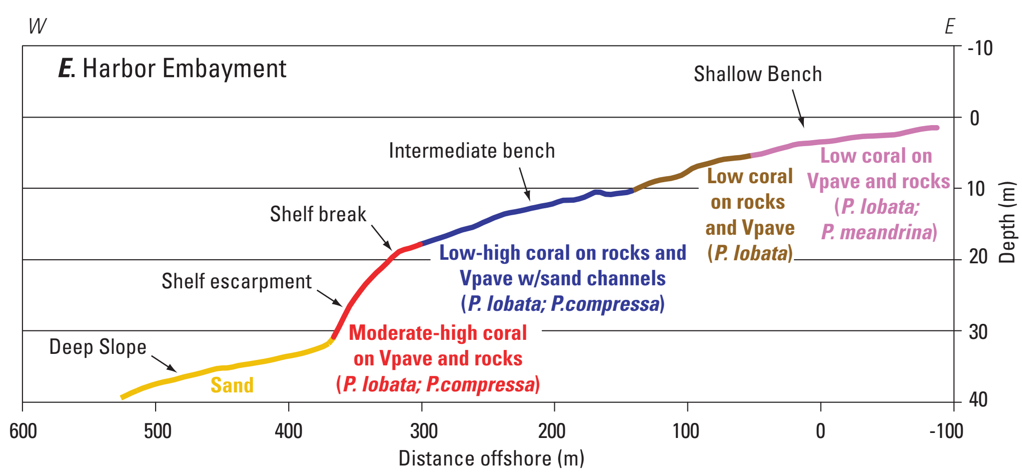


Figure 49. Cross-shelf profile (E) and typical benthic habitat transitions of the harbor embayment region of KAHO. Vpave = Volcanic Pavement. Vertical exaggeration is x3.

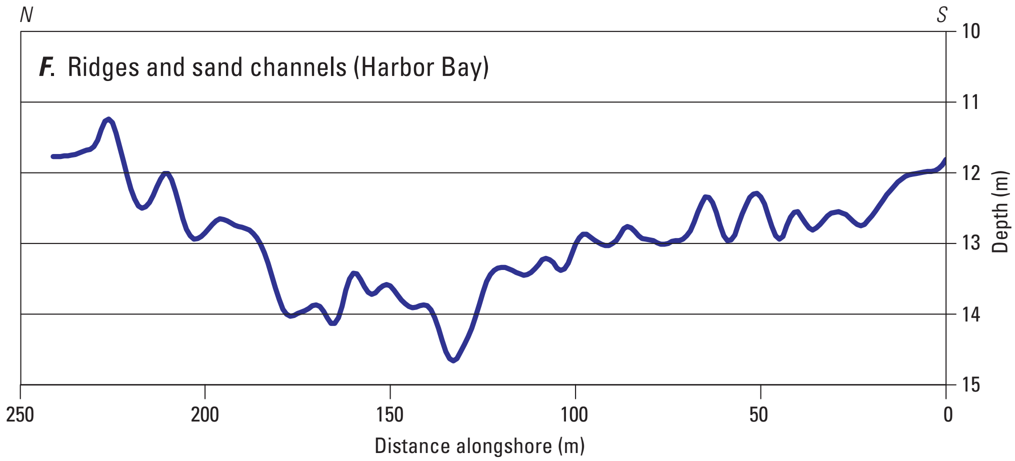


Figure 50. Cross-shelf profile (F) of the ridges and sand channels located on the intermediate bench of the harbor embayment region of KAHO. Note the different scale and vertical exaggeration from other profiles. Vertical exaggeration is x16.

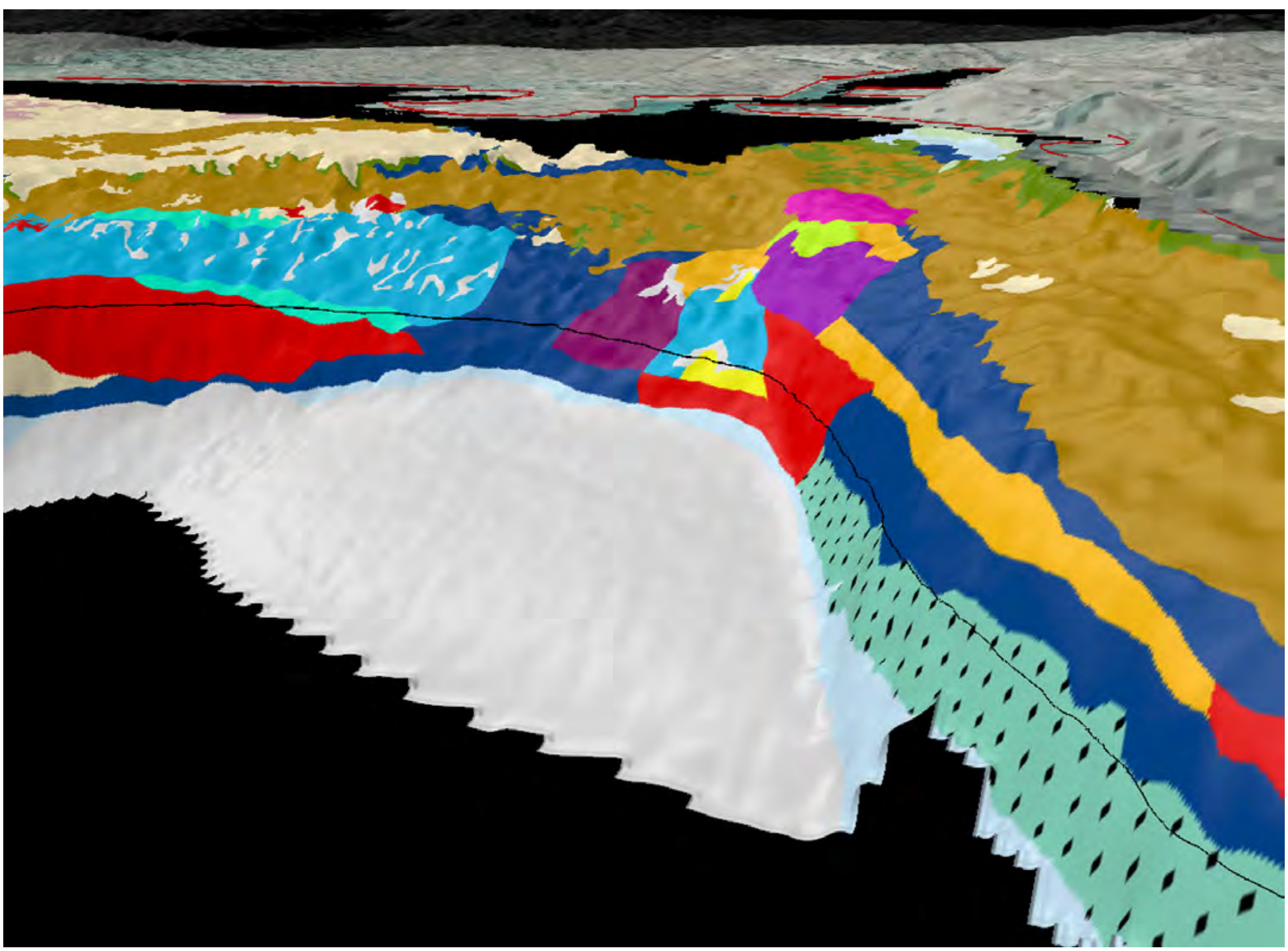


Figure 51. Three-dimensional perspective view of the harbor embayment region of KAHO, showing benthic habitat classifications draped on lidar bathymetry. The colors are the same as in figure 48. The red line is the shoreline, and the black line is the 20-m isobath. Habitat classifications are only displayed where lidar data exist. Vertical exaggeration is x3. View is toward the northeast. Approximate distance along the bottom of the figure is 0.4 km.

emergent volcanic platform located along this part of the coast (3.0-1.5 ka in the south versus 5.0-3.0 ka in the north) that ends abruptly at the shoreline. West of Alula Bay, a near-vertical cliff rises 2-3 m from the surface of the water and drops another ~ 2-3 m to the intermediate bench below (fig. 52).

