Benthic Habitat Map of Olowalu Reef, Maui, Hawaii—Geomorphological Structure, Biological Cover, and Geologic Zonation Determined with Spectral, Lidar, and Acoustic Data

Open-File Report 2025–1010

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

Cover. Top, Google Earth view of the fringing reef off Olowalu, Maui, Hawaii, with kayakers and a catamaran visible on the surface. Bottom, A *Porites lobata* colony, as seen from a still-frame of ground validation imagery used in this study (Gibbs and others, 2013).

Benthic Habitat Map of Olowalu Reef, Maui, Hawaii—Geomorphological Structure, Biological Cover, and Geologic Zonation Determined with Spectral, Lidar, and Acoustic Data

By Liana N. Heberer, Kristen A. Alkins, Curt D. Storlazzi, Susan A. Cochran, Ann E. Gibbs, Russell Sparks, Kristy Stone, Itana Silva, Tatiana Martinez, Cole Peralto, Arielle S. Levine, Douglas Stow, and Jillian Maloney

Open-File Report 2025–1010

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

U.S. Geological Survey, Reston, Virginia: 2025

Suggested citation:
Heberer, L.N., Alkins, K.A., Storlazzi, C.D., Cochran, S.A., Gibbs, A.E., Sparks, R., Stone, K., Silva, I., Martinez, T., Peralto, C., Levine, A.S., Stow, D., and Maloney, J., 2025, Benthic Habitat Map of Olowalu Reef, Maui, Hawaii—Geomorphological Structure, Biological Cover, and Geologic Zonation Determined with Spectral, Lidar, and Acoustic Data: U.S. Geological Survey Open-File Report 2025–1010, 32 p., https://doi.org/10.3133/ofr20251010.

Associated data for this publication:
Heberer, L.N., Alkins, K.A., Storlazzi, C.D., Cochran, S.A., Gibbs, A.E., Sparks, R., Silva, I., Stone, K., Martinez, T., and Peralto, C., 2025, Benthic habitat map of the geomorphological structure, biological cover, and geologic zonation of Olowalu reef, Maui: U.S. Geological Survey data release, https://doi.org/10.5066/P9ICJ7CF.

ISSN 2331-1258 (online)

Contents

Figures

Tables

Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8.$$

Datums

Horizontal coordinate information is referenced to the North American Datum of 1983, National Adjustment of 2011 fixed to the Pacific tectonic plate and epoch 2010.00, projected to Universal Transverse Mercator (UTM) Zone 4N (Range 162W–156W) for the Hawaiian Islands (NAD 1983 PA11, UTM Zone 4N).

Vertical positions used for depth are referenced to the Local Mean Sea Level (LMSL) tidal datum.

Abbreviations

AA	accuracy assessment
BPI	Bathymetric Position Index
BTM	ArcGIS Benthic Terrain Modeler
CRAMP	Coral Reef Assessment and Monitoring Program (Hawai‘i)
CZMIL	Coastal Zone Mapping Imaging Lidar
DAR	Division of Aquatic Resources (Hawai‘i DLNR)
DBM	digital bathymetric model

DLNR	Department of Land and Natural Resources (Hawai‘i)
FAHU	Fish and Habitat Utilization (DAR)
GV	ground validation
JALBTCX	U.S. Army Corps of Engineers Joint Airborne Lidar Bathymetry Technical Center of Expertise
lidar	light detection and ranging
MLLW	Mean Lower Low Water
MMA	Marine Management Area
NGCE	U.S. Department of Agriculture National Resources Conservation Service National Geospatial Center of Excellence
LMSL	Local Mean Sea Level
MMU	minimum mapping unit
MNMRC	Maui Nui Marine Resource Council
NCCOS	National Centers for Coastal Ocean Science (NOAA)
NCRMP	National Coral Reef Monitoring Program (NOAA)
NOAA	National Oceanic and Atmospheric Administration
sonar	sound navigation and ranging
USGS	U.S. Geological Survey

Benthic Habitat Map of Olowalu Reef, Maui, Hawaii—Geomorphological Structure, Biological Cover, and Geologic Zonation Determined with Spectral, Lidar, and Acoustic Data

By Liana N. Heberer,[1] Kristen A. Alkins,[2] Curt D. Storlazzi,[2] Susan A. Cochran,[2] Ann E. Gibbs,[3] Russell Sparks,[3] Kristy Stone,[3] Itana Silva,[3] Tatiana Martinez,[3] Cole Peralto,[3] Arielle S. Levine,[1] Douglas Stow,[1] and Jillian Maloney[1]

Abstract

The fringing coral reef off Olowalu, Maui, Hawaii, has been identified as a local conservation priority site. In 2007, the National Oceanic and Atmospheric Administration (NOAA) produced a benthic habitat map of the Hawaiian Islands that was used as a foundation for this study. To support place-based management of the reef in the future, the U.S. Geological Survey (USGS) mapped the geologic zone, major and dominant geomorphological structure, biological cover type, and percent of biological cover for 11 square kilometers (km^2) of Olowalu Reef at a minimum mapping unit (MMU) of 100 square meters (m^2) to create a benthic habitat map. Heads-up digitization was employed on 0.50-meter (m) natural color satellite orthoimagery with ancillary 1-m acoustic backscatter imagery from single-scan sonar (sound navigation and ranging). A 1-m, 4-m, and 8-m digital bathymetric model (DBM) was interpolated from bathymetric lidar (light detection and ranging), and various geomorphometric layers derived from the DBMs were used for habitat interpretation. Still-frame imagery of the seafloor extracted from vessel-towed underwater video transects on Olowalu Reef served as ground validation points (n=870) during active mapping and accuracy assessment points (n=216) for thematic accuracy assessment. Thematic accuracy was cross-validated by the Hawai‘i Department of Land and Natural Resources Division of Aquatic Resources. Final thematic accuracy was 88.8 percent for major structure, 85.6 percent for dominant structure, 86.0 percent for major biological cover, and 78.6 percent for type and percent of major biological cover. Reef and hardbottom constituted 52 percent of the total mapped habitat, comprising mostly aggregate reef (31 percent) and pavement (11 percent), with large swaths of spur-and-groove (9 percent). Of this hardbottom, 17 percent was covered with moderate (10 to <50 percent) coral and 27 percent with high coral cover (50 to <90 percent). High (50 to <90 percent) macroalgae cover dominated the continuous sand sheets in offshore bank/shelf zones.

The map created in this study supplements the NOAA 2007 map and expands on the observations made by USGS sampling of the reef. The NOAA 2007 map and our map differed in total areal extent by a negligible 6 m^2 and were in general thematic agreement. Our map is intended to serve as a baseline for public access, general research, local-level management, and reef change for future studies.

Introduction

The 410,00 acres of coral reef surrounding the eight main Hawaiian Islands (hereafter Hawai‘i) sustain endemic marine species (Friedlander and others, 2006), support nearshore fisheries valued at more than $10 million annually (Grafeld and others, 2017), and are natural breakwaters preventing $492 million in yearly flood damage to vital coastal infrastructure (Storlazzi and others, 2019; Reguero and others, 2021). To support place-based management of the reef for future studies, the U.S. Geological Survey (USGS), Hawai‘i Department of Land and Natural Resources’ Division of Aquatic Resources (DAR), and San Diego State University (SDSU) mapped the geologic zone, major and dominant geomorphological structure, biological cover type, and percent of biological cover for 11 square kilometers (km^2) of Olowalu Reef at a minimum mapping unit (MMU) of 100 square meters (m^2). Hawaiian reefs are currently assessed as “fair” condition; however, live coral cover, benthic structure, and fish populations have been in decline for decades (National Oceanic and Atmospheric Administration [NOAA], 2018). The main threats to Hawaiian reefs are (1) upland runoff causing terrigenous sedimentation and nutrient imbalance (Friedlander and others, 2005; Maui Nui Marine Resource Council [MNMRC], 2015); (2) marine heat waves triggering mass coral bleaching

[1]San Diego State University.

[2]U.S. Geological Survey.

[3]Hawai‘i Department of Land and Natural Resources Division of Aquatic Resources.

events (NOAA, 2018); and (3) overfishing and overuse, due in part to insufficient Marine Management Areas (MMA) enforcing sustainable fishing and recreation (Hawai‘i Department of Land and Natural Resources Division of Aquatic Resources [DAR], 2020). One purpose of an MMA is to preserve complex benthic habitat with diverse live coral cover supporting high species biomass (Friedlander and others, 2006). Currently just 6 percent of the waters in Hawaii are MMAs, but in 2016, the State committed to the “Holomua Marine Initiative” (formerly the “Marine 30×30 Initiative”) with the intention to effectively manage nearshore marine resources by implementing a comprehensive management strategy for State waters (DAR, 2020). DAR is leading the “Holomua Marine Initiative” efforts and prioritizing place-based planning targeting conservation priority sites. MMA is an umbrella term that includes various management areas that will count toward the “Holomua Marine Initiative”: Community-Based Subsistence Fishing Areas, Marine Life Conservation Districts, Fisheries Management Areas, Fish Replenishment Areas, Netting Restricted Areas, Limu Management Areas, Public Fishing Areas, Harbors, Canals, Natural Area Reserves and Wildlife Sanctuaries (DAR, 2020).

Olowalu Reef

A likely candidate for protection in the near future is Olowalu Reef, Maui’s largest fringing reef with 800 acres of submerged habitat spanning 10 undeveloped kilometers (km) of the island’s leeward west-central coastline between Olowalu and Ukumehame (fig. 1). The Olowalu area sits atop an alluvial fan on a coastal terrace abutting the ‘Īao Valley and other upland valleys and peaks of the Līhau section of the West Maui Natural Area Reserve. Olowalu Reef’s central positioning in the converging ‘Au‘au, Kealaikahiki, and ‘Alalākeiki Channels created by neighboring Kaho‘olawe, Lāna‘i, and Moloka‘i buffers the reef from the winter Kona (dry or leeward side of an island) and open-ocean trade swells that typically impede reef accretion on windward north shores (Fletcher and others, 2008). Sheltered from direct ocean swells and in the rain shadow of the West Maui Mountains, the area’s sunny and relatively low energy conditions have fostered complex benthic structure, moderate to high coral cover, and standalone massive *Porites lobata* (Dana, 1846) colonies an estimated 200 years old (Prouty and Gallagher, 2017). The habitat is known for beautiful spur-and-groove structure and unique blue

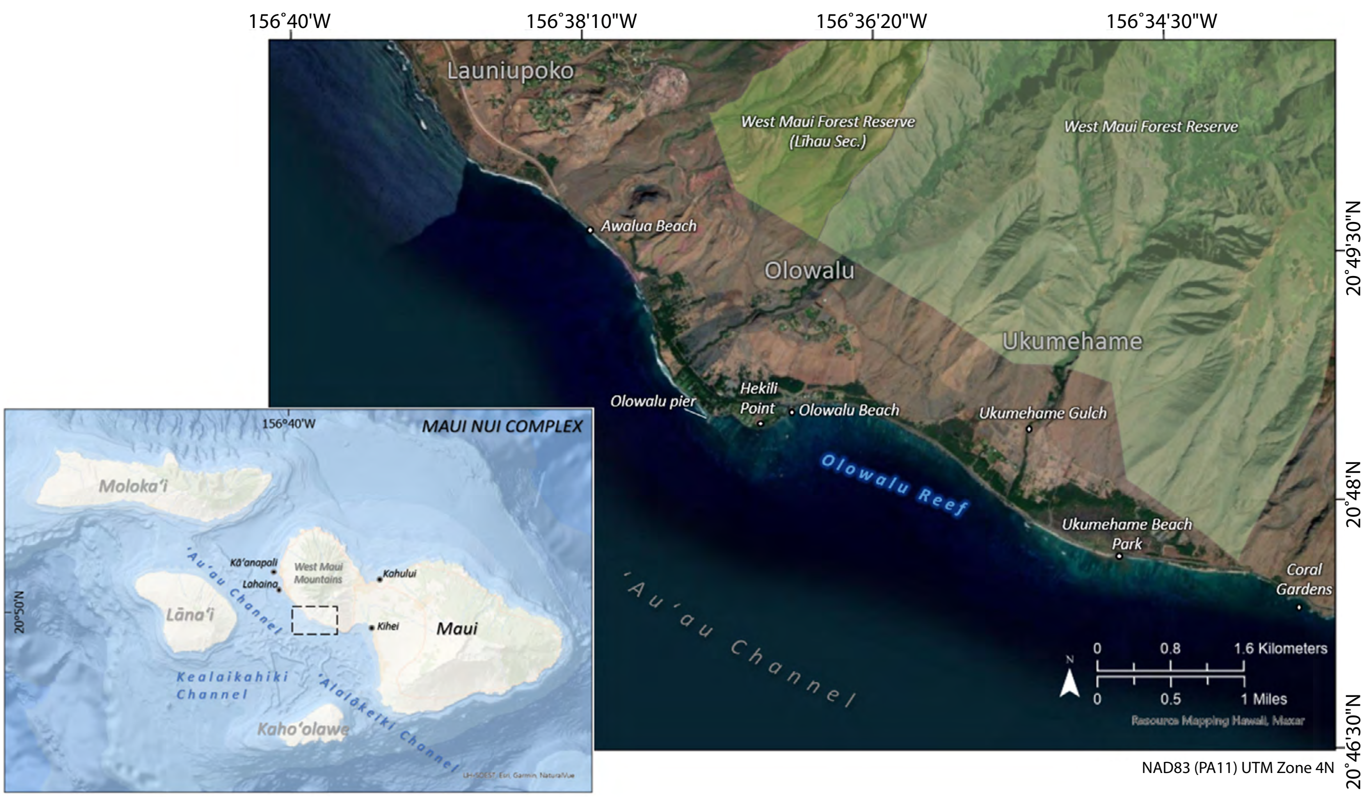


Figure 1. Map of Olowalu Reef, Maui’s largest fringing reef, which encompasses 800 acres of submerged habitat off west-central Maui in the Maui Nui complex of the main Hawaiian Islands between Olowalu and Ukumehame.

hole morphology (Brown, 2004; Gibbs and others, 2005; Field and others, 2019). Olowalu Reef is also considered an important “mother reef,” spawning essential coral larvae that drift on currents in the adjacent channels to seed surrounding reefs in the Maui Nui complex (Storlazzi and others, 2017).

Historically, the coastal site was a “pu‘uhonua” (sanctuary) where Hawaiians would take refuge and heal, as evidenced today by hieroglyphics and archaeological remains (Smith, 2011). Today, Olowalu is considered Maui’s “crown jewel” and is a popular recreation and fishing destination having pelagic sharks, sea turtles, and the largest population of manta rays in the United States (Maui Coral Reef Recovery Team, 2012). Given its large size and interconnected nature, cultural importance, and ecological value, Olowalu was nominated by the local community as a conservation priority site and as the first global Mission Blue Hope Spot for international recognition in Hawai‘i (MNMRC, 2015; Mission Blue, 2020).

Mapping Olowalu Reef

The reef has been a long-term monitoring site for the NOAA National Coral Reef Monitoring Program (NCRMP), the Hawai‘i Institute of Marine Biology Hawai‘i Coral Reef Assessment and Monitoring Program (CRAMP) since the early 1990s, and DAR’s Fish and Habitat Utilization (FAHU) monitoring since the mid-2010s. The NOAA National Centers for Coastal Ocean Science (NCCOS) mapped the Olowalu Reef tract as part of their larger mission to create the first digital maps of the nearshore waters of all U.S. states, territories, and commonwealths between 2002 and 2007 (Coyne and others, 2003; Battista and others, 2007). The NOAA team used heads-up digitization and visual interpretation of spectral signatures and bathymetry points derived from spectral data of 0.6-m satellite orthoimagery to map Olowalu at a 4,046-m^2 (1-acre) MMU. After applying common de-glinting, water column, and atmospheric corrections, a log-linear regression of spectral values with ground-validated depth values produced a few thousand depth sounding estimates then interpolated into a triangulated irregular network (BAE Systems, 2007). Mapping and thematic accuracy was validated by in situ diving observations at ground validation and accuracy assessment points. In the process, NOAA established the now industry-standard hierarchical reef classification scheme of nested major and dominant geomorphological structure, biological cover, percent biological cover, and reef zone. This 2007 NOAA map (Battista and others, 2007; hereafter, the 2007 map) identified nine geologic zones, two major geologic structures with 98.1 percent accuracy, six dominant geologic structures with 90.0 percent accuracy, and five major biological cover types with 92.1 percent accuracy (BAE Systems, 2007; Battista and others, 2007).

