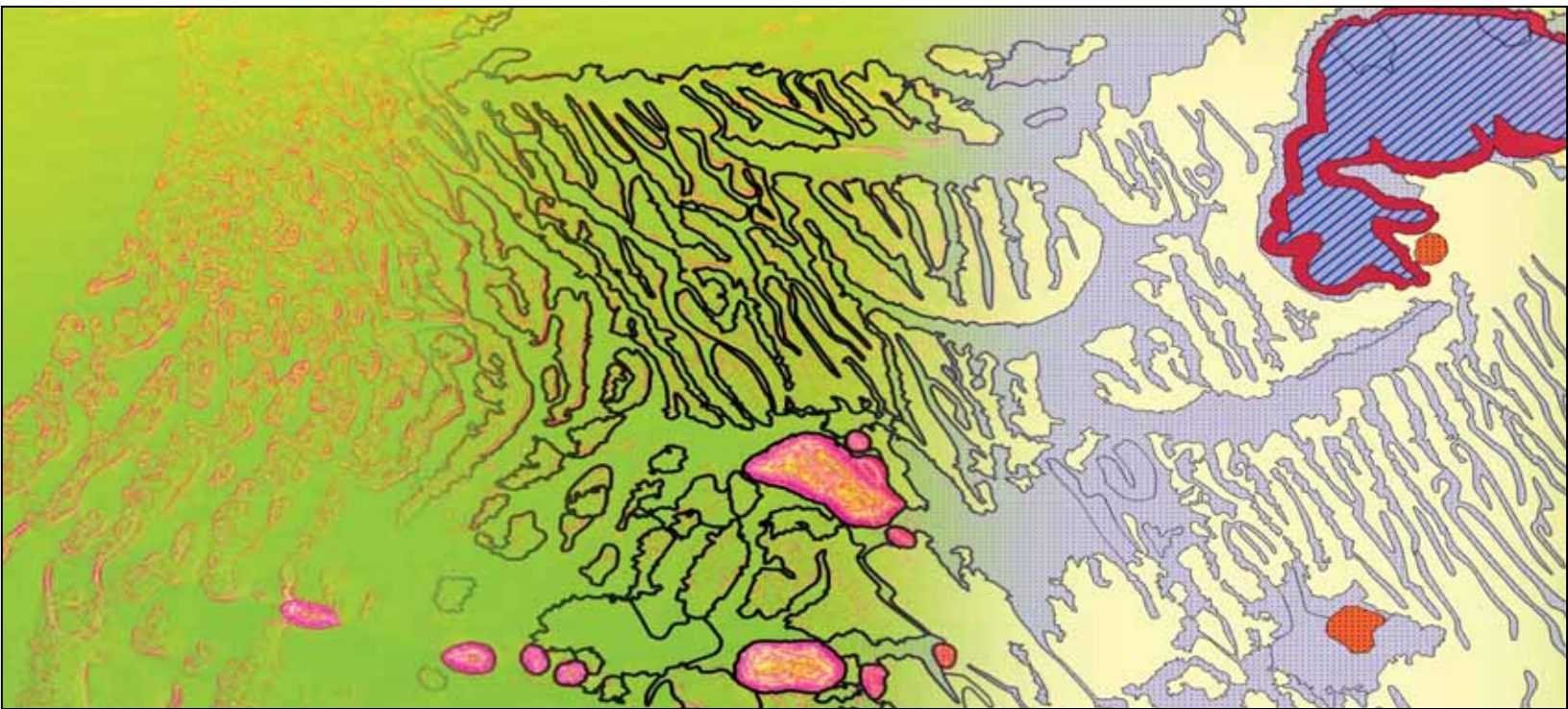


Moderate-Depth Benthic Habitats of St. John, U.S. Virgin Islands



Bryan M. Costa
Laurie J. Bauer
Timothy A. Battista
Peter W. Mueller
Mark E. Monaco
NOAA CCMA Biogeography Branch

Project Report Produced by NOAA's Biogeography Branch in Cooperation with U.S. National Park Service



NOAA TECHNICAL MEMORANDUM NOS NCCOS 105



Mention of trade names or commercial products does not constitute endorsement or recommendation for their use by the United States Government.

Citation:

Costa, B.M., L.J. Bauer, T.A. Battista, P.W. Mueller and M.E. Monaco. 2009. Moderate-Depth Benthic Habitats of St. John, U.S. Virgin Islands. NOAA Technical Memorandum NOS NCCOS 105. Silver Spring, MD. 57 pp.

Moderate-Depth Benthic Habitats of St. John, U.S. Virgin Islands

Biogeography Branch
Center for Coastal Monitoring and Assessment (CCMA)
NOAA/NOS/NCCOS
1305 East-West Highway, SSMC4, N/SCI-1
Silver Spring, MD 20910

NOAA Technical Memorandum NOS NCCOS 105

November 2009

Authors:

Bryan M. Costa
Laurie J. Bauer
Timothy A. Battista
Peter W. Mueller
Mark E. Monaco



United States Department
of Commerce

Gary Locke
Secretary

National Oceanic and
Atmospheric Administration

Jane Lubchenco
Administrator

National Ocean Service

John H. Dunnigan
Assistant Administrator

This page intentionally left blank.

ABOUT THIS DOCUMENT

This report describes the creation and assessment of a moderate-depth benthic habitat map for the Virgin Islands Coral Reef National Monument (VICRNM) south of St. John, U.S. Virgin Islands. The objective of this effort, conducted by NOAA's Center for Coastal Monitoring and Assessment's Biogeography Branch in partnership with the U.S. National Park Service (NPS), was to provide spatially-explicit information describing the moderate-depth (30 - 60 m) benthic habitat types and live coral cover present in and around VICRNM's southern boundaries. The resulting fine-scale habitat map, generated using a combination of semi-automated classification and visual interpretation techniques, represents the first acoustically-generated digital map of these moderate-depth areas.

This report consists of three primary components: 1) a description of the classification scheme used to categorize the different seafloor habitats, 2) a discussion of the techniques used to create the habitat map, and 3) an assessment of the habitat map's thematic accuracies. This habitat map will be used by the U.S. National Park Service and other local partners for planning research and monitoring activities, and will support the management and conservation of St. John's VICRNM.

This work is part of NOAA Coral Reef Conservation Program's national coral reef ecosystem integrated mapping and monitoring studies throughout the U.S. Caribbean (Monaco et al., 2001).

For more information on this effort please visit:

http://ccma.nos.noaa.gov/ecosystems/coralreef/usvi_nps.html

Direct questions or comments to:

Bryan M. Costa
GIS and Remote Sensing Specialist
NOAA/NOS/NCCOS/CCMA/Biogeography Branch
1305 East West Highway
SSMC4, N/SCI-1, 9th floor, #9232
Silver Spring, MD 20910
Phone: (301) 713-3028 x146
Email: Bryan.Costa@noaa.gov

Or

Timothy A. Battista
Chief Scientist
NOAA/NOS/NCCOS/CCMA/Biogeography Branch
1305 East West Highway
SSMC4, N/SCI-1
Silver Spring, MD 20910
Phone: (301) 713-3028 x171
Email: Tim.Battista@noaa.gov



All photographs provided in this document were taken by NOAA/NOS/NCCOS/Center for Coastal Monitoring and Assessment Biogeography Branch in St. John, USVI.

This page intentionally left blank.

EXECUTIVE SUMMARY

Shallow-water (< 30 m) and moderate-depth (30 - 60 m) coral reef ecosystems in the surrounding waters of St. John, U.S. Virgin Islands are unique natural resources that must be preserved. The mosaic of habitats, including hard and soft corals, are home to a diversity of marine organisms, which provide many important ecosystem services to the community of St. John, including fishing, tourism and shoreline protection. However, coral reef ecosystems throughout the U.S. Caribbean are under increasing pressure from environmental and anthropogenic stressors that threaten to destroy these valuable marine communities. Mitigating these threats requires that resource managers first understand the spatial distribution of these resources, making benthic habitat mapping an integral component to any effective ecosystem-based approach to management.



Underwater photo depicting hard corals, soft corals and sponges at moderate-depths.

With this goal in mind, the National Oceanic and Atmospheric Administration's (NOAA) Center for Coastal Monitoring and Assessment's (CCMA) Biogeography Branch and the U.S. National Park Service (NPS) have completed mapping the moderate-depth marine environment south of St. John. This work is an expansion of ongoing mapping and monitoring efforts conducted by NOAA and NPS in the U.S. Caribbean. The standardized protocols used in this effort will enable scientists and managers to quantitatively compare moderate-depth coral reef ecosystems around St. John to those throughout the U.S. Territories. These protocols and products will also help support the effective management and conservation of the marine resources within the National Park system.

This report documents the process and methods used to create benthic habitat maps of the areas in and around the Virgin Islands Coral Reef National Monument (VICRNM). Chapter 1 provides a overview of the benthic habitat classification scheme used to partition the different habitats into ecologically relevant groups. Chapter 2 describes the steps required to create a benthic habitat map using a combination of semi-automated classification and visual interpretation techniques. Chapter 3 details the steps used in the accuracy assessment and reports on the thematic accuracy of the final map. Finally, Chapter 4 summarizes the type and size of habitats found outside and inside the southern boundaries of the VICRNM.

A habitat classification scheme allows scientists to systematically group habitat types based on common ecological characteristics. The habitat classification scheme used to map moderate-depth habitats south of St. John grouped benthic communities based on four primary coral reef ecosystem attributes: 1) broad geographic zone, 2) geomorphological structure, 3) dominant biological cover, and 4) amount of live coral cover. Every polygon in the benthic habitat map was assigned a structure and cover type within a geographic zone (e.g., *Aggregate Reef* dominated by *Algae* on the *Bank/Shelf*). These polygons were delineated and attributed using a combination of semi-automated classification and visual interpretation techniques of acoustic imagery. The acoustic imagery, which was collected using a multibeam echosounder (MBES), proved to be an excellent source from which to derive the location, extent and attributes of moderate-depth marine habitats. In total, 90.2 km² of the seafloor south of St. John was mapped using the acoustic imagery. Approximately half of this area (43.2 km²) fell within the boundaries of the VICRNM. To date, 93% of the VICRNM has been mapped using acoustic and optical imagery.

An independent accuracy assessment was conducted to evaluate the thematic accuracy of the final moderate-depth benthic habitat map. Thematic accuracy was characterized for major and detailed geomorphological structure types, major and detailed biological cover types, and percent coral cover. This accuracy assessment

revealed overall map accuracies of >95% for major structure and cover classes, 88.7% for detailed structure, 74.2% for detailed cover classes, and 88.3% for live coral cover. The 88.7% accuracy achieved for detailed structure in NOAA's moderate-depth benthic habitat map is similar to the accuracies of recent NOAA shallow-water benthic habitat map for St. John (85.7%), as well as for the Florida Keys (86.2%), Palau (90.0%), and the Main Eight Hawaiian Islands (90.0%). Given these high thematic accuracies, the digital map products originating from this project may be used with confidence by scientists and resource managers for a variety of different applications.



Underwater photograph of Staghorn Coral (*Acropora cervicornis*), which is listed as "threatened" under the Endangered Species Act.

Several patterns emerged from the summary map statistics for the total mapped area, as well as for the mapped area inside and outside the VICRNM park boundaries. In particular, *Coral Reef and Hardbottom* constituted the majority of the total mapped area, as well as the majority of the mapped areas inside and outside the VICRNM boundaries. *Coral Reef and Hardbottom* constituted the majority of these three areas because the *Rhodoliths* habitat type dominated the entire moderate-depth region south of St. John. If the *Rhodoliths* category is excluded, *Coral Reef and Hardbottom* only accounted for 14.9% of the total mapped area, as well as 14.6% and 15.4% of the mapped area outside and inside the VICRNM, respectively. After *Rhodoliths*, *Sand* was the second most dominant detailed structure type for all three areas. Although ecologically significant, *Individual Patch Reefs* and *Aggregated Patch Reefs* comprised just over 4% of the total mapped area, 3% of the mapped area outside the VICRNM, and 5% of the mapped area inside the VICRNM.

In looking at major biological cover, the three mapped areas followed the same general trends for major and detailed biological cover types. Namely, all three areas were dominated by continuous, high density algae (i.e., *Algae* 90% - 100%), followed respectively by *Algae* 50% - <90%, *No Cover* 90% - 100% and *Algae* 10% - <50%. In terms of coral cover, the majority (>96%) of all three areas were colonized by 0% - <10% live scleractinian and/or soft corals. It is important to note, however, that the mapped area outside the VICRNM had one 0.25 km² polygon dominated by live coral (i.e., *Live Coral* 50% - <90%), whereas the mapped area inside the VICRNM did not. In addition to this one polygon, the mapped area outside the park was found to have 1.9% more *Live Coral* 10% - <50% habitat than the mapped area inside the VICRNM. This difference suggests that there is slightly more live coral outside (than inside) the current VICRNM boundaries.

In 2009, NOAA's Biogeography Branch has successfully mapped the majority of the shallow-water (< 30m) benthic habitats and a significant portion of the moderate-depth (30 – 60 m) benthic habitats around St. John in the U.S. Virgin Islands. The moderate-depth benthic habitat map begins at the optical limit of the shallow-water map, and continues to the edge of the acoustic imagery. The integration of these two maps is possible, given that the same general habitat classification schemes and MMUs were applied to both the shallow-water and moderate-depth maps. That being said, the differences between these two maps must be thoroughly understood, in order to recognize the limitations associated with using the maps in an integrated fashion. Integration of the shallow-water and moderate-depth maps will provide NPS and others with a seamless benthic habitat map, extending from the shoreline of St. John southward to the 55 m isobath.

TABLE OF CONTENTS

INTRODUCTION1

CHAPTER 1: BENTHIC HABITAT CLASSIFICATION SCHEME3

1.1. COMPARISON TO PREVIOUS NOAA HABITAT CLASSIFICATION SCHEMES3

1.2. GEOGRAPHIC ZONES.....4

1.3. GEOMORPHOLOGICAL STRUCTURE TYPES4

1.4. BIOLOGICAL COVER CLASSES10

1.5. LIVE CORAL COVER CLASSES15

LITERATURE CITED17

CHAPTER 2: BENTHIC HABITAT MAP CREATION19

2.1. GENERAL MAPPING APPROACH.....19

2.2. REMOTELY SENSED IMAGERY.....20

2.3. HABITAT BOUNDARY DELINEATION AND CLASSIFICATION24

2.4. GIS QUALITY CONTROL37

LITERATURE CITED38

CHAPTER 3: CLASSIFICATION ACCURACY ASSESSMENT41

3.1. FIELD DATA COLLECTION41

3.2. EVALUATION OF ASSESSMENT DATA.....41

3.3. ANALYSIS OF THEMATIC ACCURACY42

3.4. ACCURACY ASSESSMENT RESULTS AND DISCUSSION43

3.5. CONCLUSIONS46

LITERATURE CITED48

CHAPTER 4: CONCLUSION.....49

4.1. MAP SUMMARY STATISTICS.....49

4.2. INTEGRATION WITH SHALLOW-WATER NOAA HABITAT MAPS OF ST. JOHN53

4.3 NEXT GENERATION OF MAPPING54

LITERATURE CITED55

ACKNOWLEDGEMENTS57

List of Tables

Table 1.1.	Changes made to the 2009 NOAA shallow-water classification scheme.	3
Table 2.1.	Morphometrics used to characterize the complexity of the seafloor.	22
Table 2.2.	Amount (%) of variance explained by a single complexity surface in a principal component.	23
Table 2.3.	Spatial metrics calculated for each habitat polygon identified during the edge-detection process.	25
Table 2.4.	Textual, ratio, hue saturation and intensity (HSI), and spectral metrics calculated for each habitat polygon identified during the edge-detection process.	26
Table 2.5.	Input parameters used when building the QUEST classification trees.	34
Table 2.6.	Polygon metrics identified as being significant for classifying coral reef habitats and soft bottom/rhodolith habitats.	35
Table 2.7.	Estimated number of polygons that were manually deleted, added or merged.	36
Table 2.8.	Estimated number of polygons that were manually reattributed.	36
Table 3.1.	Error matrix for major geomorphological structure.	43
Table 3.2.	Error matrix for major geomorphological structure using individual cell probabilities.	44
Table 3.3.	Error matrix for detailed geomorphological structure.	44
Table 3.4.	Error matrix for detailed geomorphological structure using individual cell probabilities.	45
Table 3.5.	Error matrix for major biological cover.	45
Table 3.6.	Error matrix for major biological cover using individual cell probabilities.	46
Table 3.7.	Error matrix for detailed biological cover.	46
Table 3.8.	Error matrix for detailed biological cover using individual cell probabilities.	47
Table 3.9.	Error matrix for major geomorphological structure and percent live coral cover.	47
Table 4.1.	Final deliverable items for NOAA's moderate-depth benthic habitat map of St. John.	49
Table 4.2.	Statistics describing the mapped area by major and detailed geomorphological structure types.	49
Table 4.3.	Statistics describing the mapped area by major and detailed biological cover type, as well as by amount of live coral cover.	50
Table 4.4.	Estimated time required to map St. John's shallow-water habitats using the heads-up digitizing and attribution method, and St. John's moderate-depth habitats using the semi-automated delineation and classification technique.	54