The intermediate bench, the largest habitat in this region, is flat (mean slope = 7°), narrow (50-150 m wide) and relatively shallow (<13 m water depth). From the base of the cliff to water depths of about 10 m, the sea floor is almost completely covered with large, rounded volcanic boulders, sparsely colonized (10 to <50 percent) with small *P. lobata* and lesser amounts of *P. meandrina*. As water depth increases toward the shelf break, boulders decrease in size and frequency and coral cover is variable. The percentage of *P. meandrina* versus *P. lobata* increases with water depth and to the south, reaching moderately high cover (50 to <90 percent) of primarily *P. meandrina* on and between boulders south of Noio Point (figs. 53-55).

Some of the highest coral cover observed in the park (90-100 percent) is located in the south bench/escarpment region where the northeast-southwest-trending intermediate bench and shelf break habitat zones converge with the more gently sloping (~<15°), north-south-trending terrain of the intermediate bench zone off the mouth of the Honokōhau Harbor (figs. 51, 55). This is the only area where vertically accreted or aggregate reef is mapped within the study area. A relatively abrupt transition from poorly colonized rocks and boulders to moderately high (50 to <90 percent) coral cover on rocks and boulders occurs in water depths between 6 and 9 m. Moderately high to high (90 to 100 percent) coral cover on aggregate reef begins in about 9 m of water and continues over the shelf break to about 15-m water depth. Nearby mooring buoys that were regularly visited by commercial snorkel boats during our surveys indicate this is a very popular recreational destination.

The bottom habitat changes dramatically at the shelf break, where the offshore slope steepens (slope = 12-20°) between about 12 and 15 m water depth. The shelf break habitat here is characterized by scattered rocks and boulders, with two areas that lack significant rocks off Noio Point. The habitat is colonized with generally less than 50 percent coral cover of primarily *P. lobata*. Coral cover increases to moderately high (50 to <90 percent) on the northeast-southwest-trending section of the shelf break between Noio Point and the harbor. High coral cover (90 to 100 percent) on aggregate reef exists

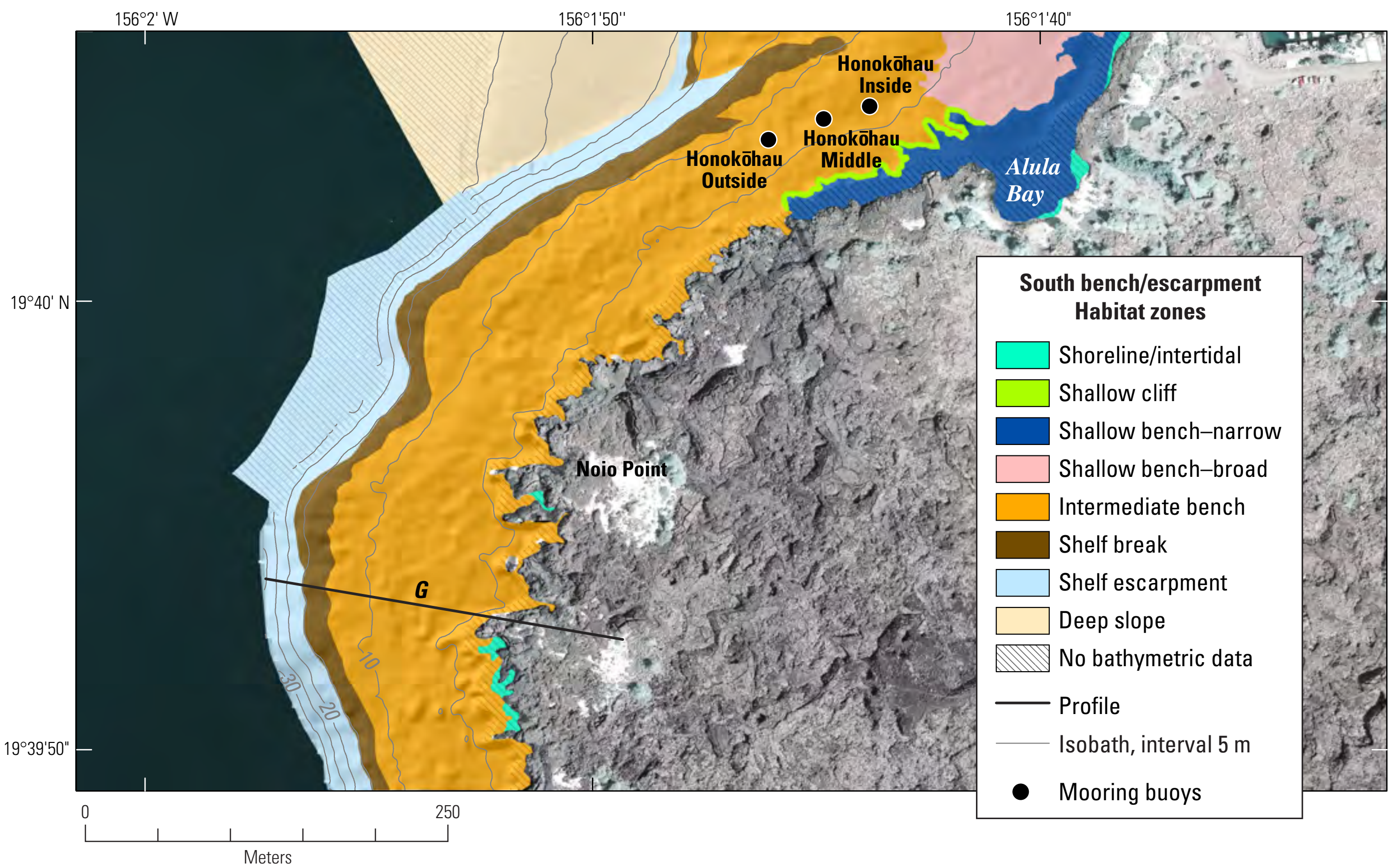


Figure 52. Habitat zones of the south bench/escarpment region of KAHO overlaid on shaded relief bathymetry. Hatched lines indicate areas lacking bathymetric data. Line G shows the location of the cross-shelf profile shown in figure 54.