Whereas the 1-acre MMU and use of orthoimagery alone was appropriate for the project’s scale and timeline, many of Olowalu’s distinctive standalone microatolls, sand patches, and reef hole morphology smaller than 4,046 m^2 were omitted from the NOAA 2007 map (Battista and others, 2007). A finer resolution benthic habitat map of the reef was warranted to identify these smaller features that may prove important in local place-based planning in the future. More current, expansive, and high-resolution bathymetric datasets acquired from lidar (light detection and ranging) and sonar (sound navigation and ranging) are available for the Olowalu Reef area. These datasets provide continuous digital bathymetric models (DBM) and acoustic imagery, respectively, allowing for the inclusion of seafloor depth, geomorphometry, and acoustic reflectivity signatures (hardness) in identifying reef habitat rather than relying on spectral signatures from optical imagery alone (Cochran and others, 2014).

A variety of such finer scale supplements of the NOAA benthic habitat maps have been created in Hawai‘i to support local-level management objectives (Wedding and others, 2010; Cochran and others, 2014). In 2012, the USGS used a lidar DBM, sonar acoustic imagery, and a DBM-derived slope layer integrated with satellite orthoimagery to produce a finer scale map for the habitat off Kā‘anapali, just north of Olowalu (Cochran and others, 2014) (fig. 1). The USGS team used visual interpretation and heads-up digitization methods to map Kā‘anapali’s benthic habitat at an MMU of 100 m^2 with the established NOAA hierarchical classification scheme. Compared to the existing 4,046 m^2 MMU NOAA map for Kā‘anapali, the reduction in MMU and integration of high-resolution bathymetric data increased the total mapped acreage of coral cover by 62 percent, from roughly 327,795 to 870,074 m^2 (Field and others, 2019) and increased the possible mapping extent from 30 to 58 m depth (Cochran and others, 2014; Gibbs and others, 2013).

Purpose

Our objective is to provide a detailed fine-scale benthic habitat map of Olowalu in support of future local-level management of the reef. In this study, the USGS mapped Olowalu Reef at a 100 m^2 MMU (in contrast to the existing 4,046 m^2 MMU 2007 NOAA map), so that smaller features may be identified to increase the precision of the assessment, which may prove important to future work.

Data

Satellite Orthoimagery

Multispectral, 50-centimeter (cm) spatial resolution optical imagery of the west Maui coastline was acquired by the DigitalGlobe WorldView-2 satellite sensor on November 19, 2012. The U.S. Department of Agriculture National Resources Conservation Service National Geospatial Center of Excellence (NGCE) orthorectified select images with visible seafloor, low winds, no rainfall, low sun glint, and 10 percent or less cloud cover using 10-m and 30-m USGS digital elevation models (DEMs). The positional accuracy of the orthoimagery was estimated by DigitalGlobe as 0.154 m. The NGCE pansharpened and rescaled the original 8-band, 16-bit orthoimages to produce a final 3-band, 8-bit seamless orthomosaic of the entire west Maui coastline with blue (450–510 nanometers [nm] wavelength), green (510–580 nm), and red (625–690 nm) bands (fig. 2).

Lidar Bathymetry

Airborne topographic/bathymetric lidar mapping was conducted over the west Maui coastline between October 16 and November 25, 2013, by the U.S. Army Corps of Engineers Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX). The Coastal Zone Mapping Imaging Lidar (CZMIL) system (Teledyne Optech, Toronto, Canada) mapped from the shoreline to approximately 60 m depth at a mean sensor operating altitude of 400 m, a 20° circular prism scan angle at a scan frequency of 27 hertz (Hz), a laser pulse of 10 kilohertz (kHz), and an estimated 0.23 m horizontal point spacing (NOAA Office for Coastal Management Partners, 2019). The JALBTCX georeferenced the lidar points to the North American Datum of 1983 (NAD 83) (NA11) ellipsoid in meters and to the vertical Local Mean Sea Level (LMSL) tidal datum before classifying points as ground, bathymetric, or unclassified based on American Society for Photogrammetry and Remote Sensing Laser (LAS) standards. The JALBTCX also generated a LMSL shoreline contour vector equivalent to the North American Vertical Datum of 1988 (NAVD 88) 0-m contour for the island of Maui from the CZMIL topobathymetry lidar data (fig. 2).

Acoustic Imagery

Side-scan sonar data were collected with a 234-kHz interferometric Submetrix Bathyswath system (formerly SWATHplus, ITER Systems, Saint-Jorioz, France) by the USGS during R/V (research vessel) *Alyce C* Cruise A–01–13–HW on February 12, 2013 (Gibbs and others, 2023). Horizontal positions were referenced to NAD 83 (NA11), and the vertical datum was shifted from the geodetic World Geodetic System 1984 (WGS 84) ellipsoid to the Mean Lower Low Water (MLLW) tidal datum based on tides observed at surveying. For the Maui region, this vertical datum shift was about 16.1 m. The side-scan sonar data were processed using SonarWiz software (Chesapeake Technology, Inc., Los Altos, Calif.) to produce a 1-m resolution backscatter image showing possible hard substrate as pixels of darker hues (0) and possible soft substrate as pixels of brighter hues (129).

Seafloor Reference Imagery

The USGS conducted Cruise A–02–11–MU off west-central Maui between Launiupoko and Ukumehame on March 19–21, 2011, to collect underwater video footage of the seafloor as in situ mapping reference data (Gibbs and others, 2013). A SplashCam marine video system was equipped with depth, temperature, and direction sensors, a SideWinder 360 dual video camera unit with a nadir-viewing Sony 8.5-millimeter (mm) camera, and a 360° panning Sony 8.5-mm camera. The camera sled was towed behind R/V *Alyce C* underway along 16 shore-normal seaward transects and 1 shore-parallel transect totaling to 7.7 km (fig. 2). Transects started from the shallowest depth accessible by the vessel and terminated where (1) the benthic environment was free of coral, or the seafloor was an unchanging vegetated or non-vegetated sand sheet, (2) the limit of visibility was reached, or (3) the maximum 60 m of cable was deployed (Gibbs and others, 2013). Towed camera transects (8 percent of total imagery) generally occurred in 10–40 m depth with the camera kept at least 50 cm above the seafloor to protect corals. For drop-camera imagery (92 percent of total imagery), the camera was lowered by hand or winch to avoid harming coral while the vessel drifted slowly over 214 stations, located at 5-, 10-, 15-, 20-, 25-, and 30-m isobaths.

Acquisition time, date, vessel speed, and vessel location were overlaid on live video using the SeaViewer Sea-Trak GPS Video Overlay system (SeaViewer Cameras Inc., Tampa, Florida). Vessel location was acquired by a Novatel ProPak-G2plus and transmitted at 2-second intervals for simultaneous encoding onto the video audio track using the VMS200 system (Systems with Intelligence, Inc., Ontario, Canada). JPEG still frames were extracted from the video every 10 seconds using MediaMapper (v. 5.3, Red Hen Systems, LLC, Fort Collins, Colo.). The final JPEG images retained the time, date, vessel-based Global Positioning System (GPS) location, and vessel speed. Video and still-frame points were indexed on the transect line and hyperlinked to the USGS Hawaiʻi Seafloor Imagery repository of the Coastal Video and Photograph Portal of the Integrated Ocean Observing System (https://video.ioos.us/#metadata/e09f6cde-2d3a-4658-bc59-d357f5eba2a0/69c2e4a8-60c2-11e5-bcbc-00265529168c) as an interactive shapefile.

Methods

Data Reprocessing

All datasets were transformed in Esri ArcMap 10.8.2 (Esri, Redlands, Calif.) from their native geographic coordinate systems to the NAD 83 (PA11) epoch 2010.00 fixed to the Pacific Plate and projected to Universal Transverse Mercator (UTM) zone 4N (range 162°–156° W.) for the Hawaiian Islands. Vertical positions used for depth remained referenced to the LMSL tidal datum. Only lidar bathymetry data were used to infer depth, whereas the acoustic backscatter imagery was used to infer substrate type independent of depth. No vertical adjustments were made to match the LMSL tidal datum used in the lidar surveying to the MLLW tidal datum used in the acoustic surveying. Based on the NOAA National Geodetic Survey datum information for Kahului Harbor, Hawaiʻi (1983–2001 epoch), LMSL is +0.339 m from MLLW, which is within Hawaii's microtidal annual range of 0.8 m.

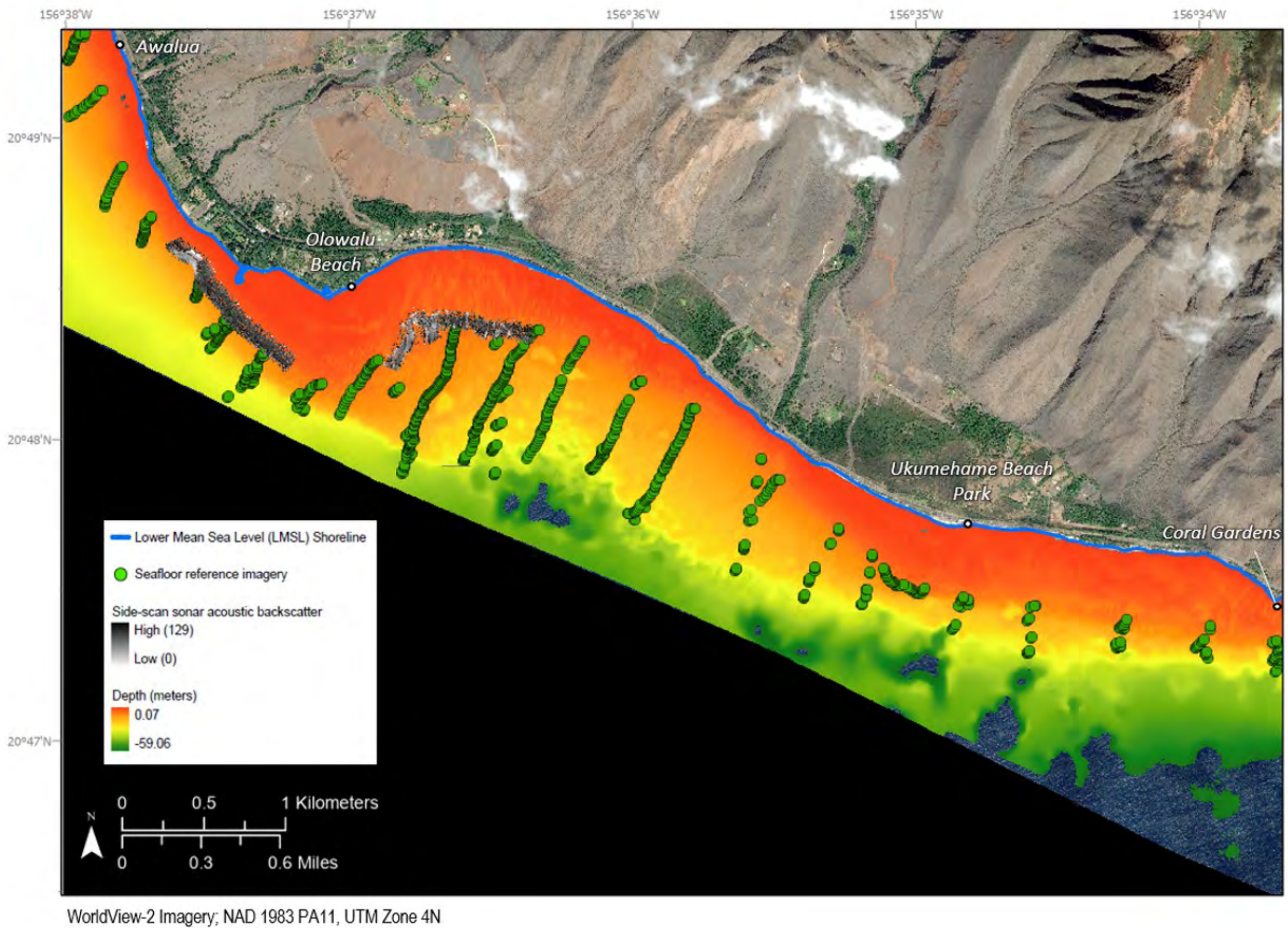


Figure 2. Map of lidar bathymetry, acoustic imagery, seafloor reference imagery locations, and the shoreline vector for the Olowalu Reef, Maui, Hawaii.

Olowalu Reef Extent

A polygon was created to clip all remote sensing datasets to the Olowalu Reef extent for mapping. The LMSL shoreline contour vector was snapped to the visible seaward extent of the orthoimage basemap, resulting in an 11.2 km^2 (11,225,309 m^2) area from the shoreline to 1.8 km seaward, bounded by Awalua beach in Olowalu and Coral Gardens in Ukumehame (fig. 1).

Digital Bathymetric Models from Lidar Bathymetry

A custom extent covering Olowalu was created with the NOAA Digital Coast Data Access Viewer to select ground and bathymetric CZMIL lidar points of all returns (NOAA Coastal Services Center, 2014). A total of 21,762,345 bathymetric lidar points within the Olowalu extent were interpolated into 1-m, 4-m, and 8-m DBM GeoTIFFs by the average interpolation method using the online Data Access Viewer interface. The average interpolation method was selected because it does not extrapolate values outside of the surveyed dataset, instead averaging the values of all lidar soundings within the defined DBM cell spatial resolution (NOAA Coastal Services Center, 2014). If a cell contained no lidar points, depth was interpolated by inverse distance weighting from at least three surrounding cells with lidar points and average depth values, identified by a graduating search box first at 3×3 cells, then 5×5, and lastly 7×7. If no more than three usable depth values were found by the 7×7 box, the DBM cell was assigned a no data (−999999) value. The DBM tiles were mosaicked and clipped to the Olowalu Reef extent.

Subsetting the Ground Reference Imagery

A total of 1,256 video points and 1,086 still-frame image points fell within the Olowalu Reef extent; however, only the still-frame image points were associated with known coordinates for reference during later cross-validation. The still-frame image point coordinates were referenced to the vessel-based GPS and not to the physical location of the underwater camera, producing a “layback” of uncorrected positional offset estimated as less than 5 m at drop camera stations (Gibbs and others, 2005) and a maximum of 10 m for towed camera transects. A 10-m radius spatial buffer was applied to each image point to provide the most conservative boundary of estimated layback during habitat interpretation. Ship speed and heading information for each image, as annotated on the individual JPEG, was manually populated into the point feature attribute table.

The 1,086 image points were subset by random sampling to produce two separate feature classes: (1) ground validation (GV) points, comprising 870 points (80 percent of the data) for reference during mapping, and (2) accuracy assessment (AA) points, comprising 216 points (20 percent of the data) withheld for post-mapping thematic accuracy assessment.

Deriving Geomorphic Layers from the Digital Bathymetric Model (DBM)

Geomorphic attributes useful in visually differentiating habitat such as seafloor surface gradient, position, and rugosity were derived from various analysis window sizes on the 1-m, 4-m, and 8-m DBMs using the ArcGIS Benthic Terrain Modeler (BTM) extension (Wright and others, 2012) in ArcMap (fig. 3). Comprehensive attribute and equation descriptions available in the BTM are detailed by Walbridge and others (2018).

1. Surface gradients:
    - Planar slope (SLOPE) in degrees
    - Mean depth (MN) in meters
    - Statistical aspect separating northerness (NORTH), due north (1) and south (−1), and easterness (EAST), due east (1) and west (−1), to avoid confounding numerically distant numbers oriented in the same direction (for example, 359° and 1° both represent north)
2. Rugosity:
    - The slope-corrected surface-to-planar-area (SAPA), calculated with the arc-chord ratio using contoured surface area divided by the cell area projected onto the plane of the local slope, rather than the projected plane-of-best-fit which confounds the effects of slope over distance.
    - Vector ruggedness measure (VRM) captures variability in slope and aspect into a single continuous metric from 0 (no terrain variation) to 1 (complete terrain variation).
    - Depth standard deviation (DSD)
    - Depth variance (VAR)
3. Position:
    - Curvature (CURV) in degrees
    - Plan curvature (PLAN) in degrees
    - Profile curvature (PROF) in degrees
    - Bathymetric position index (BPI) calculated at two scales: fine scale BPI calculated using an analysis annulus inner radius (Ri) of 5 cells and outer radius (Ro) of 25 cells, and broad scale BPI with Ri:25, Ro:250. Using the options in the BTM, the BPI layers were standardized to 1 standard deviation to avoid the influence of spatial autocorrelation, as the range of BPI values increases with scale. Larger analysis window sizes (broad-scale BPI) average out small variations in the terrain, whereas smaller neighborhood sizes (fine scale BPI) include smaller, localized variations in the terrain (fig. 3).

Mapping and Classification

The satellite orthomosaic was established as the basemap, with slight adjustments to contrast and brightness to aid visual interpretation. The acoustic imagery, 1-m, 4-m, and 8-m DBMs, geomorphic layers, and GV image points were overlaid as active reference layers during mapping. The USGS hierarchical reef classification scheme (table 1) was loaded into the NOAA Habitat Digitizer extension (https://coastalscience.noaa.gov/project/habitat-digitizer-extension/), with the MMU set to 100 m^2 and digitizing scale left unrestricted. The USGS scheme slightly modified the NOAA scheme for the main Hawaiian Islands (Battista and others, 2007) to attributes common to fringing reefs in Hawaii (Cochran and others, 2014). Most habitat descriptions contained a depth and geomorphic qualifier, such as “formations with high relief and complexity” for aggregate reef or “having a seaward-facing slope” for fore reef. Habitat descriptions, definitions, and image examples are detailed in appendix 1. Shore-normal seaward bathymetric profiles were interpolated from the 1-m and 4-m DBMs using ArcMap 3D Analyst tools to help with identifying reef zonation during mapping.