List of Figures

Figure 0.1.	Overview of the benthic habitat maps produced in 2009 for St. John, U.S. Virgin Islands.....	1
Figure 0.2.	Optical and acoustic imagery sources that were used to produce the NOAA 2009 shallow-water and moderate-depth benthic habitat maps.	2
Figure 1.1.	Cross-section of geographic zones where no emergent reef crest is present.....	4
Figure 1.2.	Underwater photograph of <i>Aggregate Reef</i>	5
Figure 1.3.	Underwater photograph of <i>Individual Patch Reef</i>	5
Figure 1.4.	Underwater photograph of <i>Aggregated Patch Reefs</i>	6
Figure 1.5.	Underwater photograph of <i>Pavement</i>	6
Figure 1.6.	Underwater photograph of <i>Pavement with Sand Channels</i>	7
Figure 1.7.	Underwater photograph of <i>Rhodoliths</i>	7
Figure 1.8.	Underwater photograph of <i>Rhodoliths with Scattered Coral and Rock</i>	8
Figure 1.9.	Underwater photograph of <i>Sand</i>	8
Figure 1.10.	Underwater photograph of <i>Sand with Scattered Coral and Rock</i>	9
Figure 1.11.	Examples of artifacts or noise in the acoustic imagery.....	9
Figure 1.12.	Description of how biological cover modifier represents a confounded measure of density and patchiness.....	10
Figure 1.13.	Underwater photographs of Lesser Starlet Coral (<i>Siderastrea radians</i>) and Grooved Brain Coral (<i>Diploria labyrinthiformis</i>).....	10
Figure 1.14.	Underwater photos and associated polygons depicting the three different densities of biological cover.....	11
Figure 1.15.	Underwater photos and associated polygons depicting the three different degrees of biological cover patchiness.....	12
Figure 1.16.	Underwater photographs of <i>Algae</i>	13
Figure 1.17.	Underwater photographs of <i>Seagrass</i>	13
Figure 1.18.	Underwater photographs of <i>Live Coral</i>	14
Figure 1.19.	Underwater photographs of <i>No Cover</i>	14
Figure 1.20.	Underwater photographs of scleractinian (reef-building) corals and octocorals (non-reef building).....	15
Figure 1.21.	Underwater photograph of 0% - <10% live coral cover.....	16
Figure 1.22.	Underwater photograph of 10% - <50% live coral cover.....	16
Figure 1.23.	Underwater photograph of 50% - <90% live coral cover.....	16
Figure 2.1.	Field maps were used to collect drop camera points.....	19
Figure 2.2.	Process used to collect the data for a moderate-depth benthic habitat map.....	20
Figure 2.3.	Two types of imagery (i.e., bathymetry and intensity) collected using an MBES sensor.....	21
Figure 2.4.	Photo of the NOAA ship <i>Nancy Foster</i>	21
Figure 2.5.	Photo of the RESON SeaBat 8101 ER (240 kHz) MBES sensor.....	21
Figure 2.6.	Diagram illustrating the process used to create the moderate-depth benthic habitat south of St. John.....	24
Figure 2.7.	Habitat objects that were exported from ENVI Fx as a single ESRI shapefile.....	26
Figures 2.8a.	Screenshots of the ENVI Fx 4.6 feature extraction process.....	27
Figures 2.8b.	Screenshot showing the scale level used to identify coral reef habitat features.....	27
Figures 2.8c.	Screenshot showing the merge level used to aggregate coral reef habitat features into larger objects.....	27
Figures 2.8d.	Screenshot showing the step where the spatial, textual, HSI, ratio and spectral metrics were calculated for each coral reef habitat polygons.....	27
Figure 2.9.	Process used to manually edit habitat polygons to remove acoustic noise within their boundaries.....	28
Figure 2.10.	Photograph of the Spectrum Phantom S2 ROV, which collected underwater video and high resolution photographs of the seafloor along 13 transects.....	28
Figure 2.11.	Photograph of the SeaViewer Sea-Drop 950 camera, which collected underwater video of the seafloor at 117 discrete locations.....	29
Figure 2.12.	Photograph of the U.S. National Park Service vessel used to collect underwater video.....	29
Figure 2.13.	Photograph of the field equipment used to collect underwater video.....	30

Figure 2.14.	Map illustrating how the drop camera occasionally drifted over habitat transitions.....	30
Figure 2.15.	Process used to create a final classified set of GV points.....	31
Figure 2.16.	Process used to convert final classified GV points to ENVI 4.6 ROIs.	31
Figure 2.17.	T Screenshot of ENVI 4.6's RuleGen 1.02 add-on.....	32
Figure 2.18.	Underwater photograph of the Great Star Coral (<i>Montastraea cavernosa</i>).....	33
Figure 2.19.	Description of how QUEST uses binary decisions to split an image into classes.	33
Figure 2.20.	Description of how QUEST determines where to split super classes into two groups.	33
Figure 2.21.	Process used to merge polygons < 1,000 m ² with neighboring polygons.	35
Figure 2.22.	Process used to smooth the pixilated appearance of the polygon lines.....	36
Figure 4.1.	Map showing the major and detailed geomorphological structure types south of St. John.....	50
Figure 4.2.	Map showing the major and detailed biological cover types south of St. John.	51
Figure 4.3.	Map showing the amount of live coral cover south of St. John.	51

INTRODUCTION

NOAA CCMA's Biogeography Branch has developed analytical protocols to map benthic habitats throughout all U.S. jurisdictions, States, and Territories, including the U.S. Caribbean. NOAA, in partnership with the U.S. National Park Service, has generated both shallow-water and moderate-depth benthic habitat maps of the coral reef ecosystems surrounding St. John, U.S. Virgin Islands (Figure 0.1). The synthesis of existing geospatial data and collection of new data provides the most contemporary compilation of remotely-sensed and *in situ* data within the network of NPS-managed marine Ocean Parks. These products provide a fine-scale assessment of the status, abundance, and distribution of marine habitats in and around the VICRNM, giving the NPS an increased technical capacity for ocean exploration, management, and stewardship. Direct management implications specifically include: (1) evaluating the efficacy of management actions, (2) improving the spatial framework for monitoring activities, (3) enhancing the assessment of human-use impacts, and (4) enabling the use of marine spatial planning to support protected area boundary alternatives.

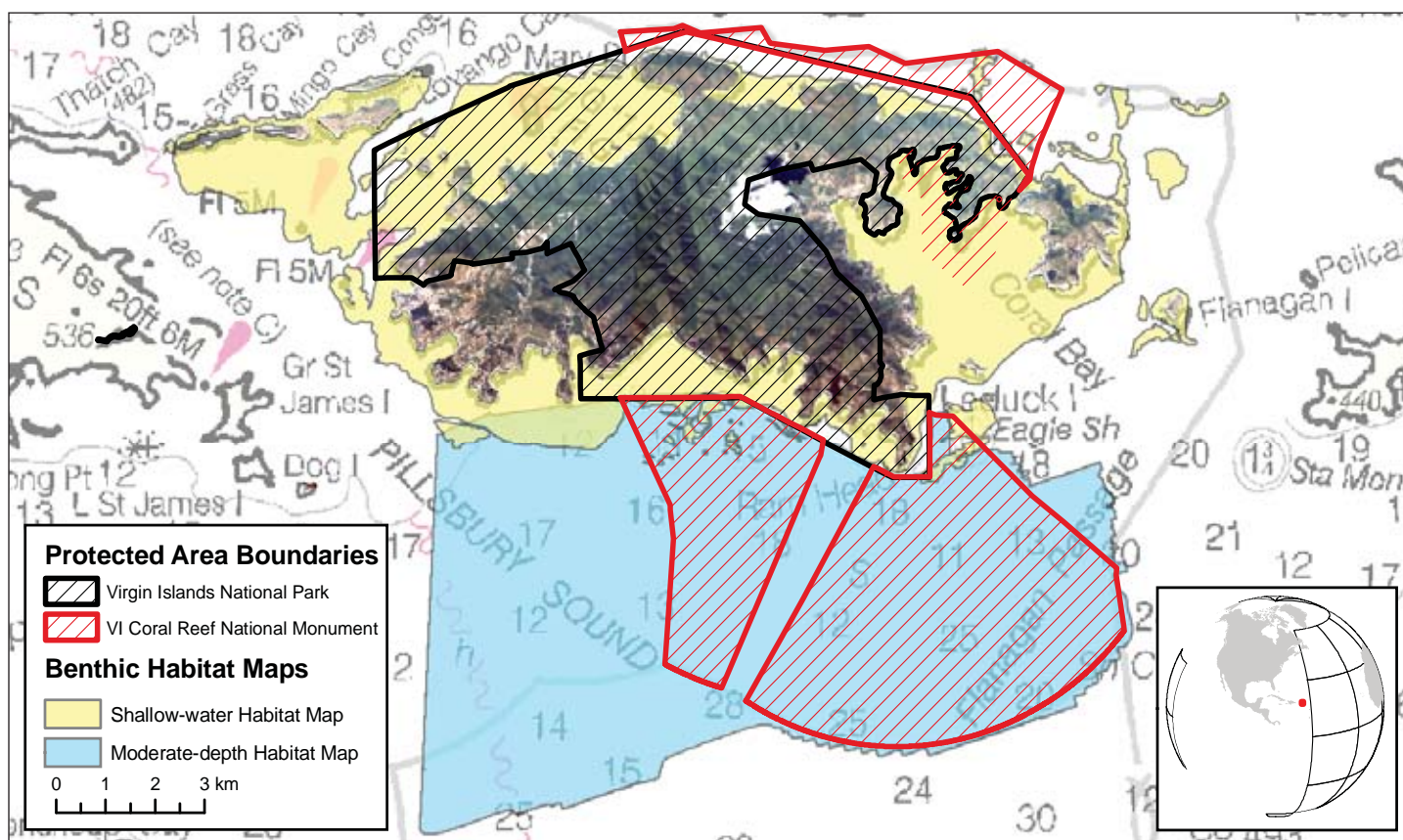


Figure 0.1. Overview of the benthic habitat maps produced in 2009 for St. John, U.S. Virgin Islands.

As a result of the U.S. Ocean Action Plan, the National Park Service developed an Ocean Park Stewardship Action Plan to focus organizational and scientific capacity on conserving marine, estuarine, and Great lakes resources. The Ocean Park Stewardship Action Plan aims to prevent the loss of productive fisheries, habitats, and wildlife, and continue to conserve ocean resources and recreational activities for park visitors. The National Park Service manages and protects more than 250,000 acres of coral reef in ten National Park units, two of which are located in St John. The Virgin Islands Coral Reef National Monument includes 12,722 acres (51.4 km²) of federal submerged lands off the coast of St. John. These waters contain some of the most biologically rich and economically important coral ecosystems in U.S. waters, supporting a diverse and complex system of coral reefs, shoreline mangrove forests, and seagrass beds. Additionally, the Virgin Islands National Park includes 5,637 acres (22.8 km²) of submerged federal lands to protect and conserve a rich but fragile coral reef seascape. As part of the ocean stewardship effort, the Ocean Park Stewardship Action Plan serves to improve scientific capacity in order to better understand ocean ecosystems and the impact of humans on ecosystems. This includes providing improved spatial products to better inform resource managers of the current distribution of benthic habitats.

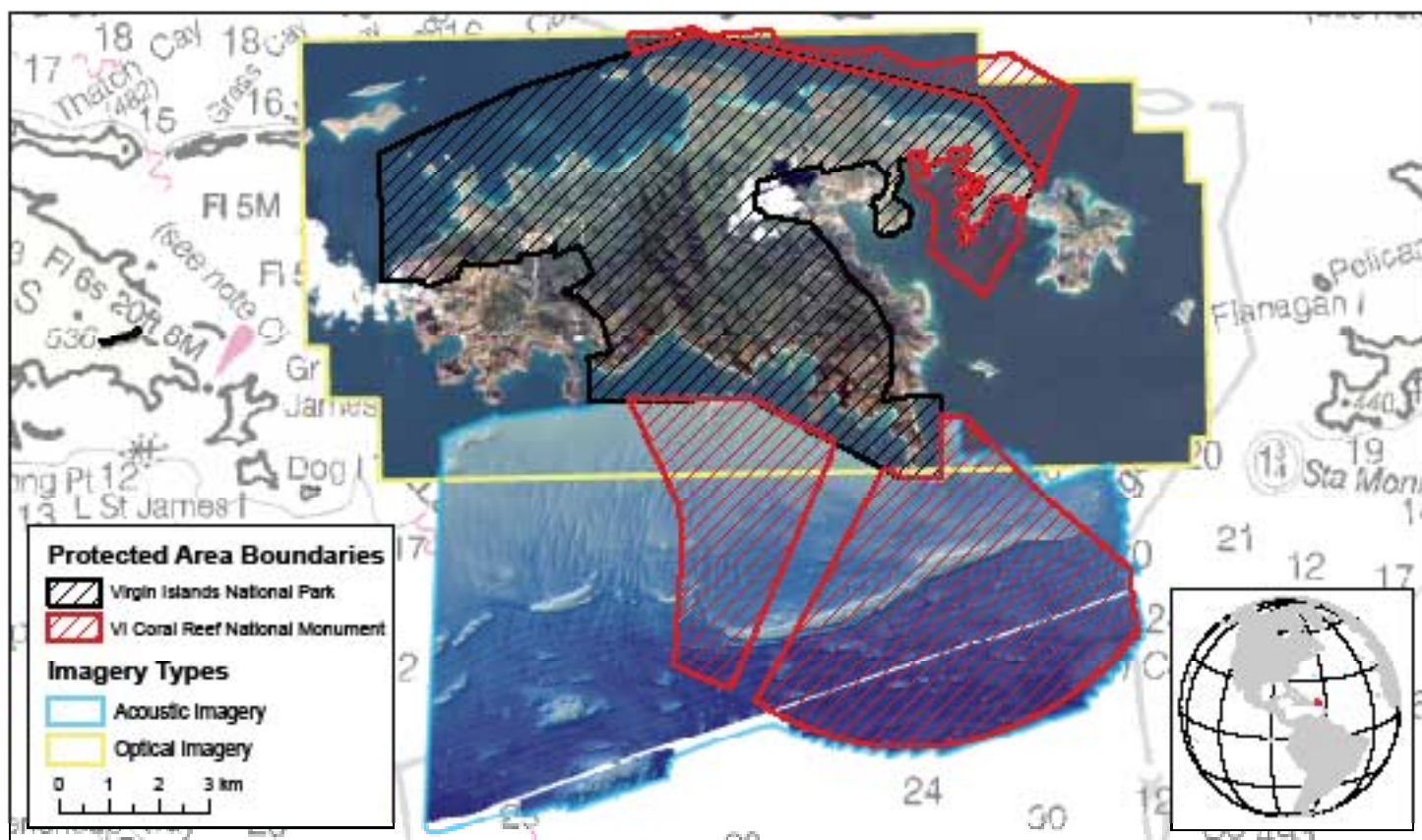


Figure 0.2. Optical and acoustic imagery sources that were used to produce the NOAA 2009 shallow-water and moderate-depth benthic habitat maps (respectively) for St. John, U.S. Virgin Islands.

NOAA's effort to map the moderate-depth benthic habitats of St. John has resulted in a suite of spatial products. The project deliverables specifically include:

- Primary data sources, including acoustic imagery, ground validation field data, and accuracy assessment field data
- Derived datasets, including GIS files of benthic habitats
- Classification manual
- Description of the methods used to create the habitat maps
- Assessment of the thematic accuracy of the maps

This moderate-depth mapping effort compliments a recently completed NOAA project, which mapped the shallow-water (< 30 m) benthic habitats of St. John. These two benthic habitat maps represent one of the first attempts to spatially integrate products developed from acoustic and optical imagery (Figure 0.2), as well as from using manual and semi-automated classification techniques.

CHAPTER 1: BENTHIC HABITAT CLASSIFICATION SCHEME

A habitat classification scheme allows scientists to systematically group habitat types based on common ecological characteristics. The initial task in any mapping effort is to create such a scheme by clearly identifying and defining discrete habitat classes. This scheme is subsequently used to guide the delineation and attribution of polygons throughout the mapping process. It is, consequently, critical for map users to have an understanding of the classification system, its structure and its definitions. This understanding allows users to decide on the appropriate uses and limitations of the map.

The St. John moderate-depth habitat classification scheme defines benthic communities on the basis of four primary coral reef ecosystem attributes: 1) broad geographic zone, 2) geomorphological structure, 3) dominant biological cover, and 4) amount of live coral cover. Habitat features are described by varying levels of detail (i.e. at the major and minor levels), so that users can refine the information depicted by the habitat map to best suit their research and management needs. Every polygon in the benthic habitat map was assigned a geomorphological structure, biological cover type and live coral cover percentage within a geographic zone. For example, many areas along the Mid Shelf Reef (MSR), which is located on the *Bank/Shelf*, are comprised of *Aggregate Reef* that is colonized by continuous, high density *Algae* 90% - 100% and low density live coral 0% - <10%.