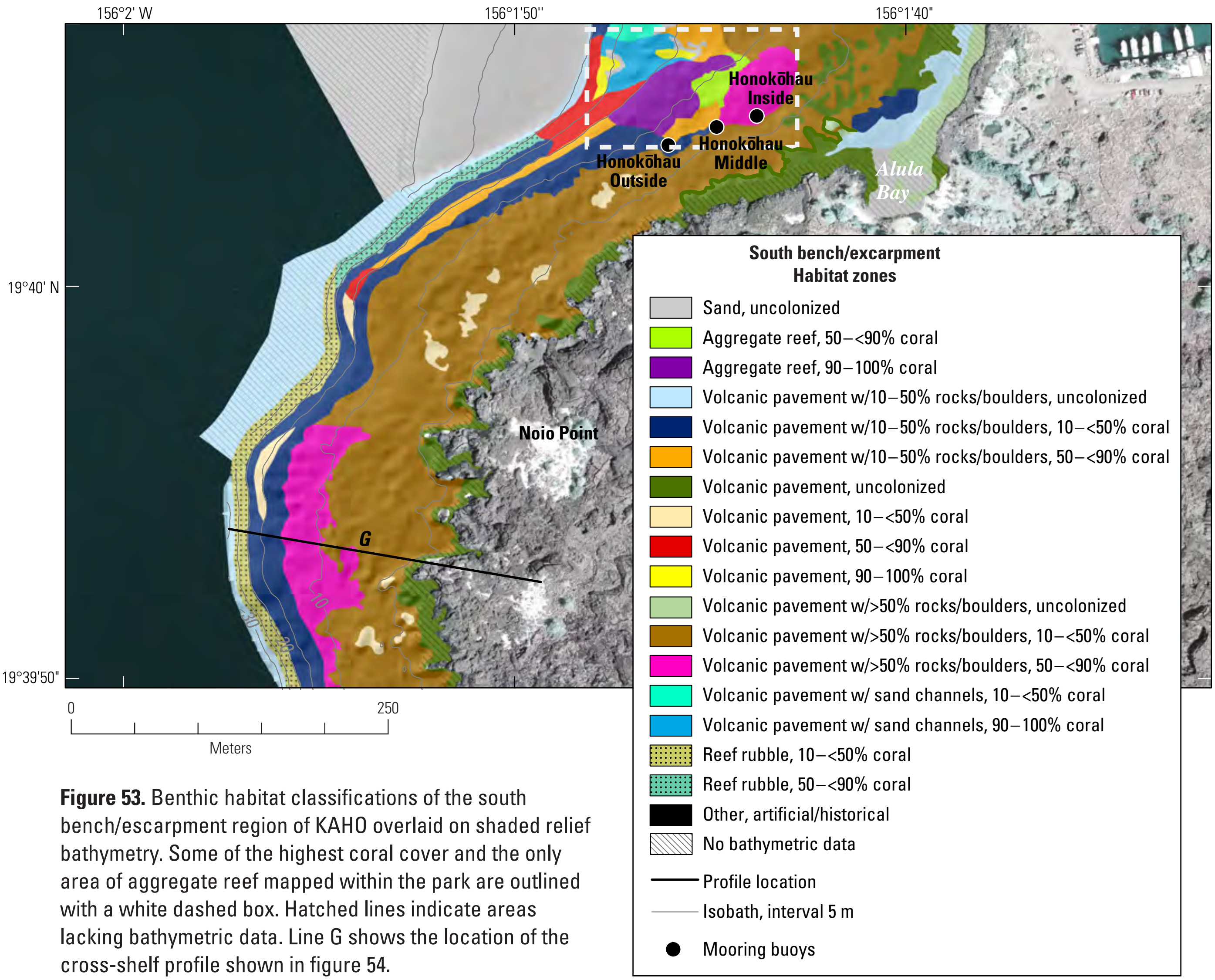


Figure 53. Benthic habitat classifications of the south bench/escarpment region of KAHO overlaid on shaded relief bathymetry. Some of the highest coral cover and the only area of aggregate reef mapped within the park are outlined with a white dashed box. Hatched lines indicate areas lacking bathymetric data. Line G shows the location of the cross-shelf profile shown in figure 54.

on the easternmost end of the shelf break, where it meets the intermediate bench of the harbor embayment region.

The shelf escarpment habitat begins in about 15 m of water and continues to water depths greater than 40 m. The slope here generally exceeds 20° (mean 28°) and reaches as high as 43°. Between about 15-m and 20-m depth, the sea floor is covered with scattered rocks and boulders with abundant *P. compressa* rubble. The percent of live coral cover in this region is typically low (10 to <50 percent) of predominantly *P. lobata* on dead *P. compressa* framework and rubble. In places, however, coral cover approaches 50 percent or greater total live cover.

In deeper water, the scattered rocks and boulder habitat transitions to a very dense, nearly continuous sheet of dead P. compressa framework and rubble with variable amounts of live coral cover. This habitat is persistent throughout the south bench region between about 20-m and 27-m depth, where the slope exceeds about 30°. Overall coral cover and in-place *P. compressa* is higher (>50 percent) in the relatively protected embayment offshore and to the north of Noio Point. In places the skeletal *P. compressa* framework looks relatively undisturbed from its natural growth form and was once likely a thriving reef habitat. Because this habitat is in such deep water and on a steep slope, it is very difficult to image using underwater video; thus, it is difficult to accurately estimate the percentage of live versus dead coral. One dive transect line near this area, however, shows some live coral (*P. compressa* and *P. lobata*) at 85-ft (26-m) water depth.

Below this band of nearly continuous *P. compressa* rubble are scattered rocks, boulders, and rubble on volcanic pavement. This habitat is mostly uncolonized, although isolated coral colonies were observed. The depth of the deepest substantial coral coverage (>10 percent) in this region is between 27-m and 30-m depth, and the landward boundary of the habitat is placed along the 27-m depth contour. It is unclear how deep this uncolonized scattered rock and rubble habitat

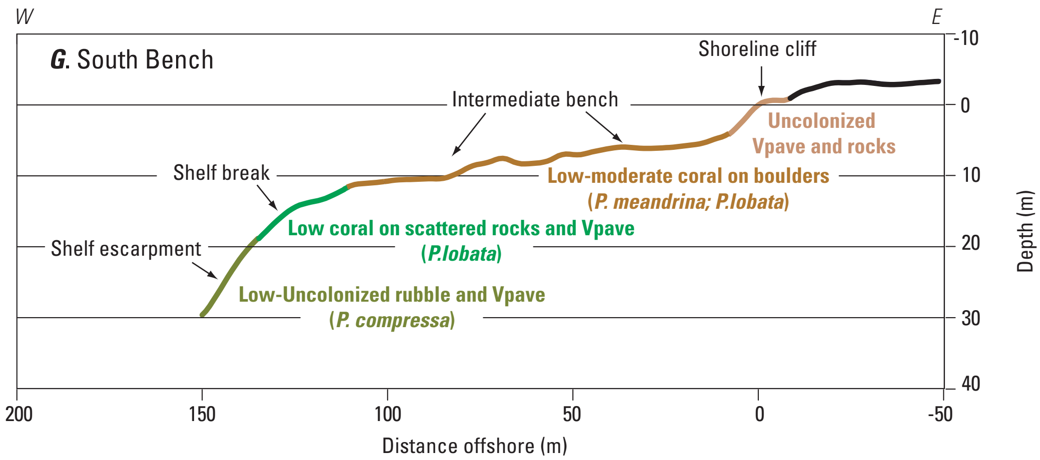


Figure 54. Cross-shelf profile (G) and typical benthic habitat transitions of the south bench/escarpment region of KAHO. Vpave = Volcanic Pavement. Vertical exaggeration is x2.