Seafloor Reference Imagery Classification

The 216 AA and 870 GV points were classified with “major” and “dominant structure,” “biological cover,” “percent cover,” and “reef zone” based on visual interpretation of the reference image with coincident geomorphic layers, acoustic imagery, DBM, and orthoimage basemap within the 10-m buffer. If the reference image included more than two class types, the dominant type covering more than 50 percent of area was used. A “high,” “moderate,” or “low” image clarity attribute indicating habitat visibility was manually added to each reference point. Most high clarity images were taken at nadir and close to the seafloor, conditions typical of drop-camera stations (fig. 4). A total of 32 AA points with low image clarity were flagged for extra attention during cross-validation.

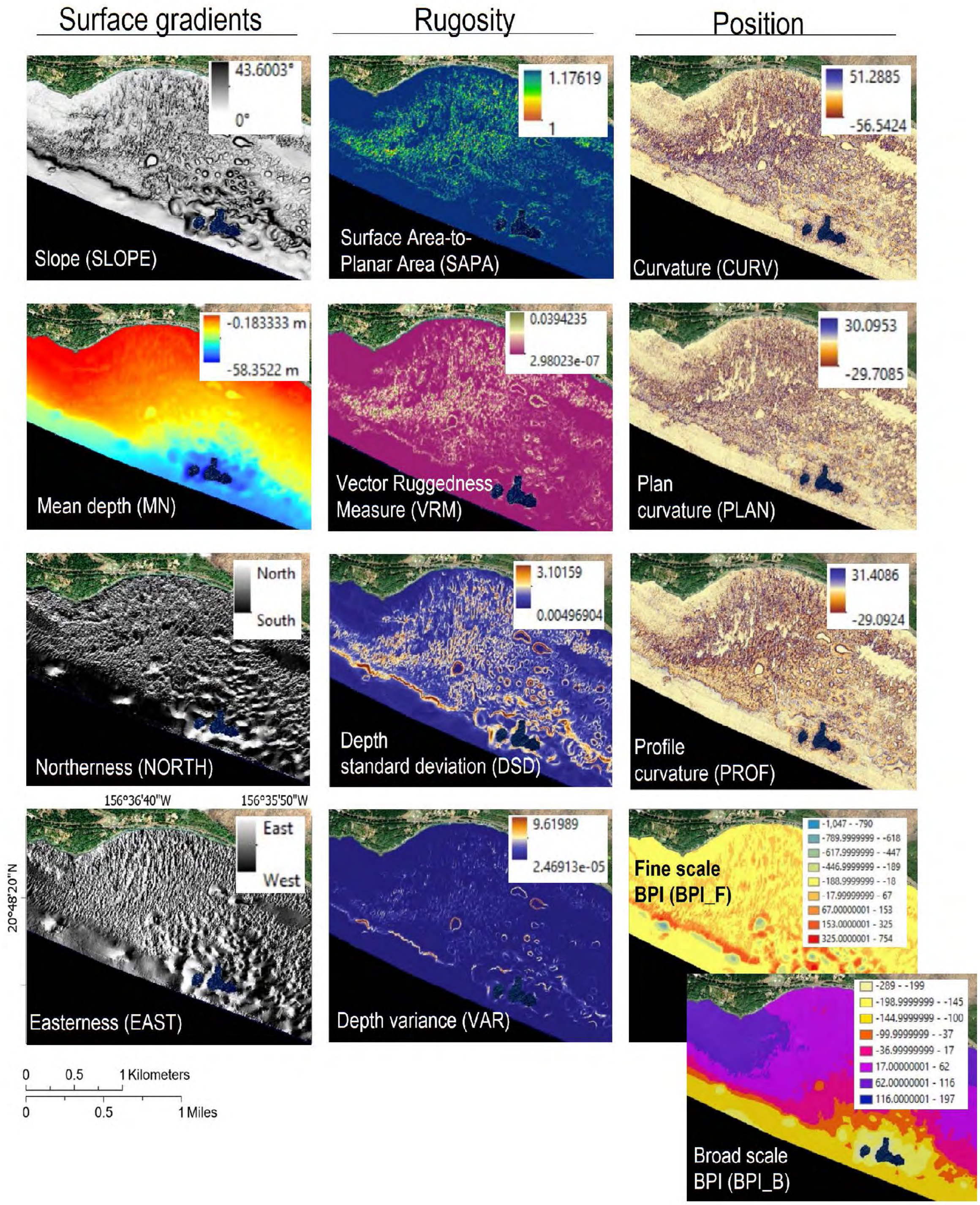


Figure 3. Images of geomorphic attributes derived using the ArcGIS Benthic Terrain Modeler (BTM) extension (Wright and others, 2012) for differentiating habitat based on seafloor surface gradient, position, and rugosity. Values shown here were computed using a 3×3 window on a 4-meter (m) digital bathymetric model (DBM). Scale and location information provided for easterness map applies to all maps.

Table 1. The U.S. Geological Survey (USGS) hierarchical reef classification scheme for geologic zone, major structure, dominant structure, major biological cover, and percent biological cover, Olowalu Reef, Maui, Hawaii.

[USGS reef classification system modified from Battista and others (2007) to attributes common to fringing reefs in Hawaii (Cochran and others, 2014). Numbers before descriptions (in bold) represent a universally unique identifier (UNIQUEID); for example, 1214=unconsolidated sediment, sand, uncolonized, 90–100%. >, less than; %, percent]

Major structure	Dominant structure	Major biological cover	Percent biological cover	Geologic zone
1 Unconsolidated sediment	**1** Mud **2** Sand	**0** Unknown **1** Uncolonized **2** Macroalgae **3** Seagrass **4** Coralline algae **5** Coral **6** Turf **7** Emergent vegetation **8** Mangrove **9** Octocoral	**0** Unknown **2** 10–<50% **3** 50–<90% **4** 90–100%	Land Shoreline/intertidal Vertical wall Lagoon Back reef (lagoon) Reef flat (no lagoon) Reef crest Fore reef Bank/shelf Bank/shelf escarpment Channel Dredged
2 Reef and hardbottom	**1** Aggregate reef **2** Spur-and-groove **3** Individual patch reef **4** Aggregated patch reef **5** Pavement, 10–50% Rocks/Boulders **6** Pavement **7** Pavement, >50% Rocks/Boulders **8** Pavement with sand channels **9** Reef rubble			
3 Other	**0** Unknown **1** Land **2** Artificial **3** Artificial/historical			
9 Unknown	**0** Unknown			

Figure 4. Still frame images of the seafloor annotated with vessel-based Global Positioning System (GPS) location, vessel speed, time, date, and camera heading as captured from drop- and towed-camera video transects over Olowalu Reef, Maui, Hawaii, in March 2011. Based on the benthic visibility, images were labeled as high (*A*), moderate (*B*), or low (*C*) clarity for help during visual classification and cross-validation.

Benthic Habitat Mapping

The NOAA Habitat Digitizer extension was used to heads-up classify habitat at least 100 m^2 in area with distinct color, shape, depth, substrate hardness, and geomorphic patterns. Occasionally, reef features smaller than the MMU deemed as important standalone habitat were outlined. “Major structure” and “dominant structure” were classified first, using mostly geomorphic data in waters deeper than 40 m; substrate hardness, geomorphic patterns, and spectral patterns were mostly used in shallower waters. “Biological cover” was then classified using visual interpretation of the 10-m buffered GV image points, which were found to correspond to habitat about 10 m shoreward of their referenced point location based on both the basemap and geomorphic layers during mapping. “Reef zones” were classified last using geomorphic data, depth, biological cover (appendix 1), and various shore-normal reef profiles. Each polygon was classified at the time of digitization from the extension’s point-and-click menu and automatically appended to the shapefile attribute table.

Accuracy Assessment

Coauthors from the DAR located in Maui County and familiar with Olowalu's benthic habitat provided cross-validation of the 216 classified AA points and reviewed the map. The DAR team was provided the detailed classification scheme (appendix 1) and all reference layers in an ArcMap package. The AA points deemed wrong within the 10-m buffer were reclassified by DAR for final accuracy assessment.

Agreement between the AA points and the map were calculated for scientists, managers, and overall accuracy. Overall accuracy was computed by dividing the total number of map polygons classified correctly by the total number of AA points. The producer's accuracy—the probability of the image object on the map being classified correctly—was calculated as the total number of polygons classified correctly within each class divided by the total number of AA points within that class. The user's accuracy—the probability that a polygon classified on the map represents that category on the actual reef—was calculated as the total number of polygons classified correctly in each category divided by the total number of AA points in that category.

The final draft and all mapping layers were sent to the DAR for review before finalization, and any misinterpreted polygons were re-identified correctly. Final quality control included correcting topology errors and merging adjacent polygons with the same attribute across all classes for visual continuity.

Map Comparison

The differences in digitizing scale and target MMU prevent the direct comparison of spatial and thematic accuracy between the existing Battista and others (2007) map and the map created in this study (hereafter, the 2025 map that accompanies this report). However, general agreement was compared by clipping both maps to the Olowalu Reef extent and calculating the areal extent and proportion of total area mapped by class within each map.

Results

Of the 216 AA points audited by DAR, 179 were validated without changes (83 percent agreement) and the remaining 37 were reclassified. Most reclassifications were within the "reef and hardbottom" structure type, particularly 19 points changed from spur-and-groove to aggregate reef, 3 of which were noted to be in transitional zones between two habitat types (for example, "aggregate reef between larger sand patches"). A total of 12 such transitional points were noted during DAR's cross-validation; however, one AA point was positioned exactly on a polygon line separating two habitat types and was omitted from assessment for a final 215 AA points.

Independent from their cross-validation of the AA points, DAR suggested reclassifying 4 of the 710 habitat polygons from spur-and-groove to aggregate reef, which were integrated into the final map. The thematic accuracy assessment of the final map resulted in 88.8 percent for major structure (table 2), 85.6 percent for dominant structure (table 3), 86.0 percent for major biological cover (table 4), and 78.6 percent for percentage of major biological cover (table 5).

Users of this map (https://doi.org/10.5066/P9ICJ7CF) should note the lowest producer's accuracy—suggesting errors of omission or undermapping—for dominant structure is for "pavement" (table 3). Most of the AA points classified as pavement were mapped as sand, likely due to similar low relief signatures in the geomorphic layers as guidance. Additionally, the lowest producer's accuracy for biological cover (table 5) shows "uncolonized, 10–<50%" was primarily mapped as "coral, 50–<90% or uncolonized, 50–<90%." However, the user's accuracy—errors of commission, a measure of reliability for the user—suggests major and dominant structure and biological cover classified on the map likely represents that category on the actual reef, particularly for "reef and hardbottom > spur-and-groove > coral."

Table 2. Accuracy assessment matrix for major structure, resulting in 88.8 percent overall accuracy, Olowalu Reef, Maui, Hawaii.

[U.S. Geological Survey reef classification system modified from Battista and others (2007) (refer to table 1). Of the 216 accuracy assessment (AA) points, 1 was omitted from the assessment for a final of 215 AA points. Producer's accuracy, probability of the image object on the map being classified correctly; user's accuracy, the probability that a polygon classified on the map represents that category on the actual reef; %, percent; —, no classification]

Major structure as mapped	Accuracy assessment points			User's accuracy (%)
	Reef and hardbottom	Unconsolidated sediment	Total	
Reef and hardbottom	[a]143	12	155	92.3
Unconsolidated sediment	12	[a]48	60	80.0
Total	155	60	—	—
Producer's accuracy (%)	92.3	80.0	—	[b]191
Overall accuracy (%)	—	—	—	**88.8**

[a]Used to calculate diagonal sum (gray shading).

[b]Diagonal sum, the number of points in agreement with the 215 total AA points.

Table 3. Accuracy assessment matrix for dominant structure, resulting in in 85.6 percent overall accuracy, Olowalu Reef, Maui, Hawaii.

[U.S. Geological Survey reef classification system modified from Battista and others (2007) (refer to table 1). Of the 216 accuracy assessment (AA) points, 1 was omitted from the assessment for a final of 215 AA points. Producer's accuracy, probability of the image object on the map being classified correctly; user's accuracy, the probability that a polygon classified on the map represents that category on the actual reef; %, percent; —, no classification]

Dominant structure as mapped	Accuracy assessment points						Total	User's accuracy (%)
	Aggregate reef	Aggregated patch reef	Individual patch reef	Pavement	Spur-and-groove	Sand		
Aggregate reef	[a]100	—	—	3	3	10	116	86.2
Aggregated patch reef	—	—	—	—	—	—	0	—
Individual patch reef	—	—	—	1	—	—	1	0.0
Pavement	—	—	—	[a]2	—	—	2	100.0
Spur-and-groove	—	—	—	—	[a]34	2	36	94.4
Sand	2	—	—	8	2	[a]48	60	80.0
Total	102	0	0	14	39	60	—	—
Producer's accuracy (%)	98.0	—	—	14.3	87.2	80.0	—	[b]184
				Overall accuracy (%)				**85.6**

[a]Used to calculate diagonal sum (gray shading).

[b]Diagonal sum, the number of points in agreement with the 215 total AA points.

Table 4. Accuracy assessment for major biological cover, resulting in 86.0 percent accuracy, Olowalu Reef, Maui, Hawaii.

[U.S. Geological Survey reef classification system modified from Battista and others (2007) (refer to table 1). Of the 216 accuracy assessment (AA) points, 1 was omitted from the assessment for a final of 215 AA points. Producer's accuracy, probability of the image object on the map being classified correctly; user's accuracy, the probability that a polygon classified on the map represents that category on the actual reef; %, percent; —, no classification]

Biological cover as mapped	Accuracy assessment points				User's accuracy (%)
	Coral	Macroalgae	Uncolonized	Total	
Coral	[a]141	2	12	155	91.0
Macroalgae	4	[a]22	9	35	62.9
Uncolonized	3	—	[a]22	25	88.0
Total	148	24	43	—	—
Producer's accuracy (%)	95.3	91.6	51.2	—	[b]185
			Overall accuracy (%)		**86.0**

[a]Used to calculate diagonal sum (gray shading).

[b]Diagonal sum, the number of points in agreement with the 215 total AA points.

Table 5. Accuracy assessment for type and percent of biological cover, resulting in 78.6 percent accuracy, Olowalu Reef, Maui, Hawaii.

[U.S. Geological Survey reef classification system modified from Battista and others (2007) (refer to table 1). Of the 216 accuracy assessment (AA) points, 1 was omitted from the assessment for a final of 215 AA points. Producer's accuracy, probability of the image object on the map being classified correctly; user's accuracy, the probability that a polygon classified on the map represents that category on the actual reef; %, percent; —, no classification]

Type and percent of biological cover as mapped (%)	Accuracy assessment points							Total	User's accuracy (%)
	Coral, 10–<50%	Coral, 50–<90%	Macroalgae, 10–<50%	Macroalgae, 50–<90%	Uncolonized, 10–<50%	Uncolonized, 50–<90%	Uncolonized, 90–100%		
Coral, 10–<50	[a]20	3	1	—	—	1	—	25	80.0
Coral, 50–<90	7	[a]111	—	1	2	—	9	130	85.4
Macroalgae, 10–<50	—	—	[a]3	1	—	2	4	10	30.0
Macroalgae, 50–<90	4	—	1	[a]17	—	1	2	25	68.0
Uncolonized, 10–<50	—	—	—	—	[a]0	—	—	0	0.0
Uncolonized, 50–<90	1	—	—	—	2	[a]2	2	7	28.6
Uncolonized, 90–100	—	2	—	—	—	—	[a]16	18	88.9
Total	32	116	5	19	4	6	33	—	—
Producer's accuracy (%)	62.5	95.7	60.0	89.5	0.0	33.3	48.5	—	[b]169
Overall accuracy (%)									**78.6**

[a]Used to calculate diagonal sum (gray shading).

[b]Diagonal sum, the number of points in agreement with the 215 total AA points.

The final map comprises 683 polygons, ranging from 30 m^2 individual and isolated coral colonies to the offshore continuous macroalgae sand sheet spanning 1,158,704 m^2 (1.15 km^2). The majority of Olowalu's benthic habitat was reef and hardbottom covered with 50 to <90 percent coral, followed by unconsolidated sediment covered with 50 to <90 percent macroalgae (fig. 5). Of the 11.2 km^2 mapped, approximately 11 percent (1.2 km^2) was classified as "unknown" across all attributes due to a lack of lidar data, GV images, and visibility in satellite imagery over deeper waters (figs. 6–9). Whereas habitat in the deeper bank/shelf areas were most likely "unconsolidated sediment, sand, 50–<90% macroalgae" given the surrounding habitat with corroborated data, they were conservatively labeled as "unknown."

