Geology and Benthic Habitats

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INTRODUCTION AND ORIGIN

The Northwestern Hawaiian Islands (NWHI) are in the middle section of the 6,126 km long Hawaiian–Emperor seamount chain, considered to be the longest mountain chain in the world (Grigg, 1983; Figure 3.1). Over many millions of years, a relatively stationary plume of hot mantle, or hot spot, located below the floor of the Pacific Plate (Grigg 1982, 1997; Rooney et al., 2008) has and continues to erupt at the seafloor creating a chain of volcanoes that comprise the islands, banks, atolls and seamounts of the Hawaiian Archipelago (Figure 3.2). Each begins as a small submarine volcano and over time can grow to reach well above sea level. Eventually the volcanoes cool and subside as they slowly move away from the hot spot in a northwestward direction at about 8 cm/yr (Clague and Dalrymple, 1987).

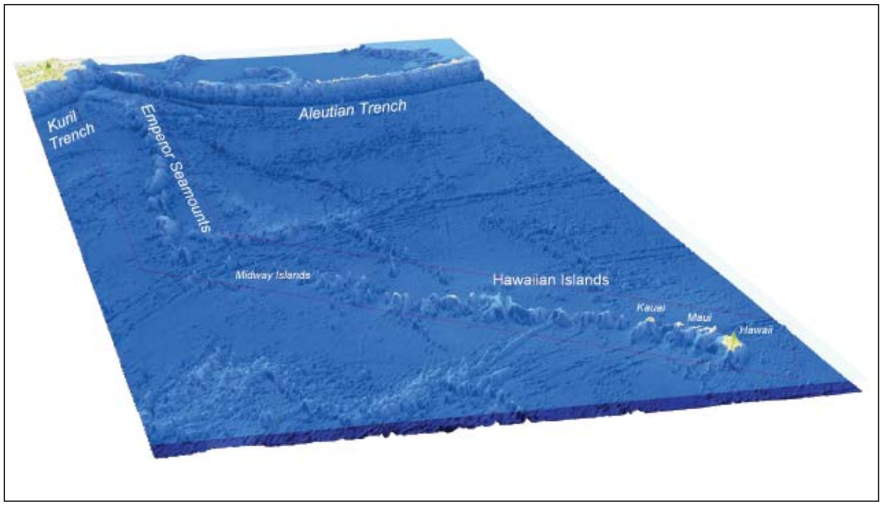

Figure 3.1. Oblique southern perspective of the bathymetry of the Pacific plate between Hawaii and the Aleutian Islands constructed to show the Hawaiian-Emperor Seamount chain and the progressive subsidence of each volcano over time. Sources: Neall and Trewick 2008; image prepared by Jon Procter.

Figure 3.2. The island of Hawaii currently sits over the hot spot that has formed the Hawaiian Archipelago over tens of millions of years. Photo: Hawaii Volcano National Park.

The tops and edges of the volcanoes, if they are at or near sea level, support large and diverse coral reef communities. As the volcanic edifice subsides, an atoll can form as reef builders keep the top of the volcano near sea level by growing vertically and creating a thick carbonate cap. The Darwin Point marks the threshold where vertical growth, or net accretion, of reef building organisms is zero or negative and the atoll drowns and becomes a guyot (Figure 3.3; Grigg et al., 2008). This point, named after Charles Darwin, who first proposed an evolutionary model for atoll formation in 1836, marks a significant milestone in the life of a Hawaiian volcano. Currently Kure Atoll lies very near its Darwin Point. It is the oldest Hawaiian island still above sea level although it consists of only 1 km^2 of emergent land and 66 km^2 of lagoon (Juvik and Juvik, 1998). Dozens of seamounts and guyots extend from north of Kure to the Aleutian Trench and mark the ancient remnants of volcanoes similar to those that comprise the Hawaiian Archipelago (Davies et al., 1972).

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General Description of the Archipelago

The youngest and largest of the emergent Hawaiian Islands is the island of Hawaii, which is composed of five volcanoes including the currently active Kilauea Volcano and Mauna Loa and Mauna Kea, which are the two massive shield volcanoes that form the bulk of the island (Figure 3.4). They both extend from the seafloor at >5,000 m below sea level to >4,000 m above sea level and Mauna Kea is the single largest mountain on Earth. Loihi is the youngest submarine volcano in the archipelago and is located 30 km southeast of Hawaii Island. Northwest of Hawaii Island the islands of Maui, Lanai, Kahoolawe and Molokai, make up the island cluster known as "Maui Nui". The highest point in Maui Nui is Haleakala volcano on Maui at 3,055 m. Further northwest is Oahu, the most densely populated island in the chain. Kauai, the Garden Isle, is approximately 5.1 million years old and is deeply eroded with lush vegetation and steep cliffs (Juvik and Juvik, 1998). Niihau and Lehua, which lie 27.7 km southwest of Kauai, are far drier than their larger and higher elevation neighbor, Kauai. Lehua is a private island inhabited by an isolated population of native Hawaiians and access to the island is strictly controlled. Kaula Rock, an uninhab-

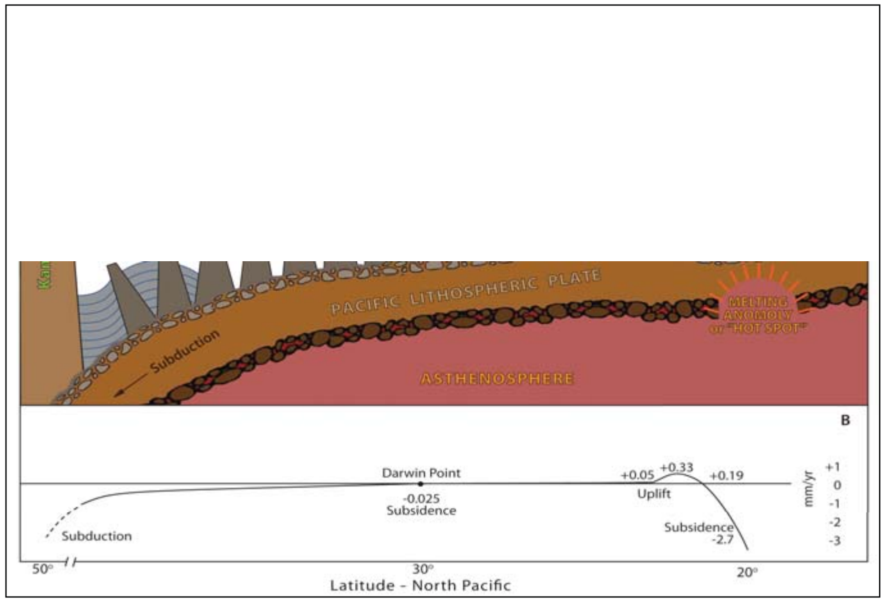


Figure 3.3. Reef accretion across the Hawaiian Archipelago. Note that the net accretion rate diminishes to zero just beyond Kure Atoll, thereby defining a threshold for atoll formation known as the Darwin Point beyond which atolls drown. Source: Grigg, 1997; image: S. Hile.

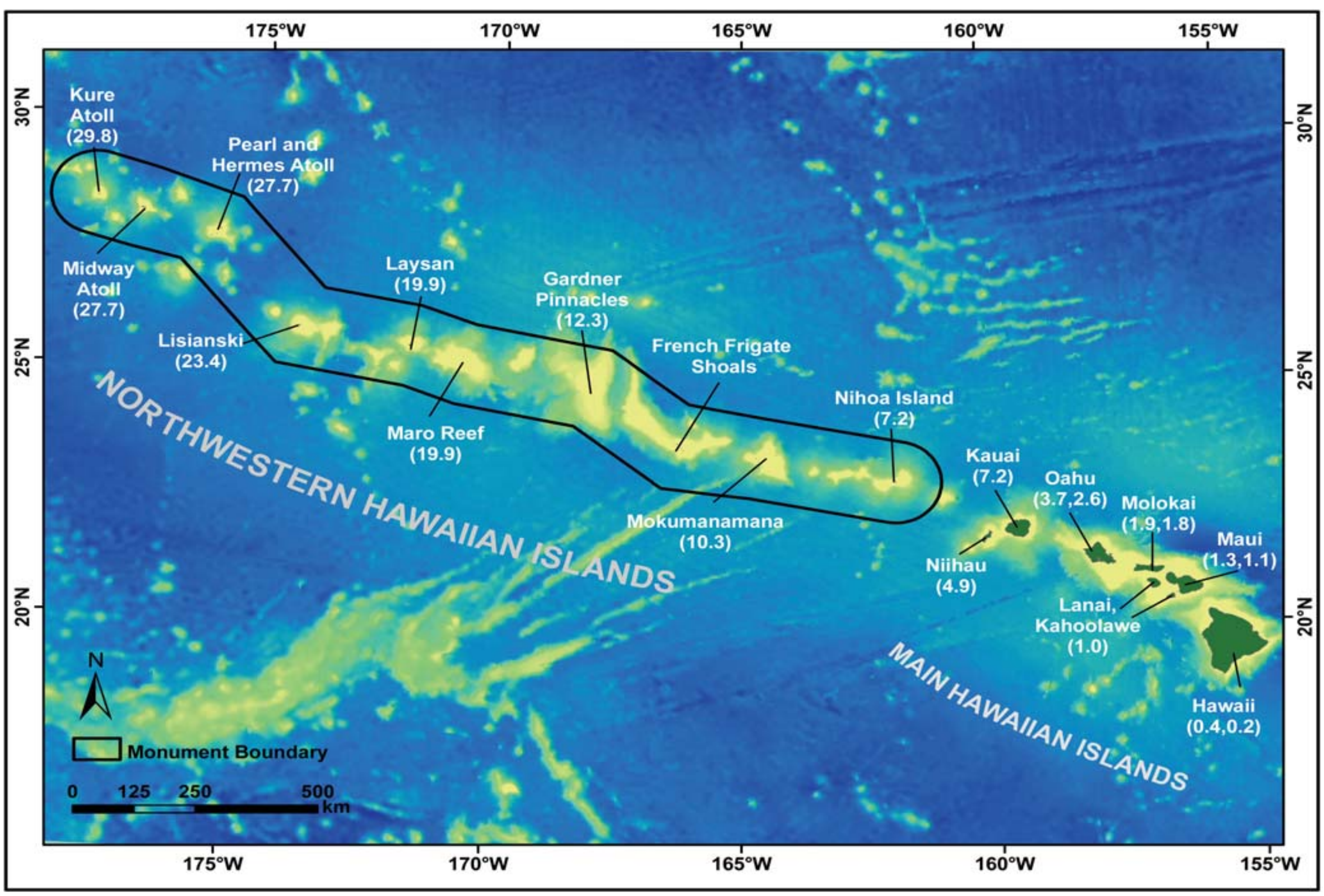


Figure 3.4. Islands, banks and atolls of the Hawaiian Archipelago.

ited island southwest of Niihau, marks the transition between the main or windward islands and the northwestern or leeward islands. The two thousand km of ocean between Kaula Rock and Kure Atoll separates the 10 islands and atolls in the NWHI and a few small emergent pieces of land with a total area of just over 15 km² (Juvik and Juvik, 1998). Northwest of Mokumanamana and Nihoa, are remnant basaltic pinnacles including La Perouse Pinnacle at French Frigate Shoals and the Gardner Pinnacles. The maximum elevation of the islands northwest of Gardner Pinnacles does not exceed 12 m and on some atolls or islands only reaches 3 m.

Table 3.1 shows the land areas of all emergent islands in the NWHI, as well as the submerged marine area encompassed by the 10-fathom (18.29 m) and 100-fathom (182.9 m) isobaths. Within 10 fathoms total shallow water habitats constitute 1,595 km², including the area within lagoons. The area of shallow water habitats within the 100 fathom isobath is 13,771 km². However, these numbers are representative of a two dimensional surface and do not truly convey the surface area of the benthos, which, due to the 3-D topographic complexity of the seafloor, is actually substantially greater. Accurate bathymetric data for the NWHI are being collected and synthesized by the NOAA Coral Reef Ecosystem Division, the Hawaii Mapping Research Group, Joint Institute for Marine and Atmospheric Research (JIMAR), and the Hawaii Undersea Research Laboratory, at the University of Hawaii's School of Ocean and Earth Science and Technology.

Table 3.1. Area mapped by aggregated habitat cover type and geographic scale (km²) based upon IKONOS satellite imagery. Source: NOAA, 2003.

ISLAND	LAND AREA (km²)	AREA (km²) <10 FM	AREA (km²) <100 FM
Kaula	0.6	0	70.5
Bank E of Nihoa	Submerged	0	146.9
Nihoa	0.7	5.6	570.8
Bank SW of Nihoa	Submerged	0	336.2
Bank NW of Nihoa	Submerged	0	63.8
Twin Banks	Submerged	2.3	72
Mokumanamana	0.2	9.1	1,557.2
French Frigate Shoals	0.2	469.4	943.4
Southeast Brooks Bank 1	Submerged	0	29.4
Southeast Brooks Bank 2	Submerged	0	142.3
Southeast Brooks Bank 3	Submerged	0	158.5
Southeast Brooks Bank 4	Submerged	0	3.4
Brooks Bank NW of St. Rogatien	Submerged	0	67.8
St Rogatien Bank	Submerged	0	383.1
Gardner Pinnacles	0.02	0.7	2,446.6
Raita Bank	Submerged	16	571.1
Maro Reef	Awash	217.5	1,935.3
Laysan Island	4.1	26.4	584.5
Northhampton Seamounts (4)	Submerged	0	404.3
Pioneer Bank	Submerged	0	434.6
Lisianski Island/Neva Shoal	1.5	215.6	1,246.6
Bank NW of Lisianski	Submerged	0	106.7
Bank SSE of Pearl and Hermes	Submerged	0	5.5
Bank ESE of Pearl and Hermes	Submerged	0	4.8
Pearl and Hermes Atoll	0.3	374.5	816.6
Salmon Bank	Submerged	0	163.2
Gambia Shoal	Submerged	0	0.5
Ladd Seamount	Submerged	54.2	144.1
Midway Atoll	64	85.4	344.1
Nero Seamount	Submerged	25	71.8
Kure Atoll	1.0	90.2	
Bank W of Kure	Submerged	NA	NA
TOTAL AREA		1,591.9	13,805.6

Pre-Holocene Reef History

The Hawaiian–Emperor chain includes at least 129 massive shield volcanoes that formed over the past 85 million years, with volcano ages generally decreasing in age towards the southeast (Jackson et al., 1975; Clague, 1996). The overall age progression of the islands has been confirmed by several studies using radiometric isotopes to date volcanic rocks from islands and seamounts along the chain (Table 3.2; Clague and Dalrymple, 1987; Garcia et al., 1987) although suitable samples for dating many of the NWHI are difficult to obtain. It has been proposed that the frequency of volcano formation has increased over time based on the decrease in volcano spacing over time. It has also been proposed that the islands at the younger end of the chain are also significantly higher than those formed earlier (Clague, 1996).

Table 3.2. Characteristics of the islands, atolls, and some submerged banks in the NWHI , listed in order from the northwest down to the southeast. Note that most of the subaerially exposed islands, sea stacks, and atolls are surrounded by extensive shallow banks. Island ages are from Clague (1996), with values in brackets from K-Ar dated basalt samples, and other ages estimated from geophysical calculations. Lagoon water volumes are from Hoeke et al., 2006.

ISLAND, ATOLL OR BANK	TYPE OF FEATURE	LONGITUDE	LATITUDE	AGE (MA)	REEF EMERGENT LAND (km^2)	LAGOON HABITAT <100 m (km^2)	BACK-REEF/ LAGOON VOLUME (10^3 m^3)	SUMMIT DEPTH (m)
Kure Atoll	Closed atoll	178° 19.55’	28° 25.28’	29.8	0.86	167	141,000	-
Nero Seamount	Bank	177° 57.07’	27° 58.88’	29.1	0.00	17	-	68
Midway Atoll	Closed atoll	177°22.01’	28° 14.28’	[27.7], 28.7	1.42	223	213,000	-
Pearl and Hermes Atoll	Closed atoll	175° 51.09’	27° 51.37’	[20.6], 26.8	0.36	1,166	2,930,000	-
Lisiankski Island Neva Shoal	Open atoll	173° 58.12’	26° 4.2’	23.4	1.46	979	242,000	-
Pioneer Bank	Bank	173° 25.58’	26° 0.71’	22.8	0.00	390	-	26
North Hampton Seamounts	Bank	172° 14.08’	25° 26.84’	[26.6], 21.4	0.00	430	-	5
Laysan Island	Carbonate island	171° 44.14’	25° 46.13’	[19.9], 20.7	4.11	57	3,600	-
Maro Reef	Open atoll	170° 38.34’	25° 30.2’	19.7	0.00	1,508	611,000	-
Raita Bank	Bank	169° 30.04’	25° 31.72’	17.9	0.00	650	-	16
Gardner Pinnacles	Basalt sea stacks	167° 59.82’	25° 0.04’	[12.3], 15.8	0.02	1,904	-	-
St. Rogoties Banks	Banks	164° 7.26’	24° 20.0’	14.7	0.00	500	-	22
Brocks Banks	Banks	166° 49.31’	24° 7.03’	[13.0], 13.6	0.00	320	-	20
French Frigate Shoals	Open atoll	166° 10.75’	23° 45.99’	12.3	0.23	733	1,910,000	-
Bank 66	Bank	165° 49.37’	23° 51.86’	11.9	0.00	0	-	120
Mokumanamana	Basalt island	164° 41.90’	23° 34.64’	[10.3], 10.6	0.21	1,538	64.2	-
Twin Banks	Bank	163° 3.78’	23° 13.08’	8.7, 8.3	0.00	9.5	-	53
Nihoa Island	Basalt island	161° 55.25’	23° 3.73’	[7.2], 7.3	0.82	246	-	-

Holocene Reef Development

Using values of island-specific coral community measures from Grigg (1982), vertical rates of reef accretion can also be estimated and are shown for four islands in Figure 3.5. As the figure suggests, Grigg (1982) found that growth rates show a strong latitudinal dependence, with corals in cooler more northerly islands growing more slowly. He also noted that, based on the work of Gross et al. (1969), at least at the more northerly atolls the carbonate contribution from coralline algae is likely to be significantly more than that from corals.

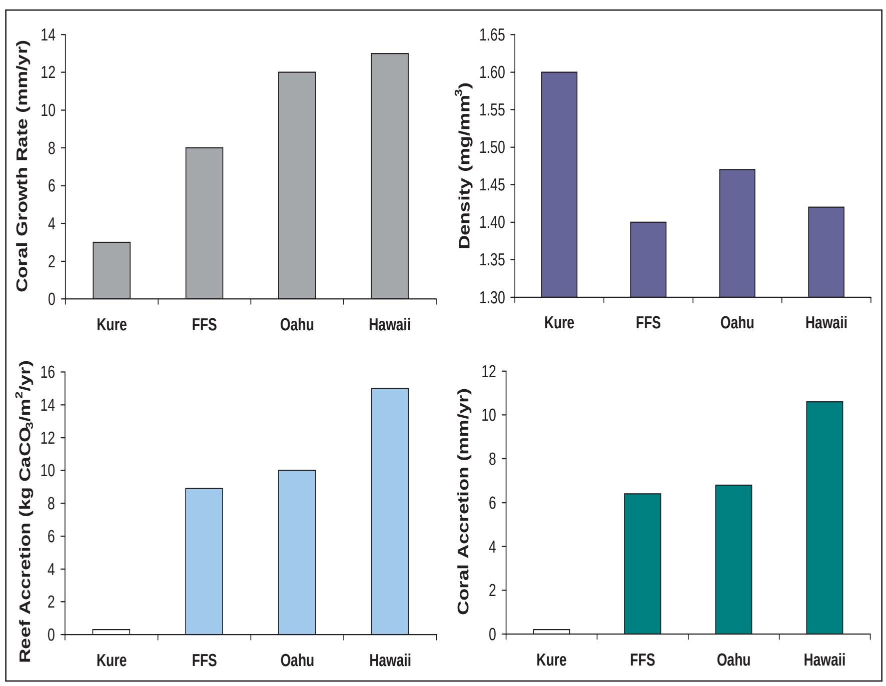


Figure 3.5. Latitudinal variations in coral colony growth rates and reef accretion across the Hawaiian Archipelago. Source: Grigg, 1982.

BENTHIC HABITAT MAPPING

Potential Reef Area

Geographic information system-based analyses were used to derive comprehensive, consistent estimates of the potential area of broadly defined, shallow-water, tropical and subtropical coral ecosystems within the territorial sea and exclusive economic zone of the United States (Rohmann et al., 2005). Nautical charts, published by NOAA's Office of the Coast Survey, provide a consistent source of 10-fathom (ca.18 m) and 100-fathom (ca. 183 m) depth curve information. The 10-fathom or 100-fathom depth curves are used as surrogates for the potential distribution and extent of shallow-water coral ecosystems in tropical and subtropical U.S. waters (Figure 3.6). The NWHI constitute between 4.3% and 12.6% of the total U.S. potential coral reef ecosystem area within 10 fathoms, depending on inclusion versus exclusion of the west Florida shelf area (Rohmann et al., 2005). The NWHI constitute 9.6% of the total U.S. potential coral reef ecosystem area within 100 fathoms, with the inclusion of the west Florida shelf area (Rohmann et al., 2005).

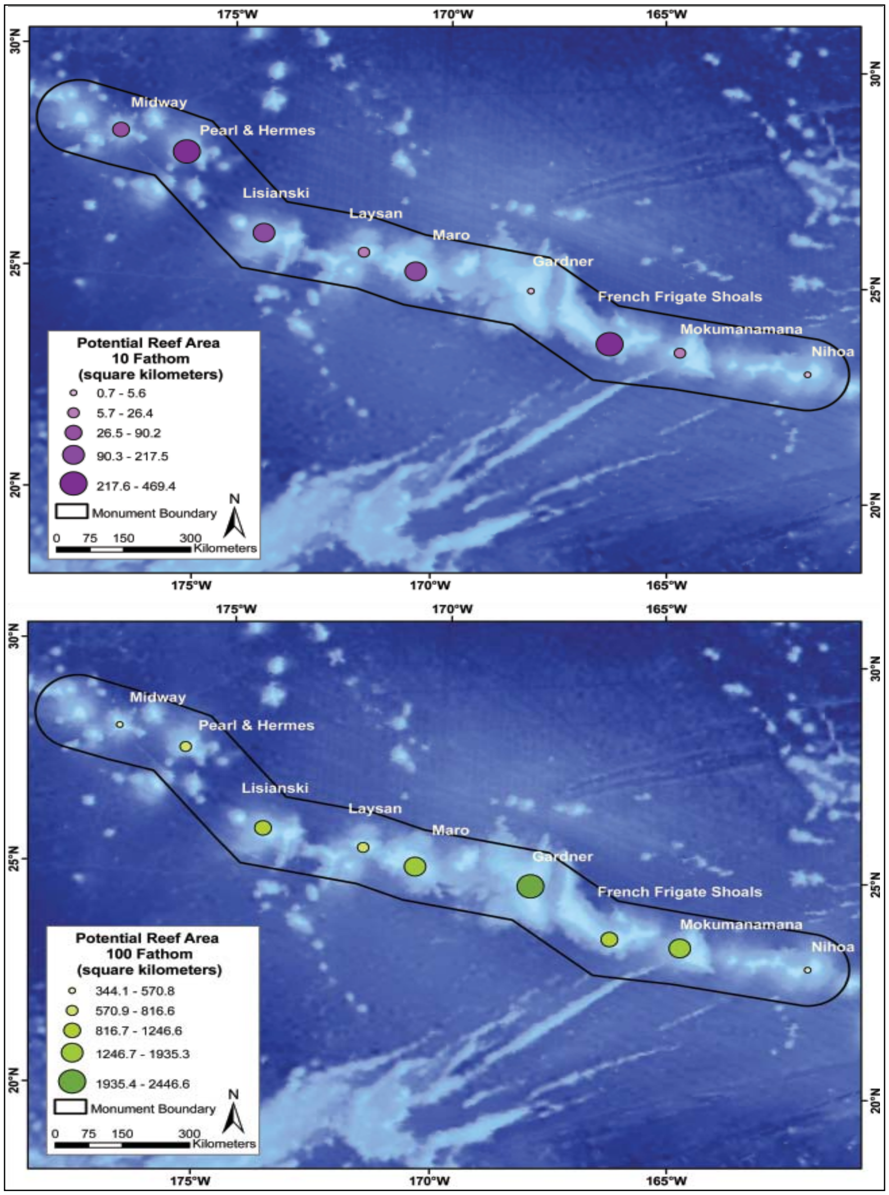


Figure 3.6. Potential reef area from the shoreline to 10-fathoms (top) and 100-fathoms (bottom) based on NOAA nautical charts. Source: Rohmann et al., 2005.