1.1. COMPARISON TO 2009 NOAA SHALLOW-WATER HABITAT CLASSIFICATION SCHEME

Many important factors were considered in the development of the St. John moderate-depth habitat classification scheme. These factors specifically included: (1) existing shallow-water classification schemes for coastal ecosystems, (2) quantitative *in situ* habitat data, (3) minimum mapping unit (MMU), (4) and limitations of the acoustic imagery (particularly, the intensity imagery).

In order to simplify this process, the St. John moderate-depth habitat classification scheme was based on the recently updated classification scheme developed by NOAA to map shallow-water (< 30 m) benthic habitats around St. John (Zitello et al., 2009). Specifically, the geographic zones, major and detailed geomorphological structure types, biological cover types and live coral cover classes used in the moderate-depth scheme were based on the same groupings developed for the shallow-water scheme. Also, a consistent MMU (i.e., 1,000 m²) was used in both the shallow-water and moderate-depth classification schemes. However despite the similarities, there were also some differences between the two schemes because not all of the habitats found in shallow-waters are present at deeper depths. Specifically, these differences included: (1) changing the definitions of *Pavement* and *Algae* slightly to broaden their meanings, (2) removing 11 geographic zones, 7 geomorphological structure and 2 biological cover types because they were not present in the mod-

Table 1.1. This table depicts the changes made to the 2009 NOAA shallow-water classification scheme, in order to tailor it to the habitats seen at deeper depths (> 30 m) on the shelf south of St. John. Classes with a line through them were not present at moderate depths. The class with a star was added to the moderate-depth classification scheme. Italicized classes had their definitions changed slightly from those used in the shallow-water scheme.

GEOGRAPHIC ZONE	GEOMORPHOLOGICAL STRUCTURE	BIOLOGICAL COVER
Land	Coral Reef and Hard Bottom (Hard)	Major Cover
Salt Pond	Rock-Outcrop	<i>Algae</i>
Shoreline-Intertidal	Boulder	Live Coral
Lagoon	Aggregate Reef	<i>Ceralline-Algae</i>
Reef-Flat	Individual Patch Reef	<i>Mangrove</i>
Back-Reef	Aggregated Patch Reefs	Seagrass
Reef-Crest	Spur-and-Groove	No Cover
Fore-Reef	<i>Pavement</i>	Unknown
Bank/Shelf	Pavement with Sand Channels	Percent Major Cover
Escarpment	Reef-Rubble	10% - <50%
Channel	Rhodoliths	50% - <90%
Dredged	Rhodoliths with Scattered Coral & Rock*	90% - 100%
Unknown	Unknown	Unknown
	Unconsolidated Sediment (Soft)	Percent Coral Cover
	Sand	0% - <10%
	Mud	10% - <50%
	Sand with Scattered Coral and Rock	50% - <90%
	Unknown	90% - 100%
	Other Delineations	Unknown
	Land	
	Artificial	
	Unknown	

erate-depth area, and (3) adding 1 new geomorphological structure type to accommodate a new habitat seen at these deeper depths (Table 1.1).

The other difference between the St. John shallow-water and moderate-depth classification schemes is how the two systems quantified percent biological cover. Specifically, in the shallow-water scheme, percent biological cover represents a measure of patchiness of the biological cover at the scale of the $\geq 1,000 \text{ m}^2$ habitat feature. It does not represent the density of biological cover observed by divers in the water. For example, a seagrass bed maybe described as covering 90% - 100% of a given polygon, but may have sparse shoot densities when observed by divers. The moderate-depth classification scheme, on the other hand, quantified percent biological cover by accounting for both the density of biological cover at the scale of the 4 m^2 pixel and the patchiness of biological cover at the scale of the $\geq 1,000 \text{ m}^2$ habitat feature. For example, a habitat feature defined as having 10% - <50% biological cover may have continuous algal cover at low densities, or it may have small, patchy areas of moderately dense algal cover scattered within large areas with no biological cover. Percent biological cover differs between the two schemes due to inherent differences in the technological approaches. Further research is being conducted to reconcile this difference in the future.

1.2. GEOGRAPHIC ZONES

One geographic zone (i.e., *Bank/Shelf*) was identified in the moderate-depth area, corresponding to typical insular shelf and coral reef geomorphology. Figure 1.1 illustrates zone types across typical cross-sections when the reef feature is fringing the shore. Zone only refers to the location of a benthic habitat feature and does not address the habitat feature's substrate or biological cover types. For example, the *Bank/Shelf* zone may include patch reefs and pavement; however, these are considered structural elements that may or may not occur within the *Bank/Shelf* zone and therefore, are not used to define it (Kendall et al., 2001). A brief description of the *Bank/Shelf* zone is provided in the proceeding text.

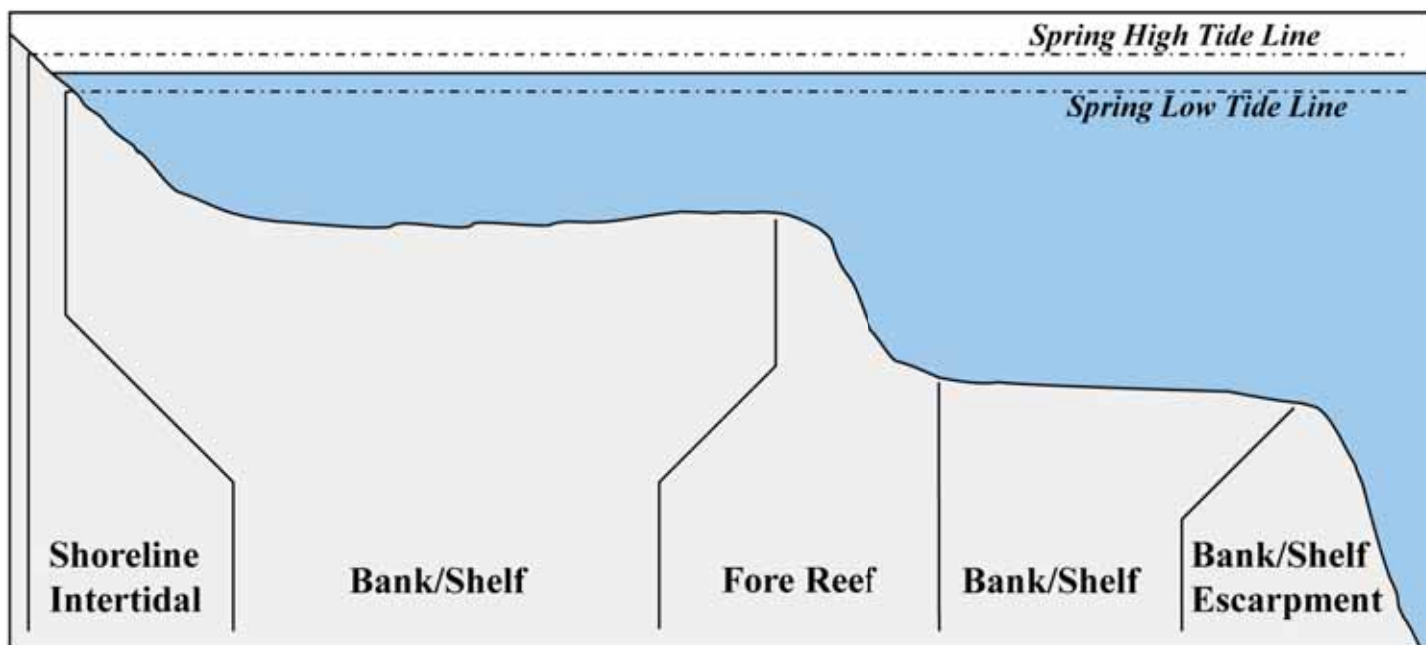


Figure 1.1. Cross-section of zone types where no emergent reef crest is present.

Bank/Shelf

Deeper water area (usually >30 m) extending offshore from the seaward edge of the *Fore Reef* or shoreline to the beginning of the bank/shelf escarpment where the insular shelf drops off into deep, oceanic water.

Unknown

Zone indistinguishable due to random or systematic noise in the bathymetry and/or backscatter, or other interference with an acoustic signature of the seafloor.

1.3. GEOMORPHOLOGICAL STRUCTURE TYPES

Thirteen distinct and non-overlapping geomorphological structure types were mapped using a combination of semi-automated classification and visual interpretation of acoustic imagery. Geomorphological structure refers to a habitat feature's dominate physical composition and does not address its location (e.g., on the *Bank/Shelf*). The structure types are defined in a collapsible hierarchy ranging from three major classes (*Coral Reef and Hard-*

bottom, Unconsolidated Sediment, and Unknown), to ten detailed classes (*Individual Patch Reef*, *Aggregated Patch Reefs*, *Aggregate Reef*, *Pavement*, *Pavement with Sand Channels*, *Rhodoliths*, *Rhodoliths with Scattered Coral and Rock*, *Sand*, *Sand with Scattered Coral and Rock* and *Unknown*). Habitat features with areas smaller than the map's minimum mapping unit or MMU (1,000 m²) were not considered. For example, sand halos surrounding individual patch reefs were often too small to be mapped independently.

Coral Reef and Hardbottom

Areas on the seafloor with solid substrates including bedrock, boulders and/or the deposition of calcium carbonate by reef or nodule building organisms. Substrates typically have no sediment cover, but a thin veneer of sediment may be present at times. Detailed structure classes include *Individual Patch Reef*, *Aggregated Patch Reefs*, *Aggregate Reef*, *Pavement*, *Pavement with Sand Channels*, *Rhodoliths* and *Rhodoliths with Scattered Coral and Rock*.

Aggregate Reef

Continuous, high-relief coral formation of variable shapes lacking sand channels. Includes linear coral formations that are oriented parallel to the shelf edge (Figure 1.2).

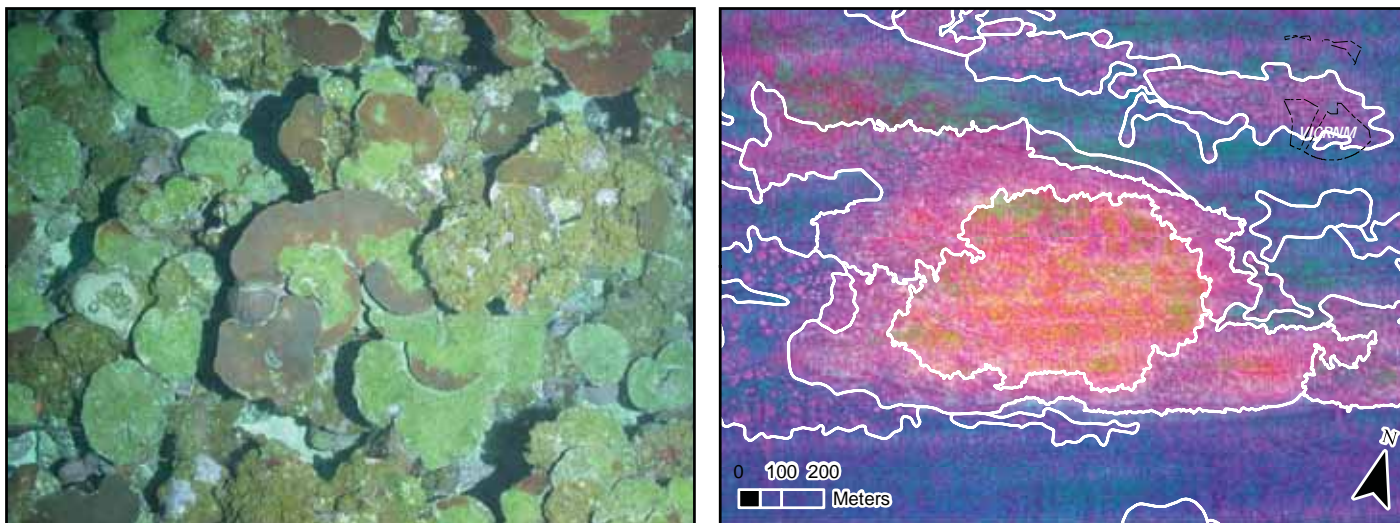


Figure 1.2. Underwater photograph (left) depicting the detailed structure type: *Aggregate Reef*. Red polygons outline the features in the acoustic imagery (right).

Individual Patch Reef

Individual Patch Reefs are coral formations with a circular or oblong shapes, and vertical reliefs of one meter or more in relation to the surrounding seafloor. They are isolated from other coral reef formations by bare sand, seagrass, rhodoliths or other habitats, and have no organized structural axis relative to the contours of the insular shelf edge. *Individual Patch Reefs* are larger than or equal to the map's MMU (Figure 1.3).

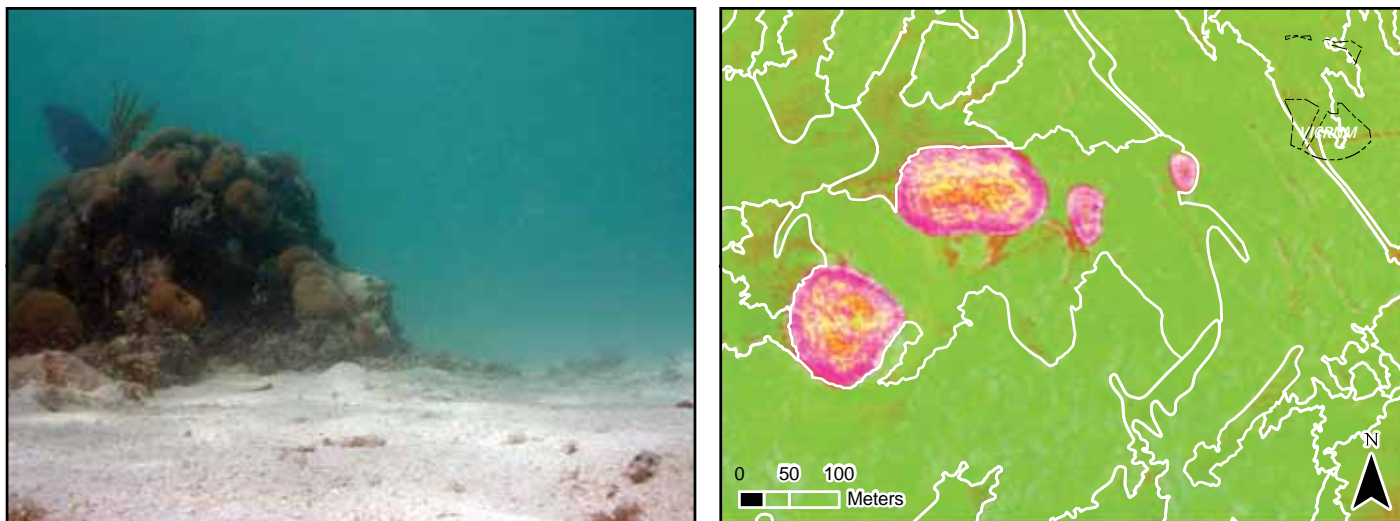


Figure 1.3. Underwater photograph (left) depicting the detailed structure type: *Individual Patch Reef*. Red polygons outline the features in the acoustic imagery (right).

Aggregated Patch Reefs

Aggregated Patch Reefs have the same defining characteristics as an *Individual Patch Reef*. This class, however, refers to clustered patch reefs that cover $\geq 10\%$ of an entire polygon's area, but are too small (less than the MMU) or are too close together to map individually. Where aggregated patch reefs share sand halos, the halo is included in the polygon (Figure 1.4). If the density of small or aggregated coral heads is $< 10\%$ of the entire polygon, then the structure type is described as either *Rhodoliths with Scattered Coral and Rock* or *Sand with Scattered Coral and Rock*.

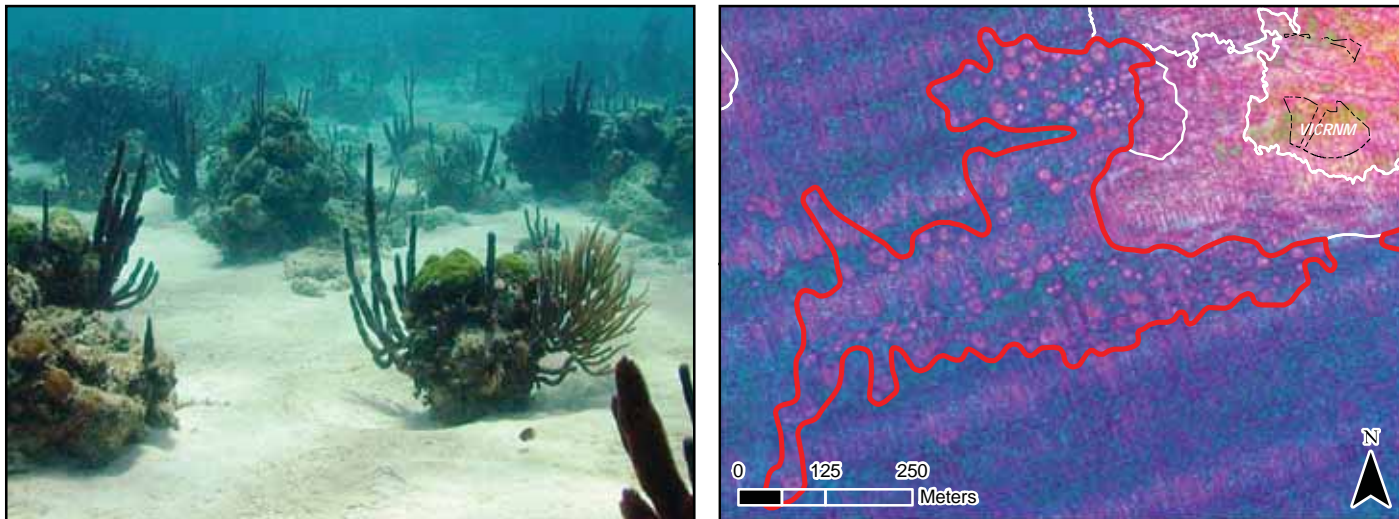


Figure 1.4. Underwater photograph (left) depicting the detailed structure type: *Aggregated Patch Reefs*. Red polygons outline the features in the acoustic imagery (right).