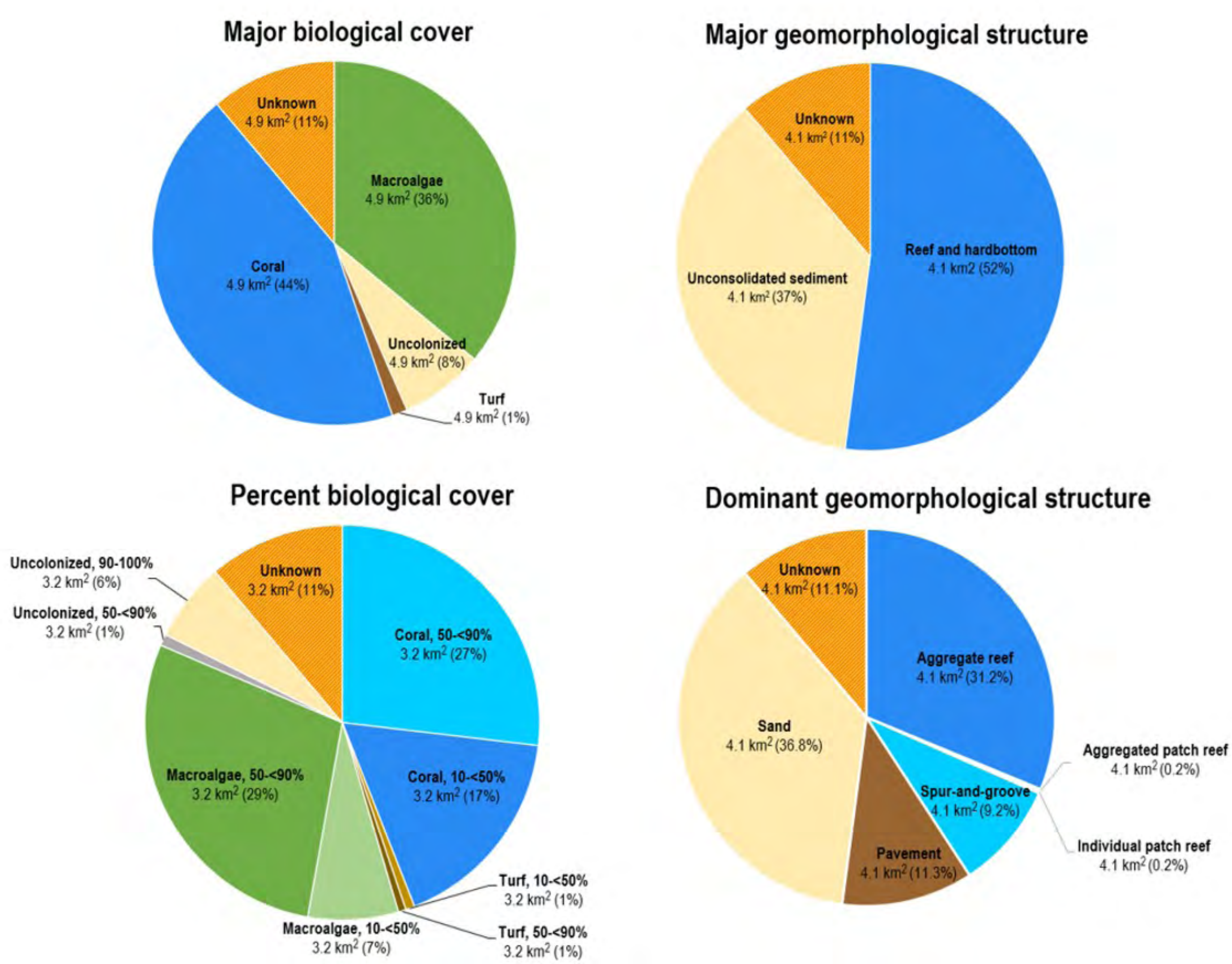


Figure 5. Pie diagrams of the extent and percent of total area mapped within major geomorphological structure, dominant geomorphological structure, major biological cover, and percent biological cover for 11.2 square kilometers (km^2) (11,225,309 square meters [m^2]) of Olowalu Reef, Maui, Hawaii. %, percent. For classification system, refer to table 1.

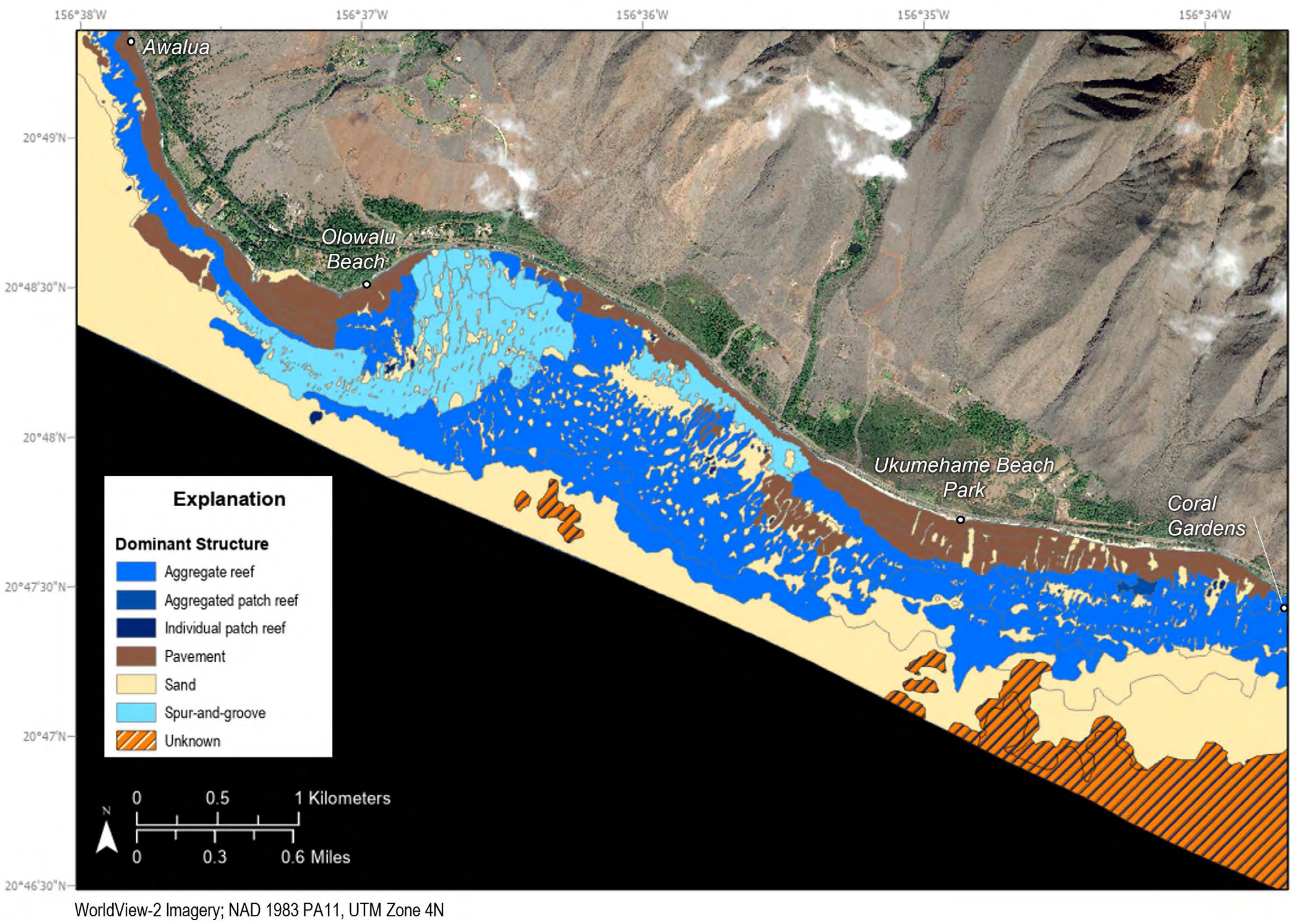
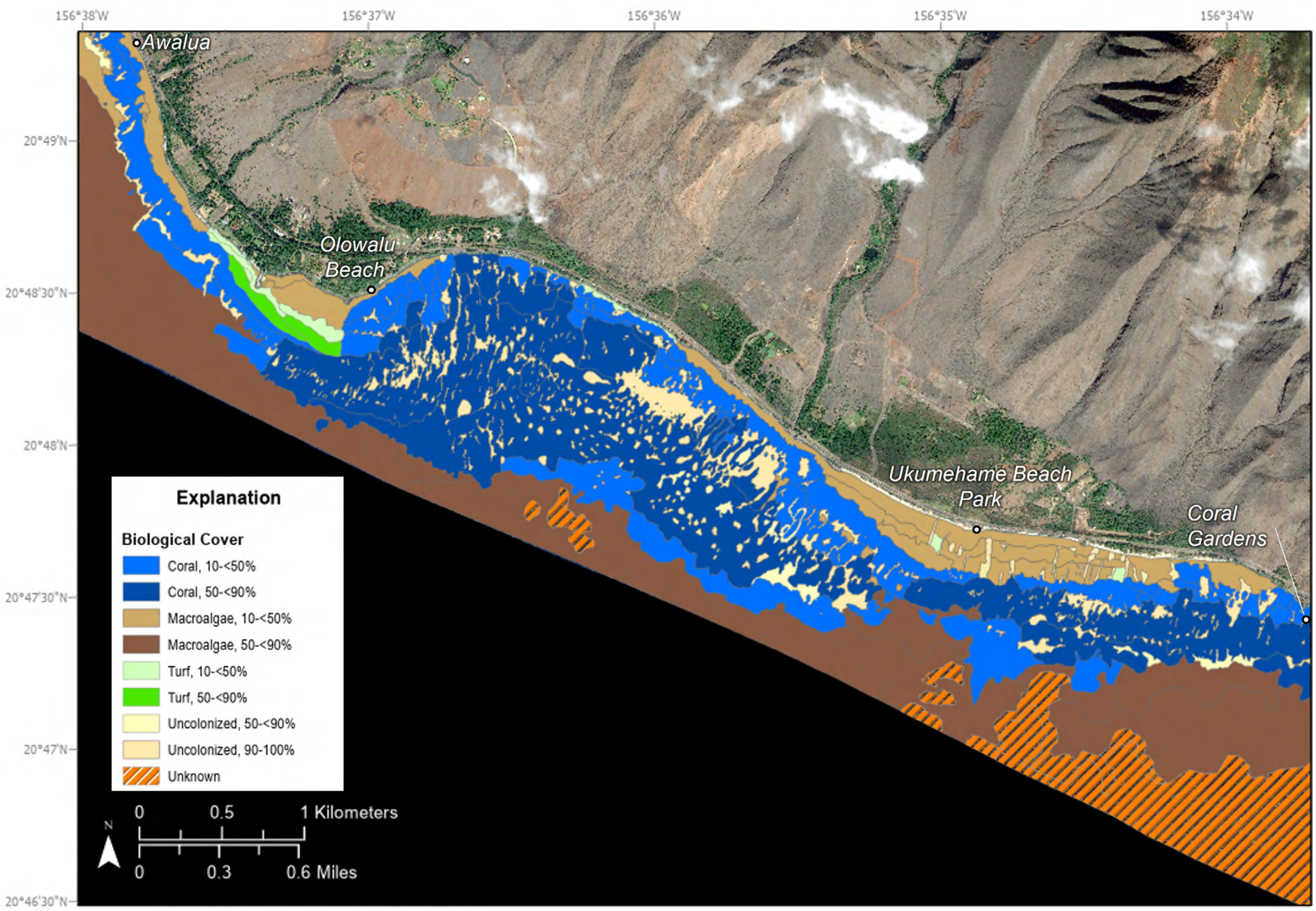
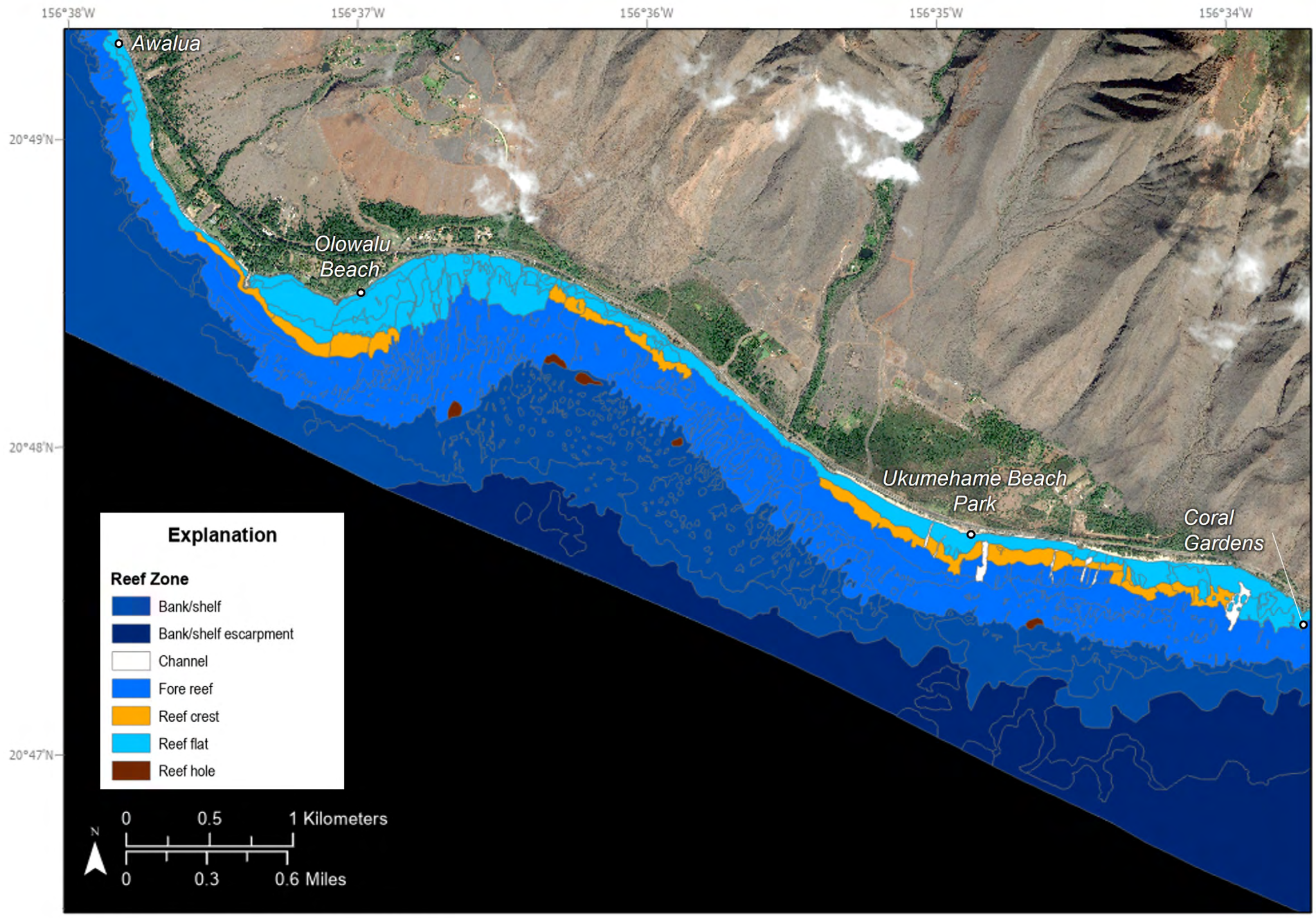


Figure 6. Map of the dominant geomorphological structure of Olowalu Reef, Maui, Hawaii, comprising majority aggregate reef, spur-and-groove, and sand. Unknown values are due in part to lack of seafloor data for interpretation. U.S. Geological Survey reef classification system modified from Battista and others (2007). For seafloor data, refer to figure 2.



WorldView-2 Imagery; NAD 1983 PA11, UTM Zone 4N

Figure 7. Map of the type and percent of biological cover of Olowalu Reef, Maui, Hawaii, comprising majority coral 10 to <50 percent, coral 50 to <90 percent, and macroalgae 50 to <90 percent. Unknown values are due in part to lack of seafloor data for interpretation. U.S. Geological reef classification system modified from Battista and others (2007). For seafloor data, refer to figure 2.



WorldView-2 Imagery; NAD 1983 PA11, UTM Zone 4N

Figure 8. Map of the reef zonation of Olowalu Reef, Maui, Hawaii. Unique reef hole geomorphology is present near the bank/shelf and fore reef transition in the central reef tract of the study area. Unknown values are due in part to lack of seafloor data for interpretation. U.S. Geological Survey reef classification system from Battista and others (2007). For seafloor data, refer to figure 2.