NOAA Mapping Programs

In support of the U.S. Coral Reef Task Force's mission to "Produce comprehensive digital maps of all shallow (<30 m) coral reef ecosystems in the United States and characterize priority moderate-depth reef systems by 2009," NOAA has developed a comprehensive mapping program in the Pacific Region using IKONOS satellite imagery in shallow water (<30 m) and multibeam sonar technology in depths as deep as 3,000 m (Table 3.3). In intermediate depths (10-30 m) IKONOS and multibeam mapping techniques can provide complementary or overlapping coverage. In addition, IKONOS images can be used to create "estimated depths" to fill bathymetric gaps in very shallow water (<15 m) where multibeam vessels cannot safely survey (Stumpf and Holderied, 2003).

Table 3.3. Area in the NWHI mapped by aggregated habitat cover type based upon IKONOS satellite imagery. Source: NOAA 2003.

AGGREGATED HABITAT COVER TYPE	AREA MAPPED	PERCENT TOTAL
Hardbottom with >10% live coral	108.8	4.61
Hardbottom with >10% crustose coralline algae	7.3	0.31
Hardbottom (uncolonized)	101.4	4.30
Hardbottom with >10% macroalgae	105.2	4.46
Hardbottom with indeterminate cover	822.8	34.85
Unconsolidated with 10% or less macroalgae or seagrass	1,149.6	48.70
Unconsolidated with >10% macroalgae or seagrass	65.8	2.79
Total Habitat Area Classified	**2,360.8**	**100.00**

Shallow Water IKONOS Satellite Mapping

NOAA's Biogeography Branch has sponsored a shallow water (0-30 m) benthic habitat mapping program using IKONOS satellite imagery, which in 2003 produced the Atlas of the *Shallow-Water Benthic Habitats of the Northwestern Hawaiian Islands* (available at http://ccma.nos.noaa.gov/ecosystems/coralreef/nwhi/welcome.html). IKONOS high-resolution satellite imagery was used to derive benthic habitat maps, estimated depth, and the color images. The detailed benthic habitat classification scheme was designed to categorize benthic habitat by substrate category (e.g., unconsolidated and hardbottom), structure (e.g., linear reef or pavement) and cover (e.g., coral or macroalgae; Figure 3.7, Table 3.4; http://biogeo.nos.noaa.gov). Of the area mapped, 49% was unconsolidated sediment while 35% was indeterminate.

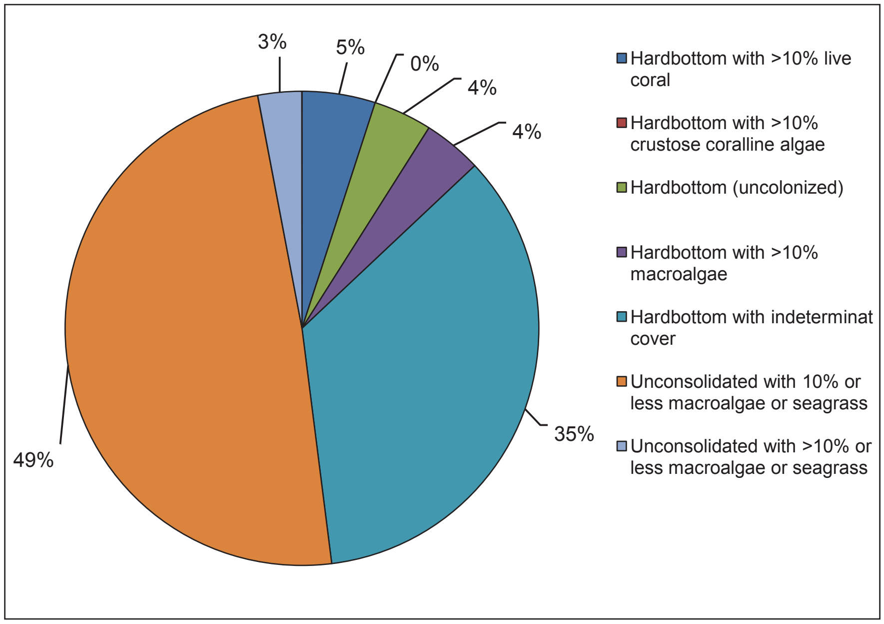


Figure 3.7. Area in the NWHI mapped by aggregated habitat cover type based upon IKONOS satellite imagery. Source: NOAA, 2003.

Table 3.4. Area mapped by aggregated habitat cover type and geographic scale (km²) based upon IKONOS satellite imagery. Source: NOAA, 2003.

TOTAL	KURE ATOLL	MIDWAY ATOLL	PEARL & HERMES ATOLL	LISIANSKI ISLAND	LAYSAN ISLAND	MARO REEF	FRENCH FRIGATE SHOALS	MOKUMANA-MANA	NIHOA ISLAND
Hardbottom with >10% live coral	1.8	1.4	20.3	16.4	5.8	14.8	48.3	0	0.1
Hardbottom with >10% crustose coralline algae	0.7	0.1	0	0	0.5	1.3	4.7	0	0
Hardbottom (uncolonized)	11.6	14.9	13.7	0.9	2.9	6.8	49.9	0	0.7
Hardbottom with >10% macroalgae	5.8	22.4	62.2	6.1	0.1	0.4	3.7	0	4.5
Hardbottom with indeterminate cover	8.4	6.7	49.3	183.5	81.7	180.1	46.1	208.1	58.9
Unconsolidated with 10% or less macroalgae or seagrass	38.8	49.9	226.2	231.8	36.2	295.7	241.5	19.5	10
Unconsolidated with >10% macroalgae or seagrass	2.7	0.2	19.9	0	0	19.6	23.4	0	0
Total Habitat Area Classified	69.8	95.5	391.6	438.7	127.2	518.7	417.6	227.6	74.1

Moderate-Depth Multibeam Mapping

NOAA's Coral Reef Ecosystem Division (CRED) initiated a moderate-depth multibeam mapping program which was conceived in 2001, implemented between 2002 and 2005, and has produced over 45,000 km^2 of bathymetric data in the NWHI since 2002 (Table 3.5; Miller et al., 2003). This mapping program is designed to extend and be complementary to the shallow-water IKONOS mapping program discussed above.

In 2002 multibeam surveys to define 25, 50, and 100-fm isobaths in the NWHI were conducted by NOAA and University of Hawaii (UH) personnel aboard UH's R/V *Kilo Moana*, using Kongsberg/Simrad EM1002

Table 3.5. NWHI multibeam mapping statistics and estimates.

	MAPPING COMPLETED 2002-2008		**ESTIMATE TO COMPLETE**
	km^2	Days	Days Remaining
Deep (100-5,000 m)	41,664	28	67
Mid-Depth (10-100 m)	3,854	134	275
Totals	**45,518**	**162**	**342**

the banks and atolls that are shown in Figure 3.8. Moderate depth multibeam sonar surveys were conducted in the NWHI between 2003 through 2008 by personnel from CRED, NOAA's Office of National Marine Sanctuaries, and other partners using mapping systems aboard the NOAA Ship *Hiialakai* and the survey launch R/V *Acoustic Habitat Investigator (AHI)*. The *Hiialakai* is equipped with two Kongsberg/Simrad multibeam sonars: a 30-kHz EM300 with mapping capability from approximately 100-3000+ m and a 300-kHz EM3002D with mapping capability from about 5-150 m. The R/V *AHI* has a 240-kHz Reson 8101ER with mapping capability from about 5-300 m. Both vessels have Applanix POS/MV motion sensors, which provide navigation and highly accurate readings of the vessel motion in all axes. Optical validation data have also been collected since 2001 using towed and drop camera systems aboard the *Hiialakai*, *AHI* and the NOAA Ship *Oscar Elton Sette*.

Bathymetric data from these 2003-2008 *Hiialakai* and *AHI* surveys add to previously published data (Miller et al., 2003) from the 2002 R/V *Kilo Moana* surveys as well as estimated depths from IKONOS imagery Figure 3.8 and Table 3.5 show current bathymetric coverage in NWHI.

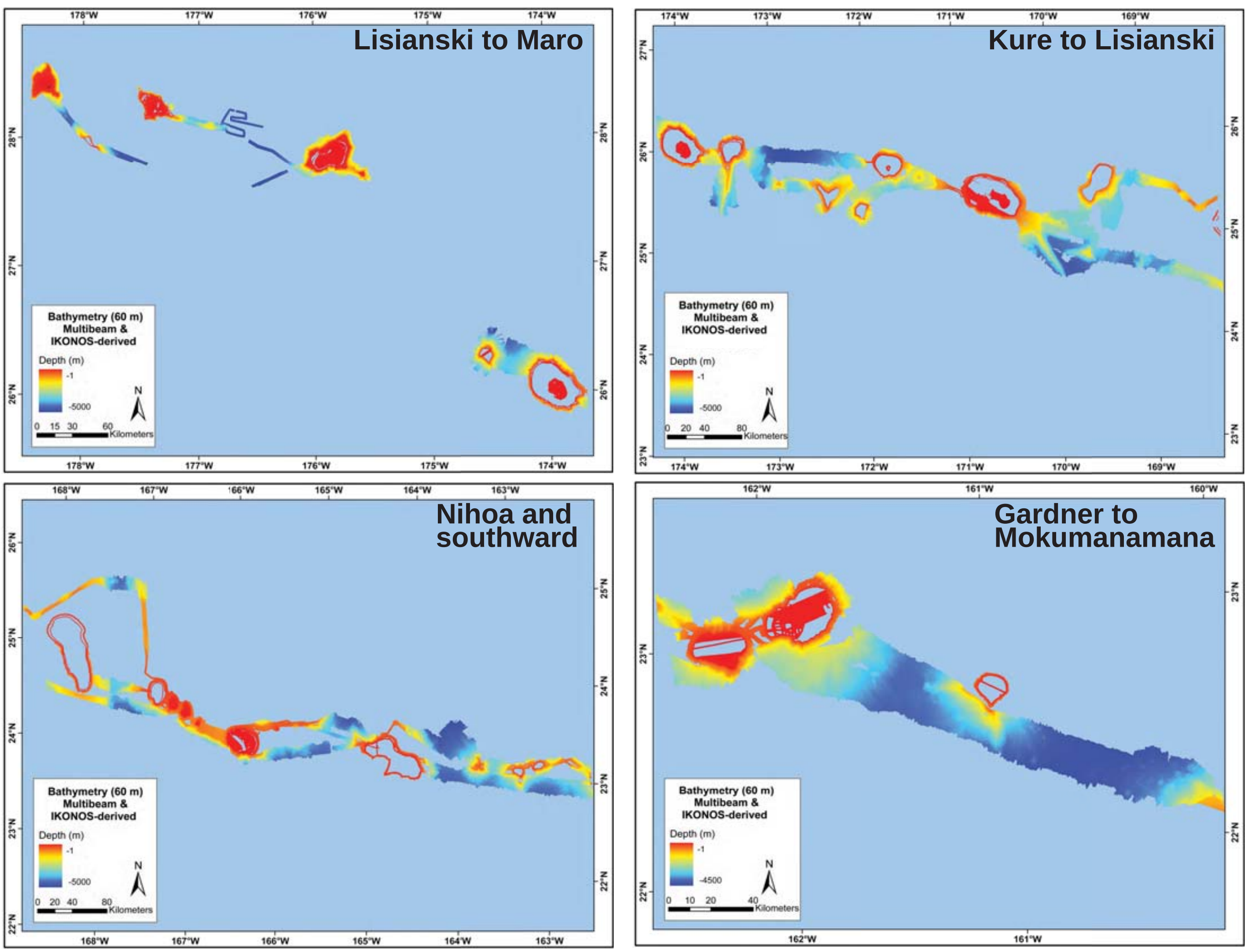


Figure 3.8. Multibeam maps of all data collected in the NWHI through 2006. Maps: L. Wedding.

Bathymetric grids at various resolutions are updated annually and published on the web at the Pacific Islands Benthic Habitat Mapping Center (PIBHMC; www.soest.hawaii.edu/pibhmc). As shown in Figure 3.8, some bathymetric data have been collected and processed at all of the islands and banks in the NWHI in water depths ranging from 3 to 3,000 m with almost complete coverage at Kure, Midway, Pearl and Hermes, Brooks Banks and French Frigate Shoals, and partial coverage at other locations. The bank on the southwest side of French Frigate Shoals was the first area to be mapped in early 2005 and 95% completed in 2008, and this data set is used later in this chapter to illustrate the various benthic habitat mapping products, their potential uses, and interpretation. Similar products for other banks are regularly added to the PIBHMC web site as mapping, data processing, product and metadata generation, and interpretation are completed.

The geomorphological data layers of substrate, slope, rugosity, and bathymetric position index (BPI) produced at the PIBHMC are derived from multibeam bathymetry. Derivative data products (e.g., slope, rugosity and BPI) add geomorphological information about characteristics (e.g., roughness) that may assist in determining benthic habitat utilization. An explanation of each derivative type is given here. At this time a complete set of derivate products has been developed only for French Frigate Shoals.

Rugosity: Cell values reflect the surface area to planimeteric area ratio (surface area) / (planimetric area) for the area contained within that cell's boundaries. This measure provides an index of topographic roughness and convolutedness (Jenness, 2003). Distributions of fish and other mobile organisms are often found to positively correlate with increased complexity of the seafloor. Investigations are underway for the development of the most appropriate spatial metrics for quantifying benthic complexity for the purposes of relating these metrics to fish distributions in Pacific coral reef ecosystems. Results of the Jenness (2003) method are provided as a standardized and well-documented interim product.

Slope: Cell values reflect the maximum rate of change (in degrees) in elevation between neighboring cells.

Substrate: This is a preliminary product that is still under development. Cell values reflect whether the seafloor is hard bottom or soft bottom based on an unsupervised classification run in Environment for Visualizing Images (ENVI) software. The classifications (hard bottom versus soft bottom) are based on backscatter, bathymetry, acoustic derivatives and optical data.

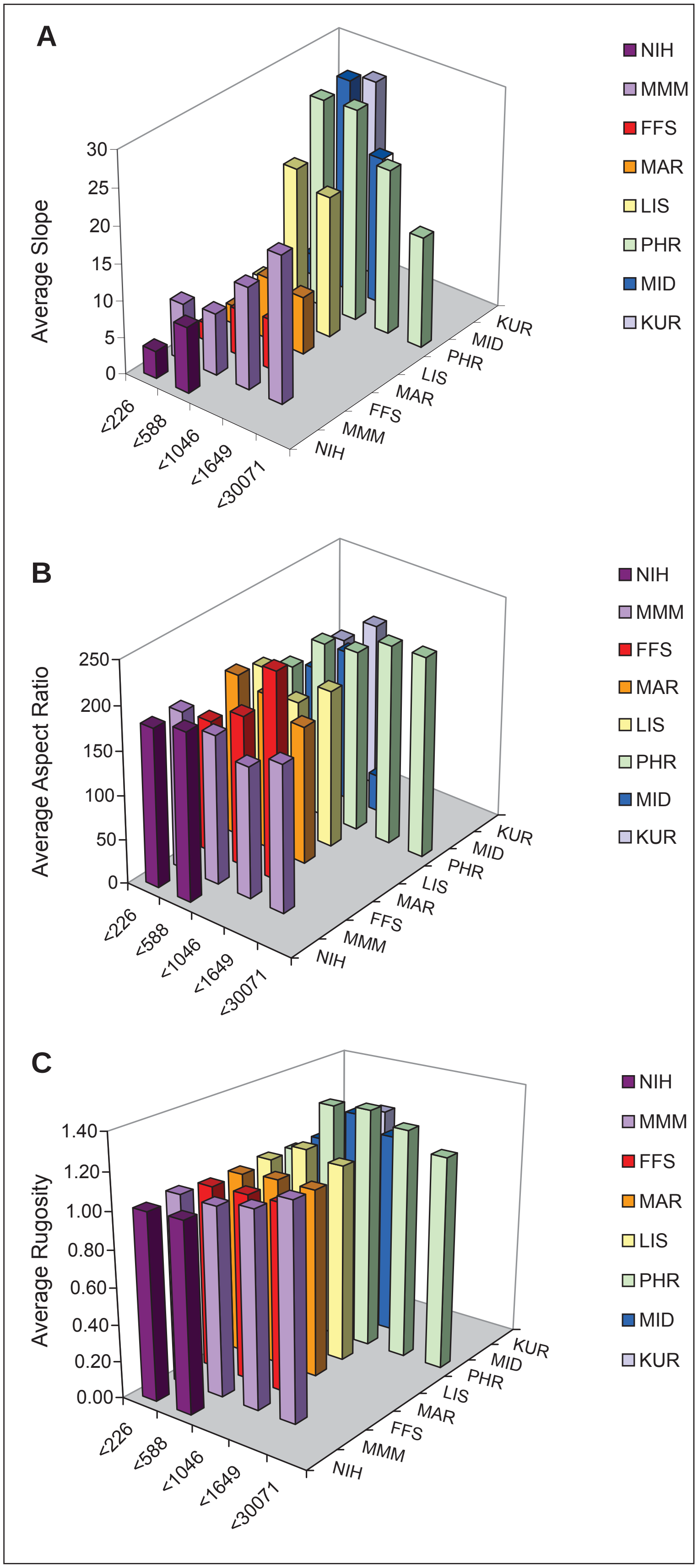
Bathymetric Position Index: BPI is a second order derivative of bathymetry. The derivation evaluates elevation differences between a focal point and the mean elevation of the surrounding cells within a user defined annulus or circle. A negative value represents a cell that is lower than its neighboring cells (depressions) and a positive value represents a cell that is higher than its neighboring cells (crests). Larger numbers represent more prominent features on the seafloor, which differ greatly from surrounding areas. Flat areas or areas with a constant slope produce near-zero values. (Lundblad et al., 2006).

Summary of Multibeam Data

Based on available multibeam data, summary statistics (slope, aspect ratio and rugosity) were developed for five depth bins based on natural breaks (9-226 m, 226-588 m, 588-1,045 m, 1,045-1,649 m and 1,649-3,071 m). Slope values overall are lowest in the shallow (<226 m) depth bin (Figure 3.9). Islands further upchain such as Kure, Midway, Pearl and Hermes and Lisianski have higher slope values, on average, compared with locations further southeast along the chain. Aspect ratio (Δ Z/ΔX) does not vary greatly by depth bin or among reefs. Rugosity increases slightly with depth and the highest rugosity was found at Pearl and Hermes Atoll.

Island Profiles

The following sections summarize the geologic and benthic habitat information available for each emergent island in the NWHI, as of January 2009. The data include results from both IKONOS satellite imagery and multibeam data analyses.



Figures 3.9. A) Average slope by depth bin from multibeam sonar data collected at select islands within the NWHI; B) Average aspect ratio by depth bin from multibeam sonar data collected at select islands within the NWHI; and C) Average rugosity by depth bin from multibeam sonar data collected at select islands within the NWHI.

Nihoa Island

Nihoa Island is located approximately 249.4 km northwest of Kauai, the closest to the Main Hawaiian Islands (MHI). Measuring roughly 0.68 km^2, this island is the largest emergent volcanic island within the Monument and the tallest, reaching an elevation of 275.2 m at Miller Peak. It is also the geologically youngest island within the Monument, with an age calculated at 7.3 million years (Clague, 1996). Nihoa is a deeply eroded remnant of a once large volcano, and the large basaltic shelf of which it is a part stretches 28.9 km in a northeast-southwest direction and ranges between 34.1 and 66.1 m deep (NOAA, 2003). The island's two prominent peaks and steep sea cliffs are clearly visible from a distance, rising like a fortress above the sea. The island's northern face is com-

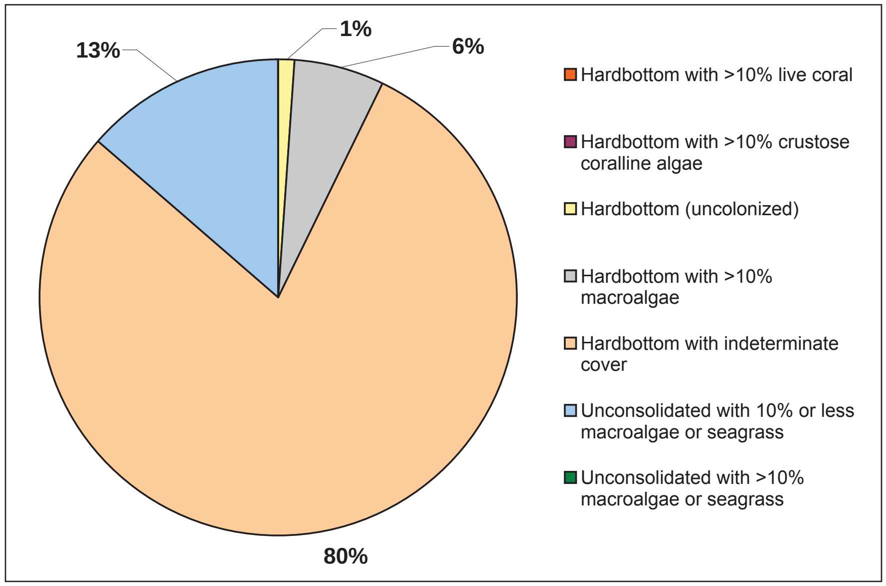


Figure 3.10. Benthic habitats around Nihoa based on IKONOS satellite data. Source: NOAA, 2003.