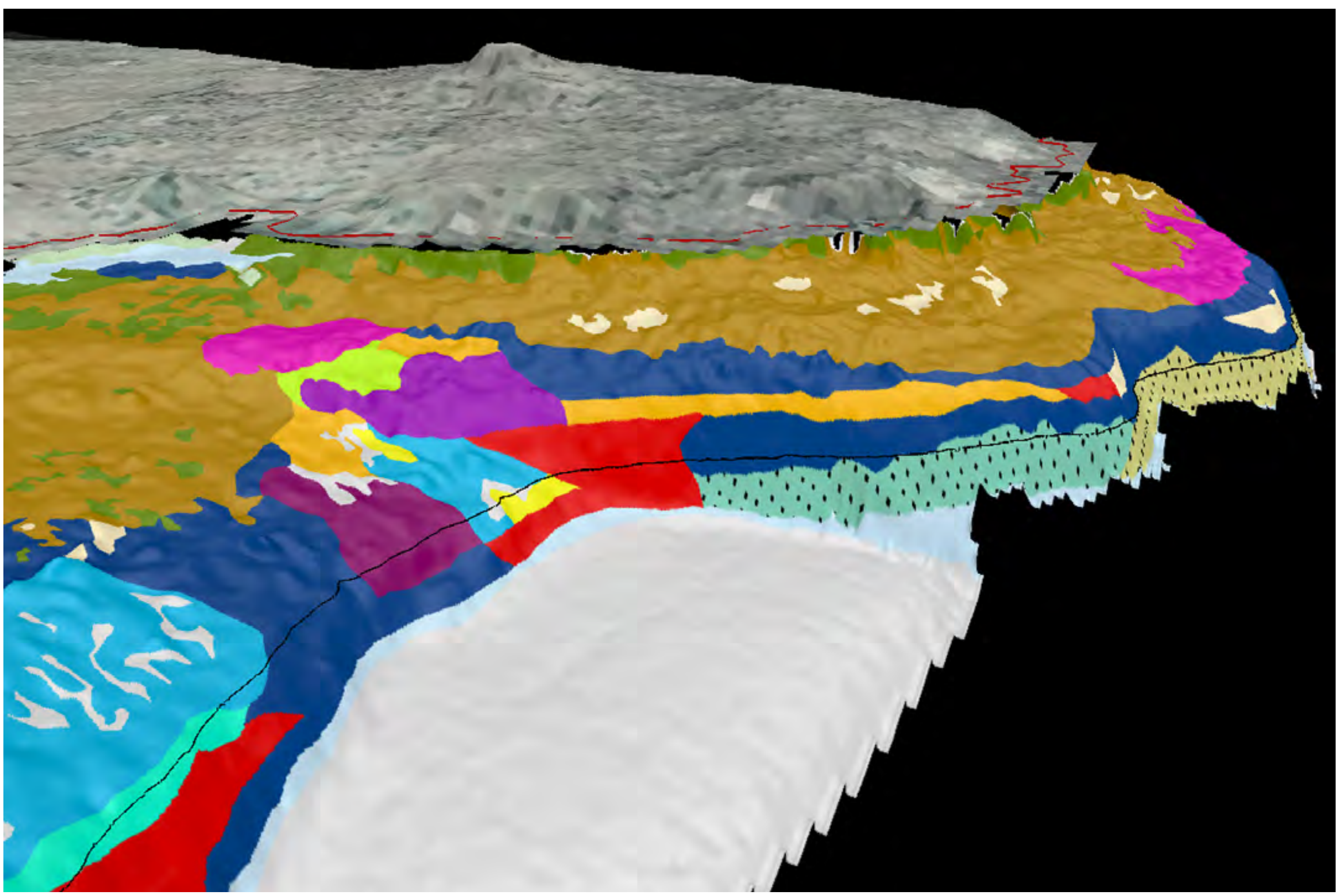


Figure 55. Three-dimensional perspective view of the south bench/escarpment region of KAHO, showing benthic habitat classifications draped on lidar bathymetry. The colors are the same as in figure 53. The red line is the shoreline, and the black line is the 20-m isobath. Habitat classifications are only displayed where lidar data exist. Vertical exaggeration is x3. View is toward the south. Approximate distance along the bottom of the figure is 0.4 km.

extends, as no base of the slope, sand sheet, or deep slope habitat was observed in this area. The one fathometer transect collected within this area shows a decrease in offshore slope in about 60 m of water (fig. 26).

Discussion

Coral Zonation and Importance of Natural Disturbances on Coral Habitat

Coral communities in Kaloko-Honokōhau NHP (KAHO) generally follow the physiographic zonation of the Kona coast described by Dollar (1982) and Dollar and Tribble (1993), where a shallow boulder zone colonized primarily with *P. meandrina* transitions to a deeper reef bench zone dominated by *P. lobata*, followed by a reef slope zone colonized primarily by *P. compressa*, and finally a largely dead coral-rubble zone below depths of about 30 m (fig. 56). Within KAHO, a shallow bench zone with no boulders and an area of pinnacles and ridges also exist.

The well-defined zonation of the coral community structure is likely a result of variable importance of wave stresses on the coral from breaking waves (Dollar, 1982). Our results show variability within this model across KAHO, reflecting differences in wave stresses and possibly other controls (for example, groundwater, recreation, harbor development). In the shallow bench and boulder zones, turbulence and high shear stresses resulting from approaching and reflected waves prevent colonization by fragile corals, and the resulting community structure is dominated by robust species such as the short, dense *P. meandrina* and encrusting *P. lobata*. Small (< 0.2-m diameter) isolated colonies of *P. lobata* in these environments indicate frequent disturbance. In the deeper, steep-sloped shelf escarpment region, where wave energy is normally low, the habitat is generally dominated by monospecific thickets of the relatively fragile but competitively superior species, *P. compressa*. Below about 30-m water depth, reduced light levels, and perhaps loose and mobile rubble and rock, limit coral growth and only scattered, small colonies of primarily *P. lobata* grow on the boulders, rubble fragments, or volcanic pavement. The highest percentage and diversity of coral speciation are between these extremes, at intermediate water depths where wave stresses are high enough to prevent monopolization by competitive species like *P. compressa* and low enough to enable settlement and growth of many different coral species.

While the zonation and community structure transitions described above are evident in KAHO, the sea-floor morphology in the park is more complex than along much of the Kona coast. The mid-shelf cliffs, the semiprotected environments provided by the pinnacles off Kaloko Fishpond and Kaloko Point, and the embayed form of the coast support localized coral ecosystems that are unique to the KAHO region.

The coral cover in the park is low overall, except for areas that are relatively protected from high wave energy—in the most deeply embayed reaches off the harbor mouth and off Kaloko Fishpond. In both of these areas, the coral communities are diverse, healthy, and thriving. The embayments are locally protected from south swell and Kona storms by Noio Point and from all but the most westerly north Pacific swell by Wawahiwa`a Point. Between the two, the deep bench and central bench/escarpment regions provide additional protection from larger waves that shoal across the relatively exposed platforms.

In the deeper water of the shelf escarpment habitat, where wave stresses are reduced, dense coral thickets of *P. compressa* framework exist, although many appear to be dead and covered with coralline algae and octocoral; live coral growth is typically limited to the ends of the fingers. Most of the thickets are interconnected and in growth form, rather than disconnected pieces of scattered rubble, suggesting that this was perhaps once a thriving coral habitat, or alternatively, is a slowly growing community struggling to survive. It is likely that this habitat is significantly stressed by wave scour

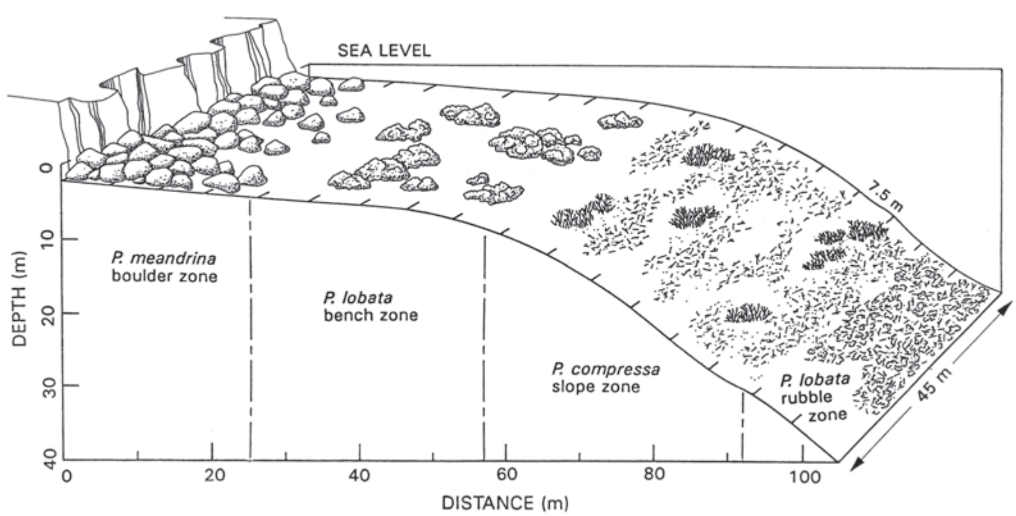


Figure 56. Schematic diagram of the physiographic zonation of coral communities along the Kona coast of Hawai`i (Dollar and Tribble, 1993).

associated with large storms that are not infrequent along the southern Kona coast (Dollar,1982; Dollar and Tribble,1993). Although *P. compressa* is one of the most rapidly growing and opportunistic species in the Hawaiian Islands, the relatively low light and steepness over the shelf escarpment may restrict or limit its ability to recover and thrive.