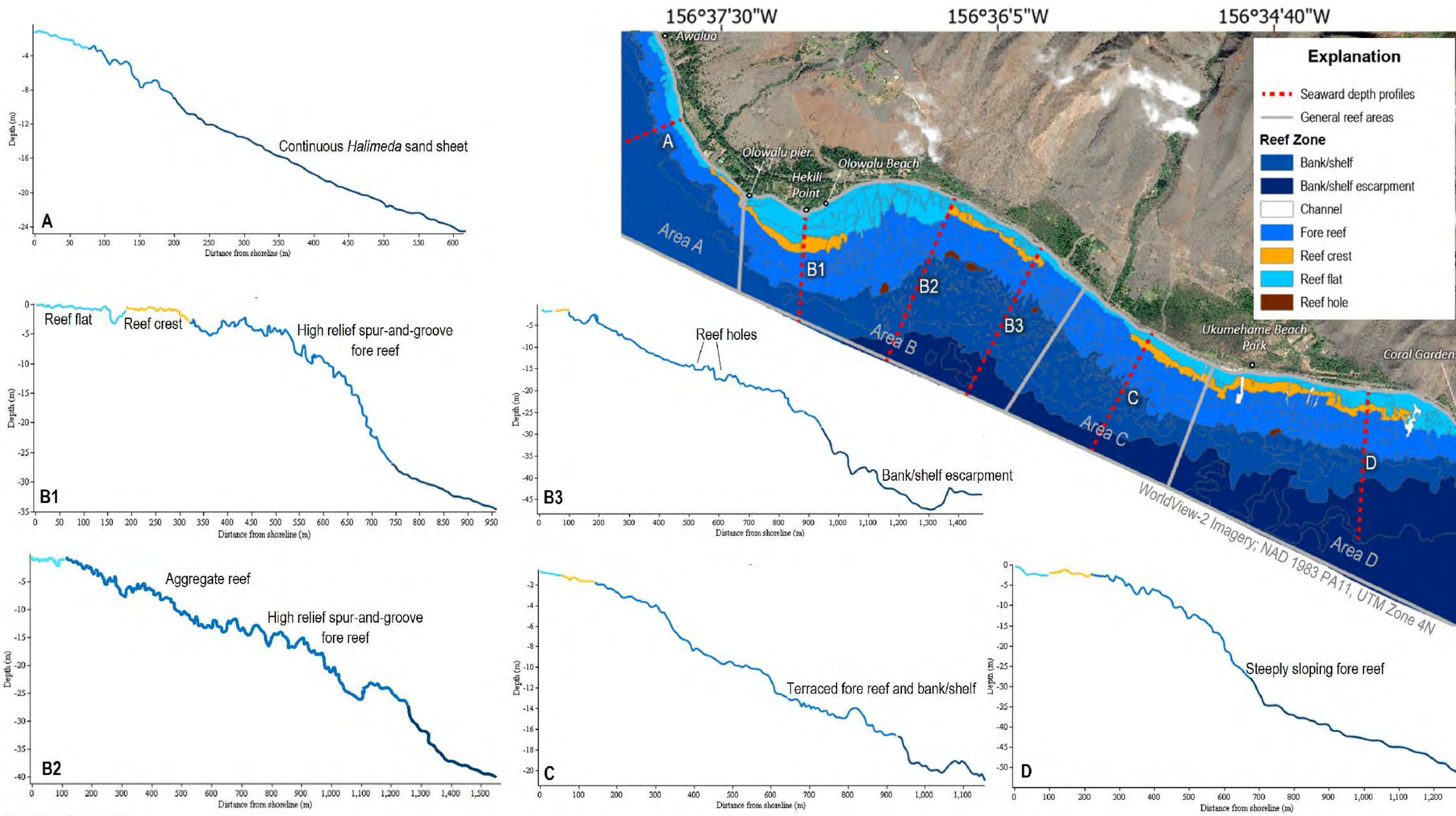


Figure 9. Map of Olowalu Reef, Maui, Hawaii, and shore-normal seaward depth profiles derived from a 1-meter (m) digital bathymetric model (DBM) of seaward transects reveal four general reef areas. These are shown in parts A–D, on Olowalu Reef with similar reef zonation and major geomorphological structure. Area A is characterized as a relatively shallow, low relief area with a consistently gradual linear slope. Area B is generally considered the main reef tract and is characterized by a broad and well-developed reef flat and fore reef, distinct sections of spur-and-groove, and large swaths of near continuous aggregate reef with 50 to <90 percent coral cover as deep as 40 meters (m). Area C marks a transition from the coral dominated spur-and-groove of Area B to more frequent pavement with variable cover. Unique to Area D are the inshore uncolonized sand channels that cut through the reef flat, consistent reef crest, and steeply sloping fore reef (refer to fig. 16). This section of reef descends into the deepest bank/shelf escarpment drop-offs of the entire mapping area, reaching at least 59 m, or the extent of the lidar signal penetration. U.S. Geological Survey classification system modified from Battista and others (2007). For seafloor data, refer to figure 2.

Benthic Habitat of Olowalu Reef

The final map of Olowalu Reef highlights the diverse and complex geomorphological structure of the reef with unique blue hole and smaller hole morphology and large swaths of spur-and-groove and aggregate reef (fig. 6) with moderate to high coral cover down to 40 m depth (fig. 7). The integration of geomorphometric layers helped identify habitat under breaking waves and clouds, discern false positive reef habitat in optical imagery as flat sand, and highlight complex seafloor structure in deep waters identified on the 2007 NOAA map as “unconsolidated sediment” (Battista and others, 2007). Notably, our map that accompanies this report included 10 new classes not included in the previous map, and we identified fewer “macroalgae” and “unknown” areas. We note that although unlikely, the addition of 10 new classes may also be due in part to actual changes in biological cover on the reef between 2007 and 2012, rather than a change in mapping workflow or data.

Slope, profile and plan curvature, statistical aspect, BPI, and surface-area-to-planar-area proved the most useful in the visual identification and classification of reef and hardbottom from unconsolidated sediment. Heberer (2023) provides a more detailed description of the geomorphometric layer combination and thresholds most useful in habitat discrimination, including a preliminary semi-automated rule set for object-based image analysis.

Comparison of the shore-normal seaward profiles (fig. 9) revealed four general areas, labeled A–D, with similar reef zone patterns and characteristics.

Area A of Olowalu Reef

This area starts south of Awalua beach down to the Olowalu pier (fig. 10) and is characterized as a relatively shallow, low relief area with a consistently gradual linear slope. The reef-flat pavement is covered with macroalgae, turf, and sparse coral cover mixed with what appears to be a thin coating of fine black basaltic sediment (Gibbs and others, 2005), likely terrigenous sedimentation. Besides a narrow reef crest near the Olowalu pier, most of the area’s reef flat shifts into a consistent 100-m to 200-m band of aggregate reef with 10 to <50 percent coral cover, interrupted by an occasional distinctive uncolonized sand clearing. A smaller section of the fore reef transitions again into pavement with sparse coral cover; however, most of the fore reef transitions abruptly into a continuous sand sheet with 50 to <0 percent *Halimeda* macroalgae cover (fig. 10*B*).

Area B of Olowalu Reef

Area B extends from the Olowalu pier and Hekili Point to just north of Ukumehame Beach Park (fig. 9) and is generally considered the main Olowalu Reef. It is characterized by a broad and well-developed reef flat and fore reef, distinct sections of spur-and-groove, and large swaths of near continuous aggregate reef with 50 to <90 percent coral cover as deep as 40 m. Unsurprisingly, this section of the reef appears to draw the bulk of recreationalists, as evidenced by the many paddleboards, kayaks, divers, and catamarans visible in the satellite imagery and the cover image for this report. The orientation of the reef mirrors the natural bend of Hekili Point into the curvature of Olowalu Beach, switching to a southwest-northeast trend wrapping around the embayment, then back to a northwest-southeast trend seen in Areas A, C, and D of figure 9. The reef flat off Hekili Point is primarily pavement covered with macroalgae, transitioning to turf and coral cover increasing seaward until the prominent reef crest 200 m from the shoreline. The reef crest is notable in the depth profile (fig. 9*B1*) but also by the white foam of breaking waves in satellite imagery, a telltale of submerged elevated reef structure. Spur-and-groove structure dominates the fore reef from Hekili Point and into the curvature of the sheltered waters leading to Olowalu Beach, where it extends

A *B*

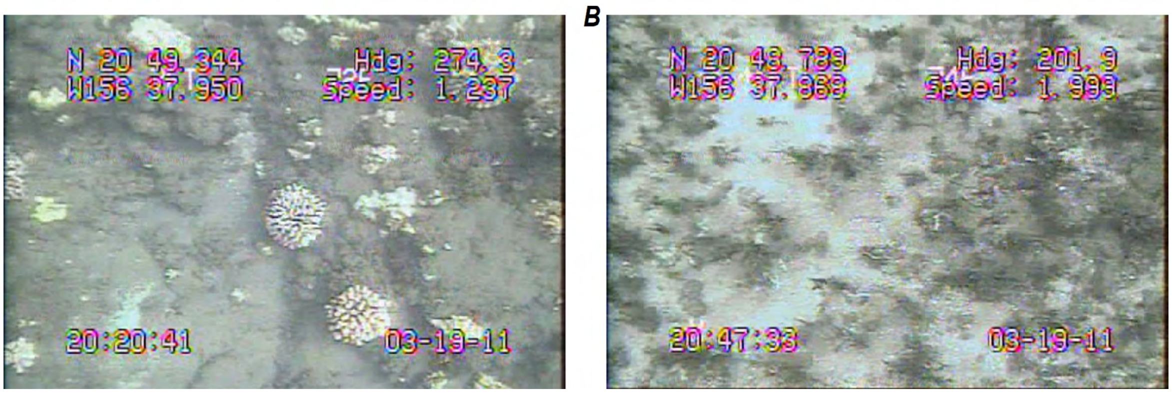


Figure 10. Seafloor reference images show sparse coral cover on pavement. *A*, A thin veneer of likely terrigenous sedimentation that characterizes some of the reef flat in Area A in figure 9*A*. *B*, The continuous sand sheet abutting the aggregate reef fore reef is covered with 50 to <90 percent *Halimeda* macroalgae cover. Seafloor images from Gibbs and others (2013).

some 700–1,000 m from the shoreline to the fore reef-bank/shelf transition (fig. 6) around 12 m depth. Consistently high coral (50 to <90 percent) covers the inner reef flat, fore reef, and bank/shelf in Area B, with standalone massive colonies of *Porites lobata* (fig. 11) that are visible from satellite imagery.

Aside from the expected sand grooves present between colonized spurs, distinct moderate (3,800 m^2; ~1 acre) to large (25,000 m^2; 6 acre) clearings of 90–100 percent uncolonized sand are present in the area. Off Hekili Point, a large patchwork of these open sand areas essentially separates the inner reef tract from a secondary reef tract. One notable area is an 86,218 m^2 (21 acre) sand patch on the edge of the fore reef in the middle of the entire mapping extent. Individual coral colonies ranging from 30 to 185 m^2 were outlined on this sand sheet, as they were readily identifiable in the more detailed fine-scale geomorphometric layers (fig. 12). Four of the five larger "blue hole" reef holes identified in the entire Olowalu Reef tract are located in Area B, accompanied by a patchwork of smaller 90–100 percent uncolonized sand holes between aggregate reef structure (fig. 12). Like Area A, the offshore habitat transitions abruptly from highly colonized aggregate reef to a continuous sheet of sand with 50 to <90 percent macroalgae cover.

Figure 11. Standalone colonies of *Porites lobata* (Dana, 1846) in shallow clear waters of Area B along the Olowalu Reef in Maui, Hawaii, are identifiable from satellite imagery. Seafloor image from Gibbs and others (2013).

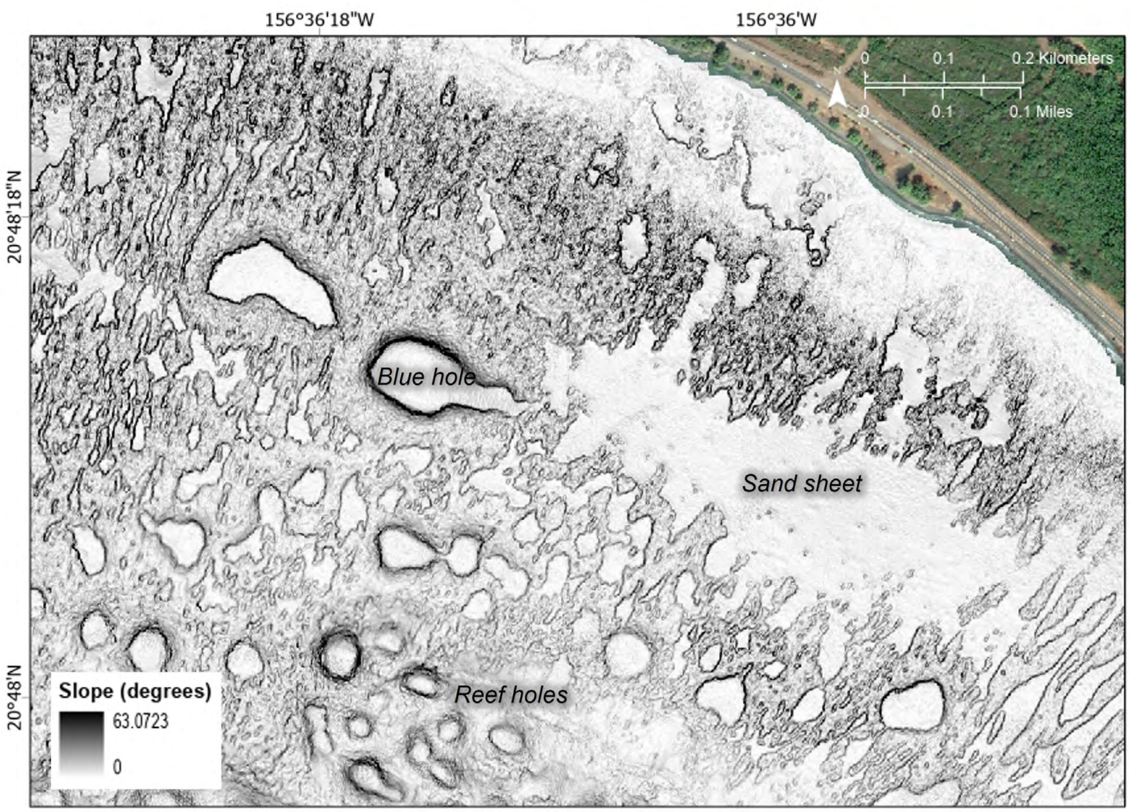


Figure 12. Larger "blue holes" (roundish, flat areas with steep sides), smaller reef hole geomorphology, and an 86,218 square meter (m^2) (21 acre) sand sheet are identified in the bank/shelf zone off Area B (fig. 9) of the Olowalu Reef in Maui, Hawaii, as demonstrated by slope derived from the 1-meter (m) digital bathymetric model (DBM).

Area C of Olowalu Reef

Area C extends from the Ukumehame Gulch outflow to the start of Ukumehame Beach Park (fig. 9) and marks a transition from the coral dominated spur-and-groove of Area B to more frequent pavement with variable cover. The reef flat and reef crest pavement is covered with 10 to <50 percent macroalgae and transitions into areas of low-relief pavement fore reef covered with 10 to <50 percent coral. The reef crest is pronounced in Area C, identifiable by northerness showing a sharp transition from a north face to a south sloping fore reef (fig. 13).

Many of the isolated sand patches in Area C are covered with 10 to <50 percent macroalgae or are 50 to <90 percent uncolonized. Despite the increased presence of macroalgae inshore, Area C exhibits some of the deepest aggregate reef with 50 to <90 percent coral cover down to 34 m (fig. 14) and 10 to <50 percent coral cover down to 38 m. However, the macroalgae sand sheet that lies offshore in all the Olowalu mapping extent starts in water as shallow as 18 m in Area C.

Area D of Olowalu Reef

The area between Ukumehame Beach Park to Coral Gardens rivals Area B in recreational popularity, complex hardbottom, and high coral cover, with the Coral Gardens diving spot serving as the most popular access spot (fig. 9).

Unique to this zone are the inshore uncolonized sand channels that cut through the reef flat, consistent reef crest, and steeply sloping fore reef (fig. 15). Area D also exhibits an aggregate patch reef (clustered coral formations smaller than 100 m^2 isolated from other coral reef formations by sand), various individual patch reefs (coral formations larger than 100 m^2 isolated from other coral reef formations by sand), and one large reef hole. The aggregate reef in Area D is primarily 50 to <90 percent coral cover transitioning into the steeply sloping offshore macroalgae sand sheet 650 m offshore at about 30 m depth (fig. 9*D*). This section of reef descends into the deepest bank/shelf escarpment drop-offs of the entire mapping area, reaching at least 59 m, or the extent of the lidar signal penetration.