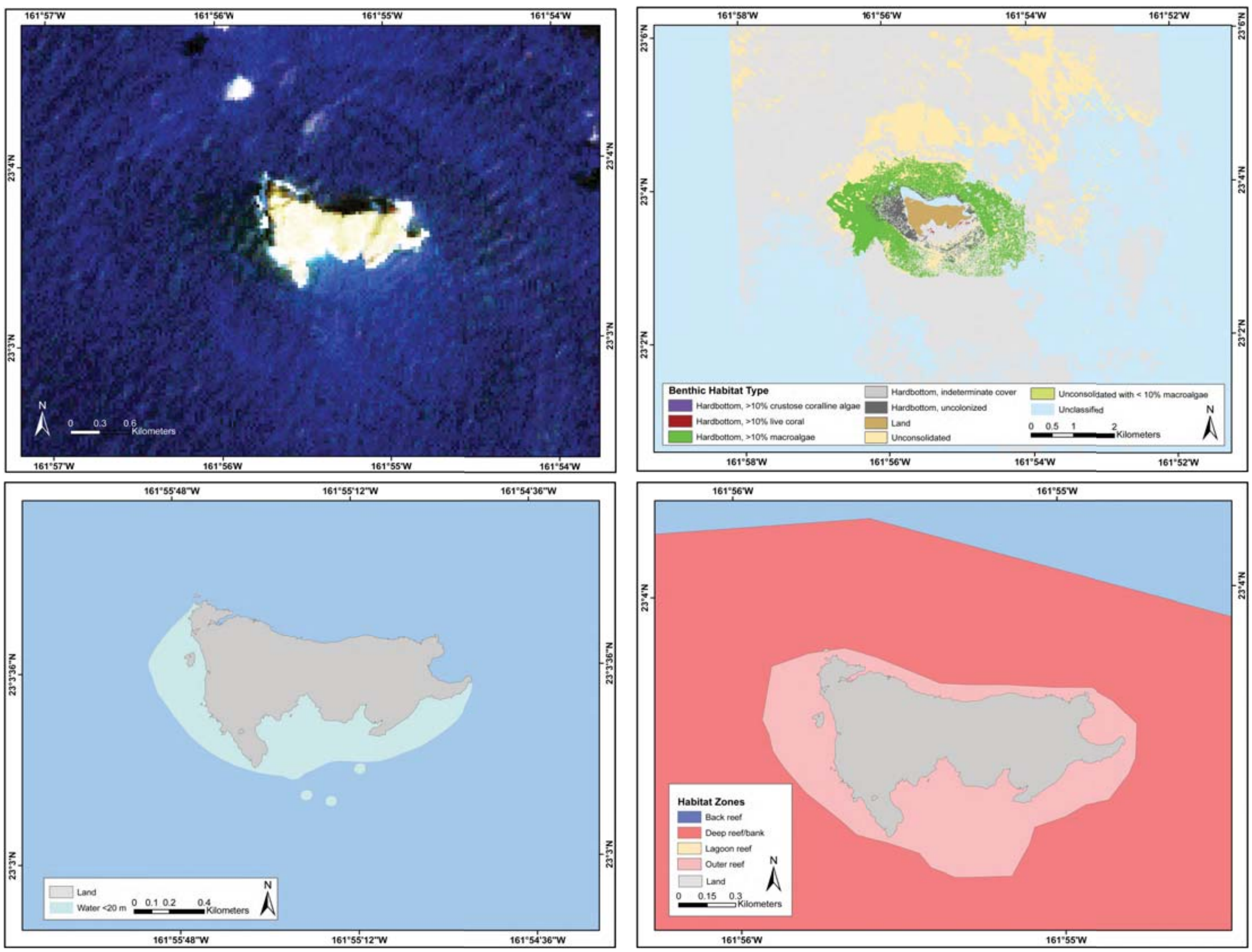


Figure 3.11. IKONOS satellite image (top left), benthic habitat map (top right), extent of water depth < 20 m (bottom left), and habitat zones for Nihoa Island (bottom right). Maps: L. Wedding.

posed of a sheer cliff made up of successive layers of basaltic lava, within which numerous volcanic dikes are visible. The island's surrounding submerged reef habitat totals approximately 574.6 km^2 and is a combination of uncolonized hard bottom, macroalgae, pavement with sand channels and live coral, and uncolonized volcanic rock (NOAA, 2003; Figures 3.10, 3.11). The principal shallow water bottom habitats around Nihoa consist of hard basalt as vertical walls, horizontal wave-cut basalt benches, elevated mounds, and large blocks and boulders. Nihoa supports coral communities with very limited total habitat, most of which is not protected from the heavy and chronic wave action that strikes this small island from all directions. These habitats have been shaped by and are constantly eroded by the pounding waves.

Multibeam surveys were conducted around Nihoa Island and on West Nihoa Bank on several different cruises, including R/V *Kilo Moana* KM-02-06, *Hiialakai* HI-05-01 and *Hiialakai* HI-06-12. The first two survey patterns around Nihoa Island were designed to delineate the 25-, 50-, and/or 100-fm boundaries needed for the National Marine Sanctuary designation process. Slope, aspect, and rugosity all increased with depth although the difference was small (Table 3.6). In Tables 3.6 -3.13 minimum, maximum, range, mean and standard deviation for bathymetry are in meters; slope and aspect are in degrees (0-360); and rugosity is a dimensionless ratio of surface area to planimetric area. High rugosity typically indicates a rough and complex substrate that often correlates with potential coral habitat.

Bathymetry data for all islands was merged into a single raster. This was reclassified into five depth classes using natural breaks - a method which seeks to equalize the variation between each class - in the ArcGIS 9.2 Spatial Analyst extension. Using these 5 classes as zones, zonal statistics were run on bathymetry, slope, aspect and rugosity by island, using the "zonal statistics as table" tool in Spatial Analyst. This resulted in

Table 3.6. Summary statistics for multibeam surveys conducted around Nihoa Island and on West Nihoa Bank.

NIHOA	DEPTH CLASS	AREA	MINIMUM*	MAXIMUM*	RANGE	MEAN	STANDARD DEVIATION
Bathymetry	9 to 226	353.68	-225.17	-25.21	199.96	-69.46	41.34
	266 to 588	248.65	-500.00	-225.17	274.82	-356.89	65.18
Slope	9 to 226	-	0.00	68.01	68.01	3.72	7.79
	266 to 588	-	0.00	75.99	75.99	8.96	7.66
Aspect	9 to 226	-	0.00	360.00	360.00	180.02	111.23
	266 to 588	-	-1.00	360.00	361.00	191.13	118.97
Rugosity	9 to 226	-	1.00	2.86	1.86	1.01	0.06
	266 to 588	-	1.00	4.44	3.44	1.03	0.05

***NOTE:** the minimum represents the minimum value of a given metric within a universal depth class; maximum represents the maximum value of a given metric within a universal depth class.

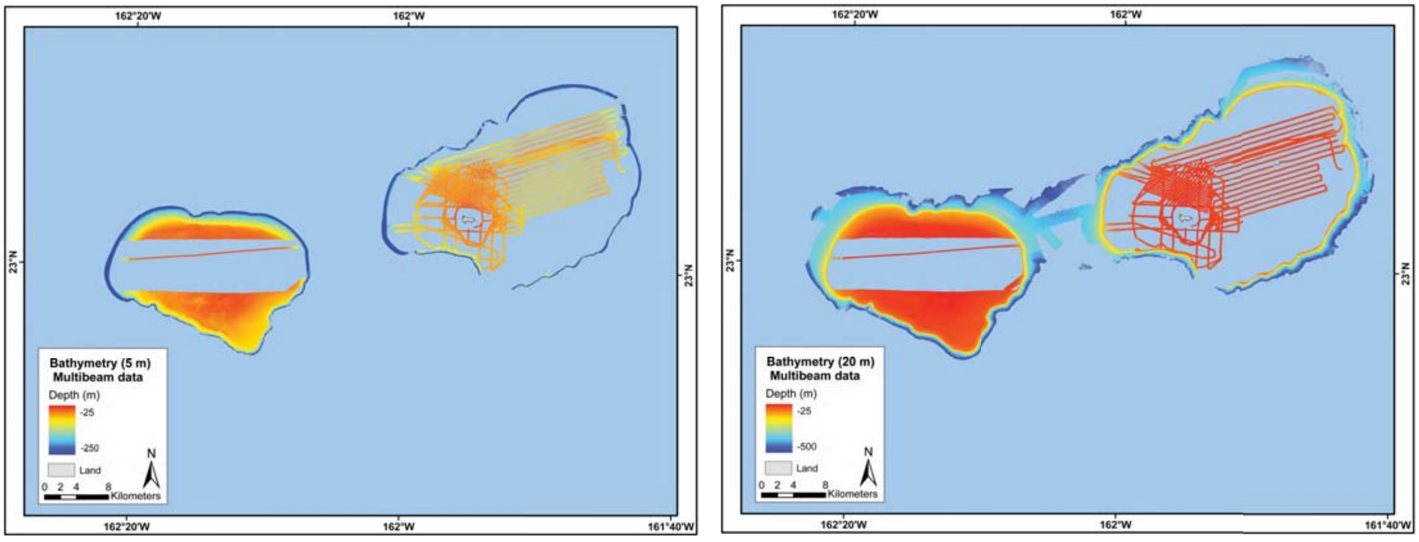


Figure 3.12. 5 m and 20 m bathymetry for Nihoa with derived depths from IKONOS imagery near island center. Maps: L. Wedding.

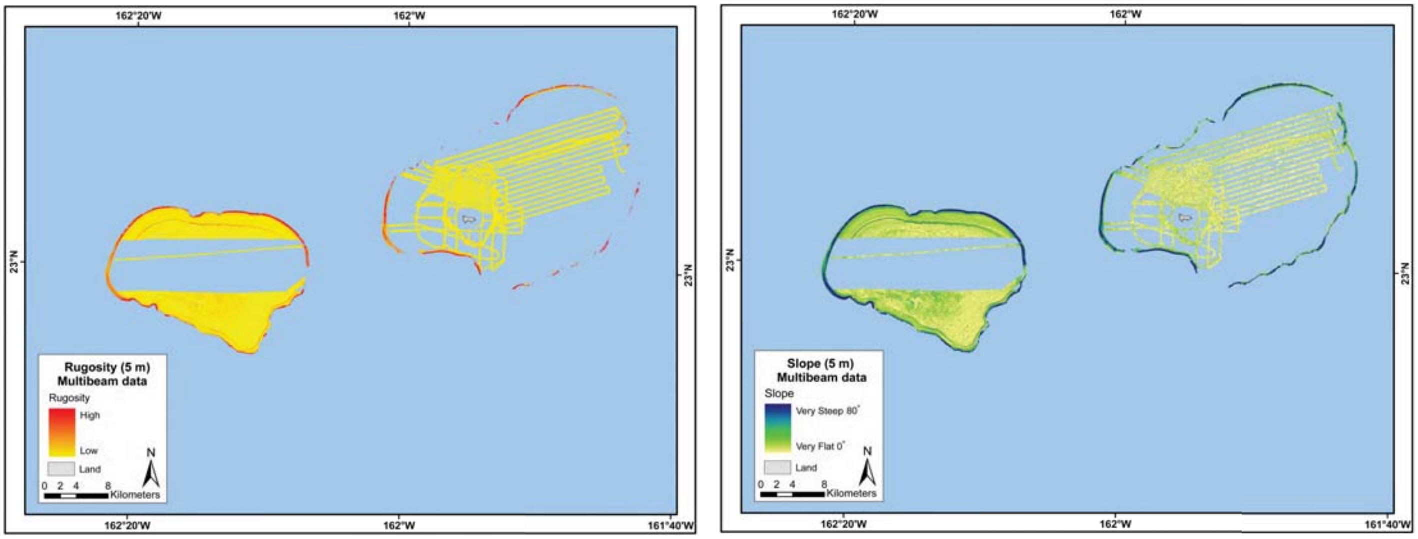


Figure 3.12 (continued). Rugosity (5 m), and slope (5 m) for Nihoa with derived depths from IKONOS imagery near island center. Maps: L. Wedding.

the generation of summary statistics for each island in terms of the NWHI as a whole, making it possible, for example, to compare the average slope of Kure with that of Maro within the same depth class.

Cruise *Hiialakai* HI-06-12 surveys on West Nihoa Bank were conducted to provide continuous coverage in order to better delineate topography on submerged banks; the resulting maps revealed some intriguing features on the southern part of West Nihoa Bank (Figure 3.12). Surveys of bottom fish habitats (Figure 3.13) and fish abundance were also conducted during *Hiialakai* HI-06-12.

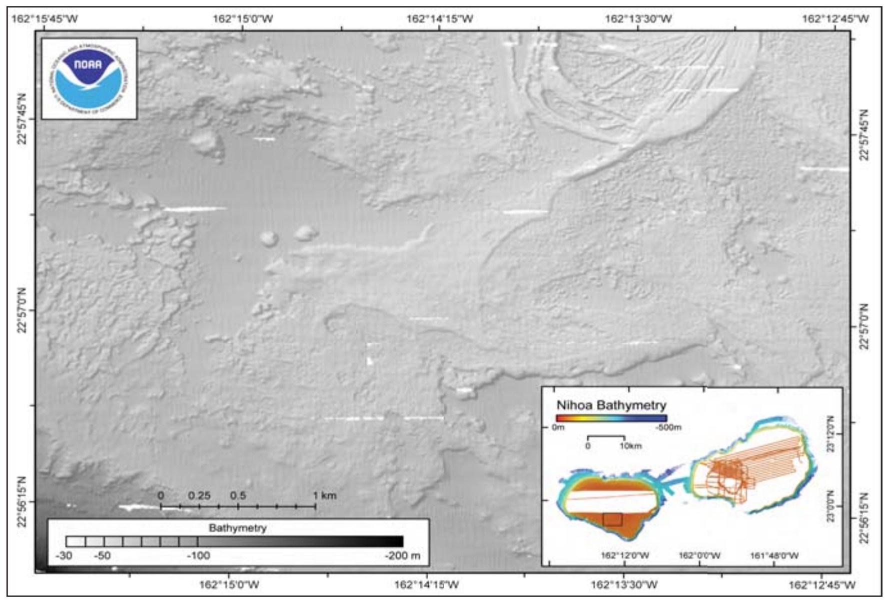


Figure 3.13. Detailed hillshade of bathymetric data on the southern portion of West Nihoa bank.

Mokumanamana Island

Mokumanamana Island is a hook-shaped dry volcanic island that includes about 18 hectares of land with 9.1 km^2 of potential coral reef habitat within 10 fathoms and a large bank that includes 1,557 km^2 of habitat within 100 fathoms. Mokumanamana is a dry volcanic island shaped like a fishhook, and includes approximately 0.18 km^2 of land. Geologists believe the island, with an estimated age of 10.6 million years, was once the size of Oahu in the MHI, with a maximum paleo-elevation of 1,036 m (Clague, 1996), but due to centuries of erosion its highest point, at Summit Hill, is now only 84.1 m above sea level. All shallow

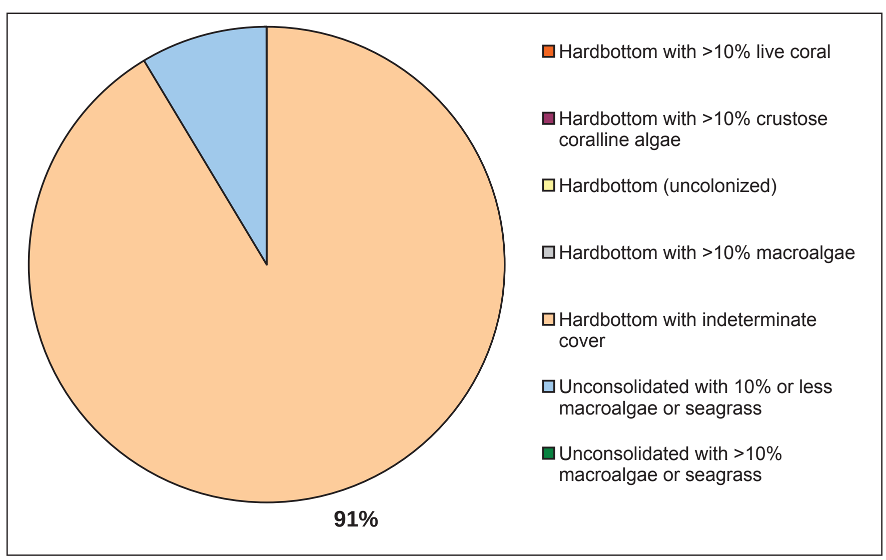


Figure 3.14. Percent composition of mapped benthic habitats at Mokumanamana based on NOAA benthic habitat maps. Source: NOAA, 2003.

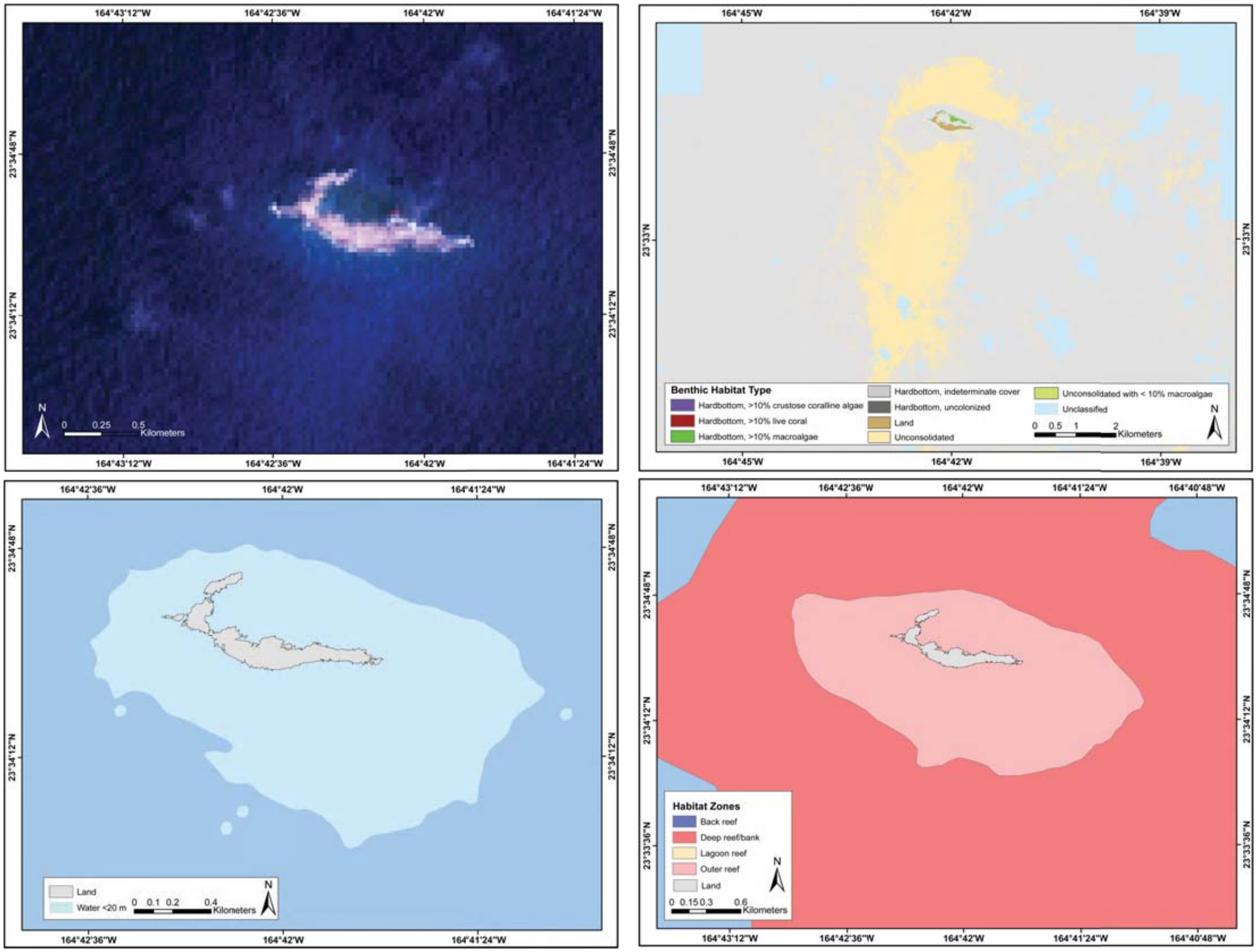


Figure 3.15. IKONOS satellite image (top left), benthic habitat map (top right), extent of water depth < 20 m (bottom left), and habitat zones (bottom right) for Mokumanamana. Maps: L. Wedding.

Table 3.7. Summary statistics for multibeam surveys conducted around Mokumanamana in 2002.

MOKUMANAMANA	DEPTH CLASS	AREA	MINIMUM*	MAXIMUM*	RANGE	MEAN	STANDARD DEVIATION
Bathymetry	9 to 226	202.99	-286.14	-1.03	285.11	-90.93	57.43
	266 to 588	362.93	-737.97	-145.73	592.23	-376.12	88.38
	588 to 1,046	77.04	-1,132.92	-394.30	738.62	-812.10	125.46
	1,046 to 1,649	53.09	-1,500.00	-953.00	547.00	-1,290.05	140.25
Slope	9 to 226	-	0.00	69.72	69.72	7.81	10.13
	266 to 588	-	0.00	77.49	77.49	8.38	8.40
	588 to 1,046	-	0.00	77.45	77.45	13.91	10.48
	1,046 to 1,649	-	0.00	76.94	76.94	20.04	13.80
Aspect	9 to 226	-	-1.00	360.00	361.00	179.46	113.87
	266 to 588	-	-1.00	360.00	361.00	168.49	120.76
	588 to 1,046	-	-1.00	360.00	361.00	149.07	119.73
	1,046 to 1,649	-	-1.00	360.00	361.00	167.43	126.94
Rugosity	9 to 226	-	1.00	3.33	2.33	1.03	0.09
	266 to 588	-	1.00	5.67	4.67	1.03	0.07
	588 to 1,046	-	1.00	4.51	3.51	1.07	0.13
	1,046 to 1,649	-	1.00	4.87	3.87	1.16	0.25

***NOTE:** the minimum represents the minimum value of a given metric within a universal depth class; maximum represents the maximum value of a given metric within a universal depth class.

marine habitats are basalt surfaces exposed to high wave action and the effects of scour (surge combined with sand and other sediments) is evident from the wave-cut bench in West Cove and the deeply cut sand channels and chasms at several locations in deeper water (Figures 3.14, 3.15). Reef growth in shallow waters, if any, is minimal and the punishing effects of large waves as demonstrated by the high wave cut sea cliffs above sea level and wave planed benches and shelves below sea level. The bank provides excellent habitat for spiny lobsters (*Panulirus marginatus*) and slipper lobsters (*Scyllarides squammosus*), especially in habitats of less than 27.4 m depth and high benthic relief (Parrish and Polovina, 1994).

Multibeam surveys around Mokumanamana were conducted in 2002 (KM0206) and 2008 (HI0804; Table 3.7, Figure 3.16). The 2002 surveys were for 25-, 50-, and/or 100-fm boundary delineation and the survey in 2008 was planned to better delineate the Necker Ridge that runs southwest from Mokumanamana, which is under consideration as a possible extension to the U.S. Exclusive Economic Zone. The data from the 2008 surveys have not yet been fully processed and Figure 3.16 shows only data collected in 2002. Slope and rugosity increase with increasing depth while the aspect ratio is highest in the shallowest depth range (<226 m; Table 3.7).

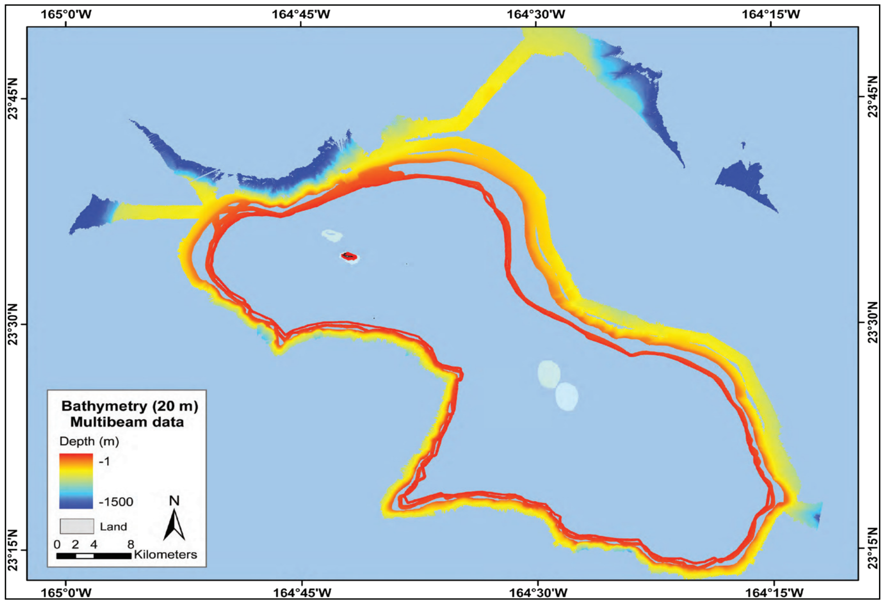


Figure 3.16. Multibeam bathymetric data around Mokumanamana Island collected in 2002 and 2006 derived depths from IKONOS imagery near island center. Map: L. Wedding.