The lack of vertical accretion of carbonate material and aggregate reef growth along the Kona coast is unusual compared to the rest of the Hawaiian Islands. This deficiency is likely due to a combination of the geologically young age of the surface upon which the corals grow (10 – 1.5 ka), combined with the episodic destruction of coral colonies by storms and transport of carbonate material downslope. Lithification, cementation, and accretion can occur only in places that are relatively protected from waves. Processes that limit reef accretion in other coral-reef habitats, such as predation (for example, by *Acanthaster planci*), loss of accommodation space (Great Barrier Reef), temperature fluctuations, sedimentation, and disease, appear to not be limiting factors along the Kona coast.

Status of the Habitat

Overall, the park's offshore region supports a healthy and relatively diverse coral habitat. Little evidence of invasive macroalgae and no diseased coral were observed. Limited occurrences of macroalgae were, however, noted (fig. 57). Several of the potentially destructive sea star *Acanthaster planci* were observed, although limited evidence for widespread destruction of coral suggests that these predators may be balanced within the ecosystem.

The low diversity, low overall coral cover, and deteriorated habitat in the slope escarpment zones suggest that the coral ecosystem in the park may be adjusting to storm-related damage over the last few decades. This is different from other stressed regions in the islands (for example, Kāne`ohe Bay and Māmala Bay on O`ahu and West Maui and Kīhei on Maui), where stresses on the corals are a combination of high sedimentation, nutrification, overfishing, and other anthropogenic stresses.

Sediment delivery is low along the Kona coast because of the relatively young geologic age of the adjacent volcanoes, poor soil development, and low annual rainfall. Few coastal streams exist along the Kona coast, and none are found within or adjacent to Kaloko-Honokōhau NHP. Thus, low sedimentation rates, along with the dearth of invasive or native macroalgae and thriving, healthy reefs in protected locations suggest that the coral habitat in KAHO is primarily controlled by natural wave-induced stresses, with little evidence of anthropogenic stresses. Areas of high visitor use, such as near the shoreline or around mooring buoys, were not specifically evaluated for impacts of the users.

The only anomalous area appears to be off the harbor mouth, where an area of low coral cover was mapped between some of the highest and most diverse coral communities within the study area (fig. 48). The causes of this apparent degradation are unclear and may warrant further investigation. Possible explanations may be related to the proximity of the harbor, such as increased sedimentation, increased wave stresses associated with the passage of boats, and water quality differences, including variations in salinity, temperature, and/or water chemistry. Coral surveys conducted outside the harbor in 1971, 1976, and 1981 revealed no substantial trends or changes in coral cover after harbor construction (Maragos, 1983), although changes in water quality were observed after the expansion of the harbor in 1979 (U.S. Army Corps of Engineers, 1983). No dredging or deposition of material from the harbor has occurred since initial harbor construction (Nancy Murphy, written commun., 2006).

An alternative hypothesis is that the degraded area, located at the apex of the embayment, may be a natural channel or pathway for water flow onto and off the shallower platforms. If this is true, locally higher bottom stresses associated with this water movement may limit the growth of coral that thrives in the adjacent environments. Measurements of currents, waves, and water quality and long-term habitat monitoring transects are needed to determine the influence of the harbor on this area of apparent coral degradation.

Ages of Submerged Volcanics and Sea-Level History

The complex structure of the sea floor in the study area results from the deposition of multiple volcanic flows and their subsequent erosion over thousands of years. Although three distinct volcanic flows are exposed within the emergent portion of KAHO, the age of the submerged flows and their depositional relationship to the emergent flows is poorly constrained. The delineation of volcanic flows on land is typically achieved using visual clues from photographic or satellite imagery in combination with radiometric age dating and the geological and morphological relationships between the volcanic deposits. Underwater, the visual and morphological relationships are obscured by sediment deposition, biological growth, and physical erosion of the deposits, which make delineation of individual flows problematic. In many places (for example, central bench/escarpment and pinnacles regions), the surface of the volcanic pavement shows textures commonly seen on exposed flows (ropey pahoehoe, pinnacles, and tubes), suggesting that little erosion has occurred in these locations. However, the presence of the shallow and deep cliffs and the abundant, well-rounded boulders that cover much of the study area indicates that extensive erosion has been modifying the shape of the sea floor over an extended period of time. No features or morphology that would indicate primary deposition underwater (for example, lava pillows) were observed, suggesting that the flows we observe today were originally deposited subaerially and have subsided to their present position below sea level.

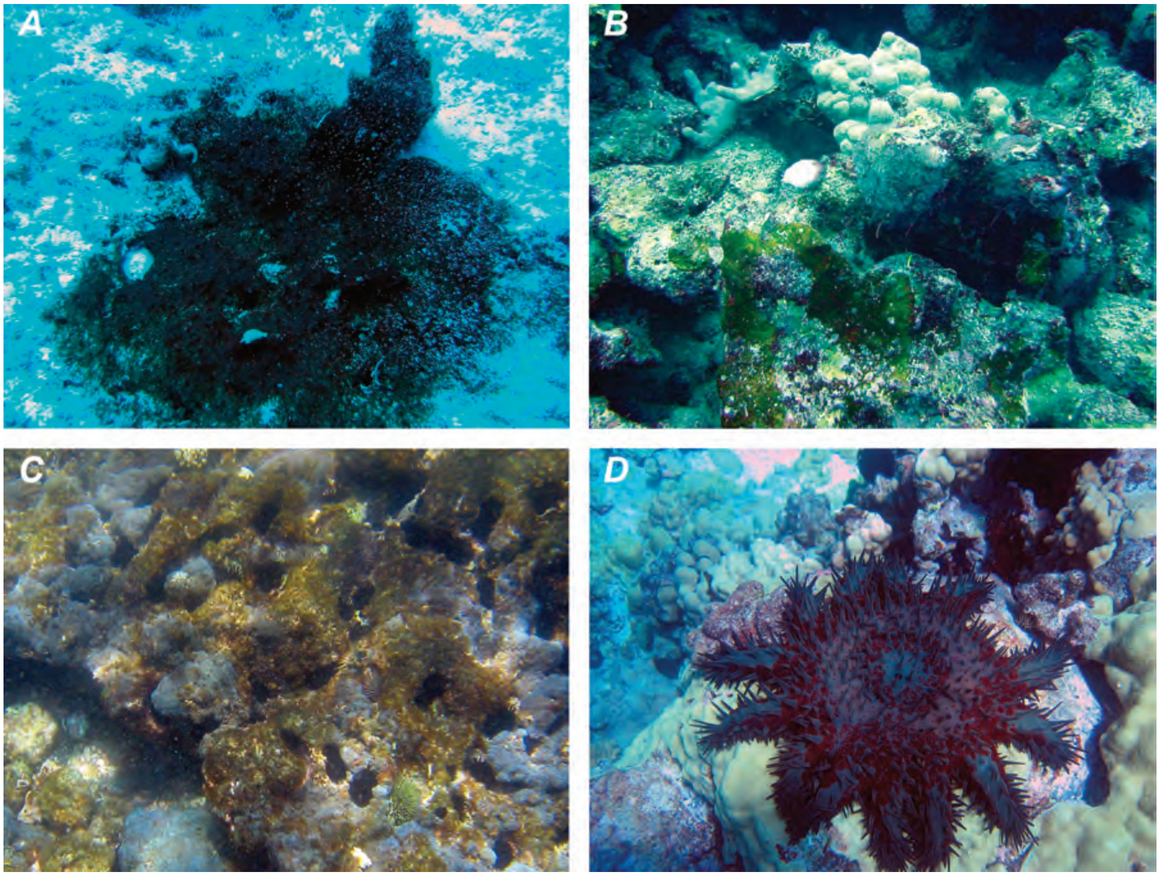


Figure 57. Photographs showing examples of the limited macroalgae and sea-stars observed in the study area. *A*, Brown macroalgae and turf algae in the deep slope habitat in the pinnacles region, depth 23 m. *B*, Green macroalgae on shelf escarpment in central bench/escarpment region, depth 23 m. *C*, *Anthelia edmonsoni* and brown turf algae on shallow bench in central bench/escarpment region; depth 1 m. *D*, Crown-of-thorns sea star *Acanthaster planci* on intermediate bench in pinnacles region; depth 8 m.