Pavement

Flat, low-relief or sloping solid carbonate rock with little or no fine-scale rugosity that is covered with algae, hard coral, gorgonians, zooanthids or other sessile vertebrates that are dense enough to partially obscure the underlying surface. On less colonized *Pavement* features, rock may be covered by a thin sand veneer (Figure 1.5).

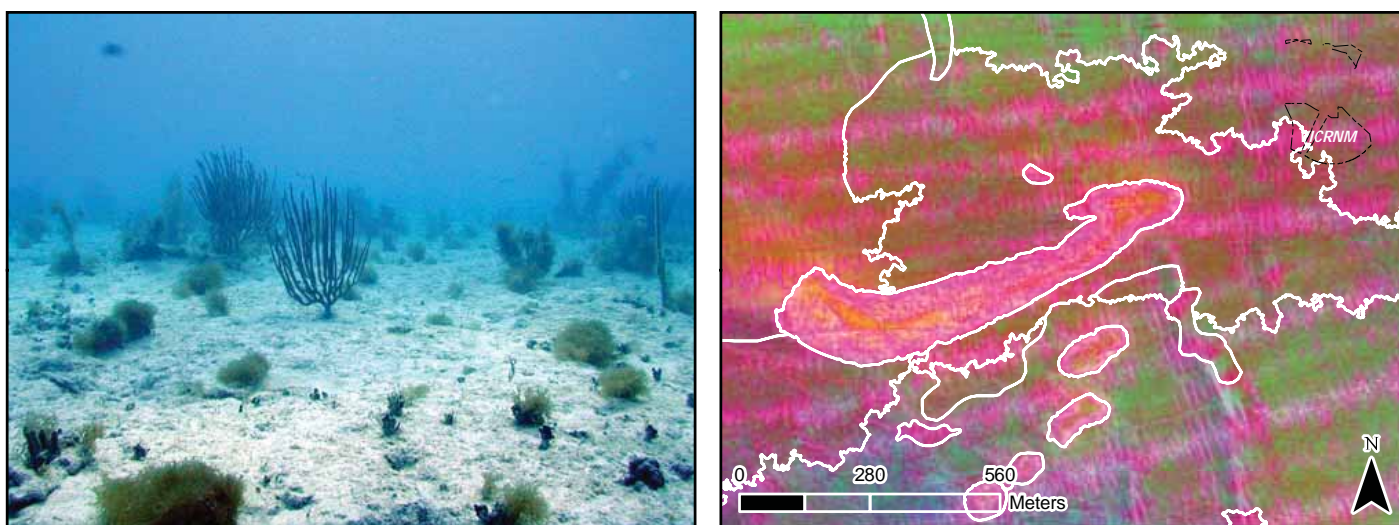


Figure 1.5. Underwater photograph (left) depicting the detailed structure type: *Pavement*. Red polygons outline the features in the acoustic imagery (right).

Pavement with Sand Channels

Pavement with Sand Channels have the same defining characteristics as *Pavement*, in addition to having periodic sand/surge channels oriented perpendicular to the *Bank/Shelf Escarpment*. The sand/surge channels of this feature have low vertical relief and are typically erosional in origin. This habitat type occurs in areas exposed to moderate wave surge, such as the *Bank/Shelf* zone (Figure 1.6).

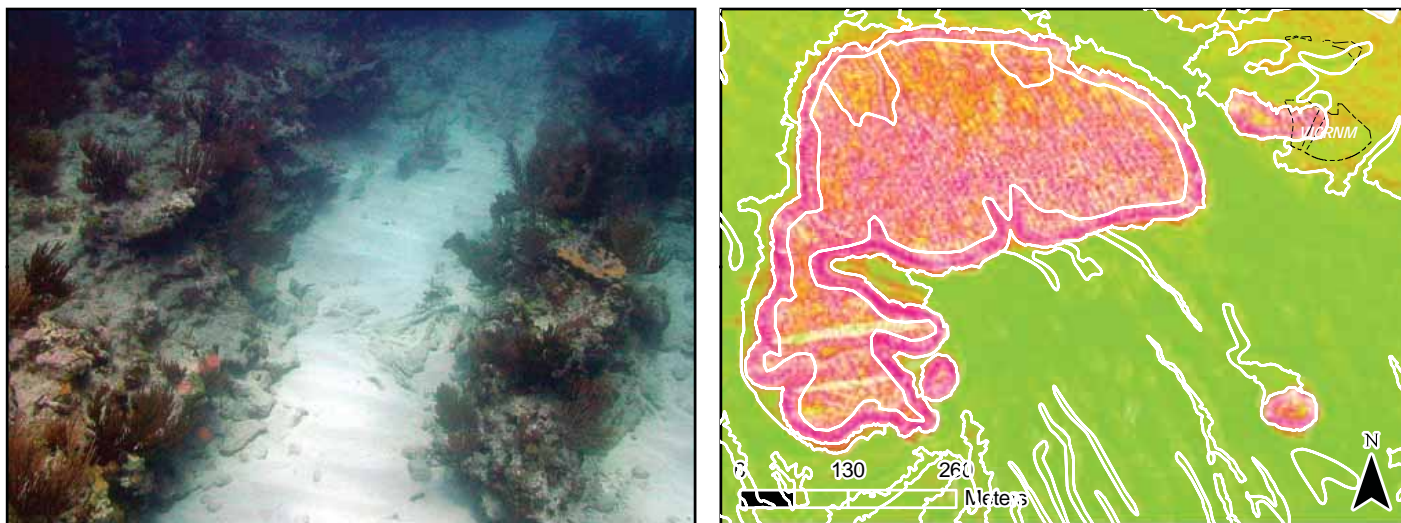


Figure 1.6. Underwater photograph (left) depicting the detailed structure type: *Pavement with Sand Channels*. Red polygons outline the features in the acoustic imagery (right).

Rhodoliths

Areas on the seafloor that are covered by $\geq 10\%$ rhodoliths. Rhodoliths are cylindrical, discoidal, or irregular shaped calcareous nodules averaging approximately 6 cm in diameter (Foster 2001). These unattached nodules are colonized by successive layers of coralline red algae, and are commonly found in offshore topographic depressions (Figure 1.7). Since Rhodoliths are unattached to the seafloor and mobile, their distributions can change quantifiably from year to year.

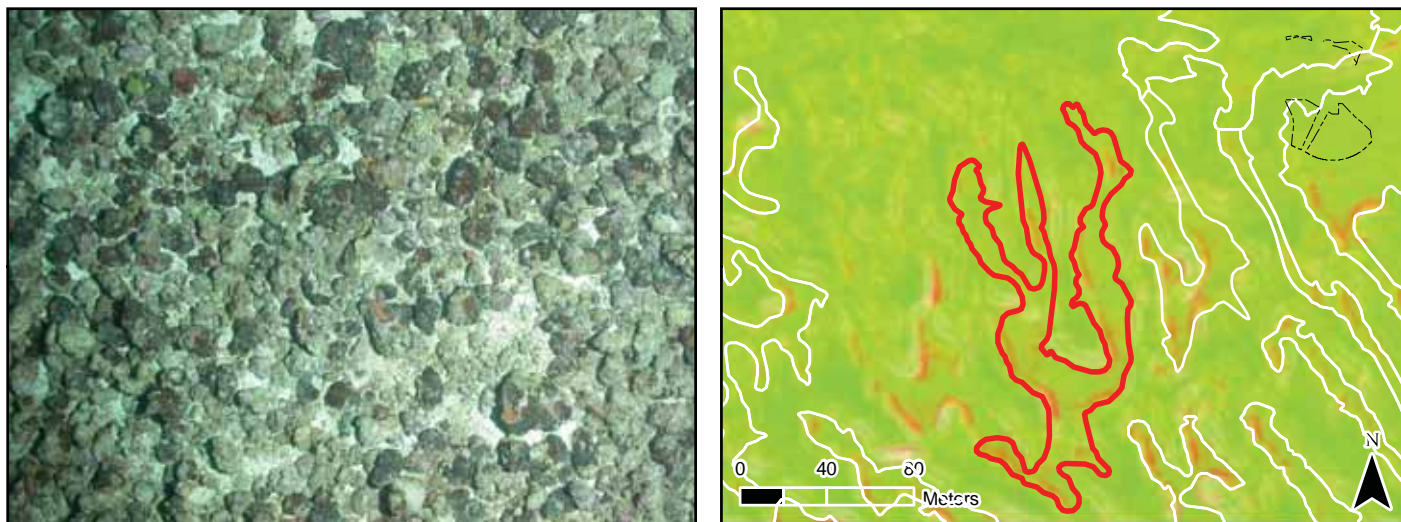


Figure 1.7. Underwater photograph (left) depicting the detailed structure type: *Rhodoliths*. Red polygons outline the features in the acoustic imagery (right).

Rhodoliths with Scattered Coral and Rock

Areas on the seafloor where $\geq 10\%$ of the entire polygon is covered by rhodoliths, and $< 10\%$ of the entire polygon is covered by scattered rocks or isolated coral heads that are too small to be delineated individually (Figure 1.8). If the density of the rocks and/or coral heads is $\geq 10\%$ of the entire polygon's area, then the structure type is described as *Aggregated Patch Reefs*.

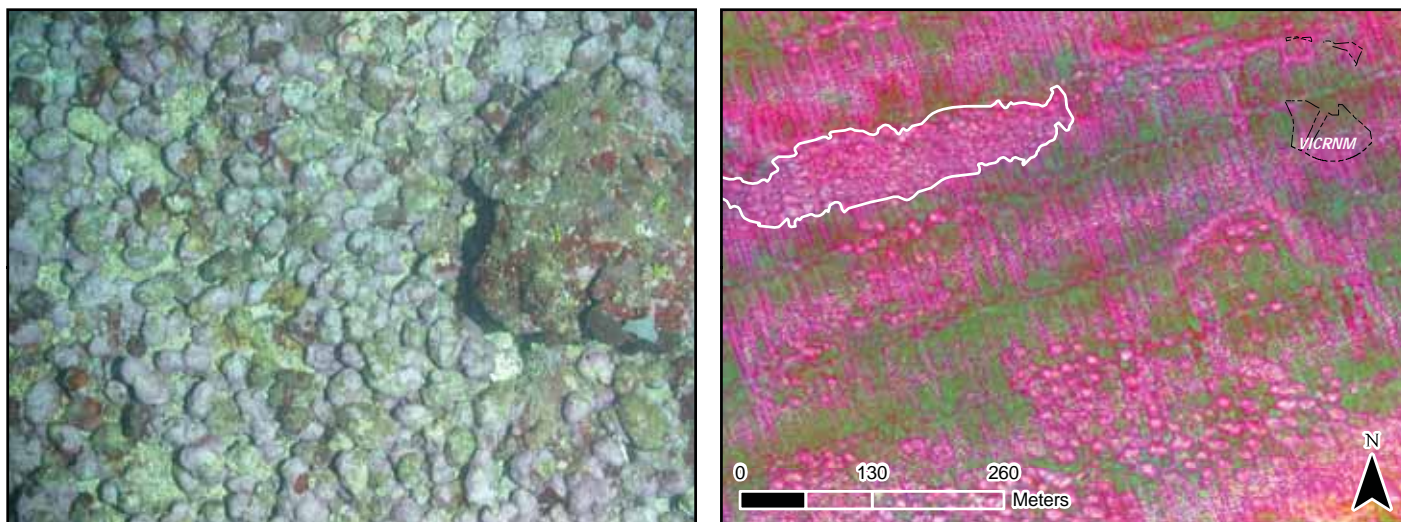


Figure 1.8. Underwater photograph (left) depicting the detailed structure type: *Rhodoliths with Scattered Coral and Rock*. Red polygons outline the features in the acoustic imagery (right).

Unconsolidated Sediment

Areas on the seafloor consisting of small particles (< 256 mm) with less than 10% cover of rhodoliths or large stable substrate. Detailed structure classes include: *Sand* and *Sand with Scattered Coral and Rock*.

Sand

Areas on the seafloor covered by coarse sediments (Figure 1.9). Particle sizes for these coarse sediments range from 0.0625 – 256 mm, including pebbles and cobbles (Wentworth 1922). This structure type is typically found in areas exposed to currents or moderate wave energy.

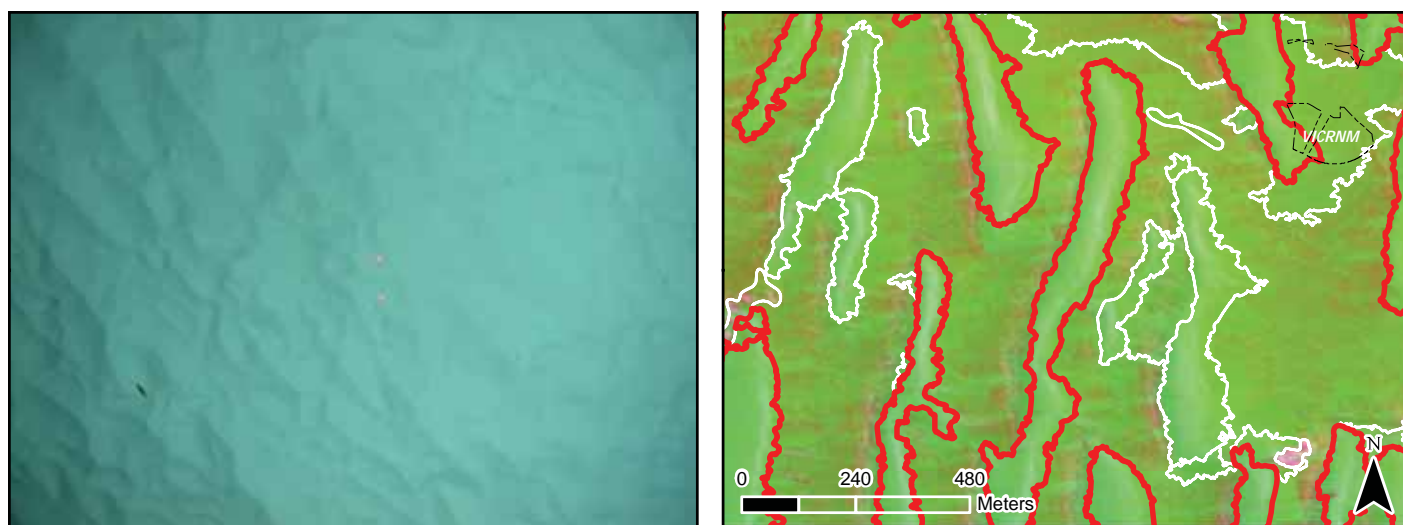


Figure 1.9. Underwater photograph (left) depicting the detailed structure type: *Sand*. Red polygons outline the features in the acoustic imagery (right).

Sand with Scattered Coral and Rock

Areas on the seafloor covered by sand, and $< 10\%$ of the entire polygon is covered by scattered rocks or isolated coral heads that are too small to be delineated individually (Figure 1.10). If the density of small coral heads is $\geq 10\%$ of the entire polygon, then the structure type is described as *Aggregated Patch Reefs*. If rhodoliths cover $\geq 10\%$ of the entire polygon, and $< 10\%$ of the entire polygon is covered by scattered rocks and isolated coral heads, then the structure type is described as *Rhodoliths with Scattered Coral and Rock*.