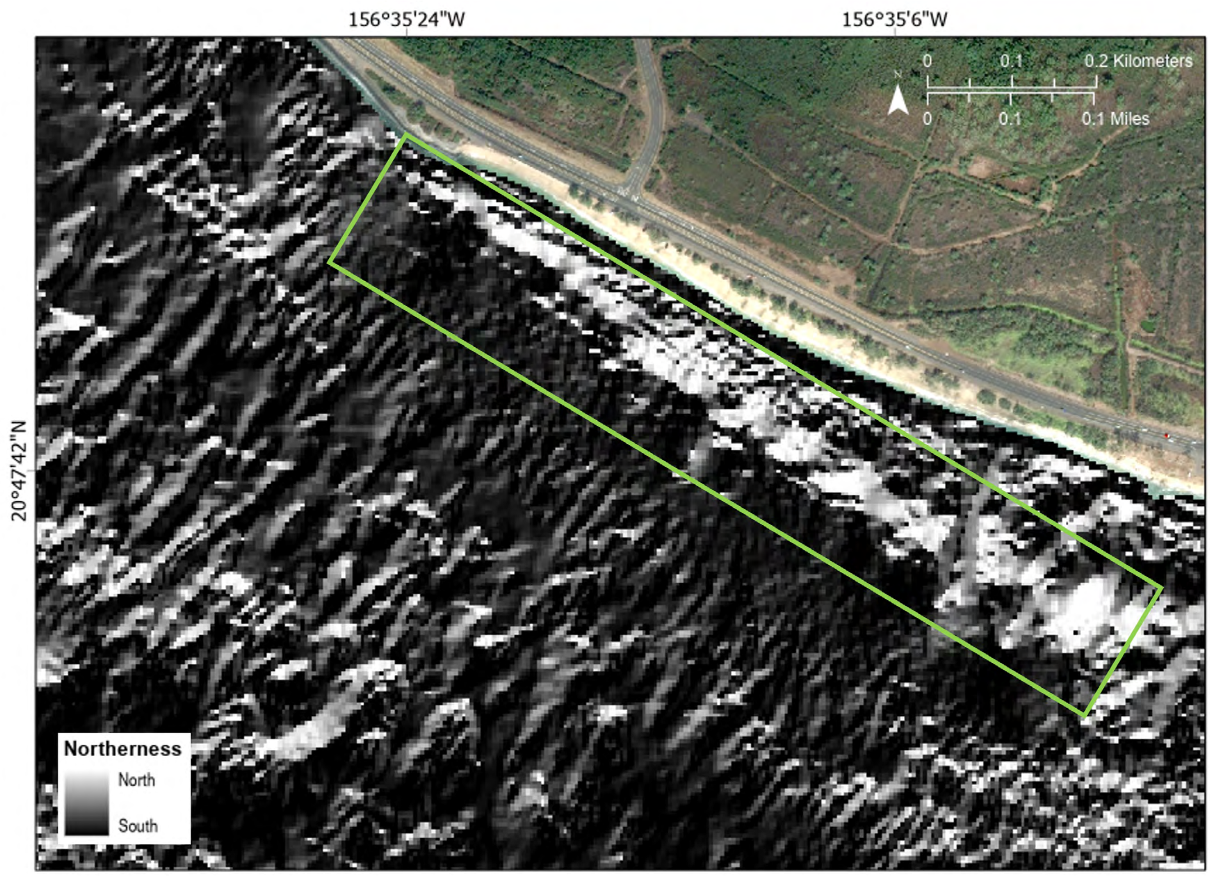


Figure 13. The reef crest, outlined in green, is pronounced in the northerness raster calculated on a 4-meter (m) digital bathymetric model (DBM), highlighting the sharp transition from a north face to a south sloping fore reef on Olowalu Reef, Maui, Hawaii.

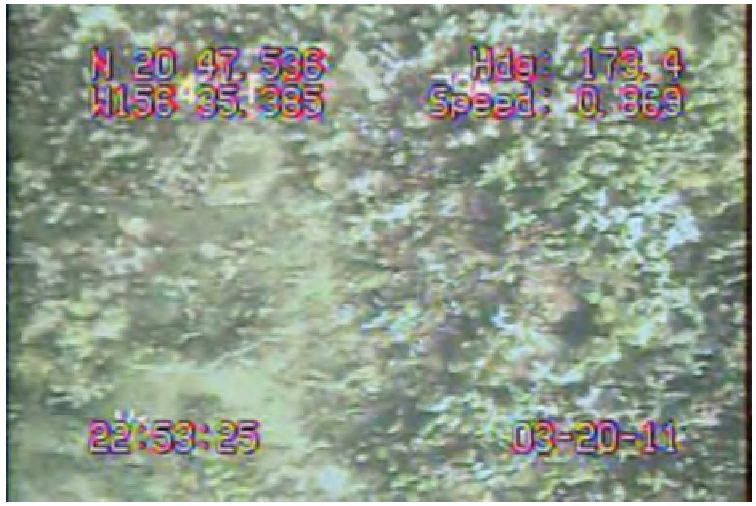


Figure 14. Video still-frame grab of aggregate reef with 50 to <90 percent coral cover was present as deep as 38 meters (m) in Area C (fig. 9) in Olowalu Reef, Maui, Hawaii. Seafloor image from Gibbs and others (2013).

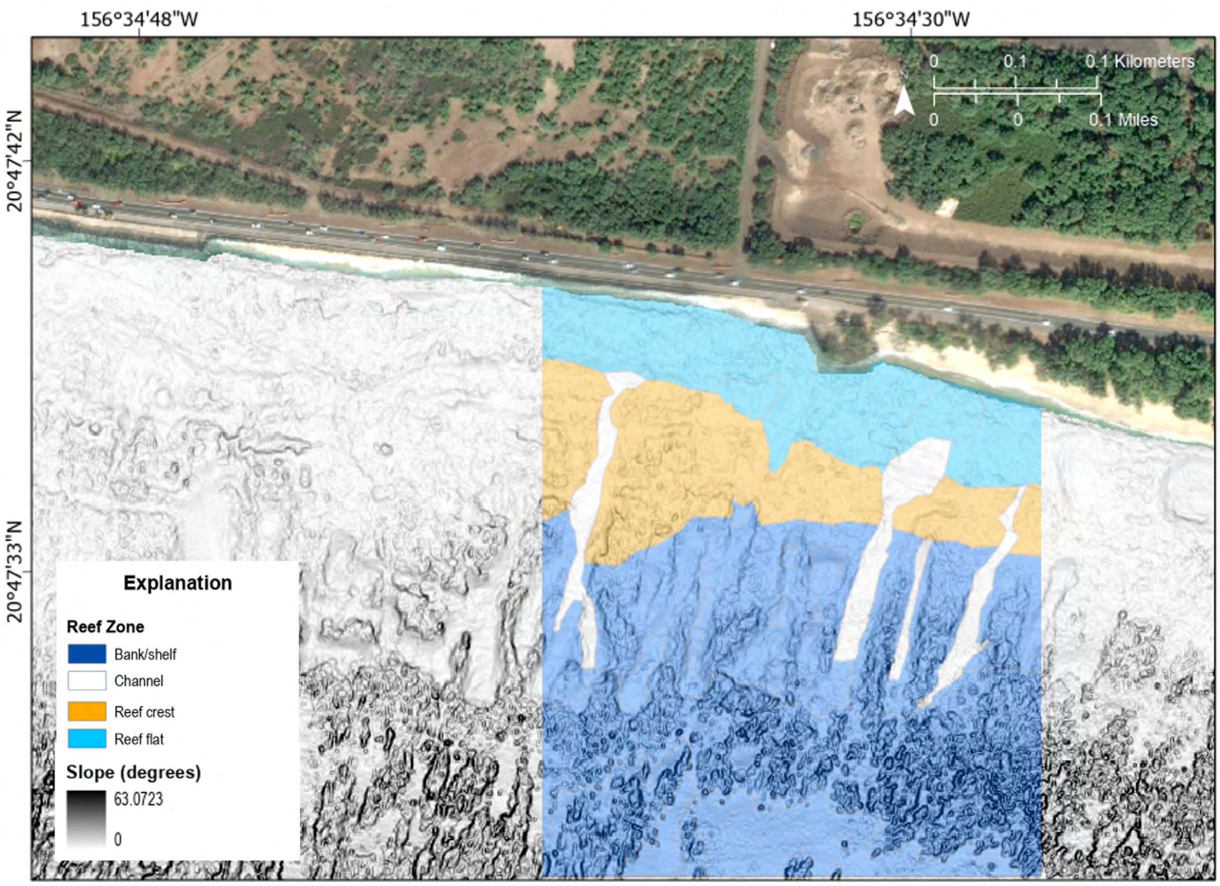


Figure 15. Map of reef zonation of Area D of Olowalu Reef, Maui, Hawaii, overlying raster imagery of slope calculated from a 1-meter digital bathymetric model. Inshore channels (white) incise the reef flat (light blue), reef crest (orange), and fore reef (dark blue) in Area D (fig. 9), visible in the slope raster calculated on a 1-meter (m) digital bathymetric model (DBM). Location of area D shown in figure 9.

Map Comparison

The NOAA 2007 map and our 2025 map differed in total areal extent by a negligible 6 m^2 and were in general thematic agreement, identifying primarily 50 to <90 percent coral cover on predominantly aggregate reef (table 6). Overall, our map identifies 19 percent more habitat, with 11 percent of total habitat classified as "unknown" compared to the 30 percent in the 2007 map. Most of the unknown habitat from the 2007 map occurred in deeper waters and wave-prone inshore areas where visibility was reduced in the satellite imagery. Overlaying the 2007 map with the 1-m DBM slope layer shows the utility of the lidar bathymetry data in bypassing optical obscurities when identifying seafloor structure (fig. 16).

In these areas, our map identified 11 percent more reef and hardbottom coral cover, split approximately evenly between 10 to <50 percent and 50 to <90 percent coral cover (table 6).

The discrepancies between MMU-dependent classes, such as individual and aggregate patch reefs, were an expected change in this study—a >1,000 m^2 coral cluster isolated by sand was classified as "aggregate patch reef" on the 2007 map with a 4,046 m^2 MMU but was classified as "individual patch reef" in this study with a 100 m^2 MMU. The identification of 8 percent more spur-and-groove in the 2025 map is also likely an artifact of scale, whereby the spurs are technically aggregate reef at a larger observation scale if the sand channels are too small for identification.

Whereas an analysis of habitat change over time is outside the scope of this study, the 22 percent difference in 10 to <50 percent macroalgae paired with the 28 percent difference in 50 to <90 percent macroalgae suggest a potential increase in macroalgae density over the 16-year period.

Discussion

The benthic habitat map created in this study supplements the NOAA 2007 map (Battista and others, 2007) and expands on the observations made by USGS sampling for the Olowalu Reef (Gibbs and others, 2013; Field and others, 2019). The accuracies achieved were comparable to maps created for west Maui at the same 100 m^2 MMU, such as the 91 percent accuracy for dominant

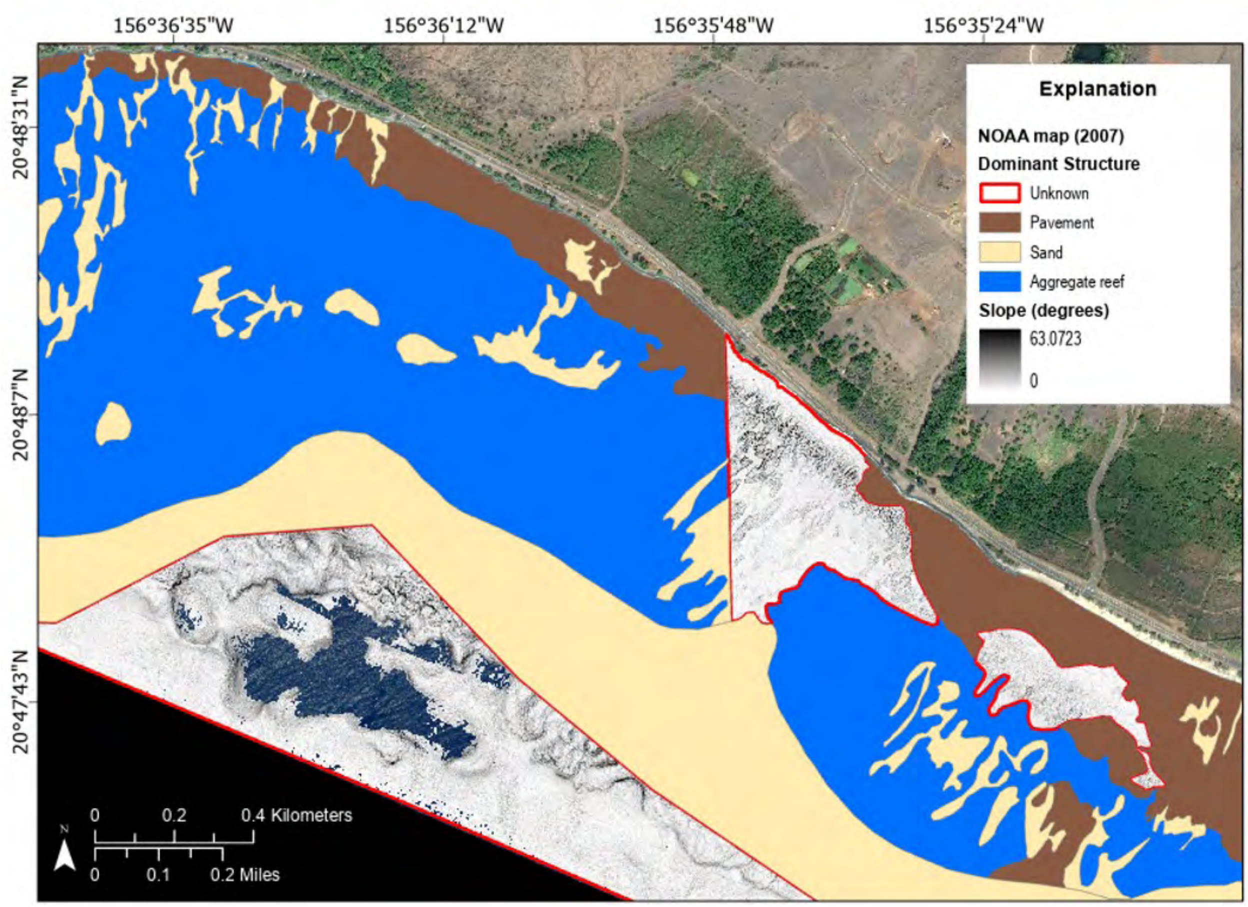


Figure 16. Map of the dominant structures of Olowalu Reef from Battista and others (2007) overlaying raster imagery of slope calculated from a 1-meter digital bathymetric model (DBM). Battista and others (2007) classified 30 percent of the total mapping extent as "unknown," likely due to low visibility in satellite imagery. The inshore and offshore geomorphology of the seafloor is more readily identifiable in the DBM for the areas previously classified as "unknown." U.S. Geological Survey reef classification system was modified from Battista and others (2007) (refer to table 1).

Table 6. Comparison of agreement for within-map reef habitat classifications between the map developed for this study created at a 100 square meters (m^2) minimum mapping unit (MMU) and the 2007 map (Battista and others, 2007) created at a 4,046 m^2 MMU, Olowalu Reef, Maui, Hawaii.

[U.S. Geological Survey reef classification system modified from Battista and others (2007) (refer to table 1). %, percent; —, no classification or no data]

Classification	This study (100 m^2 MMU)		2007 map (4,046 m^2 MMU)		Areal extent difference (m^2)	Difference in percent of total (%)
	Areal extent (m^2)	% of total	Areal extent (m^2)	% of total		
Major structure						
Reef and hardbottom	5,844,806	52	4,638,959	41	1,205,846	11
Unconsolidated sediment	4,130,210	37	3,152,869	28	977,342	9
Other delineations	—	—	10,310	0	−10,310	—
Unknown	1,250,293	11	3,423,177	30	−2,172,884	−19
Dominant structure						
Aggregate reef	3,506,391	31	2,907,469	26	598,922	5
Aggregated patch reef	17,078	0	6,871	0	10,207	0
Individual patch reef	23,296	0	—	—	23,296	—
Spur-and-groove	1,031,974	9	170,432	2	861,542	8
Pavement	1,266,067	11	1,548,360	14	−282,293	−3
Sand	4,130,210	37	3,152,869	28	977,342	9
Scattered coral/rock	—	—	5,827	0	−5,827	—
Artificial	—	—	47	0	−47	—
Land	—	—	10,262	0	−10,262	—
Unknown	1,250,293	11	3,423,177	30	−2,172,884	−19
Biological cover						
Coral	4,943,442	44	3,726,660	33	1,216,782	11
Turf	153,400	1	169,788	2	−16,388	0
Macroalgae	4,041,913	36	3,311,573	30	730,340	7
Uncolonized	836,261	7	583,808	5	252,454	2
Unclassified	—	—	10,310	0	−10,310	—
Unknown	1,250,293	11	3,423,177	30	−2,172,884	−19
Percent biological cover						
Coral, 10–<50%	1,927,690	17	1,412,660	13	515,031	5
Coral, 50–<90%	3,015,751	27	2,314,000	21	701,751	6
Turf, 10–<50%	83,274	1	16,136	0	67,138	1
Turf, 50-<90%	70,126	1	125,563	1	−55,437	0
Turf 90–100%	—	—	28,088	0	−28,088	—
Macroalgae, 10–<50%	830,454	7	3,279,880	29	−2,449,402	−22
Macroalgae, 50–<90%	3,211,460	29	31,693	0	3,179,769	28
Uncolonized, 50–<90%	104,990	1	—	—	105,010	1
Uncolonized, 90–100%	731,272	7	583,808	5	151,269	1
Unclassified	0	—	10,310	0	−10,310	0
Unknown	1,250,293	11	3,423,177	30	−2,172,884	−19
Totals						
Grand total	**11,225,309**		**11,225,315**		**−6**	**0**

structure, 86 percent for major biological cover, and 81 percent for percentage of major biological cover mapped at Kāʻanapali reef (Cochran and others, 2014).