French Frigate Shoals

French Frigate Shoals is the largest atoll in the chain, taking the form of an 28.9 km long crescent. It is estimated to be 12.3 million years old (Clague, 1996). The shoals consist of 0.27 km^2 of total emergent land surrounded by approximately 931 km^2 of coral reef habitat, with a combination of sand, rubble, uncolonized hard bottom, and crustose coralline algae in the windward and exposed lagoon areas, and patch and linear coral reefs in more sheltered areas (NOAA, 2003; Figures 3.17, 3.18). Tern Island in the atoll is the site of a U.S. Fish and Wildlife Service field station, which occupies a former U.S. Coast Guard (USCG) Long-Range Aids to Navigation (LORAN) station that closed in 1979. The lagoon is also unusual in that it contains one exposed volcanic pinnacle (La Perouse) representing the last vestiges of the high island from which the atoll was derived, as well as approximately nine low, sandy islets. The sand islets are small, shift position, and disappear and reappear.

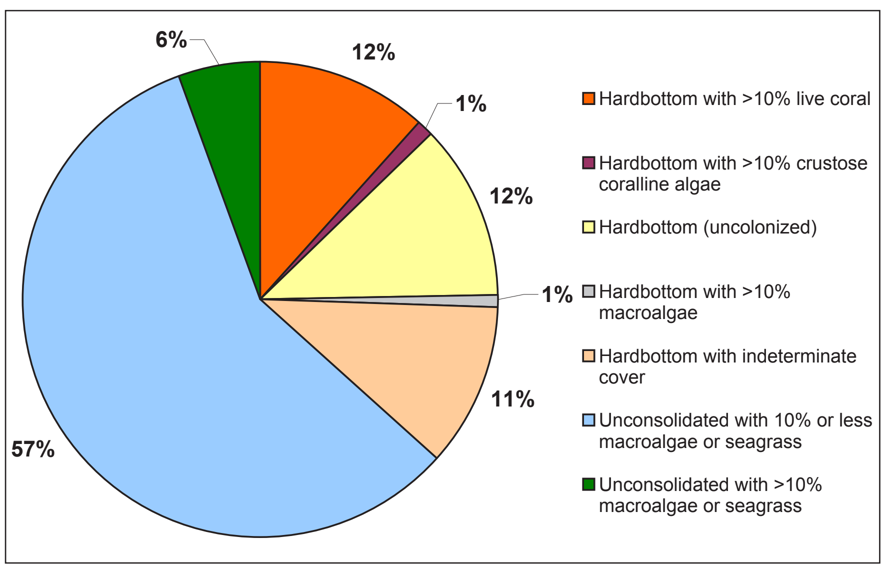


Figure 3.17. Percent composition of mapped benthic habitats at French Frigate Shoals based on NOAA benthic habitat maps. Source: NOAA 2003.

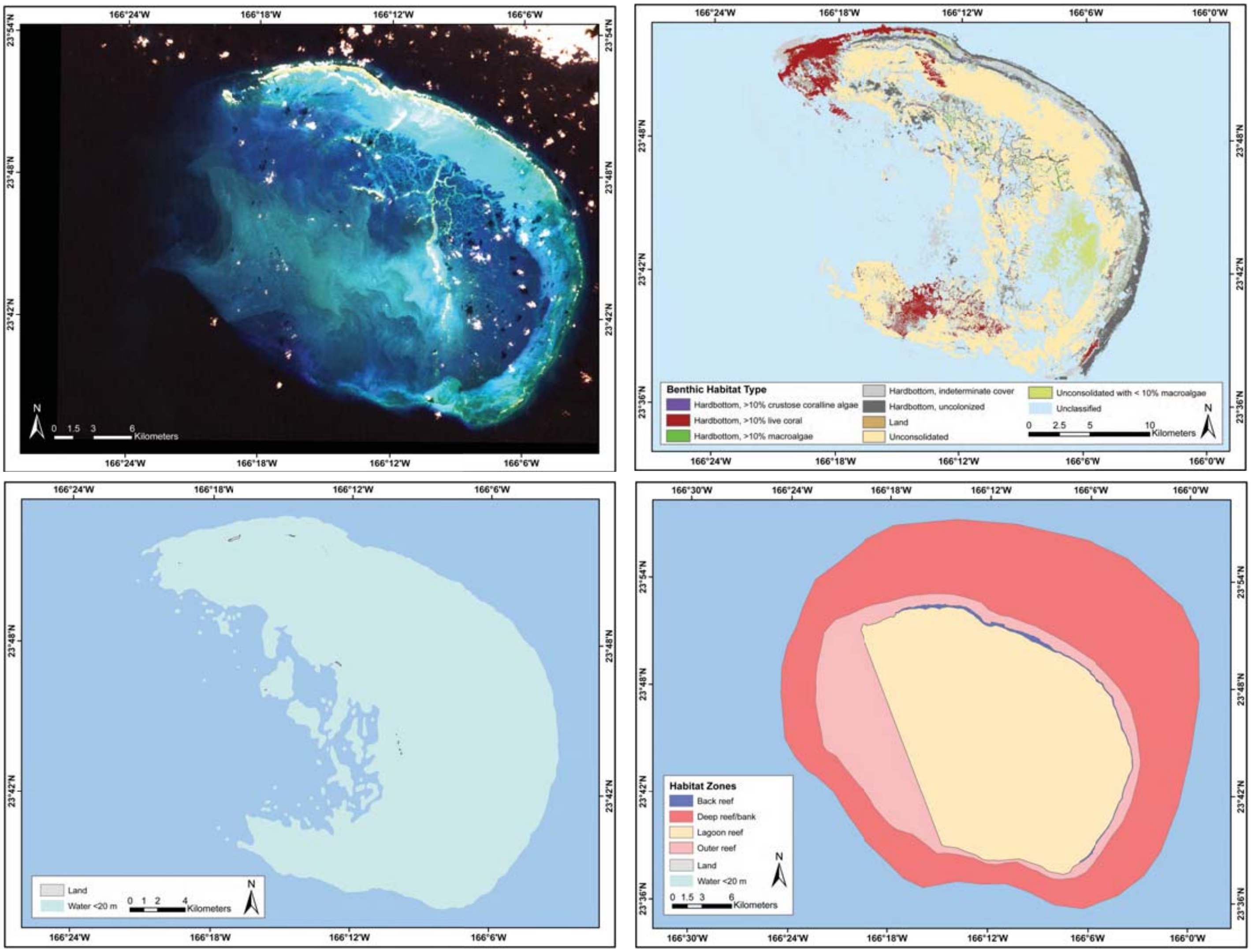


Figure 3.18. IKONOS satellite image (top left), benthic habitat map (top right), extent of water depth < 20 m (bottom left), and habitat zones (bottom right) for French Frigate Shoals. Maps: L. Wedding.

Table 3.8. Summary statistics for multibeam surveys conducted around French Frigate Shoals (2002-2008).

FRENCH FRIGATE SHOALS	DEPTH CLASS	AREA	MINIMUM*	MAXI-MUM*	RANGE	MEAN	STANDARD DEVIATION
Bathymetry	9 to 226	681.15	-294.50	0.00	294.50	-42.15	50.69
	266 to 588	284.10	-620.51	-134.19	486.32	-400.26	100.79
	588 to 1,046	54.56	-699.90	-572.38	127.52	-638.08	33.01
Slope	9 to 226	-	0.00	70.49	70.49	2.40	4.33
	266 to 588	-	0.00	73.04	73.04	6.28	6.10
	588 to 1,046	-	0.00	62.14	62.14	6.84	5.45
Aspect	9 to 226	-	-1.00	360.00	361.00	150.34	115.05
	266 to 588	-	-1.00	360.00	361.00	171.14	127.29
	588 to 1,046	-	-1.00	359.99	360.99	235.36	79.11
Rugosity	9 to 226	-	1.00	3.25	2.25	1.01	0.03
	266 to 588	-	1.00	3.74	2.74	1.01	0.03
	588 to 1,046	-	1.00	2.29	1.29	1.02	0.04

***NOTE:** the minimum represents the minimum value of a given metric within a universal depth class; maximum represents the maximum value of a given metric within a universal depth class.

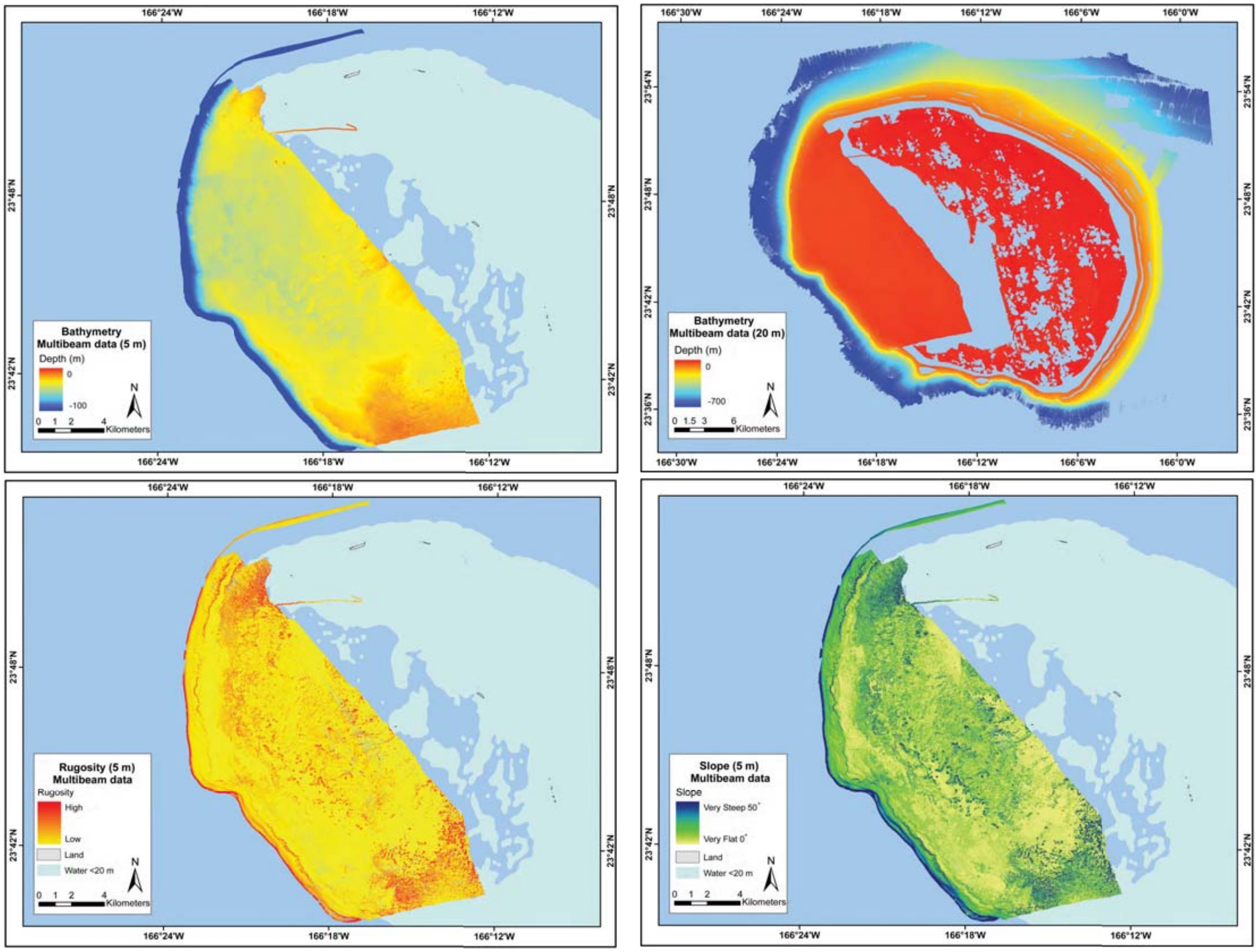


Figure 3.19. 5 m (top left) and 20 m bathymetry (top right), rugosity (5 m)(bottom left), and slope (5 m)(bottom right) for French Frigate Shoals. 20-m bathymetry plot includes derived depths from IKONOS imagery. Maps: L. Wedding.

Slope increases rapidly between the shallow and intermediate depth range (266-588 m) and then increases slightly between 588 and 1,046 m. Aspect ratio shows a gradual increase from shallow to deep depth bins while rugosity did not vary with depth (Table 3.8).

French Frigate Shoals is the first island for which a substrate type map has been produced. Using depth, backscatter, multibeam derivatives such as rugosity, slope, and variance (Figure 3.19), an unsupervised classification was performed to classify the substrate type into hard and soft bottom classes (Figure 3.20). Figures 3.21 through 3.24 shows information used in developing hard/soft and BPI maps. These products are designed to aid management agencies in developing sampling protocols that focus on hard (non-sand) substrates for coral benthic habitat studies and benthic habitat maps.

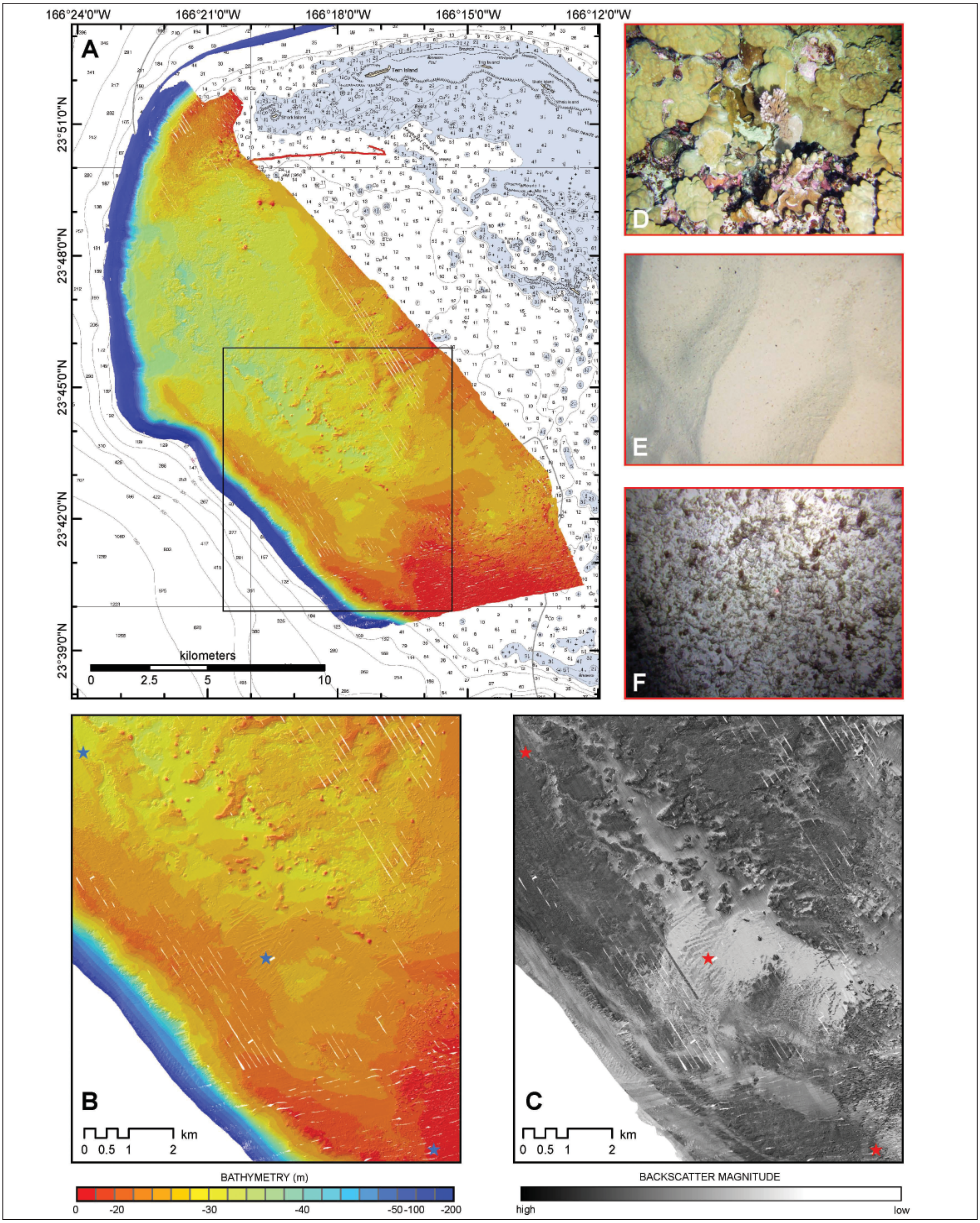


Figure 3.20. (A) Multibeam bathymetry data collected on the bank top at French Frigate Shoals. Black box corresponds to the location of the bathymetry (B) and backscatter (C) close-ups. Stars in (B) and (C) indicate the locations, from top to bottom (northwest to southeast), of the TOAD frame grabs shown in (D, E, and F). These data are used to create accurate habitat maps for moderate depth ecosystems in the NWHI using image processing techniques.

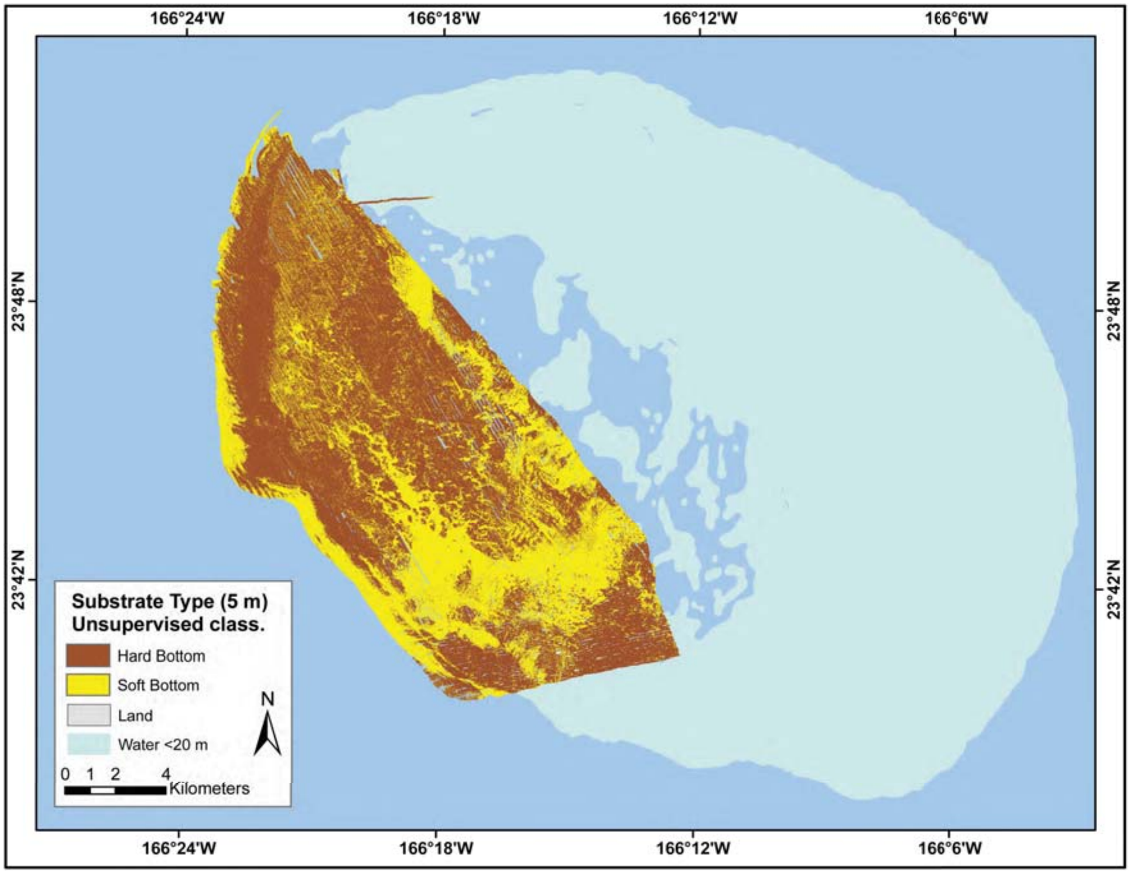


Figure 3.21. Hard/soft substrate type from French Frigate Shoals as produced by an unsupervised classification using ENVI.

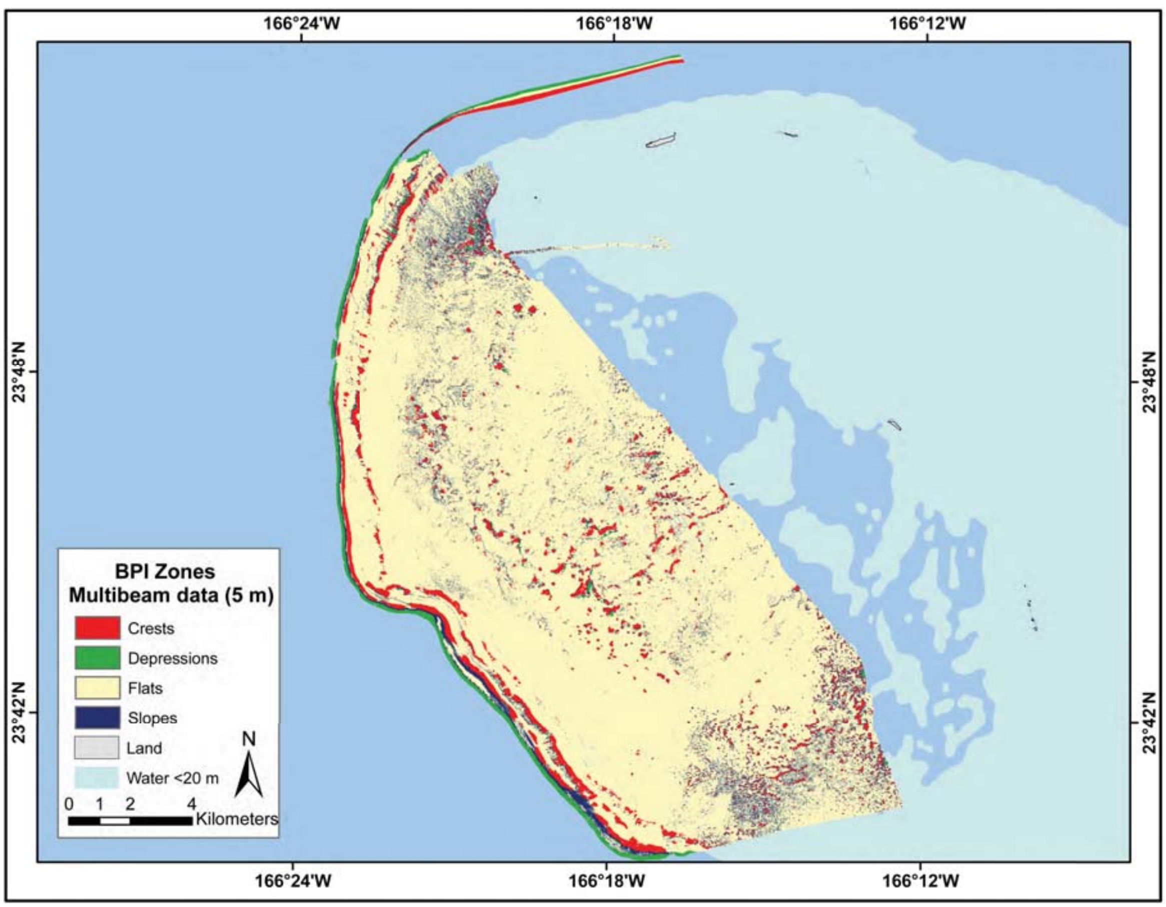


Figure 3.22. Bathymetric Position Index (BPI) zones for French Frigate Shoals. Source: Lundblad et al., 2006.