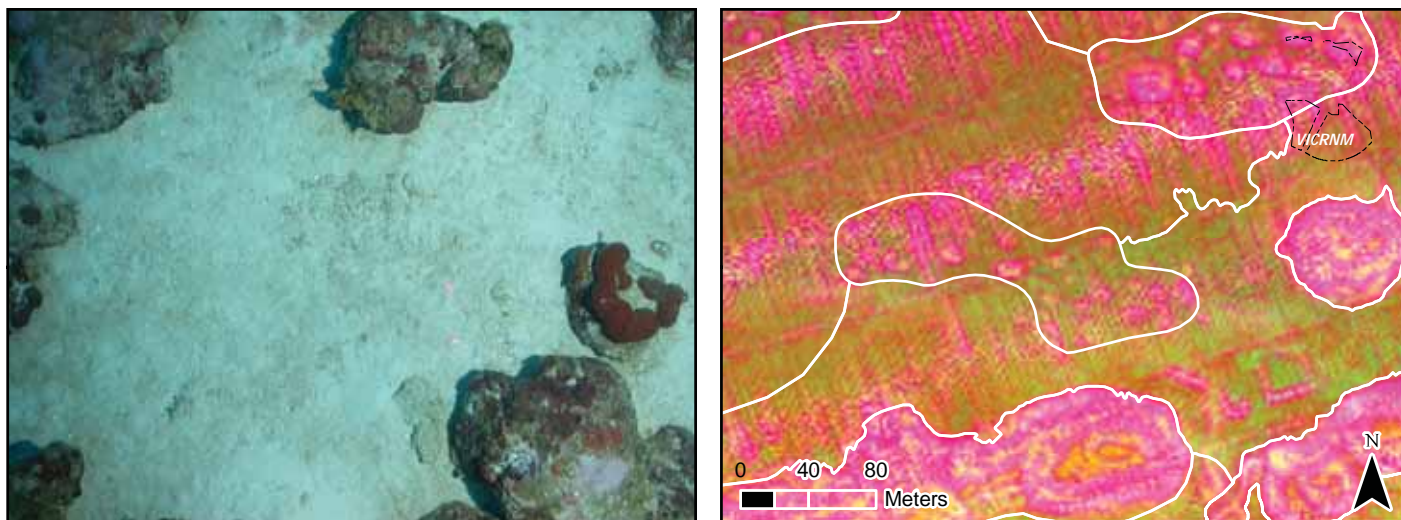


Figure 1.10. Underwater photograph (left) depicting the detailed structure type: *Sand with Scattered Coral and Rock*. A red polygon outlines the feature in the acoustic imagery (right).

Unknown

Major structure indistinguishable due to random or systematic noise in the bathymetry and/or backscatter, or other interference with an acoustic signature of the seafloor (Figure 1.11).

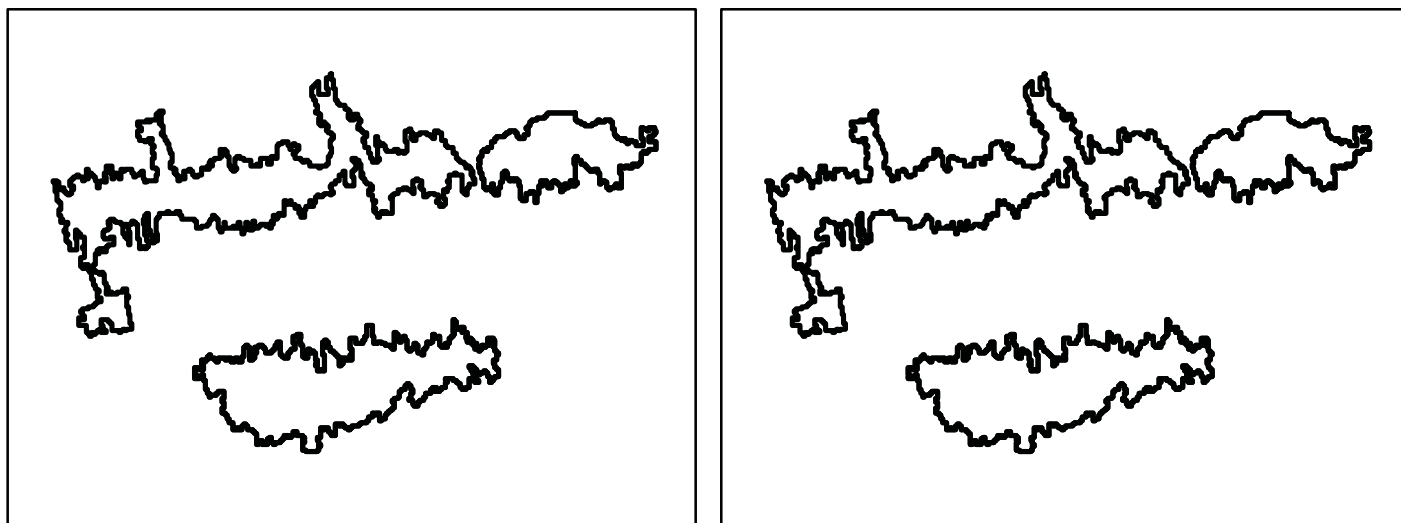


Figure 1.11. These red polygons are highlighting artifacts or noise in the acoustic imagery. This noise is depicted both in the intensity imagery (left) and the PCA imagery (right). This type of noise is akin to turbidity, wave action and/or sunglint in optical imagery, making it difficult for the cartographer to determine the habitat type underneath.

1.4 BIOLOGICAL COVER CLASSES

Five distinct and non-overlapping biological cover classes were mapped using a combination of semi-automated classification and visual interpretation of acoustic imagery. Cover classes refer to the dominant biological component colonizing the surface of the habitat feature, and does not address its location (e.g., on the *Bank/Shelf*). Habitat features that covered areas smaller than the MMU (1,000 m²) were not mapped independently. Biological cover types were grouped into five major classes (i.e., *Algae*, *Seagrass*, *Live Coral*, *No Cover* and *Unknown*), and were combined with a modifier describing the density and distribution of the dominant cover type within the habitat feature (i.e., 10%-<50%, 50%-<90%, and 90%-100%). It is important to emphasize that the percent biological cover modifier represents a combined measure of density at the scale of the 4 m² pixel and of patchiness at the scale of the ≥ 1,000 m² habitat feature. For example, a habitat feature defined as having 10%-50% biological cover may have continuous algal cover at low densities, or it may be covered by small, patchy areas of moderately dense algae scattered within large areas with no biological cover. Figures 1.12, 1.14 and 1.15 are helpful for understanding how density within a pixel and patchiness within a habitat feature affected the assignment of percent cover.

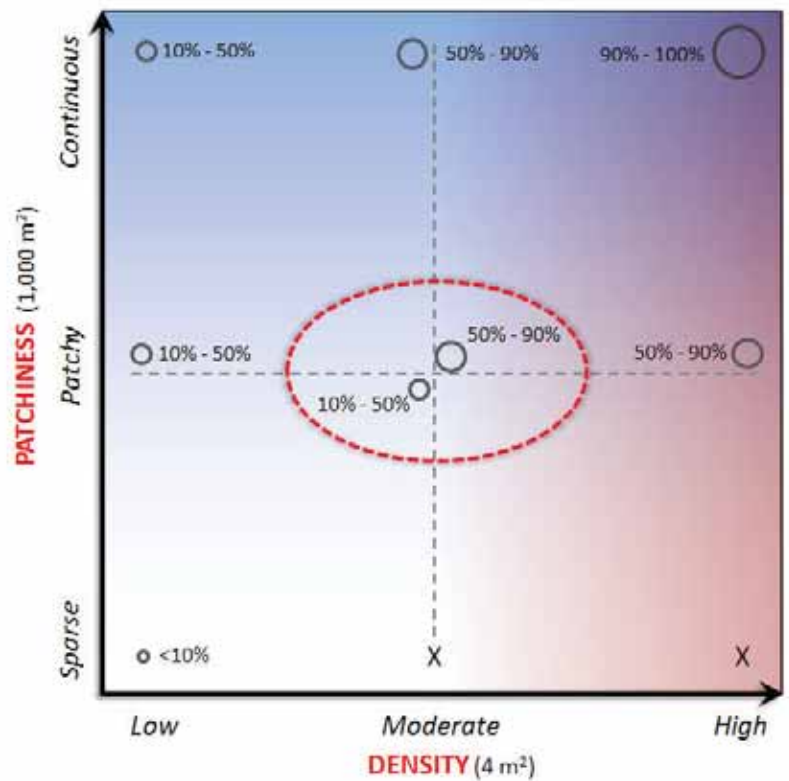


Figure 1.12. Graph denoting how the biological cover modifier represents a confounded measure of density at the scale of the 4 m² pixel and of patchiness at the scale of the ≥ 1,000 m² habitat feature. The dashed red circle in the middle denotes how the size of the patches of biological cover can influence whether a polygon is moved down into the 10% - 50% or up into the 50% - 90% category.

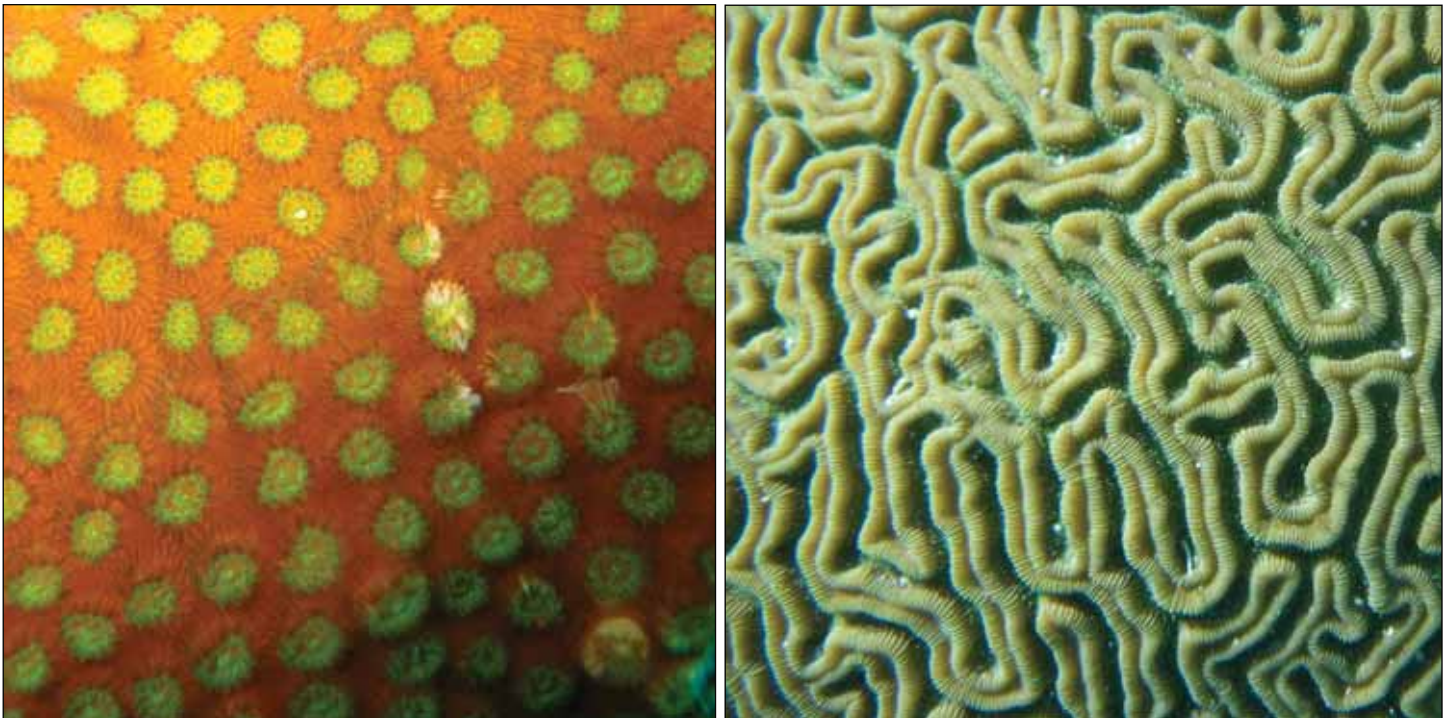


Figure 1.13. Underwater photographs of Lesser Starlet Coral (*Siderastrea radians*) (left) and Grooved Brain Coral (*Diploria labyrinthiformis*) (right).

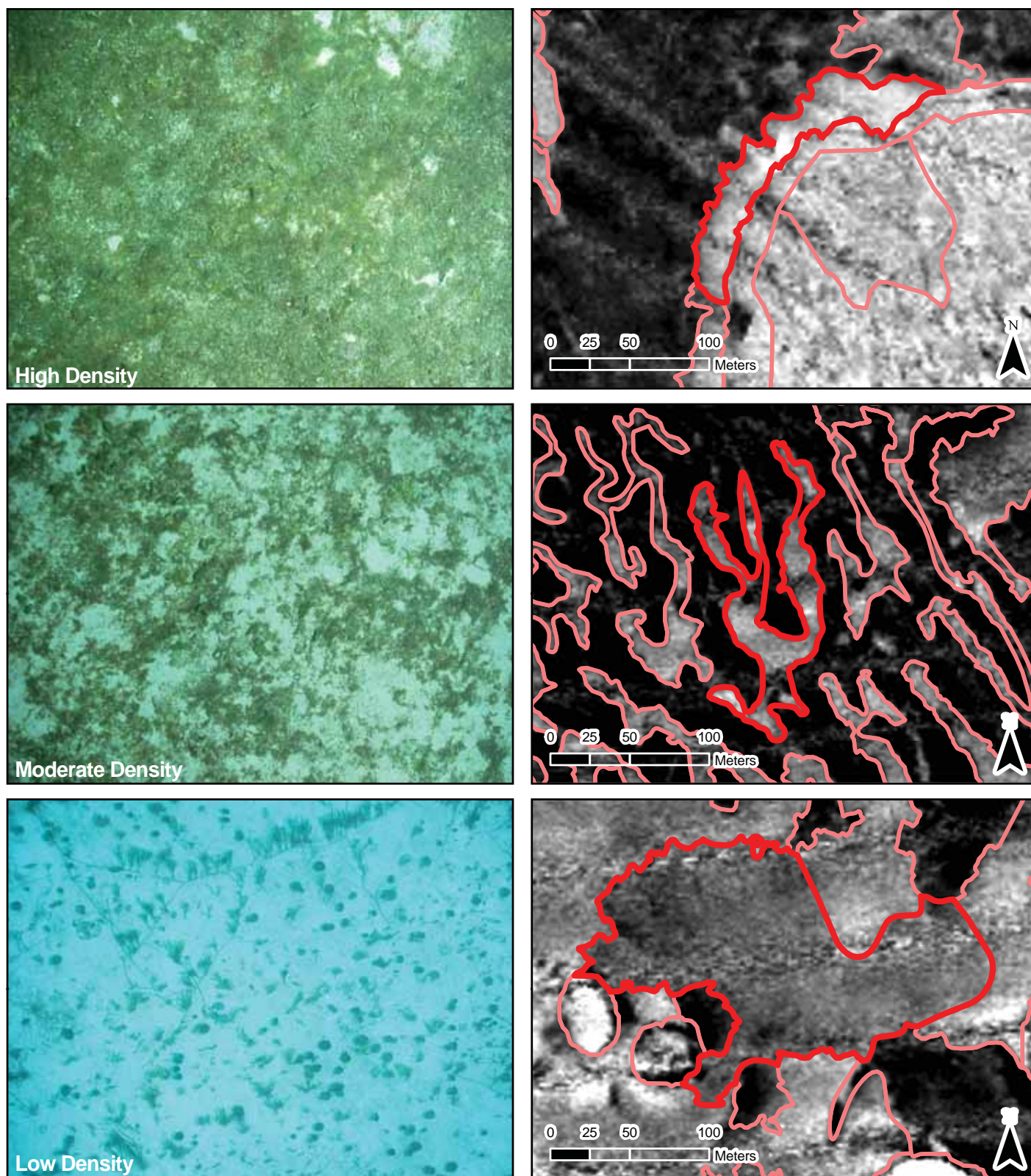


Figure 1.14. Underwater photos (left) and associated polygons highlighted in red (right) depicting the three different densities (high, moderate and low) of biological cover.