No radiometric age dates have been acquired for the volcanic substrate of offshore KAHO. This information is essential in order to definitively determine the ages of and relations between the submerged and emergent flows. The only area for which an age can be assigned with some level of confidence is the shallow narrow platform north of the central bench/escarpment region, where it appears to be a flooded surface that is topographically continuous with the shoreline and upland area mapped as the 5-3 ka volcanic flow by Wolfe and Morris (1996).

The relationship of the submerged flows to the emergent flows is further complicated by the sea-level and submergence histories of the island—each of which is poorly constrained. Historical measurements from a tide gauge in Hilo, on the east coast of Hawai`i, provide the best estimates of modern rates of relative sea-level change and island subsidence. These estimates, however, should be used with the caveat that the rates may not be linear and likely vary largely over time. Because of the proximity of the tide gauge to KAHO and the complexity of the geologic structure of the Island of Hawai`i, the rates recorded at Hilo during the modern era may not accurately reflect subsidence rates on the Kona coast over the time period of analysis. Estimates of the relative role of global eustatic sea-level rise in the Hawaiian Islands can be made using data from Grossman and Fletcher (1998).

On the basis of the present rate of local relative sea-level rise of 3.13 ± 0.30 mm/yr as measured at Hilo (1947-2003; Permanent Service for Mean Sea Level, 2006) and the eustatic positions calculated for the Hawaiian Islands by Grossman and Fletcher (1998), the elevation of the shoreline at time periods corresponding to the bounding ages of the lava flows within KAHO is summarized in table 7.

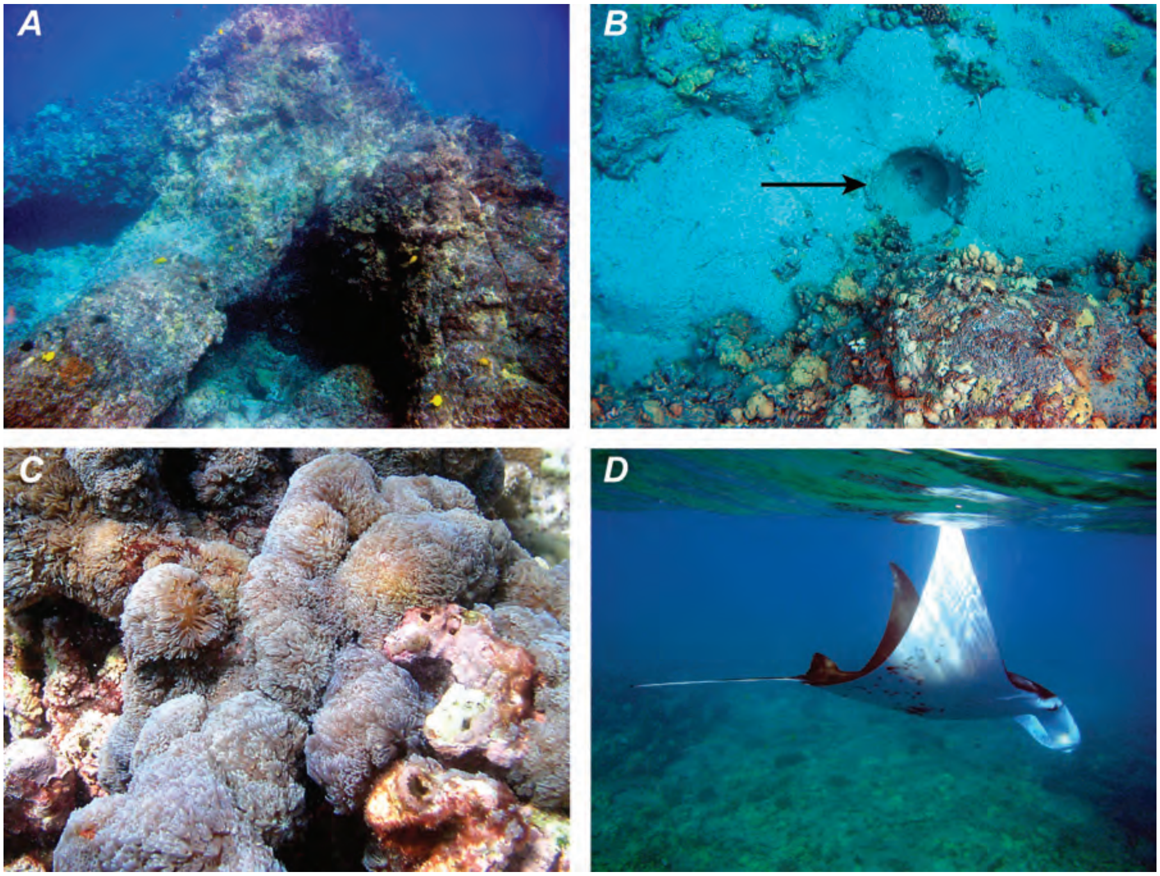


Figure 58. Photographs showing examples of some unique underwater features and organisms observed in the study area. *A*, Lava tubes (?) off Kaloko Point. *B*, Pothole (arrow) in basalt at the edge of the shallow bench in the central region. *C*, The lavender-hued octocoral *Anthelia edmonsoni. D*, A manta ray—one of the many pelagic species to inhabit the park.

Table 7. Relative sea-level position, estimated subsidence amounts, and depth of the shoreline for the ages bounding the lava flows present in Kaloko-Honokōhau National Historical Park (KAHO).

Age of flow (yr B.P)	Sea-level position relative to present[1] (m)	Subsidence[2] (m)	Depth of shoreline at time = t (m)
1,500	+0.5	4.7	-4.2
3,000	+2.0	9.4	-7.4
5,000	+0.5	15.6	-15.1
10,000	-25.0	31.3	-56.3

[1]From Grossman and Fletcher (1998); [2] 3.13 mm/yr x years

Unique Underwater Features

Numerous unique and interesting geological features are present in the offshore regions of KAHO. Many large pinnacles and arches are present between Kaloko Fishpond and Kaloko Point. Most appear to be depositional in origin and may have formed as lava tubes during original flow emplacement (fig. 58*A*). The vertical relief and coral cover on these pinnacles attract numerous fish species, and these may therefore be areas with potential archeological significance with respect to ancient fishing grounds.

Potholes observed on the outer edge of the shallow central platform were likely formed by the swirling action of sediment on the volcanic pavement surface, but may also have archeological significance (fig. 58*B*). On the basis of the island subsidence rates discussed above, the location of these potholes, along with the entire shallow bench, would have been exposed around 1.5 ka.

Caves located along the shallow cliff in the northern bench/escarpment area provide a unique environment for scuba activities and have the potential to be conduits for freshwater influx to marine waters. Studies in progress by the USGS (Grossman and others, 2006) aim to characterize the flux, pathways, and fate of ground water and associated nutrients and contaminants discharging into the nearshore waters of the park from these caves, the harbor mouth, and other sites.

Although rare in other parts of the Hawaiian Islands, the lavender-hued octocoral *Anthelia edmonsoni* is abundant in the shallows of the central bench/escarpment area, but it is present as part of the colonizing coral community in many other locations as well (fig. 58*C*) . It is fairly common along the Kona coast and is thought to be an indicator of freshwater input (Brock and Brock, 1974; Parrish and others, 1990).