Limitations of the Study

The map created in this study was based on in situ ground validation imagery and ancillary data collected between 2011 and 2013. Although the 10-year difference between data collection and final map production is unlikely to affect reef zonation and have minimal effects on major geomorphic structure and dominant geomorphic structure, the 10-year difference could account for a change in biological cover.

Sources of error include positional offset of the seafloor reference imagery due to the layback of the towed camera system from the GPS position of the vessel. A 10-m radius spatial buffer was applied to each image point to provide the most conservative boundary of estimated layback during habitat interpretation. The original collection of the video transects themselves may also be subject to some convenience sampling, as the vessel was unable to reach habitat in shallow waters, effectively omitting shallow habitats from the ground validation and accuracy assessment data.

We also acknowledge the issue of spatial autocorrelation that occurred during the holdout methods of subsetting accuracy assessment points from the linear transects. However, this holdout method used the same 2011–2013 data for both map production and map assessment to ensure temporal consistency. Currents, waves, and storms can shift coastal sediments on a reef, leading to changes in biological cover or substrate type within a single year, let alone an entire decade, which may have occurred when conducting an accuracy assessment by in situ validation of randomly selected points during the 2018–2023 timeframe of this study. Other in situ diving observations available for Olowalu Reef from 2011–2013 either did not have associated positional coordinates, or the resolutions of coordinates were too coarse for map comparison.

Olowalu Reef has been well studied by a variety of agencies and has been a surveying site for long-term monitoring by the State of Hawaii's Coral Reef Assessment Monitoring Program (CRAMP) since 1999. Based on benthic surveys at 3- and 7-m permanent sites and nearshore habitat and fish assessments as of 2010, Olowalu Reef has high overall fish biomass with primary and secondary consumer levels (Sparks and others, 2010). The extreme El Niño in 2014–2016 and a thermal anomaly event in 2019 triggered the most widespread coral bleaching ever documented in Hawaii, as temperatures on leeward reefs reached 31°C (88 °F) and nearly 60 percent of the corals bleached in 2015 (Winston and others, 2020). Such bleaching events may occur again in the future. Together with the 2007 map and future maps of Olowalu as new data become available, this map is intended to serve as a baseline for public access, general research, local-level management, and reef change for future studies.

References Cited

BAE Systems, 2007, Mapping of benthic habitats for the main eight Hawaiian Islands—Task Order I Project Completion Report: National Oceanic and Atmospheric Administration (NOAA), prepared by BAE Systems, NOAA contract no. DG133C–02CN–007, 107 p., accessed October 20, 2019, at https://products.coastalscience.noaa.gov/collections/benthic/e97hawaii/data2007.aspx.

Battista T.A., Costa B.M., and Anderson S.M., 2007, Shallow-water benthic habitats of the main eight Hawaiian Islands: National Oceanic and Atmospheric Administration (NOAA), Technical Memorandum NOS NCCOS 61, 330 p. [Available from https://archive.org/details/AtlasOfShallowWaterBenthicHabitatsOfTheMainHawaiianIslands/mode/2up.]

Brown, E., 2004, Reef coral populations—Spatial and temporal differences observed on six reefs off west Maui: Honolulu, Hawaiʻi, University of Hawaiʻi at Mānoa, Ph.D. dissertation, 277 p., accessed July 14, 2020, at http://hdl.handle.net/10125/11973.

Cochran, S.A., Gibbs, A.E., and White, D.J., 2014, Benthic habitat map of the U.S. Coral Reef Task Force Watershed Partnership Initiative Kāʻanapali priority study area and the State of Hawaiʻi Kahekili Herbivore Fisheries Management Area, west-central Maui, Hawaiʻi: U.S. Geological Survey Open-File Report 2014–1129, 42 p., accessed June 10, 2019, at https://doi.org/10.3133/ofr20141129.

Coyne, M.S., Battista, T.A., Anderson, M., Waddell, J., Smith, W., Jokiel, P., Kendall, M.S., and Monaco, M.E., 2003, Benthic habitats of the Main Hawaiian Islands, Interim product: National Oceanic and Atmospheric Administration (NOAA) Technical Memorandum NOS NCCOS CCMA 152, 48 p., accessed June 24, 2019, at https://repository.library.noaa.gov/view/noaa/17763.

Division of Aquatic Resources [DAR], 2020, Holomua—Marine 30×30—Effective management of Hawaiʻi's nearshore waters for healthy reefs, fish, and communities: Hawaiʻi Department of Land and Natural Resources, (DLNR), DAR, accessed November 24, 2024, at https://dlnr.hawaii.gov/dar/files/2024/09/Holomua_2-pager_082024.pdf.

Field, M.E., Storlazzi, C.D., Gibbs, A.E., D'Antonio, N.L., and Cochran, S.A., 2019, The major coral reefs of Maui Nui, Hawaiʻi—Distribution, physical characteristics, oceanographic controls, and environmental threats: U.S. Geological Survey Open-File Report 2019–1019, 71 p., accessed June 10, 2019, at https://doi.org/10.3133/ofr20191019.

Fletcher, C.H., Bochicchio, C., Conger, C.L., Engels, M.S., Feirstein, E.J., Frazer, N., Glenn, C.R., Grigg, R.W., Grossman, E.E., Harney, J.N., Isoun, E., Murray-Wallace, C.V., Rooney, J.J., Rubin, K.H., Sherman, C.E., and Vitousek, S., 2008, Geology of Hawaii reefs, chap. 11 *of* Riegl, B.M., and Dodge, R.E., eds., Coral reefs of the USA: Springer, Coral Reefs of the World 1, p. 435–487.

Friedlander, A.M., Aeby, G., Brown, E., Clark, A., Coles, S., Dollar, S., Hunter, C., Jokiel, P., Smith, J., Walsh, B., Williams, I., and Wiltse, W., 2005, The state of coral reef ecosystems of the Main Hawaiian Islands, chap. 9 *of* Waddell, J., ed., The state of coral reef ecosystems of the United States and Pacific Freely Associated States—2005: National Oceanic and Atmospheric Administration (NOAA) Technical Memorandum NOS NCCOS 11, p. 222–269, accessed May 14, 2019, at https://repository.library.noaa.gov/view/noaa/17792.

Friedlander, A.M., Brown, E., Monaco, M.E., and Clark, A., 2006, Fish habitat utilization patterns and evaluation of the efficacy of marine protected areas in Hawaii—Integration of NOAA digital benthic habitats mapping and coral reef ecological studies: National Oceanic and Atmospheric Administration (NOAA) Technical Memorandum NOS NCCOS 23, 213 p., accessed July 10, 2019, at https://repository.library.noaa.gov/view/noaa/475.

Gibbs, A.E., Cochran, S.A., and Tierney, P.W., 2013, Seafloor video footage and still-frame grabs from U.S. Geological Survey cruises in Hawaiian nearshore waters: U.S. Geological Survey Data Series 735, 11 p. and data, accessed June 14, 2019, at https://doi.org/10.3133/ds735.

Gibbs, A.E., Finlayson, D., and Dartnell, P., 2023, Swath bathymetry and acoustic-backscatter data collected in 2013 offshore Maui and Kahoʻolawe, Hawaii, during field activity A–01–13–HW: U.S. Geological Survey data release, accessed November 24, 2024 at https://doi.org/10.5066/P9XJLL6C.

Gibbs, A.E., Grossman, E., and Richmond, B., 2005, Summary and preliminary interpretations of USGS Cruise A–2–02–HW—Underwater video surveys collected off of Oahu, Molokai, and Maui, Hawaii, June–July 2002: U.S. Geological Survey Open-File Report 2005–1244, 57 p., accessed June 14, 2019, at https://doi.org/10.3133/ofr20051244.

Grafeld S., Oleson K.L.L, Teneva L., and Kittinger, J.N., 2017, Follow that fish—Uncovering the hidden blue economy in coral reef fisheries: PLoS ONE, v. 12, no. 8, article e0182104, 25 p., accessed July 10, 2019, at https://doi.org/10.1371/journal.pone.0182104.

Heberer, L., 2023. Integration of geomorphic data in manual and semi-automated benthic habitat mapping of a Hawaiian fringing reef: San Diego, Calif., San Diego State University, Master's thesis, 95 p., accessed November 10, 2024, at https://digitalcollections.sdsu.edu/do/780ff1fa-6d90-4ee9-b212-04db12fd2d6f.

Heberer, L.N., Alkins, K.A., Storlazzi, C.D., Cochran, S.A., Gibbs, A.E., Sparks, R., Silva, I., Stone, K., Martinez, T., and Peralto, C., 2025, Benthic habitat map of the geomorphological structure, biological cover, and geologic zonation of Olowalu reef, Maui: U.S. Geological Survey data release, https://doi.org/10.5066/P9ICJ7CF.

Kendall, M.S., Monaco, M.E., Buja, K.R., Christensen, J.D., Kruer, C.R., Finkbeiner, M., and Warner, R.A., 2002, Methods used to map the benthic habitats of Puerto Rico and the U.S. Virgin Islands: National Oceanic and Atmospheric Administration (NOAA) Technical Memorandum NOS NCCOS CCMA 152, 45 p., accessed August 28, 2019, at https://repository.library.noaa.gov/view/noaa/421.

Maui Coral Reef Recovery Team, 2012, Ola nā Papa i Mālama ʻia—A practical plan for the technical and cultural restoration of Maui's coral reefs: Kīhei, Maui, Maui Nui Marine Resource Council 101 p., accessed July 01, 2019, at https://www.researchgate.net/publication/261875669_Ola_na_Papa_i_Malama_'ia_A_Practical_Plan_for_the_Technical_and_Cultural_Restoration_of_Maui's_Coral_Reefs/link/0c960535bfbbbd1667000000/download?_tp=eyJjb250ZXh0Ijp7ImZpcnN0UGFnZSI6InB1YmxpY2F0aW9uIiwicGFnZSI6InB1YmxpY2F0aW9uIn19.

Maui Nui Marine Resource Council [MNMRC], 2015, Maui's coral reefs—Declining trends, 1993–2015: Maui Nui Marine Resource Council, 4 p., accessed May 12, 2019, at https://www.mauireefs.org/wp-content/uploads/2017/12/MNMRC-Declining-Trends.pdf.

Mission Blue, 2020, Olowalu reef hope spot: StoryMap web page, accessed July 01, 2019, at https://storymaps.arcgis.com/stories/c1cb0ebfb6664d549e5514d43b1458e5.

National Oceanic and Atmospheric Administration [NOAA], 2018, Coral reef condition—A status report for the Hawaiian Archipelago: National Oceanic and Atmospheric Administration (NOAA) Coral Reef Conservation Program, 7 p., accessed June 14, 2019, at https://repository.library.noaa.gov/view/noaa/19537.

National Oceanic and Atmospheric Administration [NOAA] Coastal Services Center, 2014, Guidance—Lidar provisioning guidance for the digital coast data access viewer: National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center, 19 p., accessed July 10, 2019, at https://coast.noaa.gov/data/digitalcoast/pdf/lidar-provisioning-guidance.pdf.

National Oceanic and Atmospheric Administration [NOAA], Office for Coastal Management, 2019, 2013 U.S. Army Corps of Engineers (USACE) National Coastal Mapping Program (NCMP) Topobathy lidar—Maui (HI) from 2010-06-15 to 2010-08-15 [database]: National Oceanic and Atmospheric Administration (NOAA), Office of Coastal Management [OCM] Partners, accessed June 18, 2019, at https://inport.nmfs.noaa.gov/inport/item/49751.

Prouty, N.G., and Gallagher, C., 2017, Olowalu chronology and geochemistry time-series, west Maui: U.S. Geological Survey data release, accessed October 20, 2019, at https://doi.org/10.5066/F72J69TH.

Reguero, B.G., Storlazzi, C.D., Gibbs, A.E., Shope, J.B., Cole, A.D., Cumming, K.A., and Beck, M.W., 2021, The value of US coral reefs for flood risk reduction: Nature Sustainability, v. 4, p. 688–698, accessed November 01, 2022, at https://doi.org/10.1038/s41893-021-00706-6.

Smith, K.K., 2011, Pu‘uhonua—The legacy of Olowalu: Maui, Hawai‘i, Olowalu Cultural Reserve (now the Kipuka Olowalu), 16 p., accessed June 18, 2019, at https://luc.hawaii.gov/wp-content/uploads/2015/10/Appendix-G.-Puuhonua-The-Legacy-of-Olowalu.pdf.

Sparks, R., Stone, K., and White, D., 2010, Maui and Lanai monitoring report—Updated to include data collected between 10/2006–09/2010: Hawaii Department of Land and Natural Resources (DLNR), Division of Aquatic Resources (DAR), 35 p., accessed October 20, 2019 at https://doi.org/10.13140/RG.2.2.33684.73606.

Storlazzi, C.D., Reguero, B.G., Cole, A.D., Lowe, E., Shope, J.B., Gibbs, A.E., Nickel, B.A., McCall, R.T., van Dongeren, A.R., and Beck, M.W., 2019, Rigorously valuing the role of U.S. coral reefs in coastal hazard risk reduction: U.S. Geological Survey Open-File Report 2019–1027, 42 p., accessed January 14, 2020, at https://doi.org/10.3133/ofr20191027.

Storlazzi, C.D., van Ormondt, M., Chen, Y.-L., and Elias, E.P.L., 2017, Modeling fine-scale coral larval dispersal and interisland connectivity to help designate mutually supporting coral reef Marine Protected Areas—Insights from Maui Nui, Hawaii: Frontiers in Marine Science, v. 4, article 381, 14 p., accessed January 14, 2020, at https://doi.org/10.3389/fmars.2017.00381.

Walbridge, S., Slocum, N., Pobuda, M., and Wright, D.J., 2018, Unified geomorphological analysis workflows with Benthic Terrain Modeler: Geosciences, v. 8, article 3, p. 94, accessed July 16, 2020, at https://doi.org/10.3390/geosciences8030094.

Wedding, L., Gibson, B., Walsh, W., and Battista, T., 2010, Integrating remote sensing products and GIS tools to support marine spatial management in West Hawai’i: Journal of Conservation Planning, v. 7, p. 60–73, accessed June 18, 2019, at http://hdl.handle.net/1834/30674.

Winston, M., Couch, C., Huntingon, B., Vargas-Ángel, B., Suka, R., Oliver, T., Halperin, A., Gray, A., McCoy, K., Asbury, M., Barkley, H., Gove, J., Smith, N., Kramer, L., Rose, J., Conklin, E., Sukhraj, N., and Morioka, J.. 2020, Preliminary results of patterns of 2019 thermal stress and coral bleaching across the Hawaiian Archipelago: National Oceanic and Atmospheric Administration (NOAA) Administrative Report H–20–04, 13 p., accessed October 20, 2021 at https://doi.org/10.25923/8pqg-tq06.

Wright, D.J., Pendleton, M., Boulware, J., Walbridge, S., Gerlt, B., Eslinger, D., Sampson, D., and Huntley, E., 2012, ArcGIS Benthic Terrain Modeler (BTM), v. 3.0: Environmental Systems Research Institute, National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center, Massachusetts Office of Coastal Zone Management, software release, accessed October 20, 2019, at http://esriurl.com/5754.

Appendix 1. U.S. Geological Survey Detailed Reef Classification Scheme

The U.S. Geological Survey's (USGS) reef classification scheme is slightly modified from the National Oceanic and Atmospheric Administration's (NOAA) scheme for the main Hawaiian Islands (Battista and others, 2007) to attributes common to fringing reefs in Hawaii (Cochran and others, 2014). The following definitions and examples were compiled from various NOAA and USGS classification guidelines (Kendall and others, 2002; Coyne and others, 2003; Gibbs and others, 2005; Battista and others, 2007; Cochran and others, 2014). In the images that accompany definitions, arrows and black cross hatching identify the features of interest. Please refer to Heberer (2023) for figures of geomorphic attributes that helped distinguish features on Olowalu Reef, Maui, Hawaii, for this study.