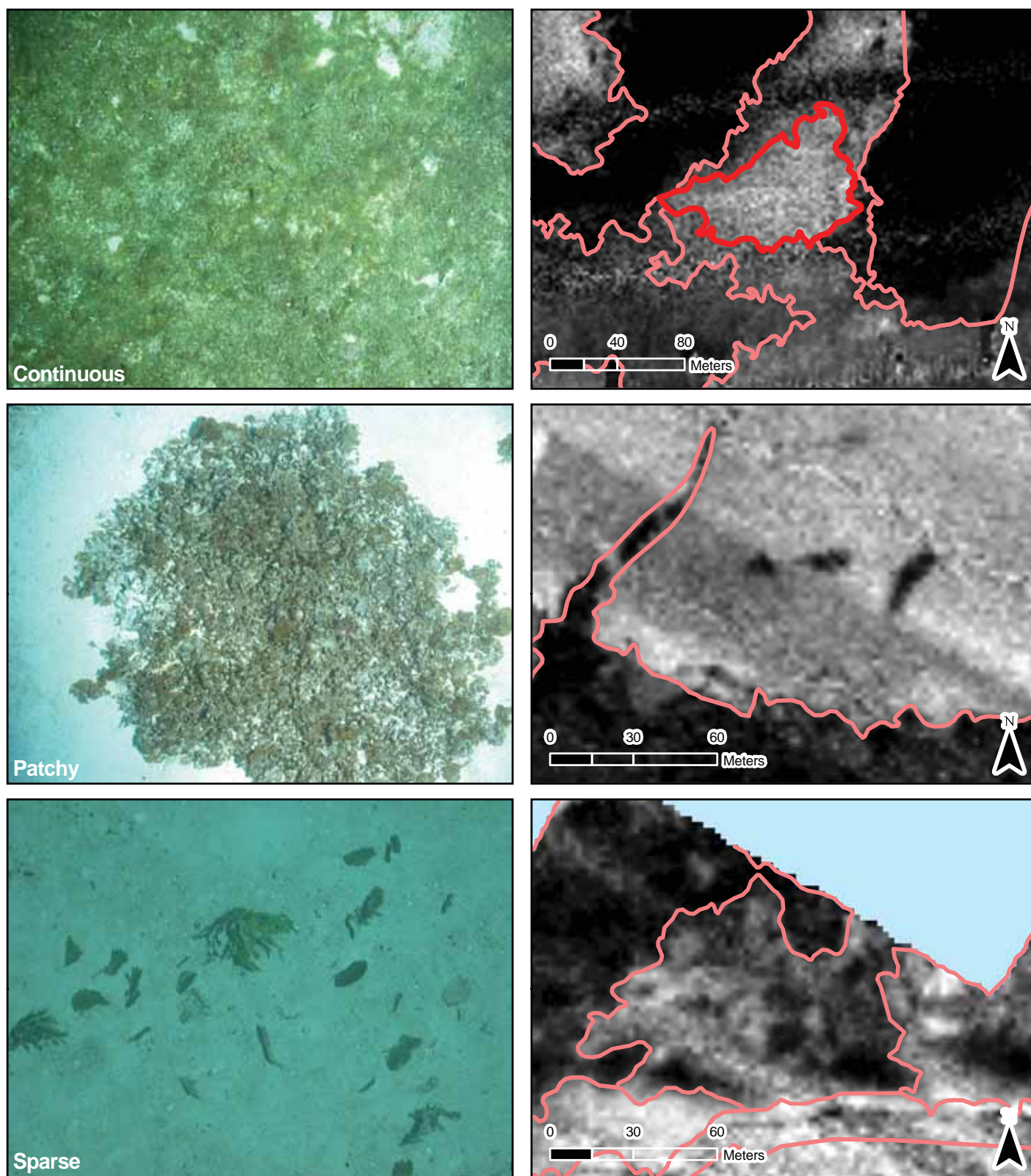


Figure 1.15. Underwater photos (left) and associated polygons highlighted in red (right) depicting the three different degrees (continuous, patchy and sparse) of biological cover patchiness.

Major Cover

Algae (1)

Substrates dominated by any combination of numerous species of red, green, or brown algae. These algae may be turf, fleshy, filamentous or crustose coralline species. This cover type occurs throughout many zones, especially on hard bottoms with low coral densities and soft bottoms in deeper waters on the *Bank/Shelf* zone. In some instances, habitat features with 10% - <50% *Algae* were attributed as such, albeit the habitat feature had more uncolonized area than colonized area. This 10% - <50% modifier was retained to explicitly denote that some *Algae* existed within a habitat feature (Figure 1.16).

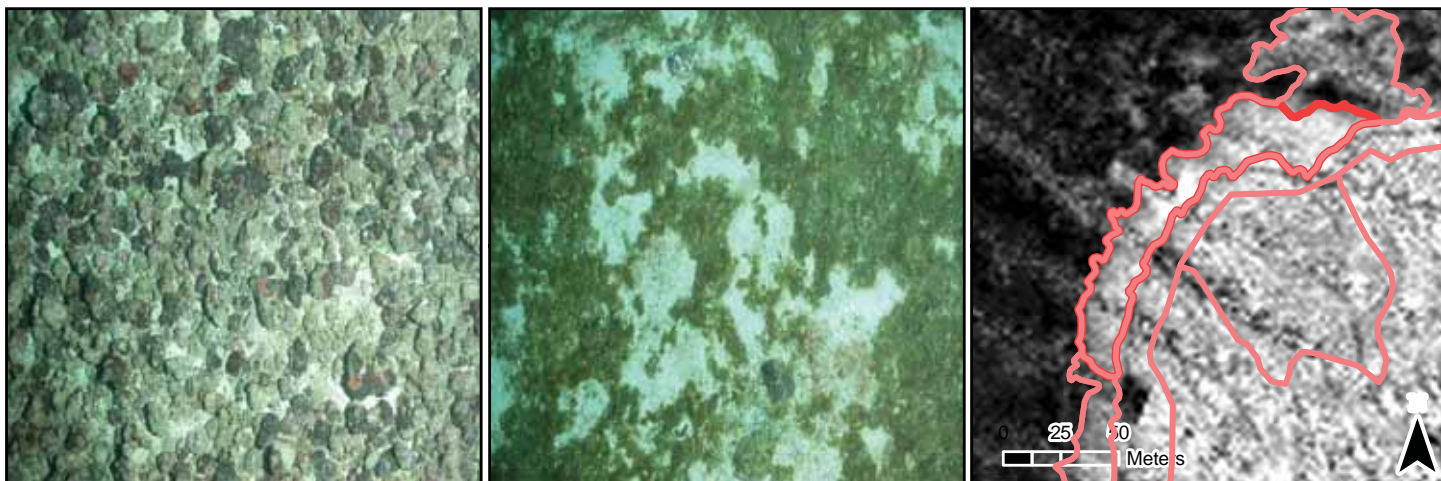


Figure 1.16. Underwater photographs depicting the major biological cover type: *Algae*. This class includes any combination of numerous species of turf, fleshy, filamentous or crustose coralline species. A red polygon outlines the feature in the acoustic imagery (right).

Seagrass (2)

Habitat dominated by any single species of seagrass (e.g. *Syringodium* sp., *Thalassia* sp., and *Halophila* sp.) or a combination of several species (Figure 1.17).



Figure 1.17. Underwater photographs depicting the major biological cover type: *Seagrass*. Turtle Grass (*Thalassia testudinum*) (left) and Manatee Grass (*Syringodium filiforme*) (middle) are both common in shallow-waters, but not in waters deeper than approximately 30 m. Red polygons outline the features in the acoustic imagery (right).

Live Coral (3)

Habitat dominated by live reef building corals, including scleractinian (e.g., *Acropora* sp.) and octocorals (e.g., *Briareum* sp.) (Figure 1.18).

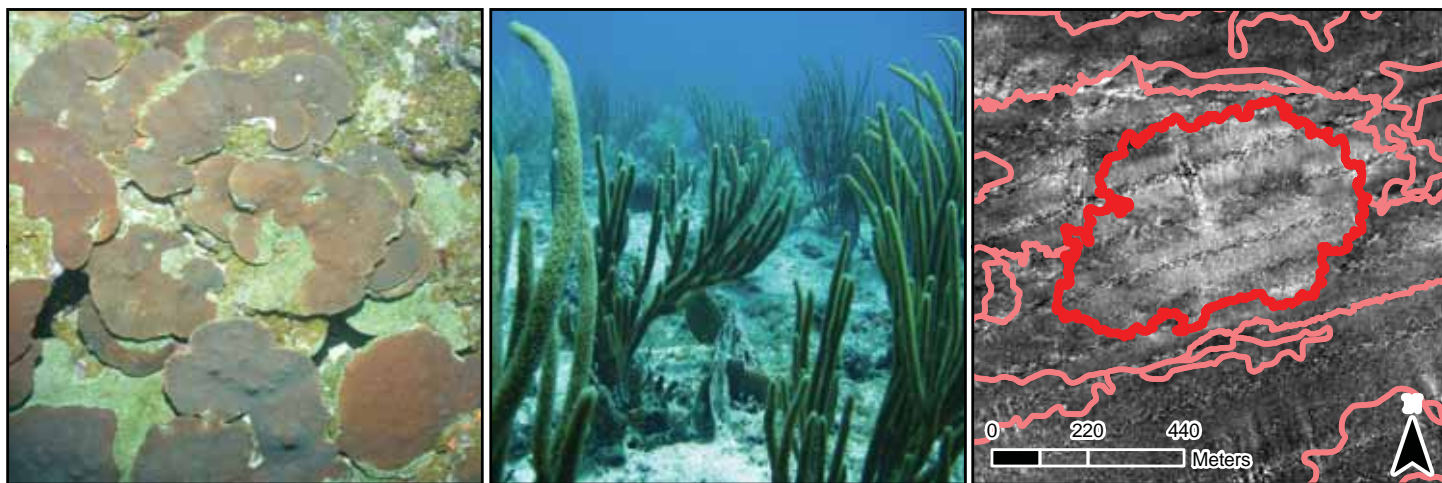


Figure 1.18. Underwater photographs depicting the major biological cover type: *Live Coral*. This biological cover type includes both scleractinian corals (left) and octocorals (middle). A red polygon outlines the feature in the acoustic imagery (right).

No Cover (4)

Substrates (usually *Sand*) covered with < 10% of any of the other biological cover types. In some instances, habitat features with 10% - <50% biological cover were attributed as such, albeit the habitat feature had more uncolonized area than colonized area. This 10% - <50% modifier was retained to explicitly denote that some biological cover existed within a habitat feature. The user may assume that the remainder of these polygons (50% - <90%) has no biological cover (Figure 1.19).

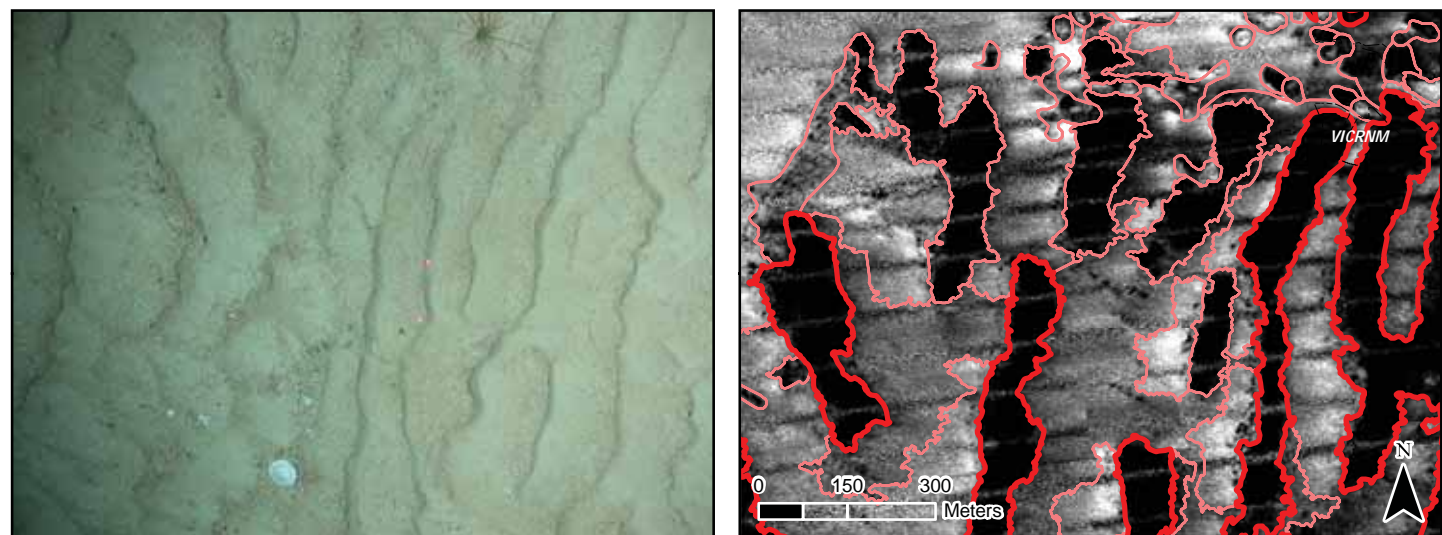


Figure 1.19. Underwater photographs depicting the major biological cover type: *No Cover*. Red polygons outline the features in the acoustic imagery (right).

Unknown (5)

Biological cover is indistinguishable due to random or systematic noise in the bathymetry and/or backscatter, or other interference with an acoustic signature of the seafloor.

Percent Major Cover

10% - <50% (1)

Continuous, low-density biological cover or patchy, moderate-density biological cover with uncolonized breaks in coverage that are too small (< 1,000 m²) to be mapped as discrete habitat features. These uncolonized areas make up 90% or less of the habitat feature's total area. The overall combined density/patchiness of the major biological cover type is estimated to be 10% - <50% of the polygon feature (Figures 1.14 and 1.15).

50% - <90% (2)

Continuous, moderate-density biological cover or patchy, high-density biological cover with uncolonized breaks in coverage that are too small (< 1,000 m²) to be mapped as discrete habitat features. These uncolonized areas make up 50% or less of the habitat feature's total area. The overall combined density/patchiness of the major biological cover type is estimated to be 50% - <90% of the polygon feature (Figures 1.14 and 1.15).

90% - 100% (3)

Continuous, high-density biological cover with uncolonized breaks in coverage that are too small (< 1,000 m²) to be mapped as discrete habitat features. These small uncolonized areas make up 10% or less of the habitat feature's total area. The overall combined density/patchiness of the major biological cover type is estimated to be 90% - 100% of the polygon feature (Figures 1.14 and 1.15).

Unknown (4)

Percent estimate of the biological cover is indistinguishable due to random or systematic noise in the bathymetry and/or backscatter, or other interference with an acoustic signature of the seafloor.

1.5. LIVE CORAL COVER CLASSES

Four distinct and non-overlapping percent live coral classes were mapped using a combination of semi-automated classification and visual interpretation of acoustic imagery. This attribute is an additional biological cover modifier used to denote information about the percent cover of live coral (both scleractinian and octocorals) (Figure 1.20), when it was not the dominant cover type. In order to provide resource managers with additional information about corals, four range classes were used (0% - <10%, 10% - <50%, 50% - <90%, and 90% - 100%). Unlike the biological cover modifier, live coral cover simply describes the density of coral on hardbottom features at the 4 m² pixel scale. It does not denote patchiness of coral at the scale of the habitat feature. For this reason, extensive *in situ* data is critical to correct attribution of the live coral cover modifier. As a result of these varying scales of interpretation, the percent biological cover and percent live coral cover modifiers are not additive properties within the same mapping unit. In many cases, they will sum to greater than 100%. For example, an *Aggregate Reef* may be covered by *Algae* 90% - 100%, as well as have 10% - <50% coral densities at the fine-scale.



Figure 1.20. Both scleractinian (hard) corals (left) and octocorals (soft) corals (right) are aggregated together when classifying live coral cover. Typical corals of St. John include the scleractinian boulder coral (*Montastraea annularis*) and several octocorals including sea fans (*Gorgonia* sp.).

0% - <10% (1)

Live coral covering of less than 10% of the seafloor at the 4 m² pixel scale (Figure 1.21).

10% - <50% (2)

Live coral covering 10% to 50% of the seafloor at the 4 m² pixel scale (Figure 1.22).

50% - <90% (3)

Live coral covering 50% to 90% of the seafloor at the 4 m² pixel scale (Figure 1.23).

90% - 100% (4)

Continuous live coral covering 90% or more of the seafloor at the 4 m² pixel scale.

Unknown (5)

Percent estimate of coral cover is indistinguishable due to random or systematic noise in the bathymetry and/or backscatter, or other interference with an acoustic signature of the seafloor.

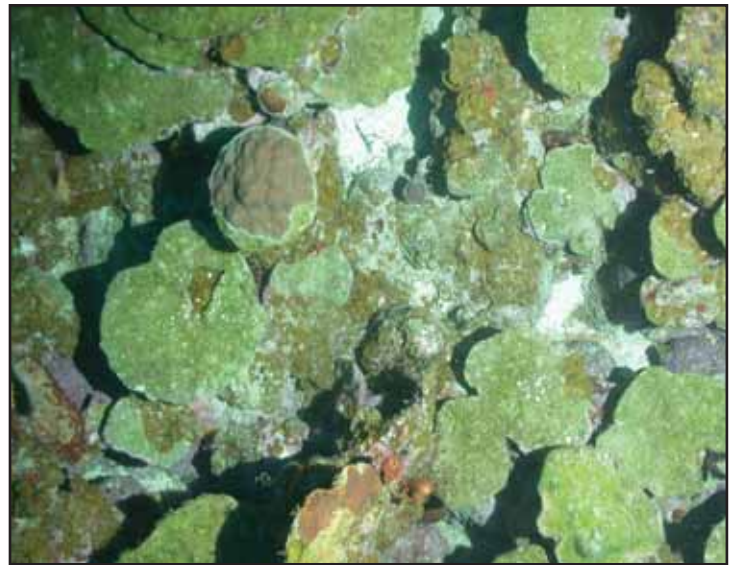


Figure 1.21. Photograph depicting the presence of live coral in the 0% - 10% cover range.

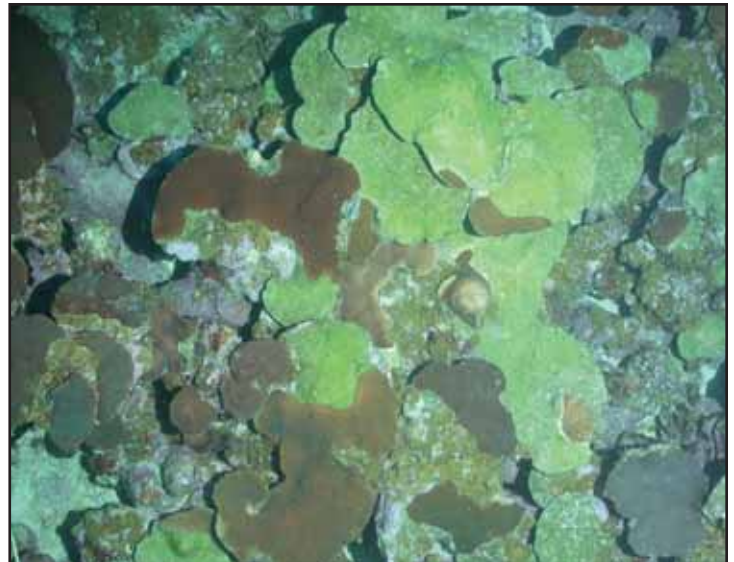


Figure 1.22. A photograph depicting the presence of live coral in the 10% - 50% cover range.