The relatively narrow shelf and steep offshore slope fronting most of the study area is also unusual compared to other locations in Hawai`i; it allows the close approach of large pelagic species such as manta rays, sharks, and whales (fig. 58*D*).

A final interesting underwater feature, or lack thereof in this case, is the relative dearth of the coral species *Montipora capitata*. This coral species is widely found within the Hawaiian island chain, but restricted to vertical walls and small colonies on the reef within KAHO and along the Kona coast in general.

No archeological features were identified, aside from the remnants of building structures and fishpond walls close to shore.

Accuracy of Maps

A total of 187 points were checked in the field by third-party investigators familiar with the NOAA habitat mapping classification scheme. There was some confusion regarding the added classes (octocoral, volcanic pavement with rocks and boulders) that may have resulted in some incorrect scoring of the evaluated polygons, but the overall accuracy assessments were good to very good.

Table 8 shows the matrix of accuracy assessment calculations for the major biological covers. Two points were deleted from the final accuracy assessment calculation for this class due to observer variation in the determination of coral cover (Will Smith, written commun.). The overall accuracy of 90.3 percent (with a 95-percent confidence interval of ± 1.3) indicates which points on the map were classified correctly according to the field check. A tau coefficient (Ma and Redmond, 1995) of 0.878 indicates that 87.8 percent more points are classified correctly than would be expected by chance alone.

Table 9 shows the matrix of accuracy assessment calculations for the dominant structure. A total of 187 points were checked in the field. The overall accuracy of 73.3 percent (with a 95-percent confidence interval of ± 1.3) indicates which points on the map were classified correctly according to the field check. A tau coefficient (Ma and Redmond, 1995) of 0.708 indicates that 70.8 percent more points are classified correctly than would be expected by chance alone.

Table 10 shows the matrix of accuracy assessment calculations for the percent cover. A total of 185 points were checked in the field. The overall accuracy of 71.4 percent (with a 95-percent confidence interval of ± 1.3) indicates which points on the map were classified correctly according to the field check. A tau coefficient (Ma and Redmond, 1995) of 0.690 indicates that 69.0 percent more points are classified correctly than would be expected by chance alone.

After accuracy assessment calculations were performed, any misinterpreted polygons identified on the map were corrected using the field check data, thus increasing the accuracy of the final map.

Special Considerations and Recommendations for Future Work

As results of the study reported in this work, the following observations and recommendations are given:

- The areas of highest coral cover within the park are located adjacent to the most highly developed (or developing) areas of adjacent coast – offshore Honokōhau Harbor and Kaloko Fishpond. We recommend that the National Park Service establish long-term monitoring stations near these locations to evaluate any changes in environmental conditions (sedimentation, water quality, direct impact) that may adversely affect the habitats in the future.

- Establish coral and water-quality monitoring and current measurement transects near the poorly colonized area off the harbor mouth and control area(s) in order to determine whether potential changes in sedimenta-

Table 8. Accuracy assessment matrix for the major biological cover classes.

		Found to be in field					Total	User's Accuracy
		Coral	Macro-algae	Octo-coral	Emergent Vegetation	Uncolo-nized		
As mapped	Coral	134	0	1	0	6	141	95%
	Macroalgae	0	0	0	0	0	3	
	Octocoral	0	1	3	0	1	5	60%
	Emergent Vegetation	0	0	0	0	0	0	
	Uncolonized	6	0	0	0	30	36	83%
Total		140	1	4	0	40		
Producer's Accuracy		96%	0%	75%		75%	185	
								Diagonal Sum =167
								Overall Accuracy =90.3%

Table 9. Accuracy assessment matrix for the percent of major biologic cover classes.

		Found to be in field														
		10-<50% Coral	50-<90% Coral	90-100% Coral	10-<50% Macroalgae	50-<90% Macroalgae	90-100% Macroalgae	10-<50% Octocoral	50-<90% Octocoral	90-100% Octocoral	10-<50% Emergent Veg.	50-<90% Emergent Veg.	90-100% Emergent Veg.	Uncolonized	Total	User's Accuracy
As mapped	10-<50% Coral	72	3	0	0	0	0	1	0	0	0	0	0	5	81	89%
	50-<90% Coral	18	20	1	0	0	0	0	0	0	0	0	0	1	40	50%
	90-100% Coral	3	9	8	0	0	0	0	0	0	0	0	0	0	20	40%
	10-<50% Macroalgae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	50-<90% Macroalgae	0	0	0	0	0	0	0	0	0	0	0	0	3	3	
	90-100% Macroalgae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	10-<50% Octocoral	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	50-<90% Octocoral	0	0	0	0	0	0	0	2	1	0	0	0	2	5	40%
	90-100% Octocoral	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	10-<50% Emergent Veg.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	50-<90% Emergent Veg.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	90-100% Emergent Veg.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	Uncolonized	6	0	0	0	0	0	0	0	0	0	0	0	30	36	83%
Total		99	32	9	0	0	0	1	2	1	0	0	0	41		185
Producer's Accuracy		73%	63%	89%				0%	100%	0%				75%	185	
																Diagonal sum = 132
																Overall Accuracy = 71.4%

tion, water quality, or bottom currents are affecting coral colonization off the harbor mouth.

- Define boundaries of the degraded area off the harbor mouth to evaluate its stability, the processes affecting it, and/or to determine if the adjacent areas of thriving coral habitat are expanding, contracting, or susceptible to these same processes.
- Evaluate freshwater conduits and establish water-quality and benthic-habitat monitoring locations along the north boundary of the park, off Kohanaiki, near areas of recent and future development of housing and golf courses.
- Establish additional scuba transects to better quantify spatial variations in the percent cover, health of *P. compressa,* and structure of the shelf-escarpment habitat.
- Establish long-term coral and fish monitoring sites to monitor coral health and ecosystem health throughout the park.
- Collect airborne infrared or hyperspectral imagery to isolate spectrally unique bio-indicators to improve delineation of intertidal habitats.

Acknowledgements

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Table 10. Accuracy assessment matrix for the dominant structure classes.

		Found to be in field												Total	User's Accuracy
		Aggregate Reef	Aggregate Patch Reef	Individual Patch Reef	Spur-and-Groove	Volcanic Pavement	VolPv w/Sand Chnls	VolPv w/ 10-50% Rx/Bldr	VolPv w/ >50% Rx/Bldr	Rubble	Sand	Mud	Land		
As mapped	Aggregate Reef	3	0	0	0	1	0	0	0	0	0	0	0	4	75%
	Aggregate Patch Reef	0	0	0	0	0	0	0	0	0	0	0	0	0	
	Individual Patch Reef	0	0	0	0	0	0	0	0	0	0	0	0	0	
	Spur-and-Groove	0	0	0	0	0	0	0	0	0	0	0	0	0	
	Volcanic Pavement	1	0	0	0	56	2	3	2	0	0	0	0	64	88%
	VolPv w/Sand Channels	0	0	0	0	7	14	4	3	0	1	0	0	29	48%
	VolPv w/ 10-50% Rx/Bldr	0	0	0	0	3	1	19	3	0	2	0	0	28	68%
	VolPv w/ >50% Rx/Bldr	1	0	0	0	3	2	8	22	0	0	0	0	36	61%
	Rubble	0	0	0	0	0	0	0	0	0	0	0	0	0	
	Sand	0	0	0	0	3	0	0	0	0	23	0	0	26	88%
	Mud	0	0	0	0	0	0	0	0	0	0	0	0	0	
	Land	0	0	0	0	0	0	0	0	0	0	0	0	0	
Total		5	0	0	0	73	19	34	30	0	26	0	0		187
Producer's Accuracy		60%				77%	74%	56%	73%		88%			187	
															Diagonal sum = 137
															Overall Accuracy = 73.3%

referred to in this document. Will Smith and other CRAMP team members performed the third-party field-check observations and provided the accuracy assessment calculations. Sallie Beavers from Kaloko-Honokōhau NHP supplied us with the smaller boats (Boston Whaler and kayaks) and assisted with logistics while we were on island. Lisa Marrack (NPS), Sallie Beavers (NPS), Jane Reid (USGS), and Mike Field (USGS) provided very helpful reviews of early drafts of the report. 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).