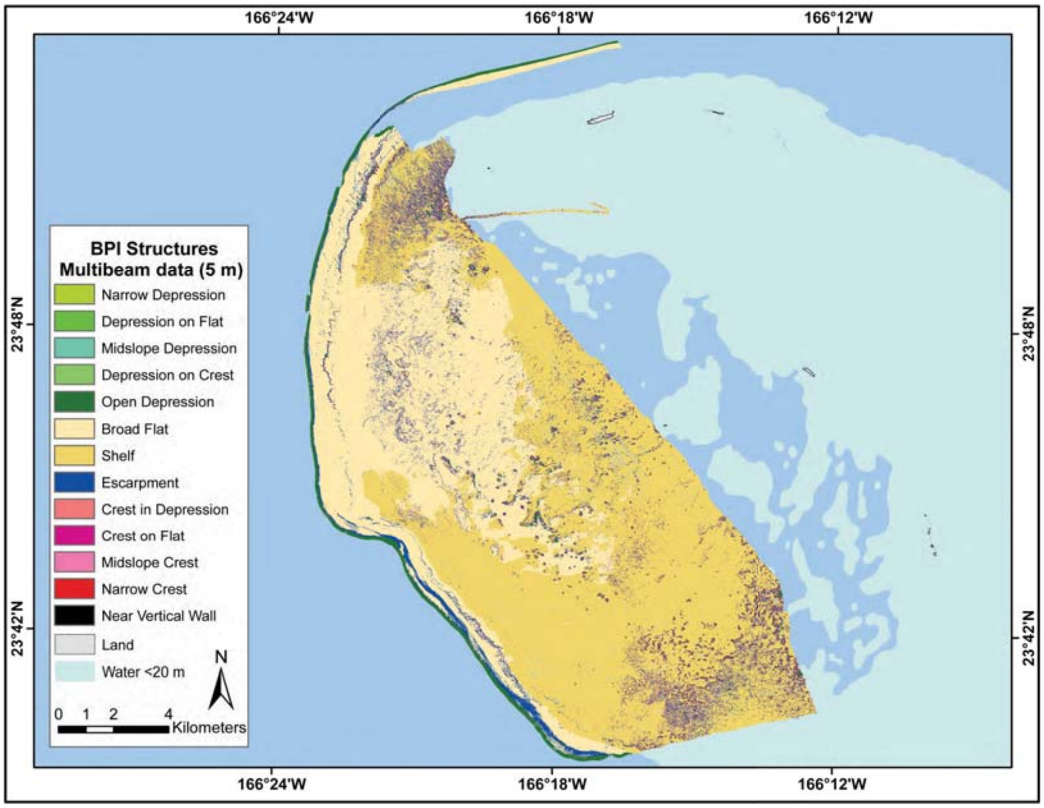


Figure 3.23. Bathymetric Position Index (BPI) structures for French Frigate Shoals. Source: Lundblad et al., 2006.

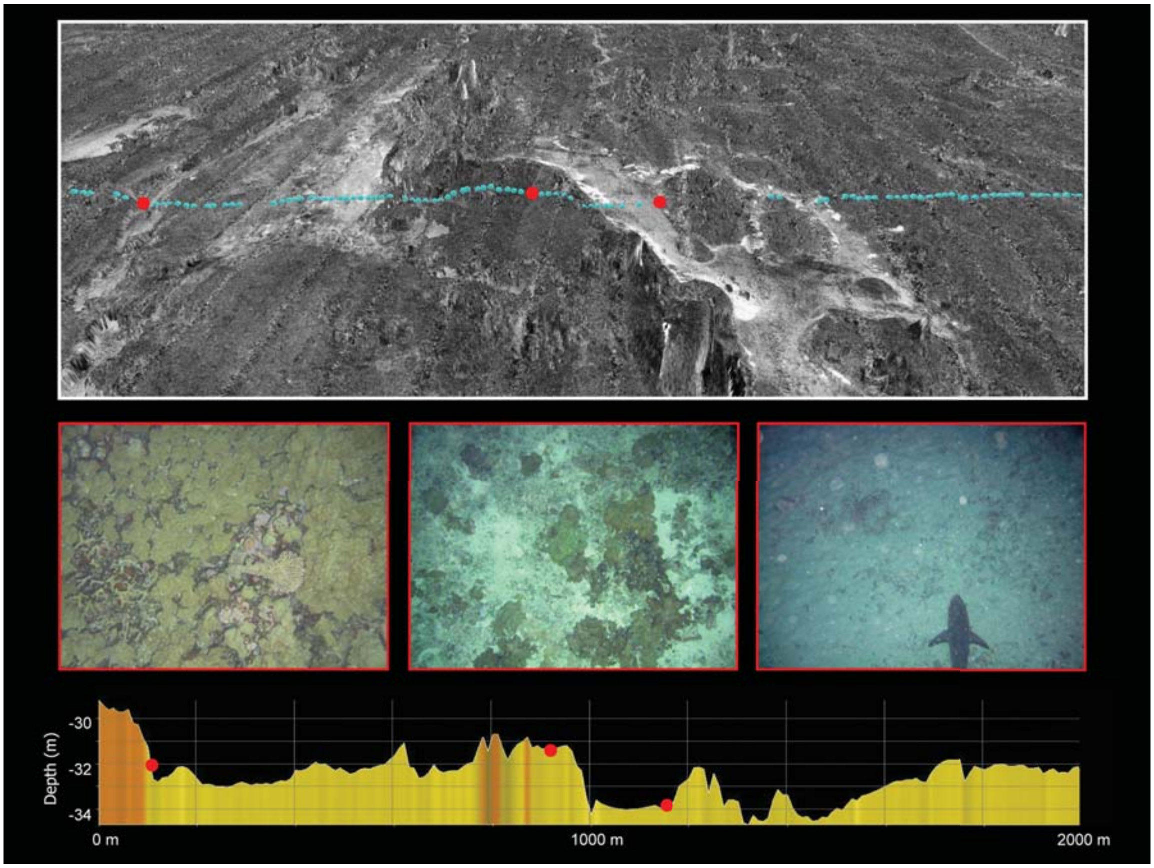


Figure 3.24. French Frigate Shoals backscatter (top) and optical data (center) used to develop hard soft maps. The bottom panel shows a profile of the terrain from concurrent bathymetric data. Red dots indicate location of three photographs. Dark areas in the backscatter indicate high intensity and can often be correlated to areas of coral cover, hard substrate, and elevated bathymetry (two left photos), while lighter areas can often be correlated with sandy, softer substrate and depressions.

Brooks and St. Rogatien Banks

The Brooks and St. Rogatien Banks include four submerged banks between French Frigate Shoals and Gardner Pinnacles (Figure 3.25). These four banks are guyots (flat-topped seamounts) and all have at least two different terraces near their summits that indicate previous sea level stands.

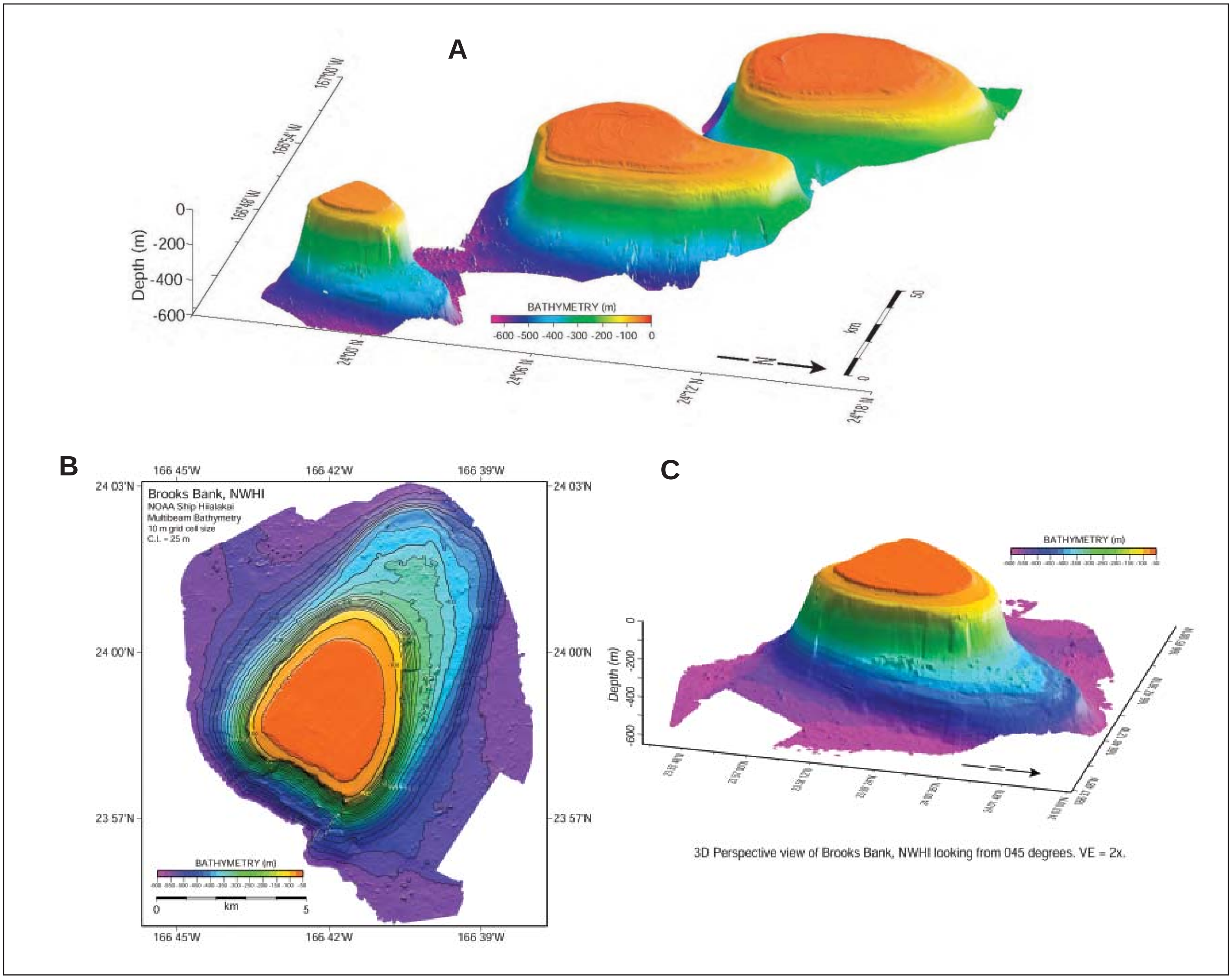


Figure 3.25. 3-D perspective of Brooks Banks. (A) Perspective view of the Brooks Banks looking from the northeast. The Brooks Banks exhibit a classic flat-topped morphology created by erosion when the banks were previously at or near sea-level. Multiple terraces around the bank edges are evidence for additional sea-level stands (B,C). Submarine canyons incise the steep bank edges and blocks of material at the base of the slopes are probably slumps or landslide deposits.

Gardner Pinnacles

Gardner Pinnacles consists of two emergent basaltic volcanic peaks estimated to be 15.8 million years in age (Clague 1996), which represent the oldest high islands in the Hawaiian chain. In scale, these pinnacles are small, the largest reaching only 54.8 m high and having a diameter of approximately 179.8 m. Due to their limited size, they support only a single species of land plant (*Portulaca lutea*) and a few terrestrial arthropod species, but they are by contrast excellent habitat for seabirds (Clapp, 1972). Guano from such seabirds gives the peaks a “frosted” appearance, indicating their importance as roosting and breeding sites for at least 12 subtropical species. These remnant volcanic pinnacles are surrounded by approximately 2,428 km^2 of coral reef habitat, most of which is in waters 18.3 m or deeper (Figure 3.26). The shallow water reef area within 10 fathoms covers less than one square kilometer (0.7 km^2) but the surrounding bank out to 100 fathoms covers 2,428 km^2. The relatively flat bank is in the 30 to 40 m depth range and consists of mostly sand and algal bottom with occasional rock outcroppings. The Pinnacles do not offer much protection from heavy waves and corals are more abundant on elevated surfaces and behind rises or mounds that are protected from wave action. The lack of shallow water environments limits the number of reef building species that can survive the conditions at the reefs and powerful wave action reduces the growth rate of corals (Grigg 1981), coralline algae and other reef-building organisms.

Multibeam data were collected in 2002 at Gardner Pinnacles on cruise KM0206 on the 25, 50 and/or 100-fm isobaths in order to delineate boundaries for the National Marine Sanctuaries program (Figure 3.27).

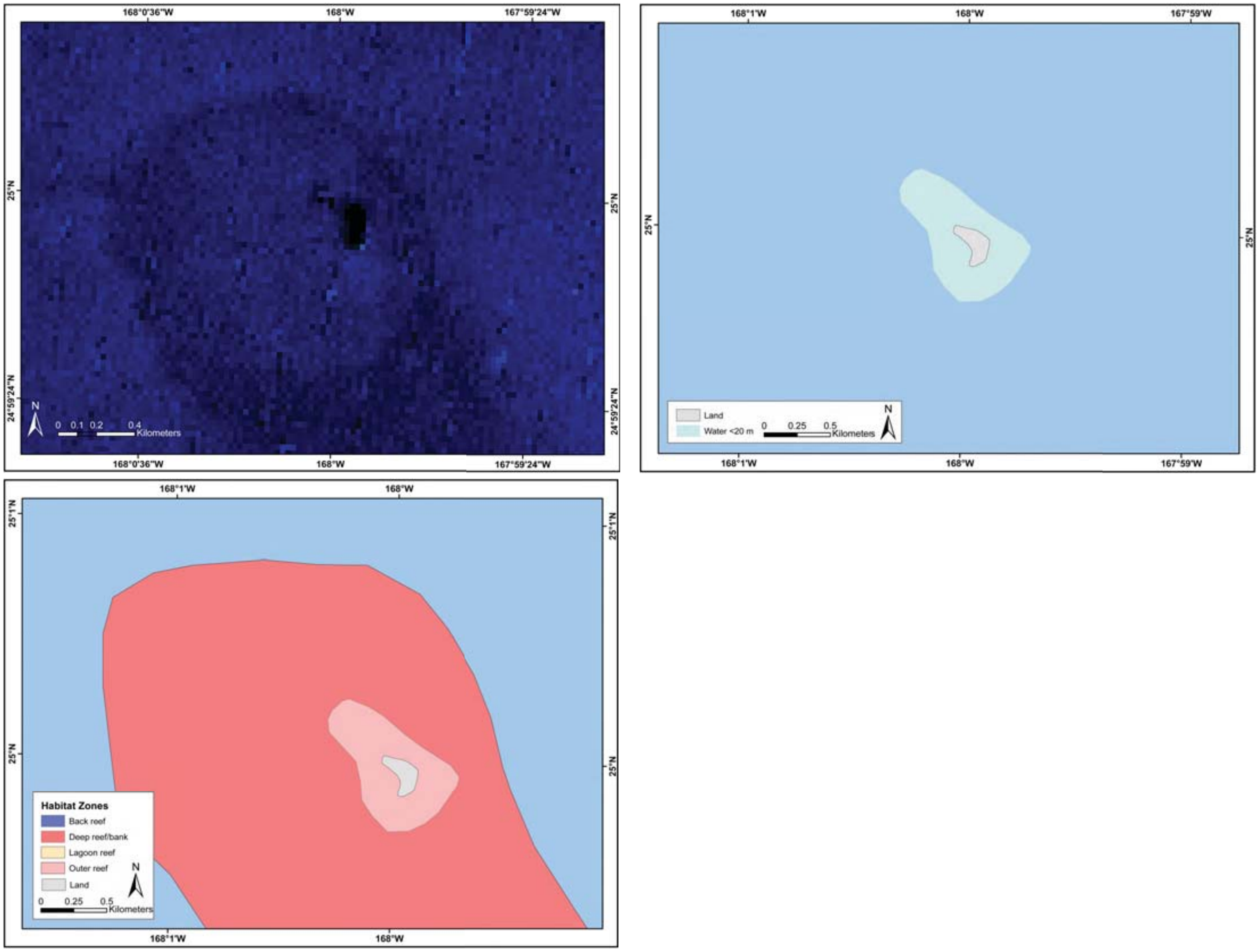


Figure 3.26. IKONOS satellite image (top left), extent of water depth <20 m (top right), and habitat zones (bottom left) for Gardner Pinnacles. Maps: L. Wedding.

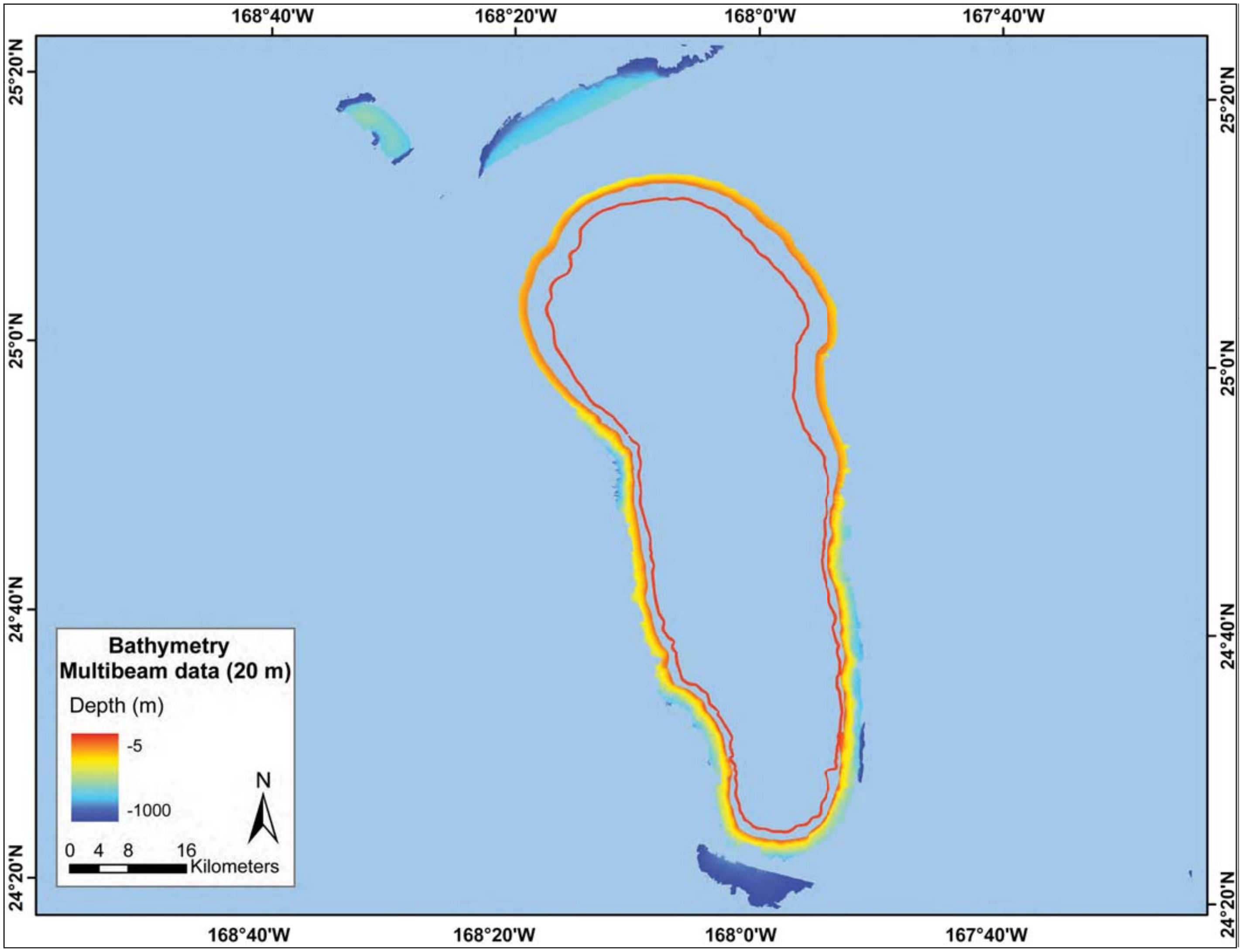


Figure 3.27. Gardner Pinnacles multibeam data collected in 2002 during KM0206.

Maro Reef

Maro Reef is a largely submerged open atoll 19.7 million years old (Clague, 1996). At very low tide, only a small coral rubble outcrop of a former island is believed to break above the surface; as a result, Maro supports no terrestrial biota. In contrast, the shallow water reef system is extensive, covering nearly 2,023 km^2, and is the largest coral reef in the Monument. Maro's reefs are intricate and reticulated, forming a complex network of reef crests, patch reefs, and lagoons. Deepwater channels with irregular bottoms cut between these shallow reef structures, but navigation through them is difficult and hazardous. Cover types range from unconsolidated with 10% or less macroalgae cover to areas with greater than 10% coral or crustose coralline algae (NOAA, 2003; Figures 3.28, 3.29).

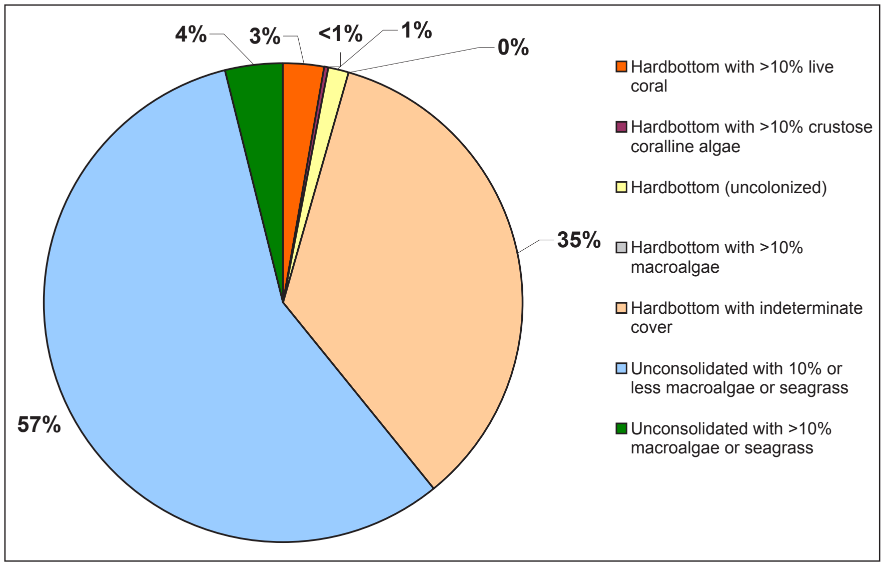


Figure 3.28. Percent composition of mapped benthic habitats at Maro Reef based on NOAA benthic habitat maps. Source: NOAA, 2003.