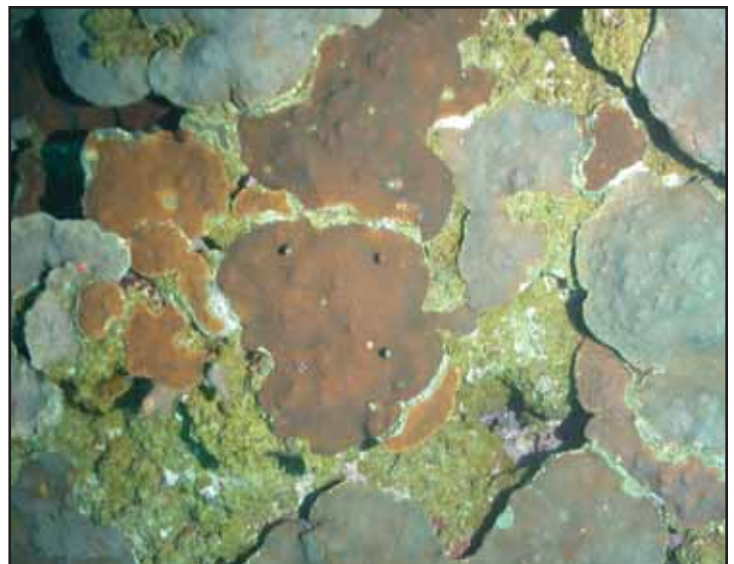


Figure 1.23. A photograph depicting the presence of live coral in the 50% - 90% cover range.

LITERATURE CITED

Foster, M.S. 2001. Rhodoliths: Between Rocks and Soft Places. *Journal of Phycology*. 37, 659-667.

Kendall, M.S., C.R. Kruer, K.R. Buja, J.D. Christensen, M. Finkbeiner, R.A. Warner and M.E. Monaco. 2001. Methods Used to Map the Benthic Habitats of Puerto Rico and the U.S. Virgin Islands. NOAA Technical Memorandum NOS NCCOS CCMA 152. Silver Spring, MD.

Wentworth, C.K. 1922. A Scale of Grade and Class Terms for Clastic Sediments. *Journal of Geology*. 30 (5): 377-392.

Zitello, A.G., L.J. Bauer, T.A. Battista, P.W. Mueller, M.S. Kendall and M.E. Monaco. 2009. Benthic Habitats of St. John, U.S. Virgin Islands. NOAA Technical Memorandum NOS NCCOS 96. Silver Spring, MD. 53 pp.

This page intentionally left blank.

CHAPTER 2: BENTHIC HABITAT MAP CREATION

Benthic habitats of the moderate-depth marine environment in and around the Virgin Islands Coral Reef National Monument were mapped using a combination of semi-automated classification and visual interpretation of acoustic imagery. Acoustic imagery has been successfully used to derive the location, extent and attributes of marine habitats (Prada et al., 2008; Kendall et al., 2005; Kostylev et al., 2001). NOAA scientists were able to accurately and reliably delineate the boundaries of features in the imagery using a combination of Geographic Information System (GIS) and remote sensing software. Field investigations were conducted on

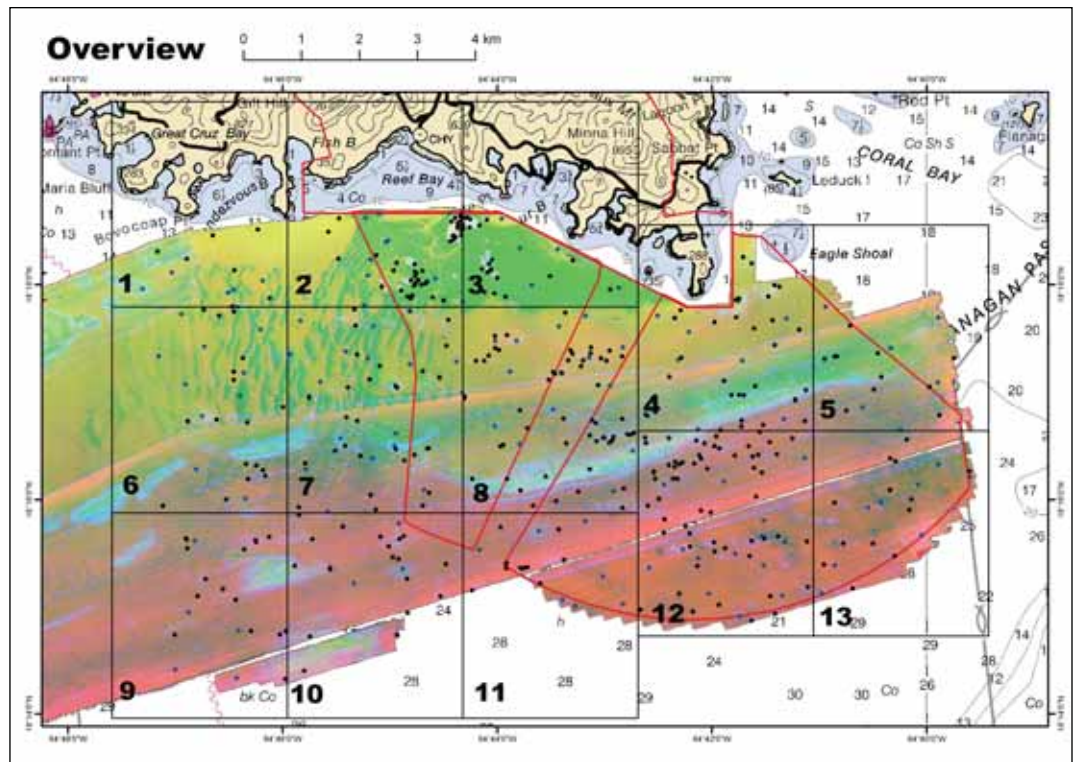


Figure 2.1. Laminated maps were used in the field to help keep track of which drop camera points had already been collected.

both small and large vessels in order to understand and validate the acoustic signatures created by habitat features on the seafloor (Figure 2.1). Spatially and thematically accurate habitat maps were developed using this process, providing researchers and natural resource managers with a quantitative understanding of the benthic resources in and around the VICRNM.

2.1 GENERAL MAPPING APPROACH

NOAA's approach to moderate-depth benthic habitat mapping was a six-step process:

1. **Imagery Acquisition and Processing** – The first step in this process was to acquire and process high-resolution acoustic imagery. Acoustic imagery was collected during two separate years, in order to map the full geographic extent of the VICRNM's southern boundaries. Several metrics were derived from the depth imagery, in order to describe the complexity of the seafloor in different ways. Principal components analysis was then used to reduce the redundancy of information contained in these metrics.
2. **Habitat Boundary Delineation** – A first draft benthic habitat map was generated using edge detection algorithms to delineate features on the seafloor with discrete acoustic signatures. During the creation of this first draft map, the cartographer placed discrete points on features in the map that had unknown acoustic signatures. Points were also placed on features with known acoustic signatures (evenly distributed throughout the geographic extent of the map) to confirm that the habitats associated with these signatures remained consistent through the area of interest. These two types of points were labeled as "ground validation" sites and were visited in the field.
3. **Ground Validation (GV)** – NOAA scientists explored these ground validation locations using two different sampling techniques and two different pieces of equipment. Specifically, underwater video was collected along 13 transects using a remotely operated vehicle (ROV), and at 117 discrete points using a manually operated drop camera. The resulting GPS and video information was processed, analyzed and used to train the classification algorithm that was used to generate the second draft map.

4. **Habitat Classification** – A CART-like (Classification and Regression Tree) algorithm was used to classify each habitat feature delineated by the edge-detection algorithms described in step 2. To simplify this classification process, coral reef habitat features, and soft bottom and rhodolith habitat features were classified separately. The classification algorithm separated these two habitat feature types into different major and detailed structure, biological cover and lives coral classes. The two, resulting classifications were merged together and manually edited to create a final seamless habitat map.
5. **Accuracy Assessment (AA)** – AA sites were generated using a stratified random sampling design (based on detailed structure type) that allowed for a statistically rigorous assessment of map accuracy. Underwater video was collected at these 299 sites using a manually operated drop camera.
6. **Final Product Creation** – A final benthic habitat map for the VICRNM was generated by correcting inaccuracies identified by the accuracy assessment. Additionally, all associated datasets, including GIS files, field video and metadata were packaged and provided to project partners.

2.2 REMOTELY SENSED IMAGERY

Multibeam (MBES) Sound Navigation and Ranging (SoNAR) sensors actively emit sound to measure the depth, hardness/softness and roughness/smoothness of the seafloor (Figure 2.2). Depth is measured by determining the time required for an individual ping of sound to travel from the sensor to the seafloor and back again. These individual measurements were used to create seamless images of the seafloor's depth, which will be referred to hereafter as "bathymetry" (Figure 2.3). Hardness/softness and roughness/smoothness are measured by calculating the intensity of an individual ping of sound scattered from the seafloor. These individual measurements were used to create continuous images of the seafloor's physical structure, which will be referred to hereafter as "intensity" (Figure 2.3). The resulting acoustic images (i.e., bathymetry and intensity) are valuable tools for natural resource managers and researchers because they provide baseline information on the location and extent of seafloor habitats in turbid waters and in deep waters beyond the limits of optical imagery (i.e., approximately 30 m).

Acquisition Of Remotely Sensed Imagery

Acoustic imagery was acquired for the southern VICRNM boundaries on two separate missions onboard the NOAA ship, *Nancy Foster* (Figure 2.4). The first mission took place from 2/18 to 3/5/2004, and the second mission took place from 2/1 to 2/12/2005. On both missions, seafloor depths between 14 to 55 m were mapped using a RESON SeaBat 8101 ER (240 kHz) MBES sensor (Figure 2.5). This pole-mounted system measured water depths across a 150° swath consisting of 101 individual 1.5° x 1.5° beams. The vessel survey speed was between 5 and 8 knots. In 2004, the ship's location was determined by a Trimble DSM 132 DGPS system, which provided a RTCM differential data stream from the U.S. Coast Guard Continually Operating Reference Station (CORS) at Port Isabel, Puerto Rico. Gyro, heave, pitch and roll correctors were acquired using an Ixsea Octans gyrocompass. In 2005, the ship's positioning and orientation were determined by the Applanix POS/MV 320 V4, which is a GPS aided Inertial Motion Unit (IMU) providing measurements of roll, pitch and heading. The POS/MV obtained its positions from two dual frequency Trimble Zephyr GPS antennae. An auxiliary Trimble DSM 132 DGPS system provided a RTCM differential data stream from the U.S. Coast Guard CORS at Port Isabel, Puerto Rico. For both years, CTD (conductivity, temperature and depth) measurements were taken approximately every 4 hours using a Seabird Electronics SBE-19 to correct for changing sound velocities in the water column. In 2004,

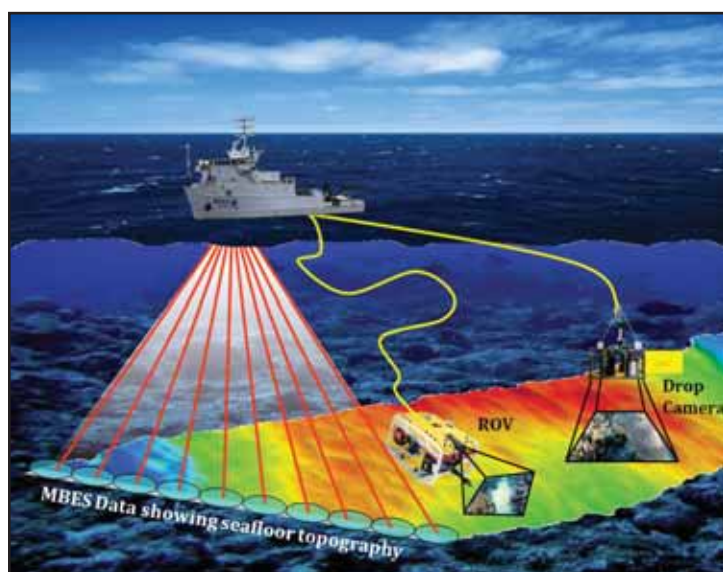


Figure 2.2. Diagram illustrating the collection of data for moderate-depth habitat mapping. The acoustic imagery and underwater video datasets are integrated to create a final map product.

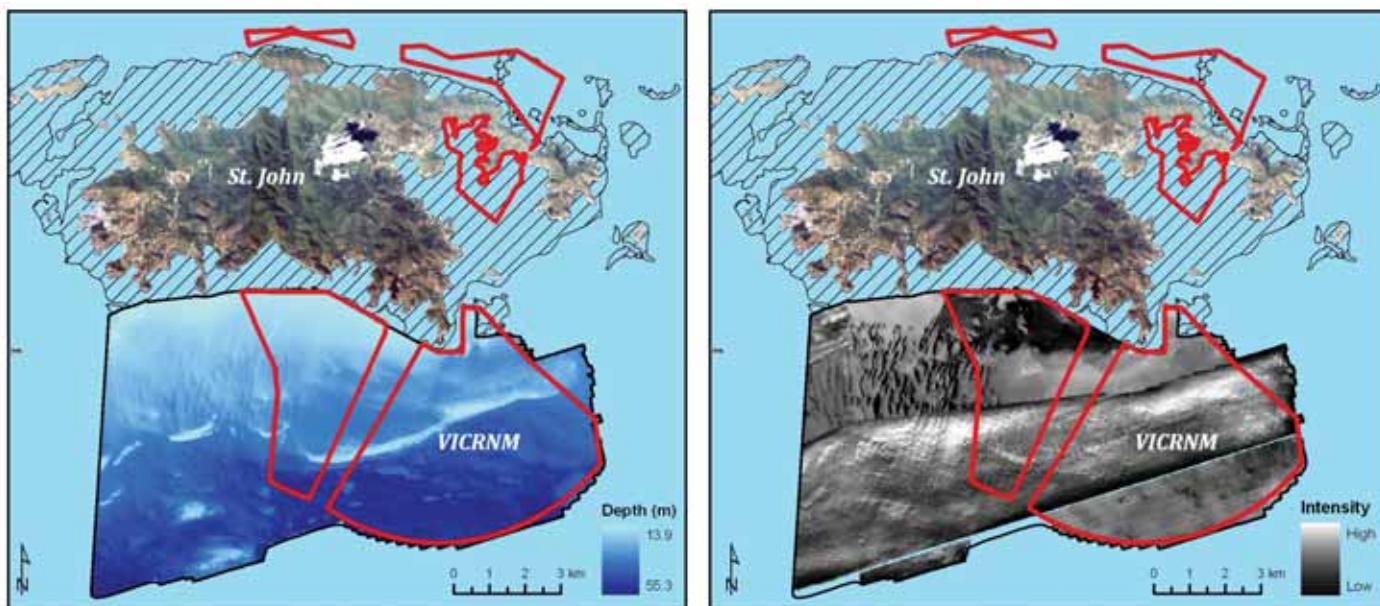


Figure 2.3. These maps depict the two types of imagery (i.e., bathymetry and intensity) collected using an MBES sensor. The bathymetry or depth surface (left) was measured by determining the time required for an individual ping of sound to travel from the sensor to the seafloor and back again. The backscatter or intensity surface (right) was determined by measuring the strength of an individual ping of sound scattered from the seafloor. The black hatched polygon denotes the area mapped using optical imagery. The red polygons show the boundaries of the VICRNM.

raw data were referenced to the WGS84 UTM 20 N horizontal coordinate system, and were logged in .xtf (extended triton format) using Triton ISIS® software 6.2. In 2005, raw data were referenced to the NAD83 UTM 20 N horizontal coordinate system, and were logged in .gsf (generic sensor format) using SAIC ISS 2000 software. Data for both years were referenced to the Mean Lower Low Water (MLLW) vertical tidal coordinate system. For a complete description of the data acquisition and processing parameters, please see the data acquisition and processing reports (DAPRs) for projects: NF-04-06-VI and NF-05-05-USVI (Monaco and Rooney, 2004; Battista and Lazar, 2005).