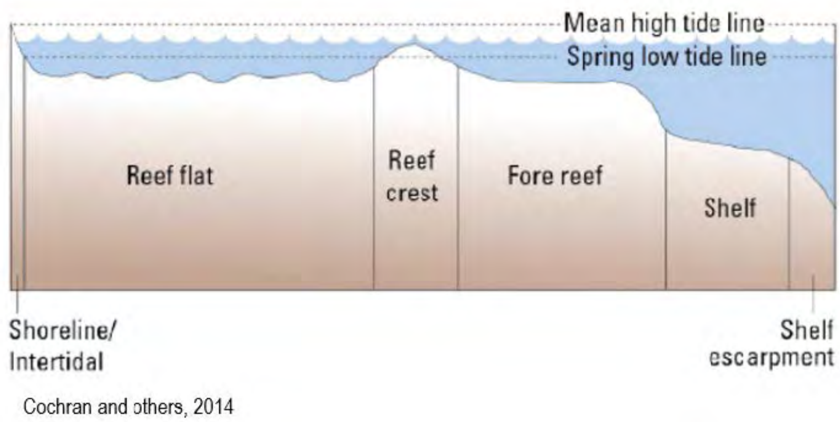
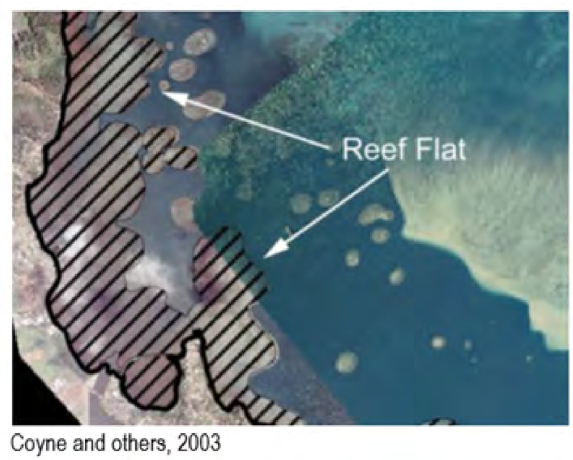


Figure 1.1. Schematic cross-sectional diagram showing generalized coral-reef zonation. Not shown: land, channel, dredged, or vertical wall. From Cochran and others (2014).

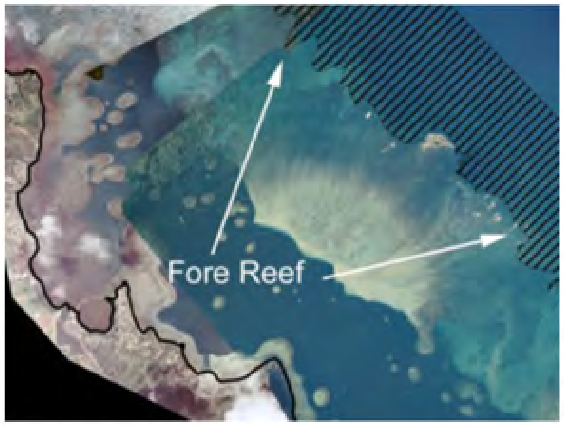
Reef Geologic Zones

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



Reef crest—Flattened, emergent (especially during low tides) or nearly emergent segment of a reef, usually where the waves break. This zone is 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. Fore reef is also defined as 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.



Kendall and others, 2002

Coyne and others, 2003

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.

Coyne and others, 2003

Kendall and others, 2002

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

Coyne and others, 2003

Kendall and others, 2002

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

Coyne and others, 2003

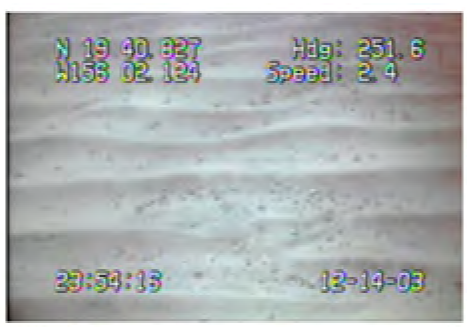
Geomorphological Structure

Major Structure—Unconsolidated Sediment

Unconsolidated sediment with less than 10 percent cover of submerged vegetation.

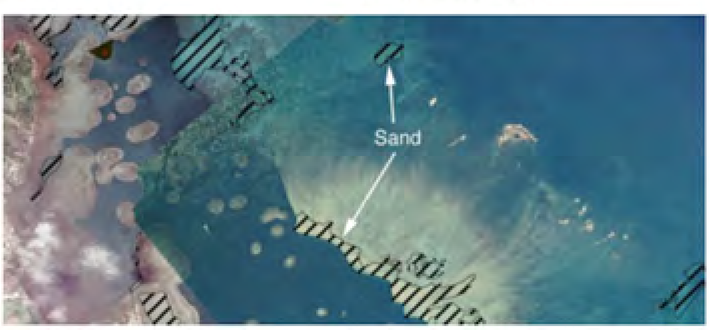
Sand—Coarse sediment typically found in areas exposed to currents or high wave energy (reef-derived) or on beaches (land-derived or reef-derived).

Coyne and others, 2003



Cochran and others, 2014

Coyne and others, 2003

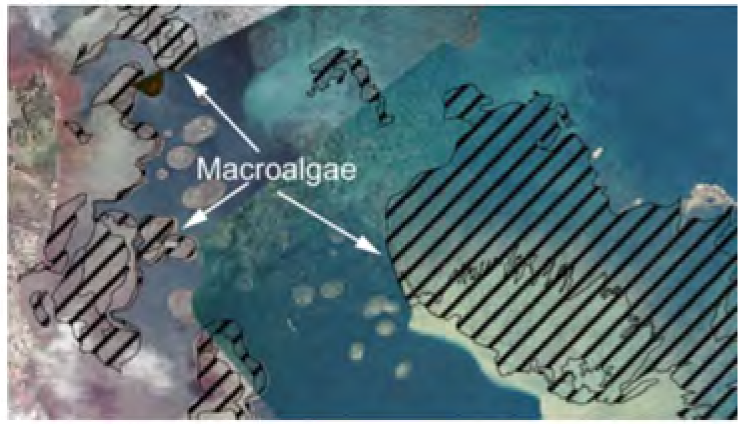


Coyne and others, 2003

Kendall and others, 2002

Macroalgae—Macroalgae covering 90 percent or more of the substrate. May include blowouts of less than 10 percent of the total area that are too small to be mapped independently (less than the minimum mapping unit [MMU]). This includes continuous beds of any shoot density (may be a continuous sparse or dense bed). Representative species include *Caulerpa* spp., *Dictyota* spp., *Halimeda* spp., *Lobophora variegata* (J.V. Lamour.) Womersley ex Oliveira, and *Laurencia* spp.

Gibbs and others, 2005



Coyne and others, 2003

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). Aggregate reef refers to the underlying hard structure and implies nothing about the nature of the biological cover, nor whether it is alive or dead.

Cochran and others, 2014

Coyne and others, 2003

Gibbs and others, 2005

Battista and others, 2007

Kendall and others, 2002

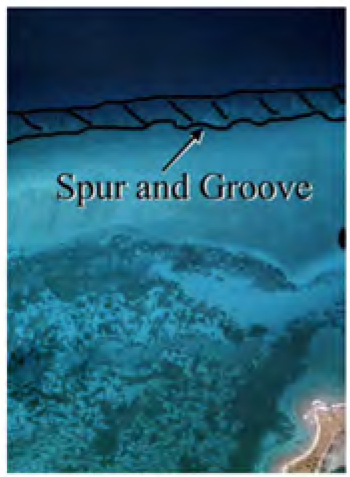
Spur-and-groove—Habitat having alternating sand and coral formations that are oriented perpendicular to the shore or bank/shelf escarpment. The coral formations (spurs) of this feature typically have high vertical relief relative to pavement with sand channels (refer to figure 1.11) and are separated from each other by 1–5 m of sand or bare hardbottom (grooves), although the height and width of these elements may vary considerably. This habitat type typically occurs in the fore reef or bank/shelf escarpment zone.


Coyne and others, 2003


Battista and others, 2007


Cochran and others, 2014

Coyne and others, 2003



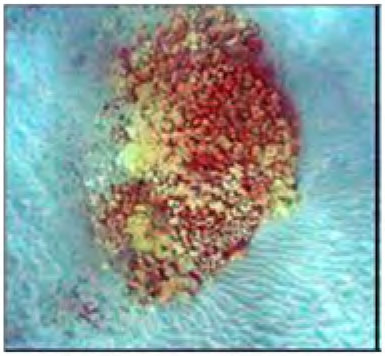
Kendall and others, 2002


Gibbs and others, 2005

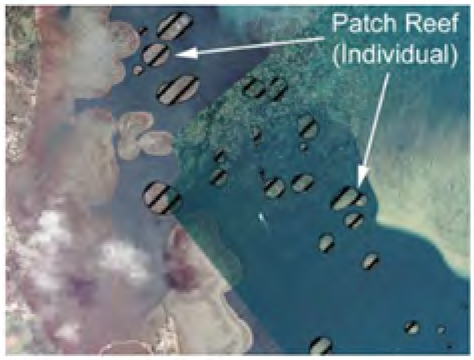
Patch reef(s)—Coral formations that are isolated from other coral reef formations by sand, seagrass, or other habitats and that have no organized structural axis relative to the contours of the shore or shelf edge.

Kendall and others, 2002

Individual patch reef—Distinctive single patch reefs, or coral formations, larger than or equal to the MMU (100 square meters [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.



Battista and others, 2007

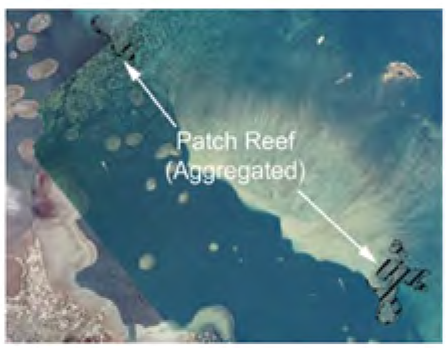


Coyne and others, 2003

Kendall and others, 2002

Aggregated patch reef—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.

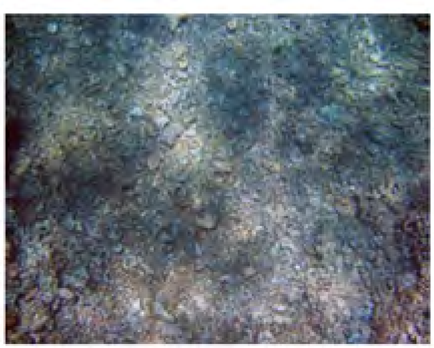
Cochran and others, 2014



Coyne and others, 2003

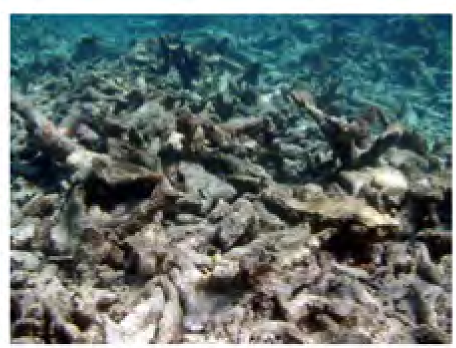
Kendall and others, 2002

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



Cochran and others, 2014

Battista and others, 2007



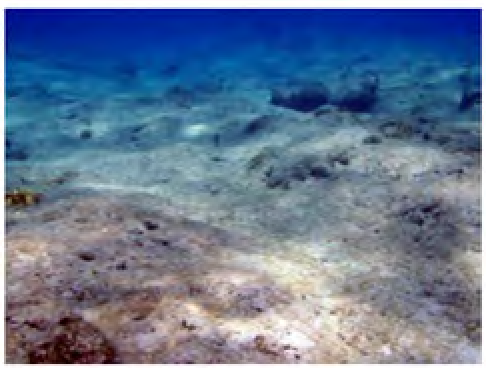
Kendall and others, 2002

Pavement—Flat, low-relief, solid carbonate rock with coverage of macroalgae, hard coral, zoanthids, and other sessile invertebrates that are dense enough to obscure the underlying surface. Carbonate substrate with less than 10 percent loose rocks or boulders scattered on the surface.

Cochran and others, 2014

Battista and others, 2007

Uncolonized pavement—Flat, low-relief, solid carbonate rock that is commonly covered by a thin sand veneer. The pavement's surface commonly has sparse coverage of macroalgae, hard coral, zoanthids, and other sessile invertebrates that does not obscure the underlying surface.

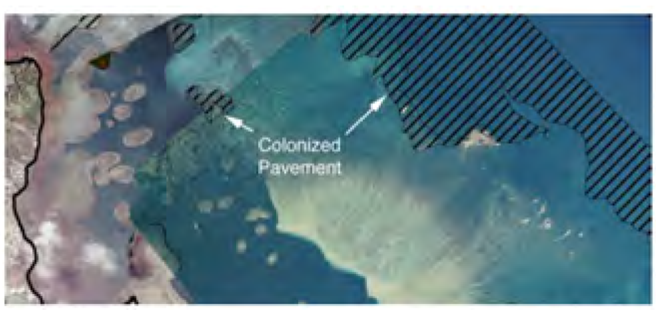


Kendall and others, 2002

Gibbs and others, 2005

Colonized pavement—Flat, low-relief, solid carbonate rock with coverage of macroalgae, hard coral, zoanthids, and other sessile invertebrates that are dense enough to obscure the underlying surface.

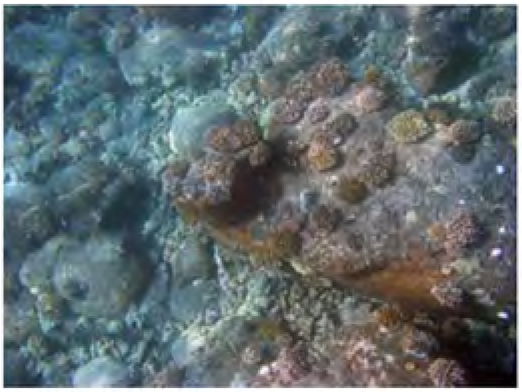
Kendall and others, 2002



Coyne and others, 2003

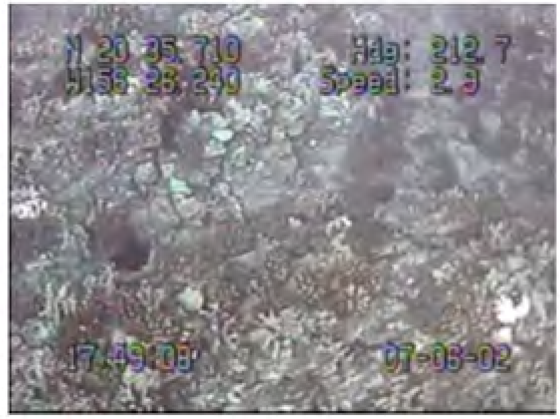
Gibbs and others, 2005

Pavement with 10 to <50 percent rocks/boulders—Substrate with 10 to <50 percent volcanic rocks and (or) boulders scattered on the surface.



Cochran and others, 2014

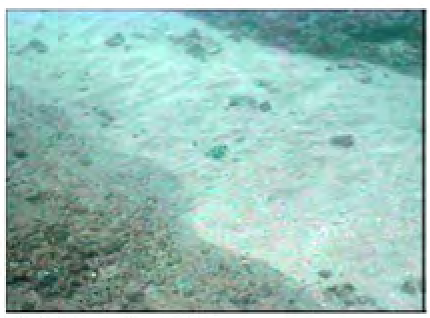
Pavement with >50 percent rocks/boulders—Substrate with >50 percent volcanic rock and (or) boulders on the surface.



Gibbs and others, 2005

Pavement with sand channels—Habitats of pavement with alternating sand/surge channel formations that are oriented perpendicular to the shore or bank/shelf escarpment. The sand/surge channels of this feature have low vertical relief relative to spur-and-groove formations and are typically erosional in origin. This habitat type occurs in areas exposed to moderate wave surge such as the bank/shelf zone. Representative species/live coral community: *Porites compressa* (Dana, 1846), *Porites lobata* (Dana, 1846), *Montipora* spp., and *Pocillopora meandrina* (Dana, 1846).

Cochran and others, 2014



Battista and others, 2007

Coyne and others, 2003

Kendall and others, 2002

Kendall and others, 2002

Coyne and others, 2003

Moffett Field Publishing Service Center
Manuscript approved February 28, 2025
Edited by Hayden Chaisson
Layout by Cory Hurd

Heberer and others—**Benthic Habitat Map of Olowalu Reef, Maui, Hawaii**—Open-File Report 2025–1010

ISSN 2331-1258 (online)
https://doi.org/10.3133/ofr20251010