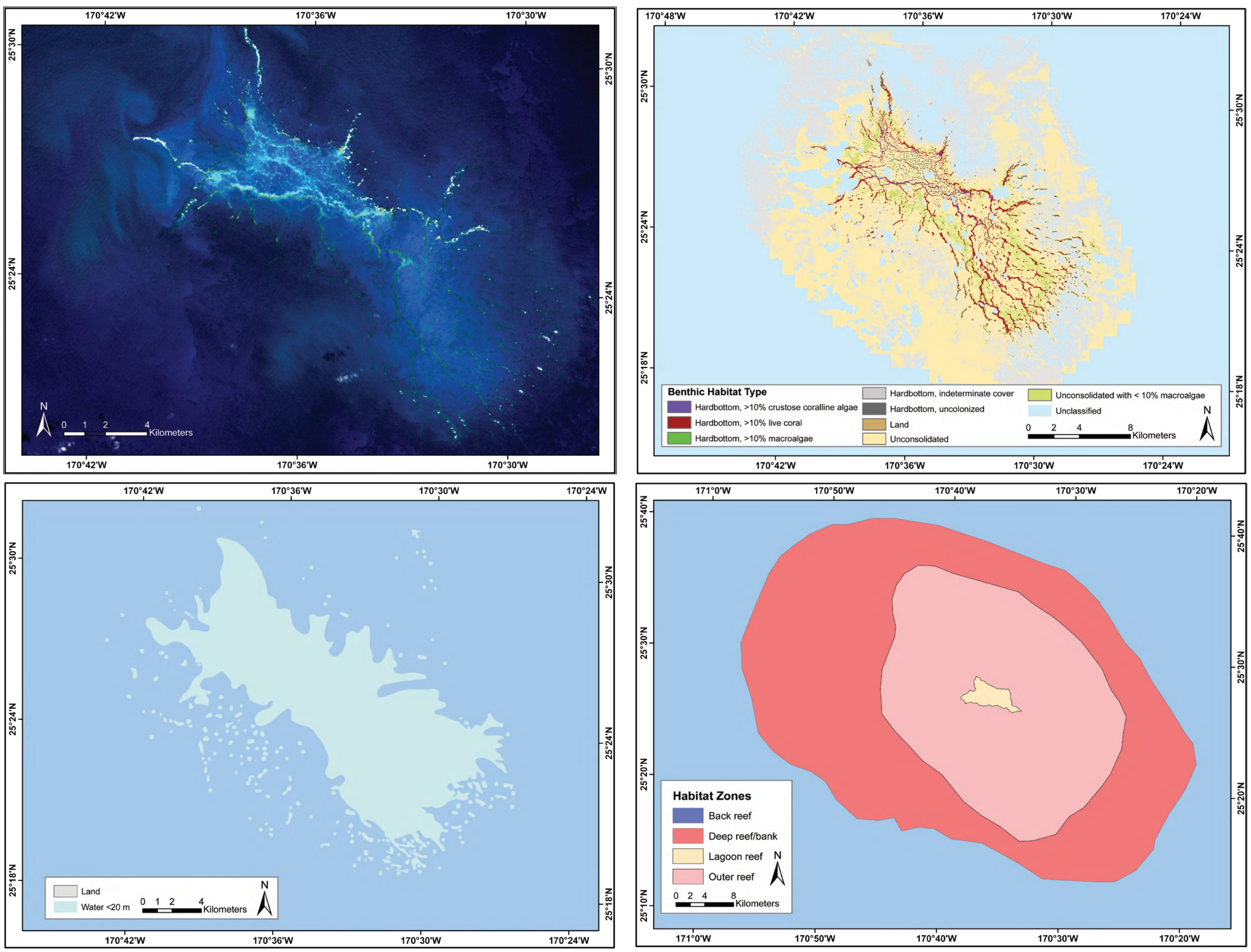


Figure 3.29. IKONOS satellite image (top left), benthic habitat map (top right), extent of water depth < 20 m (bottom left), and habitat zones (bottom right) for Maro Reef. Maps: L. Wedding.

Because the outermost reefs absorb the majority of the energy from the open ocean swells, the innermost reticulated reefs and aggregated patch reefs are sheltered and have the characteristics of a true lagoon. Given the structural complexity of this platform, its shallow reefs are poorly charted and largely unexplored.

Multibeam surveys were conducted at Maro Reef in 2002 (KM0206) and 2005 (HI0508; Figure 3.30). The 2006 “ring” surveys on the perimeter were planned to delineate the 25-, 50-, and/or 100-fm isobaths for boundary designation purposes.

At Maro, slope increases greatly between the shallow (<226 m) and intermediate depths (226-588 m) and then declines slightly with greater depths (588-1,045 m). Aspect ratio declined slightly with depth from shallow to deep while rugosity was similar among all depths (Table 3.9).

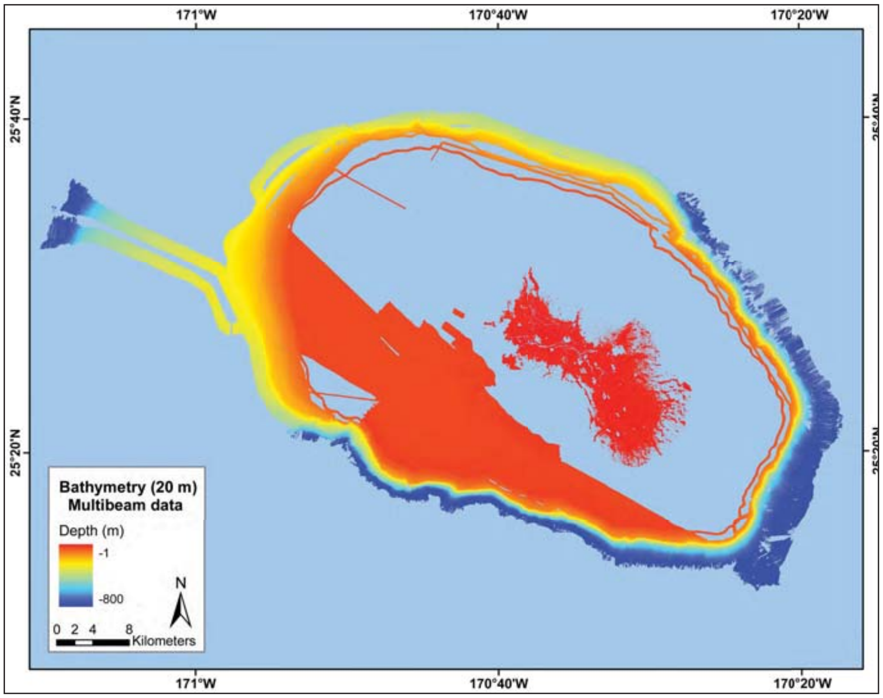


Figure 3.30. 20 m Multibeam bathymetric data collected at Maro Reef in 2002 and 2005 with derived depths from IKONOS imagery near island center. Map: L. Wedding.

Table 3.9. Summary statistics for multibeam surveys conducted around Maro Reef (2002-2006).

MARO	DEPTH CLASS	AREA	MINIMUM*	MAXIMUM*	RANGE	MEAN	STANDARD DEVIATION
Bathymetry	9 to 226	900.29	-259.40	-1.00	258.40	-65.03	56.96
	266 to 588	277.74	-616.72	-202.22	414.50	-356.19	106.15
	588 to 1,046	133.73	-800.00	-559.44	240.56	-689.07	61.27
Slope	9 to 226	-	0.00	62.67	62.67	2.47	4.30
	266 to 588	-	0.00	64.64	64.64	8.48	7.65
	588 to 1,046	-	0.00	55.35	55.35	7.82	5.76
Aspect	9 to 226	-	-1.00	360.00	361.00	184.40	108.58
	266 to 588	-	0.00	360.00	360.00	175.34	108.21
	588 to 1,046	-	-1.00	360.00	361.00	155.68	77.84
Rugosity	9 to 226	-	1.00	2.23	1.23	1.00	0.03
	266 to 588	-	1.00	2.43	1.43	1.02	0.04
	588 to 1,046	-	1.00	2.08	1.08	1.02	0.04

***NOTE:** the minimum represents the minimum value of a given metric within a universal depth class; maximum represents the maximum value of a given metric within a universal depth class.

Laysan

Laysan is a formed atoll, estimated to be 20.7 million years old (Clague, 1996), with a maximum elevation of approximately 15 m above sea level. By land area it is the second largest island in the Monument, with a land area of approximately 3.7 km^2, surrounded by close to 405 km^2 of coral reef. Most of the reef area at Laysan lies in deeper waters, with a small, shallow water reef area in a bay off the southwest side of the island. It is well vegetated (except for its sand dunes) and contains a hyper-saline lake, which is one of only five natural lakes in the state of Hawaii. Laysan's coral reef habitat totals approximately 26.5 km^2 within 10 fathoms and 584.5 km^2 out to 100 fathoms (Figures 3.31, 3.32). The fringing reef surrounding the island varies from 100 to 500 m in width and is most extensive at the northwest end of the island. Inside the

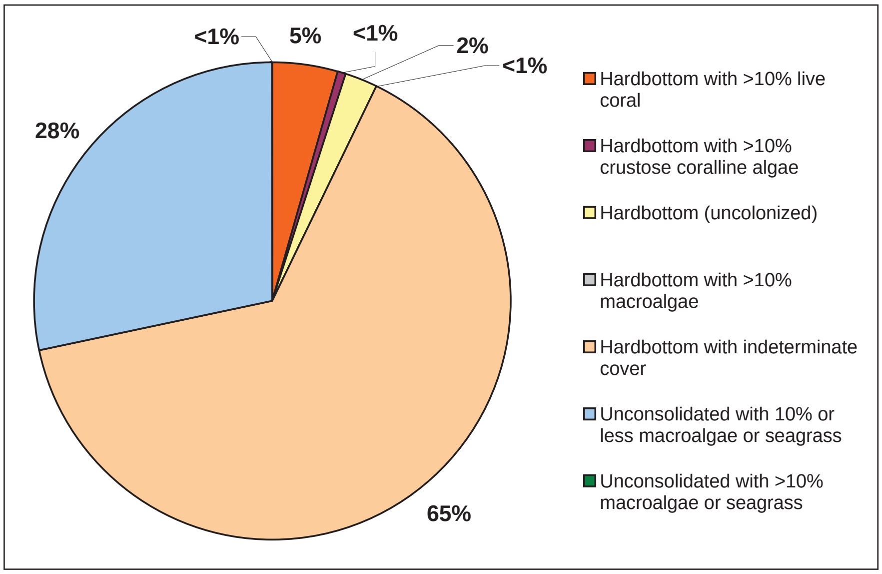


Figure 3.31. Percent composition of mapped benthic habitats at Laysan Island based on NOAA benthic habitat maps. Source: NOAA, 2003.

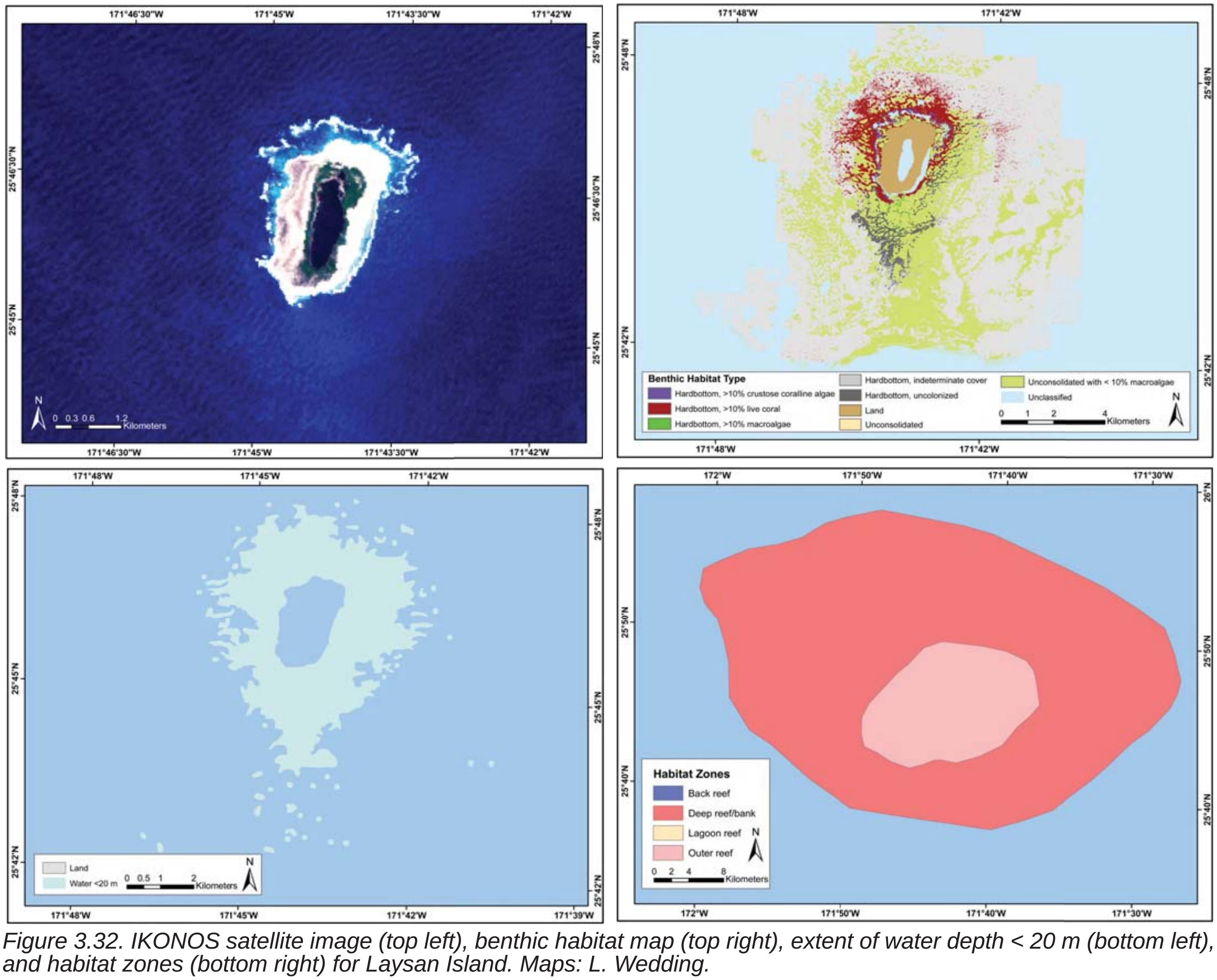


Figure 3.32. IKONOS satellite image (top left), benthic habitat map (top right), extent of water depth < 20 m (bottom left), and habitat zones (bottom right) for Laysan Island. Maps: L. Wedding.

reef is a narrow, shallow channel which nearly encircles the island except for the south and southeast sides. Deeper reef habitats are mostly robust spur-and-grooves around most of the island and a heavily eroded northern section with numerous caves, overhangs and large holes on a sloping reef with small sand channels. The base of these reefs and the spur-and-grooves ended in broad sand flats with numerous small overhangs and holes. Despite lacking much protection from the detrimental effects of waves, Laysan supports a surprisingly rich coral environment with good development along its leeward coasts. The small back reef, pass and moat near the island's western boat landing also help to diversify habitats and the number of coral species inhabiting them.

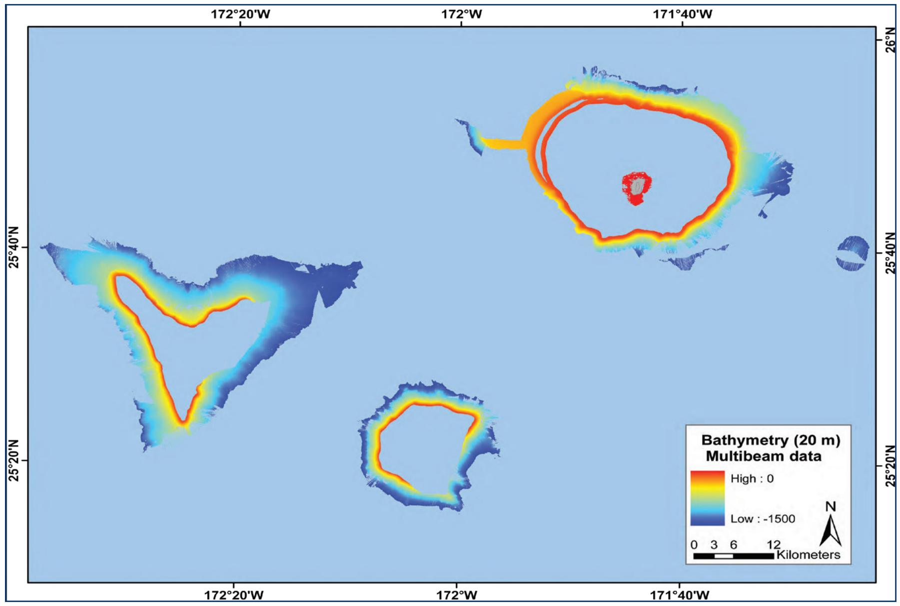


Figure 3.33. 20-m multibeam data collected around Laysan Island (upper right) and Northampton Seamounts (lower left). Derived depths from IKONOS imagery are shown around Laysan Island. Map: L. Wedding.

Multibeam surveys were conducted in 2002 during KM0206 in order to delineate 25, 50 and/or 100-fm boundaries around Laysan Island (Figure 3.33).

Lisianski-Neva Shoal

Lisianski Island (Papaapoho) is another raised atoll, rising to 12.1 m above sea level, and with approximately 1.6 km^2 of emergent land is the third largest island within the Monument. This 23.4-million-year-old island (Clague, 1996) is over 1.9 km across, consisting of an elevated rim surrounding a broad central depression, although unlike Laysan it does not enclose an interior saline lake. The coral cover on the platform around the island, called Neva Shoal, is extensive, totaling over 1,174 km^2 (Figures 3.34, 3.35).

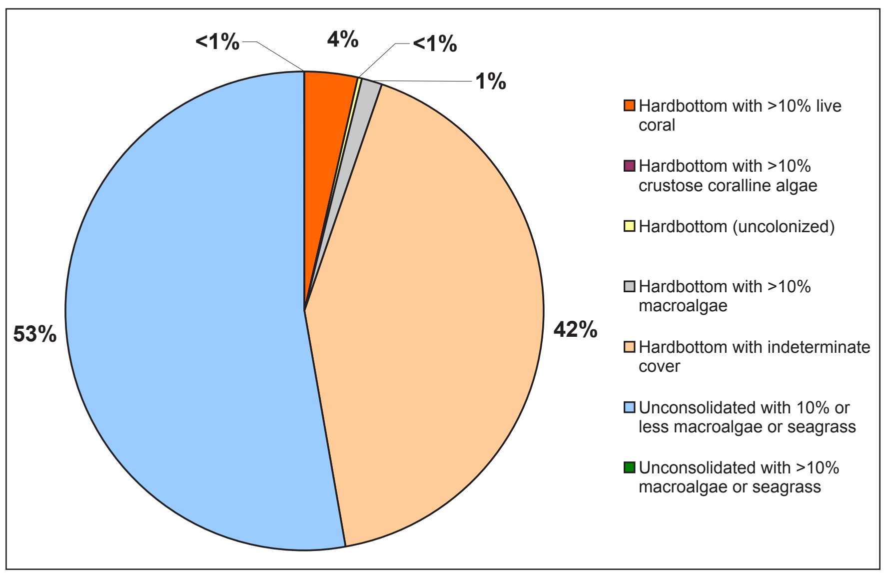


Figure 3.34. Percent composition of mapped benthic habitats at Lisianski-Neva Shoals based on NOAA benthic habitat maps. Source: NOAA, 2003.

Papaapoho describes a flat area with a depression or hollow, which is exactly how the island is shaped. Its highest point is a 12.2 m-high sand dune, and its lowest point is a depression to the south that runs as a channel toward the ocean.

Multibeam surveys were conducted in 2002 during KM0206 (Figure 3.36) in order to delineate 25, 50 and/or 100-fm boundaries around Lisianski Island and Neva Shoals. The slope increases dramatically between the shallow (<226 m) and the intermediate depth range (226-588 m) before it declines slightly in the deeper depth bin (588-1,045 m). Aspect ratio is highest in the deep and shallow depth ranges while the intermediate depth ranges (266-588 m) had the lowest aspect ratio. Rugosity increased sharply between shallow and intermediate depths with a slight decrease in the deepest depth bin (Table 3.10).

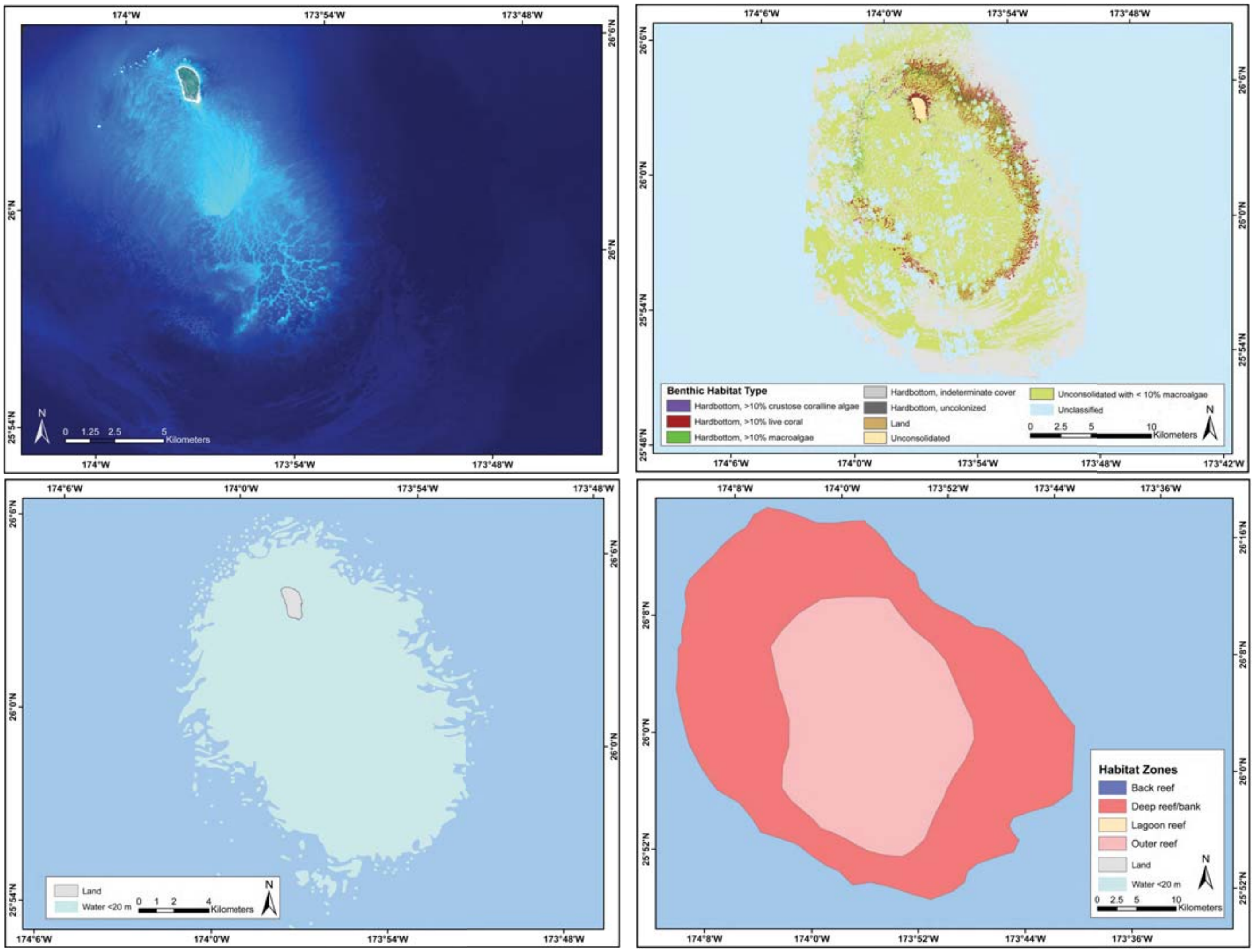


Figure 3.35. IKONOS satellite image (top left), benthic habitat map (top right), extent of water depth < 20 m (bottom left), and habitat zones (bottom right) for Lisianski-Neva Shoals. Maps: L. Wedding.

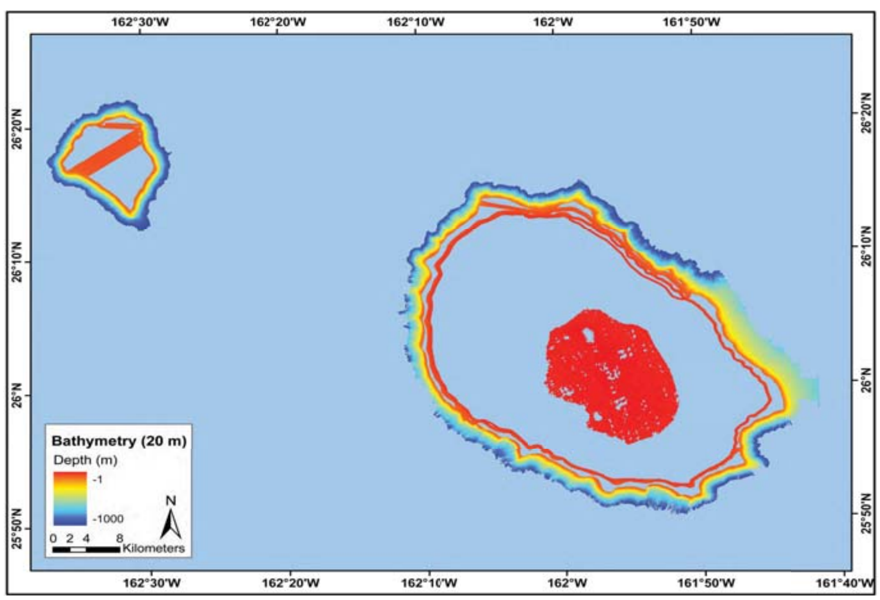


Figure 3.36. 20 m multibeam data collected around Lisianski-Neva Shoal in 2002 with derived depths from IKONOS imagery near island center. Map: L. Wedding.