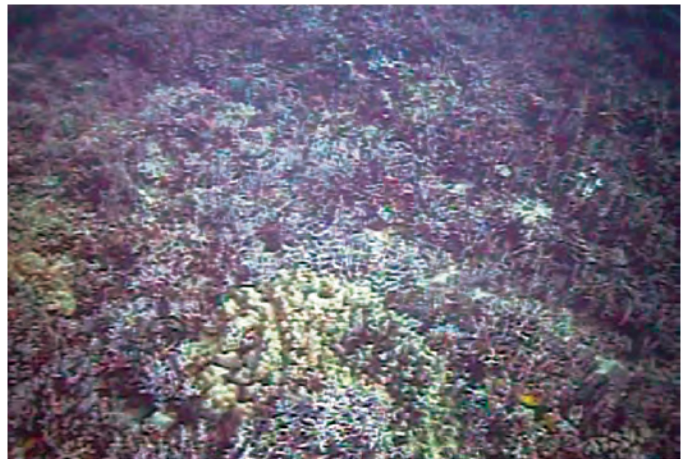
Example of muddy shallow area exposed at low tide. (Kawela, Moloka`i)

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)

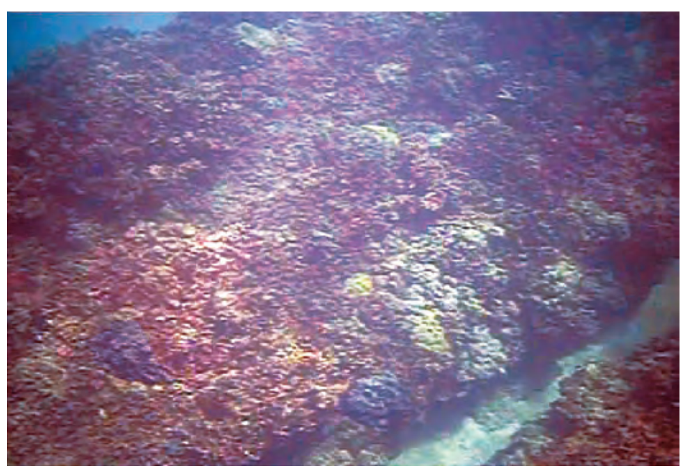
Major Structure — Reef and Hardbottom

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)

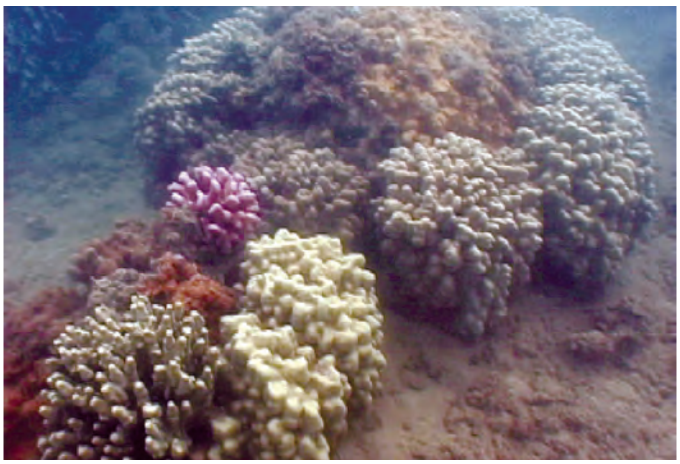
Spur-and-groove Elongate, alternating sand and coral formations that are oriented perpendicular to the shore or bank/shelf escarpment. The coral formations (spurs) of this feature typically have a high vertical relief relative to the pavement with the channels, and are separated from each other by 1–5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

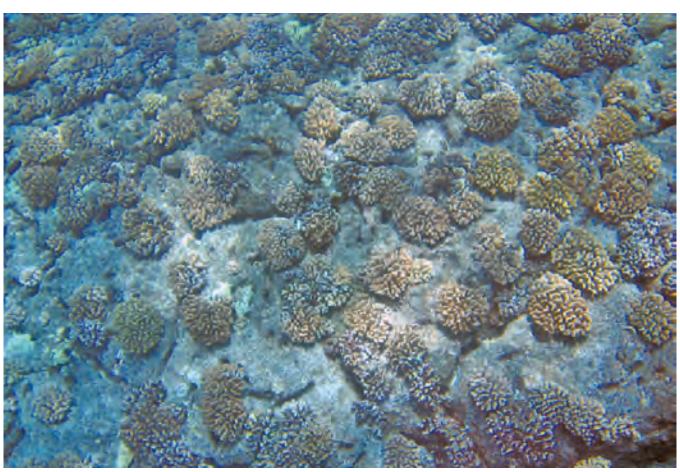
Individual patch reef Coral formations, larger than or equal to the MMU (100 m^2 in this study), that are isolated from other coral reef formations by sand, seagrass, or other habitats and that have no organized structural axis relative to the contours of the shore or shelf edge.

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, Hawai`i)

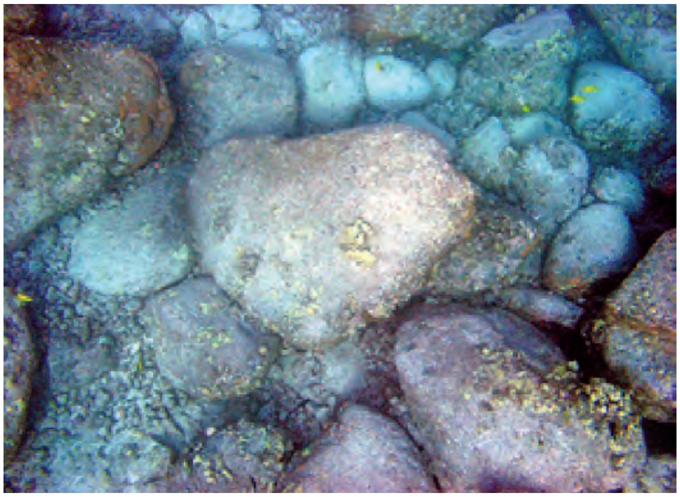
Volcanic pavement with sand channels Having volcanic substrate alternating with sand channels that are oriented perpendicular to the shore or bank/shelf escarpment. The sand channels have low vertical relief relative to spur-and-groove formations.

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.

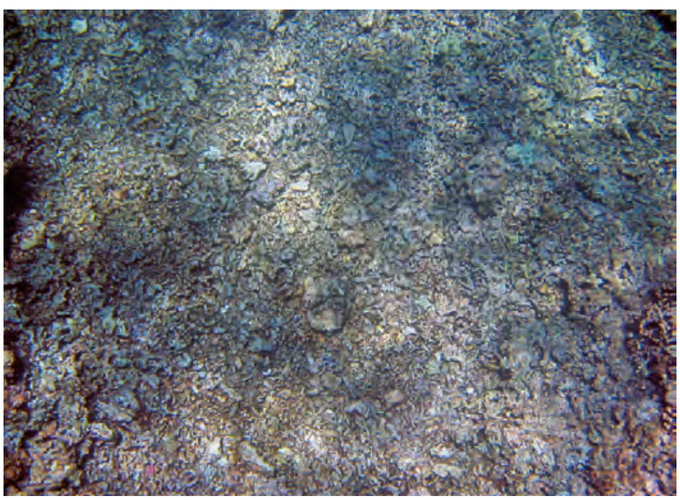
Example of volcanic pavement with 10–50 percent rocks/boulders, with 10–50 percent coral cover. (Hōnaunau Bay, Hawai`i)

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.