Table 3.10. Summary statistics for multibeam surveys conducted around Lisianki (2002).

LISIANKI	DEPTH CLASS	AREA	MINIMUM*	MAXIMUM*	RANGE	MEAN	STANDARD DEVIATION
Bathymetry	9 to 226	367.36	-366.03	-1.00	365.03	-47.61	51.89
	266 to 588	166.36	-683.59	-159.95	523.64	-430.03	102.21
	588 to 1,046	194.73	-999.99	-511.34	488.65	-785.34	119.57
Slope	9 to 226	-	0.00	78.38	78.38	4.34	8.52
	266 to 588	-	0.00	81.39	81.39	21.19	12.56
	588 to 1,046	-	0.00	72.36	72.36	19.10	8.47
Aspect	9 to 226	-	-1.00	360.00	361.00	174.50	105.29
	266 to 588	-	-1.00	360.00	361.00	149.92	103.05
	588 to 1,046	-	-1.00	360.00	361.00	177.09	105.33
Rugosity	9 to 226	-	1.00	6.83	5.83	1.02	0.08
	266 to 588	-	1.00	6.89	5.89	1.12	0.19
	588 to 1,046	-	1.00	3.39	2.39	1.08	0.08

***NOTE:** the minimum represents the minimum value of a given metric within a universal depth class; maximum represents the maximum value of a given metric within a universal depth class.

Pearl and Hermes

The name Holoikauaua celebrates the Hawaiian monk seals that haul out and rest here. Pearl and Hermes Atoll is a large atoll with several small islets, forming 0.38 km^2 of land surrounded by over 1,214 km^2 of coral reef habitat (Figures 3.37, 3.38). The atoll has an estimated age of 26.8 million years (Clague, 1996) and is over 32 km across and 19.3 km wide, with dunes rising above sea level. Unlike Lisianski and Laysan to the southeast, Pearl and Hermes Atoll is a true atoll, fringed with shoals, permanent emergent islands, and ephemeral sandy islets. These features provide vital dry land for monk seals, green turtles, and a multitude of seabirds, with 16 species breeding here. The islets are periodically washed over when winter storms pass through the area.

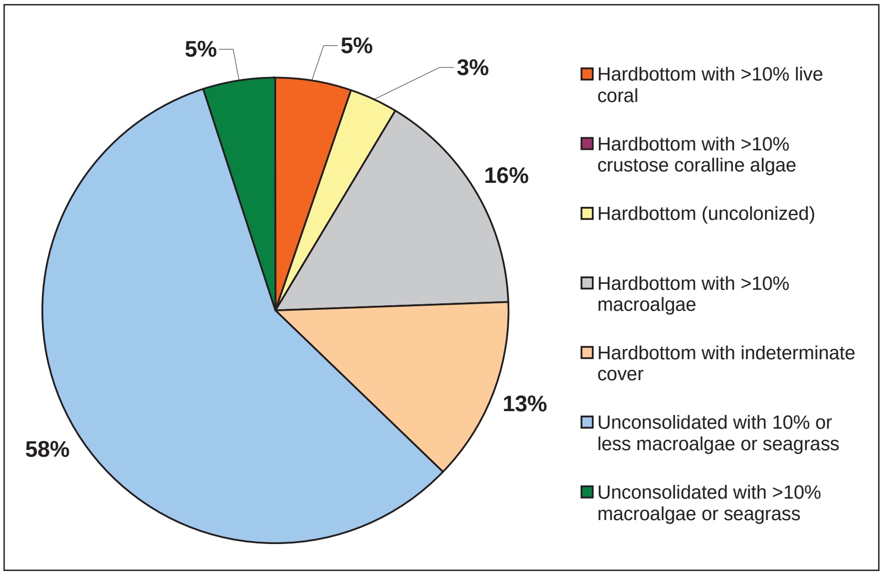


Figure 3.37. Percent composition of mapped benthic habitats at Pearl and Hermes Atoll based on NOAA benthic habitat maps. Source: NOAA, 2003.

Multibeam data were collected at Pearl and Hermes Atoll in 2005 (HI0509) to delineate the 25-, 50- and/or 100-fm boundaries and in 2006 to complete as much mapping of the atoll as possible (Table 3.11; Figure 3.39). Depths surveyed ranged from 9 m down to over 3,000 m. Slope increased by more than eight fold between the shallowest (9-226 m) and the next deepest (226-588 m) depth ranges. The slope declined slightly in the deepest depth bin (1,649-3,071 m). Aspect ratio increased steadily with increasing depth, while rugosity rose sharply between shallow (<226 m) and intermediate ranges (226-1,046 m) and then declined slightly in the deepest depth bin (Table 3.11). Figure 3.40 shows a guyot approximately 25 km southeast of Pearl and Hermes Atoll where monk seals have been reported to forage through satellite tracking.

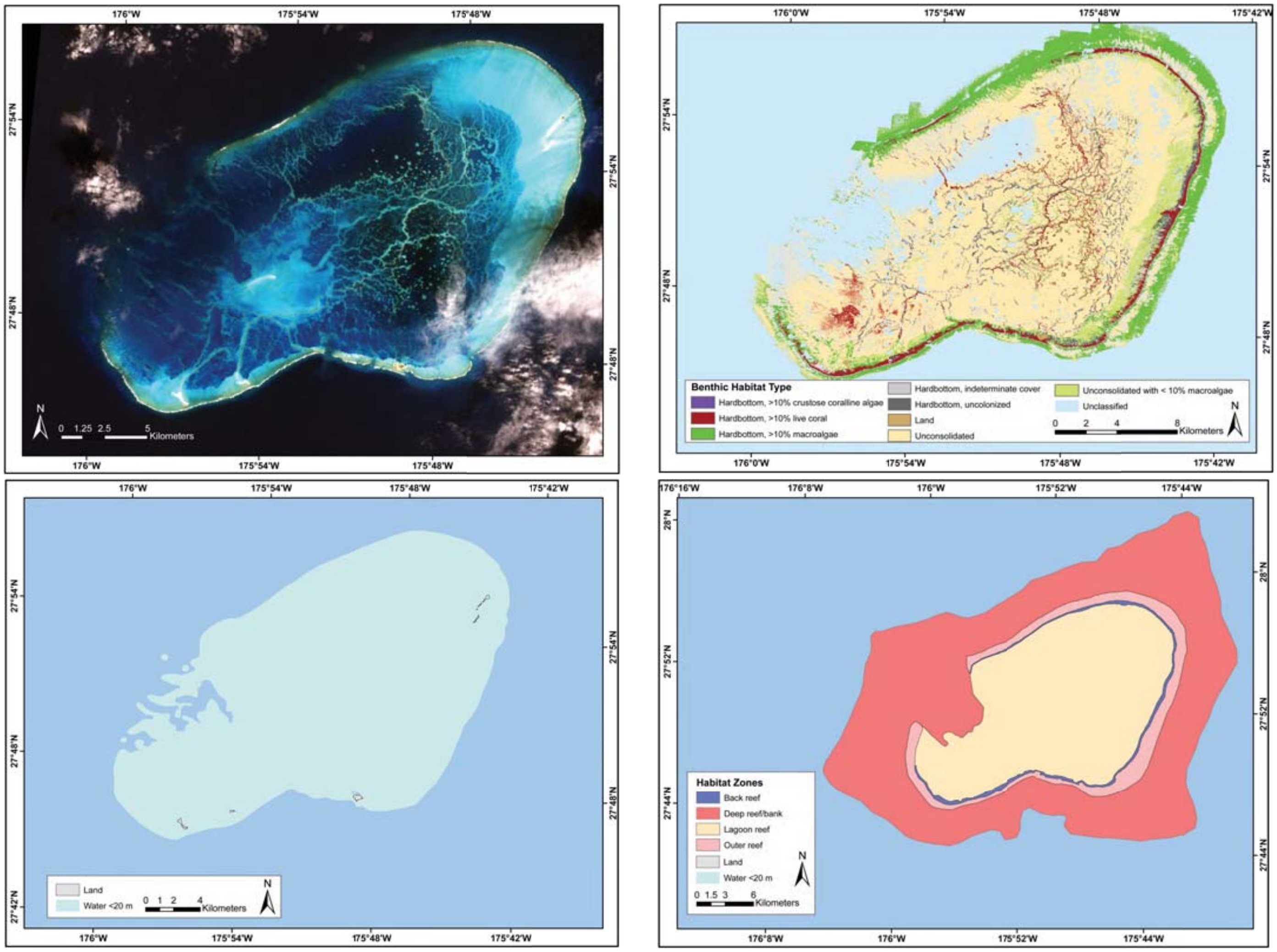


Figure 3.38. IKONOS satellite image (top left), benthic habitat map (top right), extent of water depth < 20 m (bottom left), and habitat zones (bottom right) for Pearl and Hermes Atoll. Maps: L. Wedding.

Table 3.11. Summary statistics for multibeam surveys conducted around Pearl and Hermes (2005).

PEARL AND HERMES	DEPTH CLASS	AREA	MINIMUM*	MAXIMUM*	RANGE	MEAN	STANDARD DEVIATION
Bathymetry	9 to 226	611.14	-1,818.20	0.00	1,818.20	-44.22	48.84
	266 to 588	20.70	-876.60	-10.60	866.00	-336.52	103.37
	588 to 1,046	34.20	-1,169.10	-262.60	906.50	-862.04	123.81
	1,046 to 1,649	92.48	-1,858.90	-631.80	1,227.10	-1,368.91	175.49
	1,649 to 3,071	86.96	-3,071.30	-40.70	3,030.60	-1,979.21	281.68
Slope	9 to 226	-	0.00	77.41	77.41	3.39	4.73
	266 to 588	-	0.00	82.89	82.89	28.25	11.14
	588 to 1,046	-	0.00	84.42	84.42	28.60	11.14
	1,046 to 1,649	-	0.00	84.72	84.72	22.32	10.32
	1,649 to 3,071	-	0.00	87.49	87.49	15.04	9.89
Aspect	9 to 226	-	-1.00	360.00	361.00	158.44	116.76
	266 to 588	-	-1.00	359.94	360.94	198.48	97.80
	588 to 1,046	-	-1.00	360.00	361.00	202.81	95.63
	1,046 to 1,649	-	-1.00	360.00	361.00	224.08	98.92
	1,649 to 3,071	-	-1.00	360.00	361.00	225.85	98.48
Rugosity	9 to 226	-	1.00	14.14	13.14	1.01	0.03
	266 to 588	-	1.00	12.93	11.93	1.30	0.43
	588 to 1,046	-	1.00	18.72	17.72	1.32	0.48
	1,046 to 1,649	-	1.00	19.01	18.01	1.25	0.38
	1,649 to 3,071	-	1.00	89.27	88.27	1.16	0.46

***NOTE:** minimum = minimum value of a given metric within a universal depth class; maximum = the maximum value of a given metric within a universal depth class.

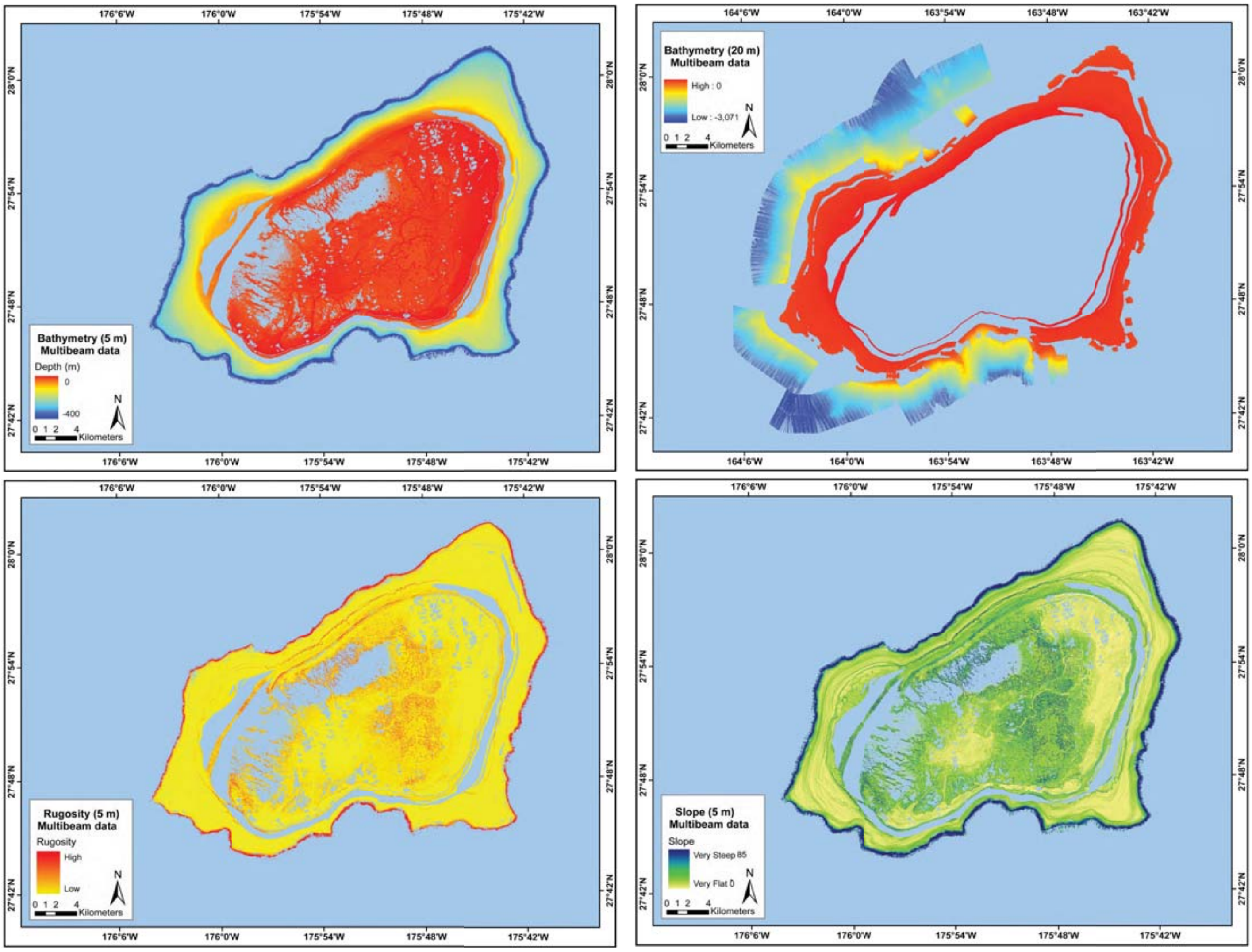


Figure 3.39. 5 m and 20 m bathymetry, rugosity (5 m), and slope (5 m) for Pearl and Hermes with derived depths from IKONOS imagery near island center. Maps: L. Wedding.

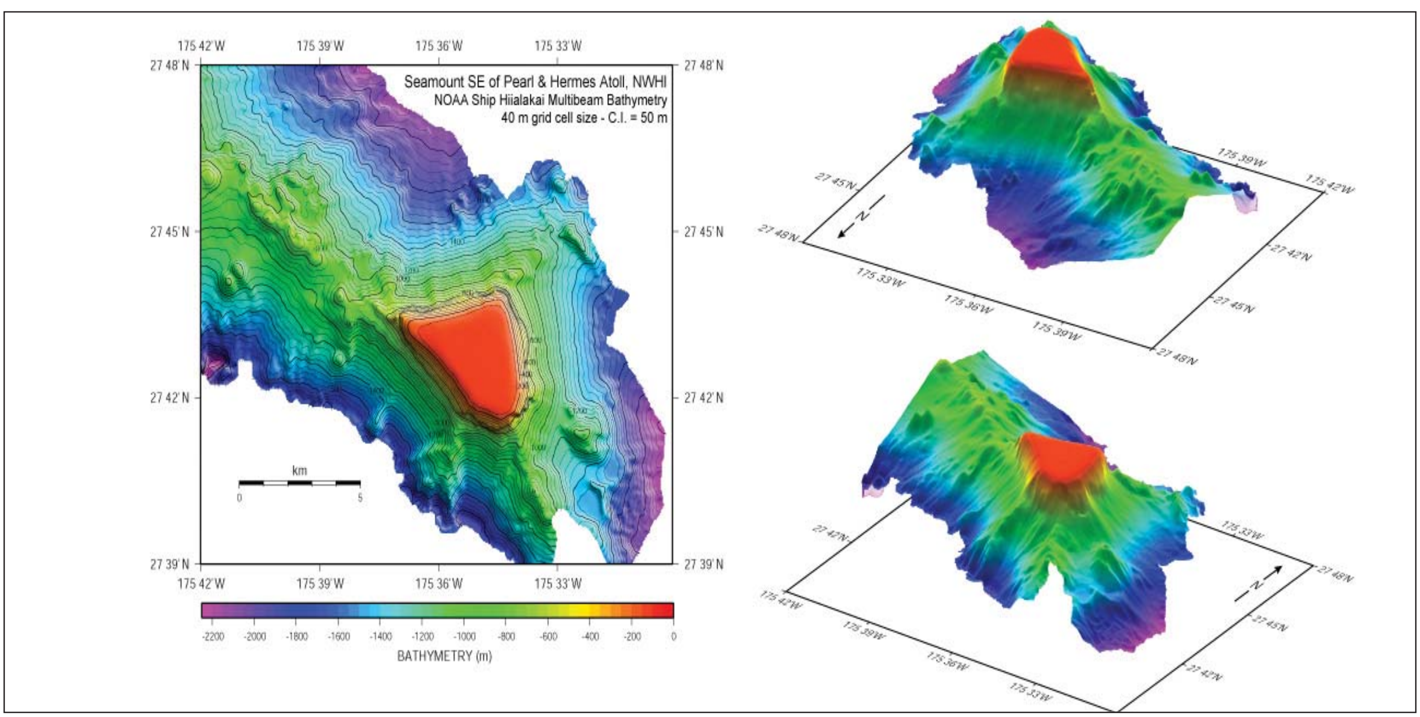


Figure 3.40. 3-D perspective of a seamount southeast of Pearl and Hermes Atoll. V.E. = 2x.

Midway Atoll

Midway Atoll consists of three sandy islets: Sand, 4.56 km^2; Eastern, 1.36 km^2; and Spit, 0.05 km^2 for a total of 1,464 5.9 km^2 in terrestrial area, lying within a large, elliptical barrier reef measuring approximately 8 km in diameter. The atoll, which is 28.7 million years old (Clague, 1996), is surrounded by more than 356 km^2 of coral reefs (Figures 3.41, 3.42). In 1965, the U.S. Geological Survey took core samples and hit solid basaltic rock 54.8 m beneath Sand Island and 377.9 m beneath the northern reef. Numerous patch reefs dot the sandy-bottomed lagoon. The atoll and surrounding seas were also the site of a pivotal battle of World War II, and Midway was an active Navy installation during the Cold War.

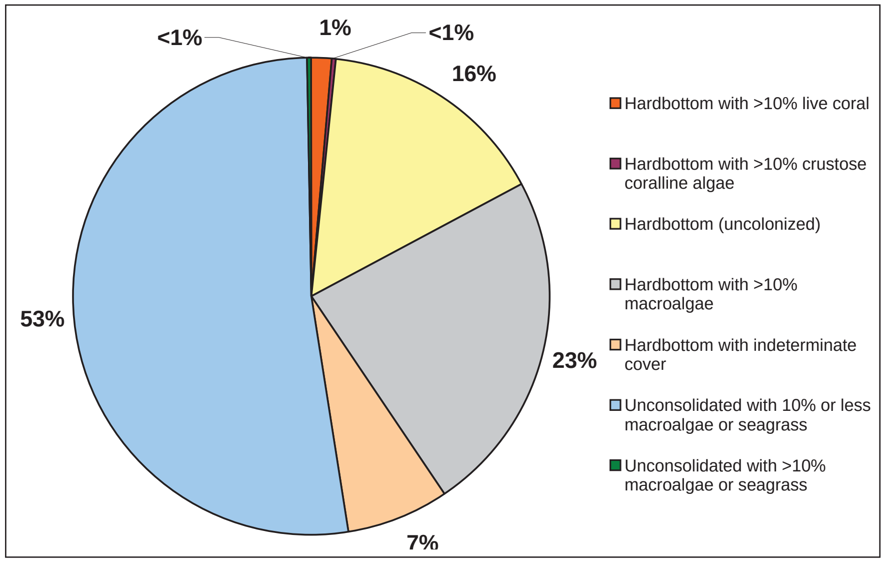


Figure 3.41. Percent composition of mapped benthic habitats at Midway Atoll based on NOAA benthic habitat maps. Source: NOAA, 2003.

Multibeam mapping surveys at Midway were conducted in 2003 (AHI0306) to delineate 25-, 50- and 100-fm boundaries and in 2005 (HI0503) and 2006 (HI0609) to add to coverage around the island for benthic habitat

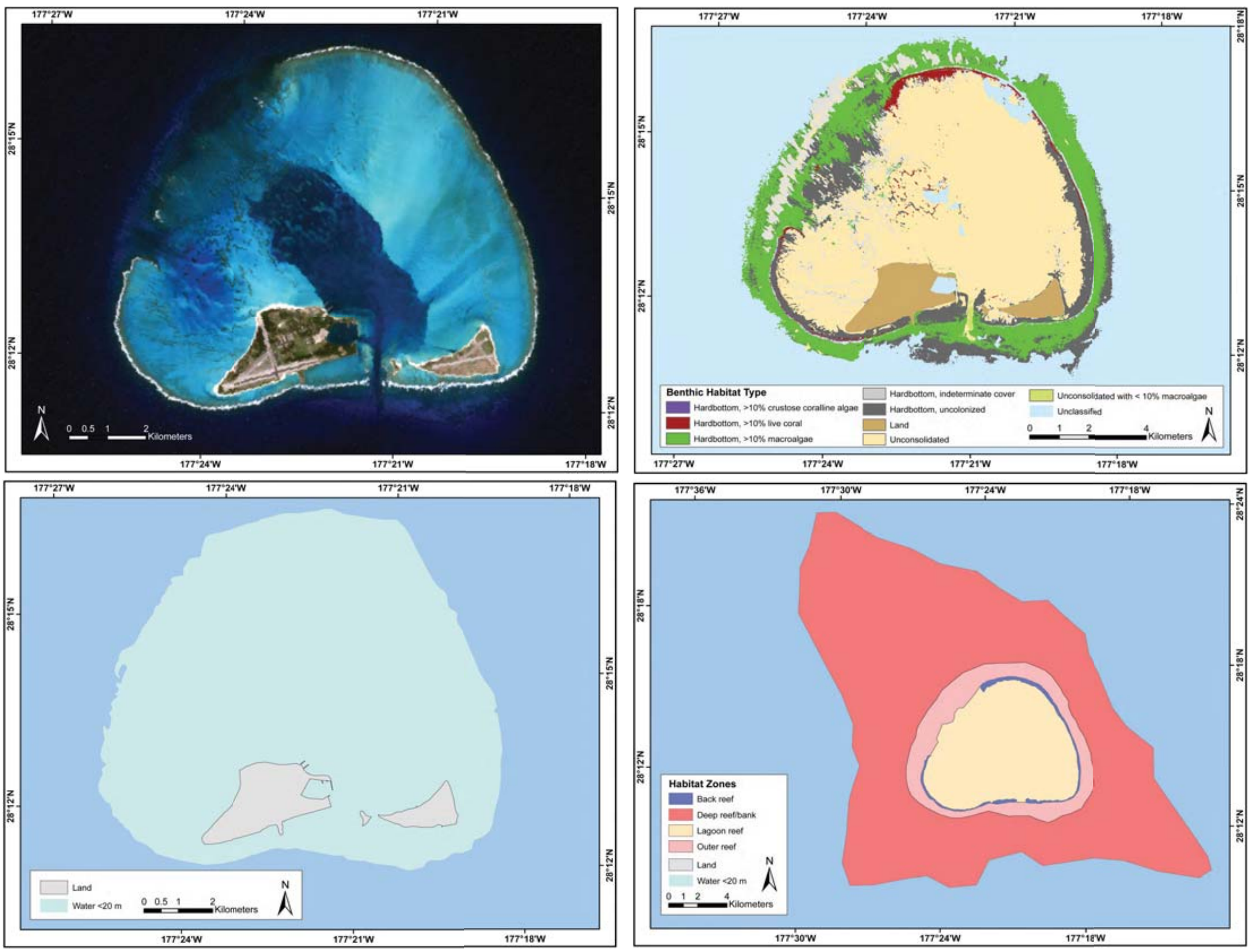


Figure 3.42. IKONOS satellite image (top left), benthic habitat map (top right), extent of water depth <20 m (bottom left) and habitat zones (bottom right) for Midway Atoll. Maps: L. Wedding.

mapping (Figure 3.43). Slope increased by 10 fold between the shallowest and intermediate depth with a modest decline in the deepest depth bin. Aspect ratio increased moderately between shallow and intermediate depth but declined sharply in the 588-1,045 m depth range. Rugosity increased from shallow to intermediate before declining slightly in the deepest depth range (Table 3.12).

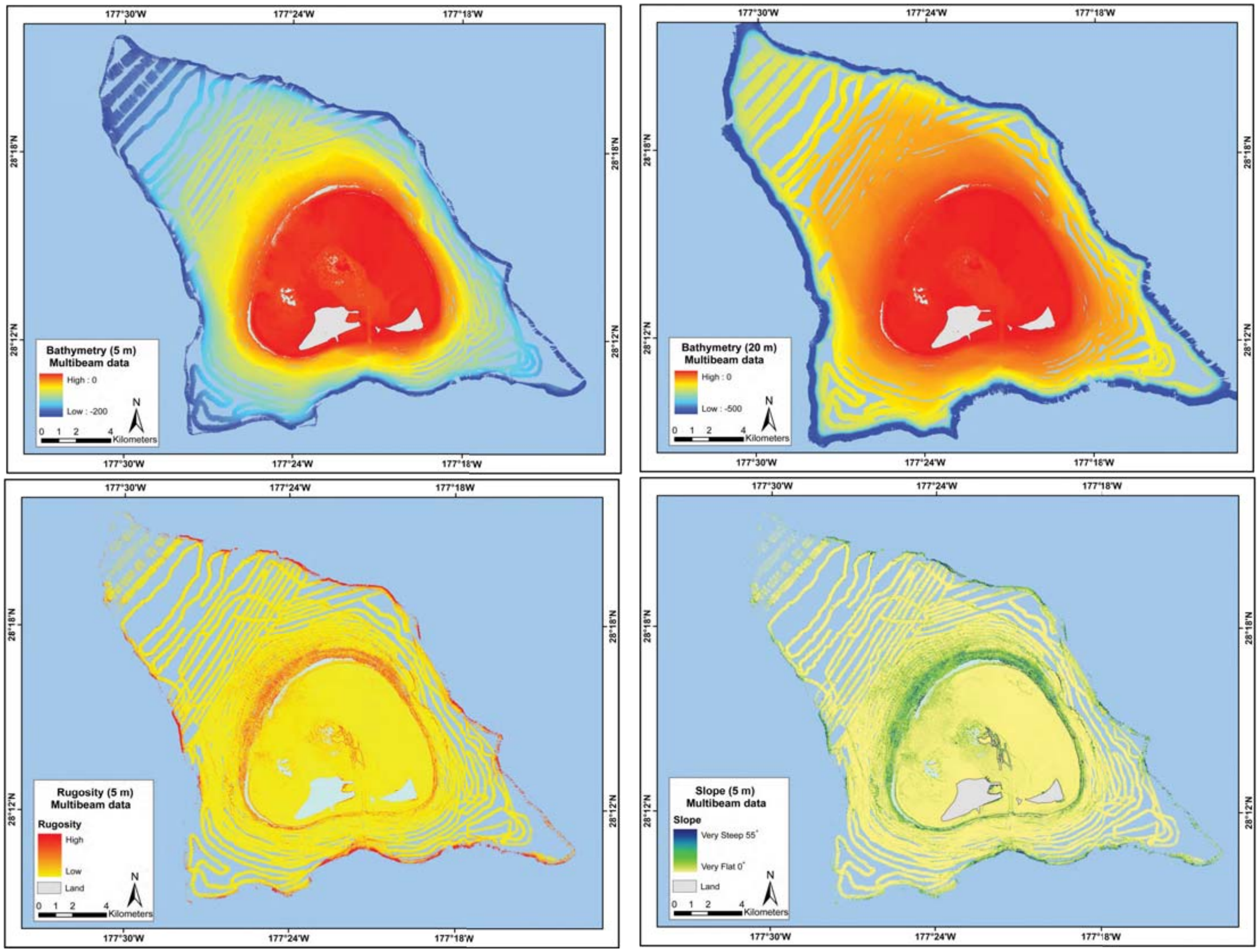


Figure 3.43. 5 m and 20 m bathymetry, rugosity (5 m), and slope (5 m) for Midway Atoll with derived depths from IKONOS imagery near island center. Maps: L. Wedding.

Table 3.12. Summary statistics for multibeam surveys conducted around Midway Atoll (2003-2006).

MIDWAY	DEPTH CLASS	AREA	MINIMUM*	MAXIMUM*	RANGE	MEAN	STANDARD DEVIATION
Bathymetry	9 to 226	306.19	-250.60	3.00	253.60	-60.98	51.15
	266 to 588	37.32	-500.00	2.00	502.00	-349.27	77.63
	588 to 1,046	0.00	-2.00	-2.00	0.00	-2.00	0.00
Slope	9 to 226	-	0.00	56.57	56.57	2.85	5.16
	266 to 588	-	0.00	79.34	79.34	28.83	9.04
	588 to 1,046	-	19.97	19.97	0.00	19.97	0.00
Aspect	9 to 226	-	-1.00	360.00	361.00	137.68	114.67
	266 to 588	-	-1.00	360.00	361.00	170.08	95.52
	588 to 1,046	-	40.82	40.82	0.00	40.82	0.00
Rugosity	9 to 226	-	1.00	2.29	1.29	1.01	0.04
	266 to 588	-	1.00	4.87	3.87	1.19	0.16
	588 to 1,046	-	1.11	1.11	0.00	1.11	0.00

***NOTE:** the minimum represents the minimum value of a given metric within a universal depth class; maximum represents the maximum value of a given metric within a universal depth class.

Kure Atoll

Kure Atoll is the most northwestern island in the Hawaiian chain and occupies a singular position at the "Darwin Point": the northern extent of coral reef development, beyond which coral growth cannot keep pace with the rate of geological subsidence. Kure's coral is still growing slightly faster than the island is subsiding. North of Kure, where growth rates are even slower, the drowned Emperor Seamounts foretell the future of Kure and all of the Hawaiian Archipelago. As Kure Atoll continues its slow migration atop the Pacific Plate, it too will eventually slip below the surface (Grigg, 1982).

This 29.8 million year old atoll (Clague, 1996) is nearly circular, with a reef 9.6 km in diameter enclosing a lagoon with two islets that include over 0.81 km^2 of emergent land, flanked by almost 324 km^2 of coral reef habitat (Figures 3.44, 3.45). The outer reef forms a nearly complete circular barrier around the lagoon, with the exception of passages to the southwest. Of the two enclosed islets, the only permanent land is found on crescent-shaped Green Island, which rises to 6.1 m above sea level and is located near the fringing reef in the southeastern quadrant of the lagoon. The USCG established a LORAN station at Kure in 1960 (Woodward, 1972) and occupied it until 1993. This land use had far-reaching effects on all the plants and animals at Kure Atoll, resulting in elevated invasive species problems and contaminants left behind when the base closed.

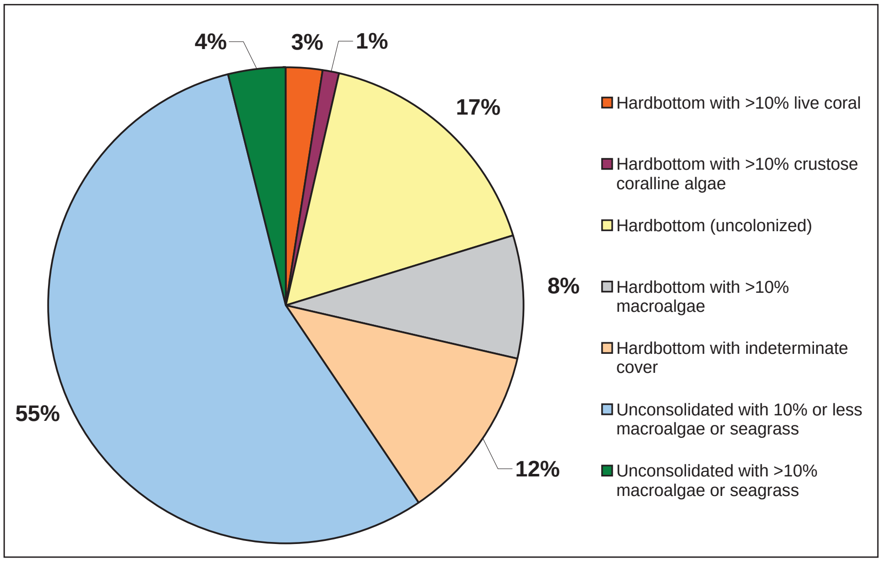


Figure 3.44. Percent composition of mapped benthic habitats at Kure Atoll based on NOAA benthic habitat maps. Source: NOAA, 2003.

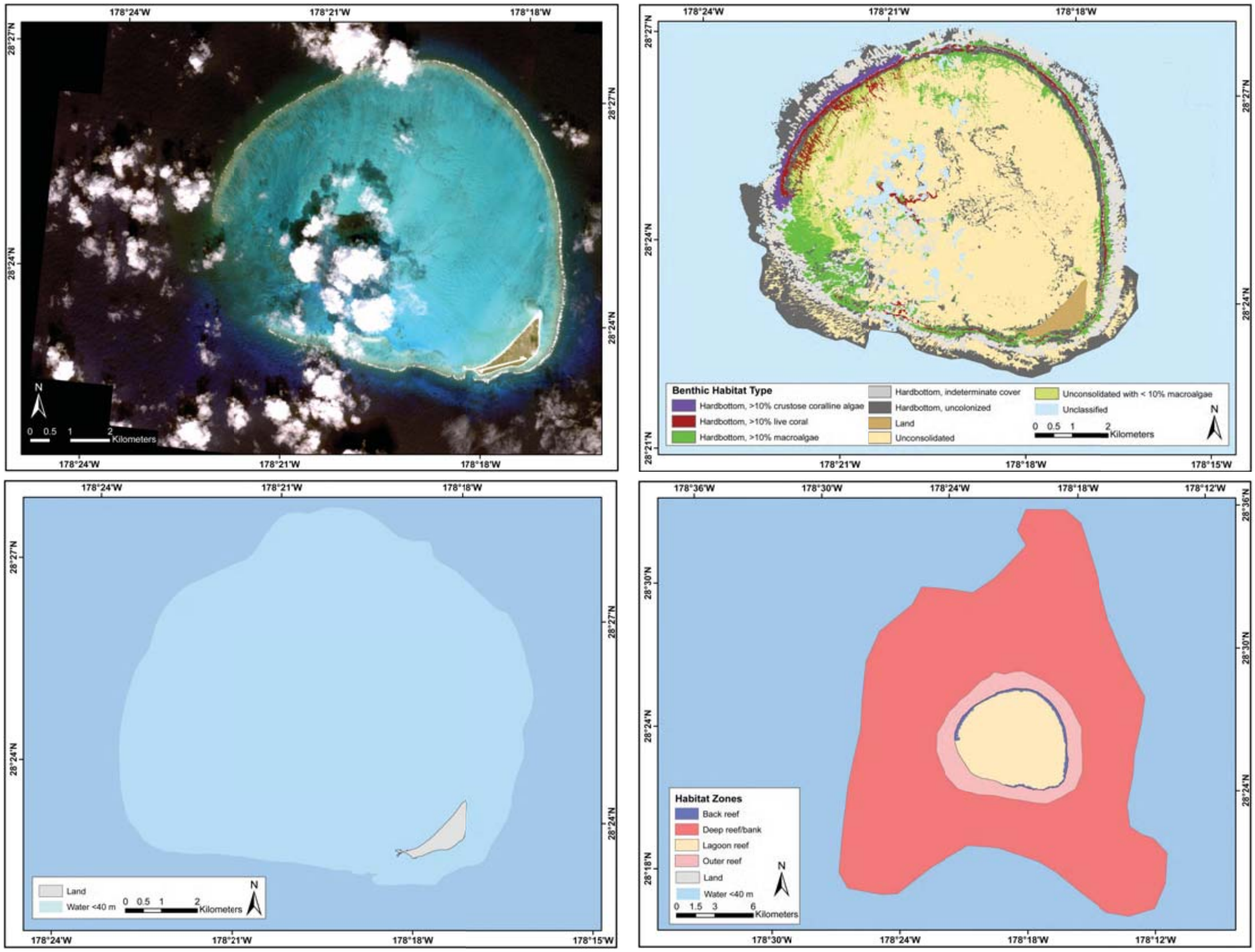


Figure 3.45. IKONOS satellite image (top left), benthic habitat map (top right), extent of water depth < 20 m (bottom left), and habitat zones (bottom right) for Kure Atoll. Maps: L. Wedding.

Multibeam data were collected around Kure Atoll in 2005 (HI0509) to delineate the 25, 50 and 100-fm boundaries and in 2006 (HI0609) to complete mapping of the atoll (Figure 3.46). Slope increased by 9 fold between the shallow and intermediate depth ranges (Table 3.13). Aspect ratio and rugosity also showed the same trend although the magnitude was not as great (Figure 3.47). Multibeam bathymetry at Kure and Midway show extensive spur and groove formations in the high resolution data.

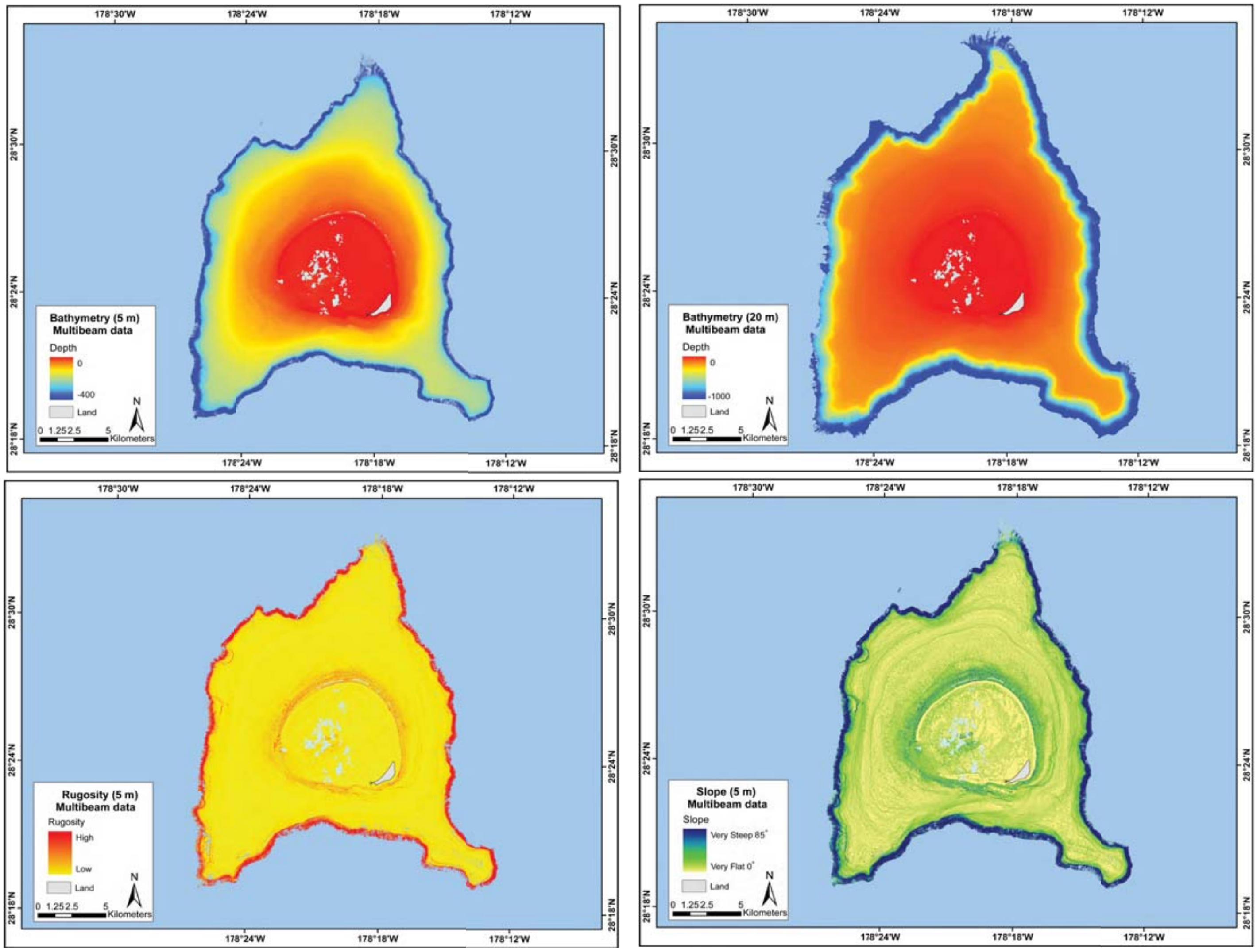


Figure 3.46. 5 m and 20 m bathymetry, rugosity (5 m), and slope (5 m) for Kure Atoll. Maps: L. Wedding.

Table 3.13. Summary statistics for multibeam surveys conducted around Kure Atoll (2005-2006).

KURE	DEPTH CLASS	AREA	MINIMUM*	MAXIMUM*	RANGE	MEAN	STANDARD DEVIATION
Bathymetry	9 to 226	323.34	-225.00	1.00	226.00	-73.27	52.46
	266 to 588	30.76	-402.00	-226.00	176.00	-314.77	50.63
Slope	9 to 226	-	0.00	77.44	77.44	2.86	4.68
	266 to 588	-	0.00	77.82	77.82	26.69	8.43
Aspect	9 to 226	-	-1.00	359.43	360.43	153.84	117.63
	266 to 588	-	-1.00	359.79	360.79	183.77	97.63
Rugosity	9 to 226	-	1.00	7.63	6.63	1.01	0.03
	266 to 588	-	1.00	8.12	7.12	1.15	0.12

***NOTE:** the minimum represents the minimum value of a given metric within a universal depth class; maximum represents the maximum value of a given metric within a universal depth class.

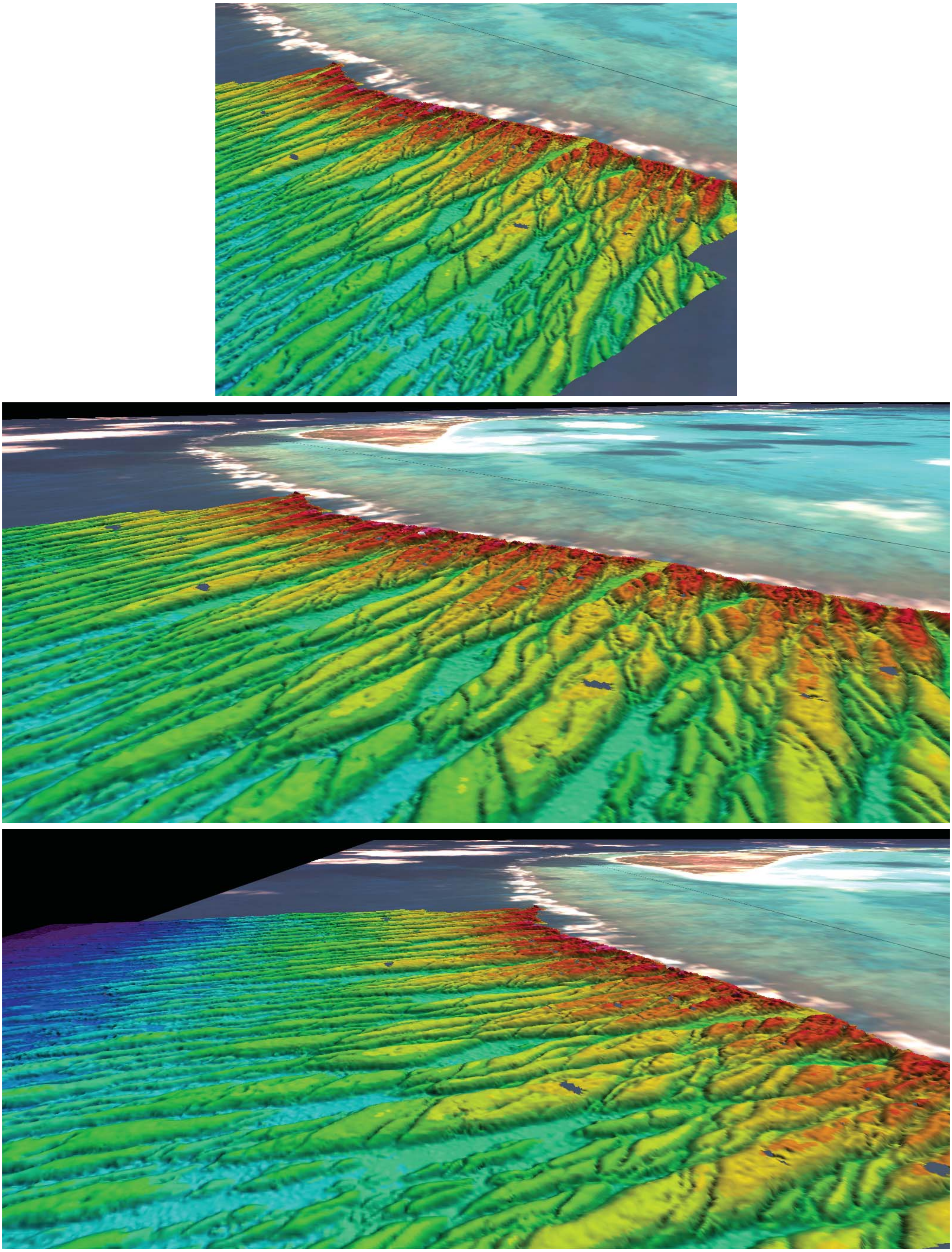


Figure 3.47. Spur and groove formations show up clearly in the high resolution bathymetry taken around Kure Atoll.

EXISTING DATA GAPS

- A comprehensive shallow-water benthic habitat map is required to support multiple research and monitoring activities. Currently only about 50% of the shallow-water area from 0-30 m has sufficient coverage and quality of imagery to produce maps.
- A complete and seamless digital terrain and bathymetric models for the Papahanaumokuakea Marine National Monument (PMNM) to at least 500 m is currently lacking and is necessary to better understand the connection of shallow and deep-water habitats. It will also help guide assessment and monitoring activities.
  - Need to complete high-resolution multibeam bathymetry for shallow to moderate (20 to 500 m) depths.
  - Need to collect shallow (<20 m) bathymetric data using Light Detection and Ranging (LIDAR) or other appropriate technologies.
- Sea level curves developed from the MHI and elsewhere around the Pacific might not be appropriate for the NWHI. Fossil coring and other methods should be employed to better understand past sea level changes in the NWHI.
- Need to determine whole reef accretion rates in different geomorphological zones.
- Need to examine rates of terrestrial habitat loss and the factors that cause it.

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