Processing Of Remotely Sensed Imagery

Creating Bathymetry and Intensity Surfaces

The 2004 and 2005 MBES bathymetric data were corrected for sensor offsets, latency, roll, pitch, yaw, static draft, the changing speed of sound in the water column and the influence of tides in CARIS Hips and Sips 5.3 and 5.4, respectively. The 2004 data was then binned to create a 1 x 1 m raster surface, and the 2005 data was binned to create a 2 x 2 m raster surface. After these final surfaces were created, the datum for the 2004 bathymetric surfaces was transformed from WGS84 to NAD83 using the “Project Raster” function in ArcGIS 9.1. The 2004 surface was transformed so that it would have the same datum as the 2005 surface. The 2004 bathymetric surface was then down sampled from 1 x 1




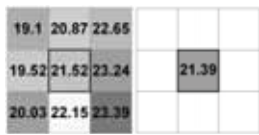
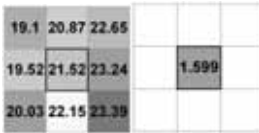
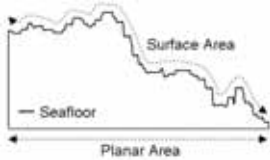




Figure 2.4. The NOAA ship *Nancy Foster* was used to acquire MBES imagery and ROV data during two, two week missions in 2004 and 2005.



Figure 2.5. The RESON SeaBat 8101 ER (240 kHz) MBES sensor was pole-mounted on the NOAA ship *Nancy Foster* during two, two week missions in 2004 and 2005. It was used to collect MBES bathymetry and intensity imagery.

Table 2.1. Descriptions of the morphometrics used to characterize the complexity of the seafloor in and around VICRNM. The GIS tools used to derive these metrics from the MBES bathymetry surface are also included in the table below.

DATASET	UNIT	DESCRIPTION	TOOL
Curvature		1/100 z units – = concave + = convex	Rate of change in curvature across the surface highlighting ridges, crests and valleys (3 x 3 cell neighborhood)
Plan Curvature		1/100 z units – = concave + = convex	Curvature of the surface perpendicular to the slope direction (3 x 3 cell neighborhood)
Profile Curvature		1/100 z units – = convex + = concave	Curvature of the surface in the direction (3 x 3 cell neighborhood)
Depth (Mean)		Meters	Average water depth (3 x 3 cell neighborhood)
Depth (Standard Deviation)		Meters	Dispersion of water depth values about the mean (3 x 3 cell neighborhood)
Surface rugosity		Ratio value	Ratio of surface area to planar area (3 x 3 cell neighborhood)
Slope		Degrees	Maximum rate of change in slope between cell and 8 neighbors (3 x 3 cell neighborhood)
Slope of the slope		Degrees of degrees	Maximum rate of maximum slope change between cell and eight neighbors (3 x 3 cell neighborhood)

to 2 x 2 m using the “Resample” function in ArcGIS 9.1. The 2004 surface was resampled so it would have the same spatial resolution as the 2005 surface. Having the same coordinate systems and spatial resolutions, the final 2004 and 2005 bathymetry rasters were then merged using the Raster Calculator function “Merge” in ArcGIS’s Spatial Analyst Extension to create a seamless bathymetry surface for the entire VICRNM area south of St. John.

The 2004 and 2005 MBES intensity data were received as raw.tif and .gsf files (respectively), which recorded the uncorrected intensity value from each snippet (i.e., from each beam of sound for each ping of sound). The .tif and .gsf files were geometrically and radiometrically corrected using Geocoder 3.0 (Fonseca and Calder, 2005). In particular, the intensity surface was geometrically corrected for navigation attitude, transducer attitude and slant range distortion using the MBES bathymetric surface. It was radiometrically corrected for changes in acquisition gains, power levels, pulse widths, incidence angles and ensonification areas. All snippets were preserved during these corrections, allowing the full resolution data to be used to create the final mosaic. Systematic noise in 2004 intensity mosaic was then filtered in frequency space using the “fast Fourier transformation” (Mather 2004; Lillesand and Kiefer, 2000) function in ENVI 4.5. The final 2004 and 2005 intensity rasters were converted to relative 8-bit (0 – 255) values, since neither intensity surface was calibrated. These 8-bit images were then color balanced and merged using ENVI’s “Mosaicing (Georeferenced)” function to create a seamless intensity surface of the entire VICRNM area south of St. John.

Creating Derivative Surfaces

A suite of eight metrics were derived from the final, merged bathymetry surface, in order to characterize the complexity and structure of the seafloor. These metrics specifically included: (1) mean depth, (2) standard deviation of depth, (3) curvature, (4) plan curvature, (5) profile curvature, (6) rugosity, (7) slope, and (8) slope of slope. Each of these metrics was calculated using a square 3 x 3 cell neighborhood, where the central pixel in the neighborhood was assigned the calculated value. These metrics are described in more detail in Table 2.1.

These eight complexity surfaces were subsequently stacked, and exported to create one image with several different bands (each band representing a specific metric). This image was then transformed into its first three principal components using the “Principal Components Analysis” (PCA) (Mather 2004; Lillesand and Kiefer, 2000) function in ENVI 4.6. This transformation reduced the dimensionality of the dataset by removing information that was redundant across the different bands. The resulting three band PCA image only contained information that uniquely described the complexity and structure of the seafloor (Table

Table 2.2. The amount (%) of variance in a principal component that is explained by a single complexity surface. For example, the bathymetry surface contributed 11.1%, 5.7% and 22.5% of the information contained in the transformed image’s first, second and third principal components, respectively.

	PC NUMBER		
	1	2	3
Bathymetry	11.1	5.7	22.5
Bathymetry (Mean)	11.1	5.7	22.3
Bathymetry (Stdev)	11.1	5.4	35.7
Curvature	11.1	5.5	2.2
Curvature (Plan)	11.1	5.5	2.3
Curvature (Profile)	11.1	5.5	0.3
Rugosity	11.1	22.1	2.8
Slope	11.1	22.1	2.3
Slope of Slope	11.1	22.5	9.6

2.2). It is important to note that each metric contributed equally to the information contained in the first principal component. Rugosity and slope explained the most amount of the variance contained in the second principal component. The three flavors of bathymetry (i.e., depth, mean depth, and standard deviation of depth) explained the most amount of the variance contained in the third principal component. Each of these three bands were converted from 16-bit, floating point values to 8-bit, integer values, so that they could be imported into ENVI

Zoom 4.6

2.3 HABITAT BOUNDARY DELINEATION AND CLASSIFICATION

The majority of shallow-water coral reef habitats have been successfully characterized at high thematic resolutions (≤ 32 classes) by conducting heads-up digitizing and interpretation of high resolution ($\leq 4 \times 4$ m) imagery (Kendall et al., 2001; Battista et al., 2007^a; Battista et al., 2007^b). These resulting maps, however, are time-intensive to produce, limited by the size of the minimum mapping unit, and ultimately subjective and irreproducible because they depend on the accuracy and interpretation of the person that is digitizing.

In order to address these difficulties and increase the repeatability and efficiency with which maps are produced, the Biogeography Branch has been experimenting with alternative techniques to automate the process of delineating and attributing features on the seafloor. This moderate-depth map represents the Biogeography Branch's first attempt to create a benthic habitat map from acoustic imagery using this new semi-automated methodology. This method specifically employs a combination of object and pixel-based classification techniques to delineate and classify benthic habitat features. This process is described in a general way in Figure 2.6, and in more detail in the following paragraphs.

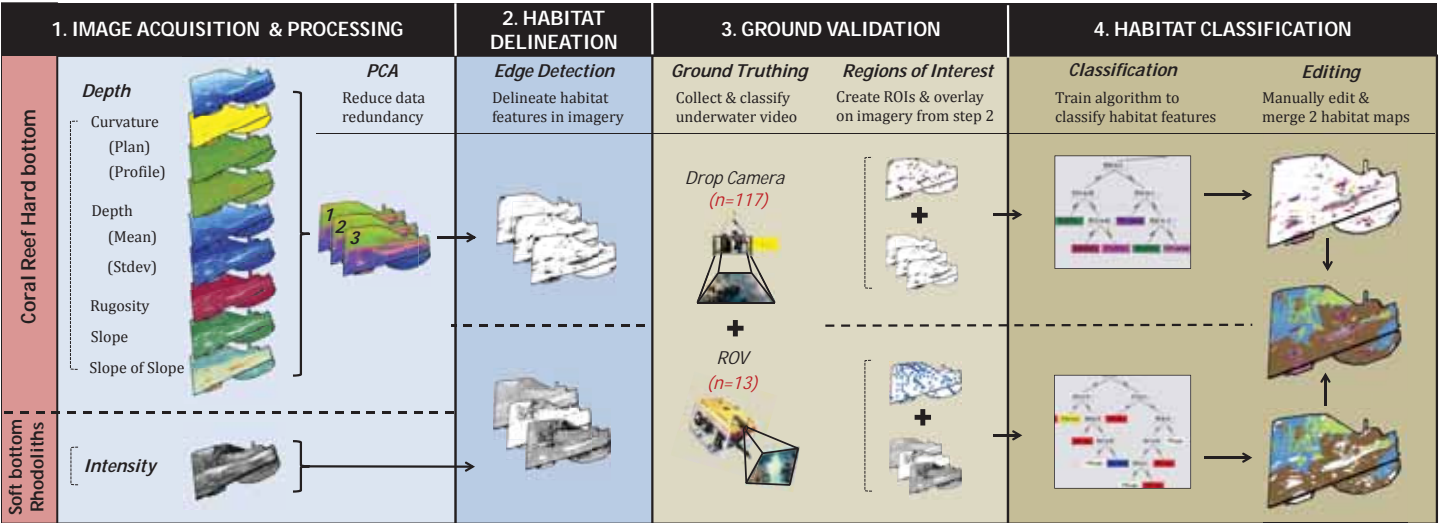


Figure 2.6. Diagram illustrating the process used to create the moderate-depth benthic habitat south of St. John.

Results from this new mapping approach suggest that it is 7x more time efficient than heads-up habitat delineation and attribution. Additionally, less than 40% of the polygons created using the semi-automated method were manually edited, indicating that the majority of the moderate-depth map produced using this method is completely reproducible. These initial results indicate that this new semi-automated approach has the potential to increase the repeatability and efficiency with which maps are produced.

Habitat Delineation

Habitat features on the seafloor were identified and extracted using ENVI Zoom 4.6 Feature Extraction (Fx) Module. This module uses edge detection algorithms to detect and delineate objects in a single image or in a suite of spatially coincident images. An object is defined as a region of interest with unique spatial, spectral (brightness and color), and/or textural characteristics that make it visually distinct from its surroundings (ITT VIS, 2008^a). There are four steps involved in extracting discrete objects from an image (or images). These steps specifically include: (1) segmenting the image, (2) merging smaller segments into larger objects, and (3) computing spatial, spectral, textual and custom attributes for each object. The first two steps are interactive, allowing the user to adjust the input parameters to extract the features in which they are most interested. In particular, step 1 allows the user to alter the “scale level” of the edge detection algorithm to determine the size of the objects to be extracted. Choosing a higher scale level (>75) causes a smaller number of larger segments to be defined, while choosing a lower scale level (<25) causes a greater number of smaller segments to be defined (ITT VIS, 2008^b). Step 2 allows the user to alter the “merge level” of the algorithm and to merge smaller segments into larger objects. Choosing a higher merge level (>75) causes segments with faded or faint edges to be merged, while choosing a lower merge level (<25) preserves more of these features with faded or faint edges (ITT VIS, 2008^b; Robinson et al., 2002). In step 3, ENVI Fx computes 14 spatial metrics, 4 textual metrics, 1 band ratio metric, 3 hue, saturation and intensity (HSI) metrics and 4 spectral metrics (for each input band) for each distinct object. These different

Table 2.3. Descriptions of the spatial metrics calculated by ENVI Fx for each habitat polygon identified during the edge-detection process (ITT VIS, 2008^b).

ATTRIBUTE	DESCRIPTION	FORMULA
AREA	Total area of the polygon, minus the area of the holes. Values are in map units.	-
LENGTH	The combined length of all boundaries of the polygon, including the boundaries of the holes. This is different than the MAXAXISLEN attribute. Values are in map units.	-
COMPACT	A shape measure that indicates the compactness of the polygon. A circle is the most compact shape with a value of $1 / \pi$. The compactness value of a square is $1 / 2(\sqrt{\pi})$.	$= \text{Sqrt}(4 * \text{AREA} / \pi) / \text{outer contour length}$
CONVEXITY	Polygons are either convex or concave. This attribute measures the convexity of the polygon. The convexity value for a convex polygon with no holes is 1.0, while the value for a concave polygon is less than 1.0.	$= \text{length of convex hull} / \text{LENGTH}$
SOLIDITY	A shape measure that compares the area of the polygon to the area of a convex hull surrounding the polygon. The solidity value for a convex polygon with no holes is 1.0, and the value for a concave polygon is less than 1.0.	$= \text{AREA} / \text{area of convex hull}$
ROUNDNESS	A shape measure that compares the area of the polygon to the square of the maximum diameter of the polygon. The "maximum diameter" is the length of the major axis of an oriented bounding box enclosing the polygon. Circle = 1 and square = $4/\pi$.	$= 4 * (\text{AREA}) / (\pi * \text{MAXAXISLEN}^2)$
FORMFACTOR	A shape measure that compares the area of the polygon to the square of the total perimeter. The form factor value of a circle is 1, and the value of a square is $\pi / 4$.	$= 4 * \pi * (\text{AREA}) / (\text{total perimeter})^2$
ELONGATION	A shape measure that indicates the ratio of the major axis of the polygon to the minor axis of the polygon. The major and minor axes are derived from an oriented bounding box containing the polygon. Square = 1 and Rectangle > 1.	$= \text{MAXAXISLEN} / \text{MINAXISLEN}$
RECT_FIT	A shape measure that indicates how well the shape is described by a rectangle. This attribute compares the area of the polygon to the area of the oriented bounding box enclosing the polygon. Rectangle = 1 and non-rectangle < 1.	$= \text{AREA} / (\text{MAXAXISLEN} * \text{MINAXISLEN})$
MAINDIR	The angle subtended by the major axis of the polygon and the x-axis in degrees. The main direction value ranges from 0 to 180 degrees. 90 degrees is North/South, and 0 and 180 degrees is East/West.	-
MAJAXISLEN	The length of the major axis of an oriented bounding box enclosing the polygon. Values are map units of the pixel size. If the image is not georeferenced, then pixel units are reported.	-
MINAXISLEN	The length of the minor axis of an oriented bounding box enclosing the polygon. Values are map units of the pixel size. If the image is not georeferenced, then pixel units are reported.	-
NUMHOLES	The number of holes in the polygon. Integer value.	-
HOLESOLRAT	The ratio of the total area of the polygon to the area of the outer contour of the polygon. The hole solid ratio value for a polygon with no holes is 1.0.	$= \text{AREA} / \text{outer contour area}$

metrics will be referred to hereafter as “Fx object attributes,” and are described in more detail in Tables 2.3 and 2.4 (ITT VIS, 2008^b). After these Fx object attributes are calculated, the user may export all of the objects and their associated spatial, textual, HSI, ratio and spectral attributes as a single ESRI shapefile (Figure 2.7).

Using this ENVI Fx workflow, discrete habitat features were identified and delineated in the acoustic imagery. Specifically, features that appeared to be coral reef habitats (i.e., either aggregate reef, patch reefs, aggregated patch reefs, pavement or pavement with sand channels) were extracted from the PCA image using a scale level of 75 and an merge level of 99.2 (Figures 2.8 a-d). Features that appeared to be soft bottom habitats (i.e., either sand or scattered coral and rock) or a mixture of soft bottom and rhodolith habitats were extracted from the intensity surface using a scale level of 25 and a merge level of 99.1. The final coral reef habitats features, as well as soft bottom and rhodolith habitat features, were exported from ENVI Zoom as two separate shapefiles. The attribute tables of these shapefiles contained the spatial, textual, HSI, ratio and spectral metrics calculated for each habitat feature. Each shapefile was then visually inspected and polygons (or pieces of polygons) were manually removed, if they appeared to be the result of acoustic noise (Figure 2.9). Each of the Fx object attributes associated with each habitat feature were then converted to rasters using a custom script built in ArcGIS’s Model Builder. In total, there were 34 attribute rasters associated with the 1,287 coral reef features and 22 attribute rasters associated with the 11,421 soft bottom and rhodolith features. The 34 coral reef rasters and 22 soft bottom and rhodoliths rasters were respectively stacked, and exported to create two separate images with several different bands (each band representing a specific metric). The next step in the mapping process sought to better understand, identify, and quantify the correlations between these object-based metrics and specific habitat classes.

Table 2.4. Descriptions of the textual, ratio, hue saturation and intensity (HSI), and spectral metrics calculated by ENVI Fx for each habitat polygon identified during the edge-detection process (ITT VIS, 2008^b).

	ATTRIBUTE	DESCRIPTION
TEXTUAL	TX_RANGE	Average data range of the pixels comprising the region inside the kernel. A kernel is an array of pixels used to constrain an operation to a subset of pixels.
	TX_MEAN	Average value of the pixels comprising the region inside the kernel.
	TX_VARIANCE	Average variance of the pixels comprising the region inside the kernel.
	TX_ENTROPY	Average entropy value of the pixels comprising the region inside the kernel. ENVI Zoom computes entropy, in part, from the Max Bins in Histogram preference.
RATIO	BANDRATIO	"Values range from -1.0 to 1.0. ENVI Zoom computes a normalized band ratio between two bands, using the following equation: $(B2 - B1) / (B2 + B1 + \text{eps})$, where eps is a small number to avoid division by zero."
HSI	HUE	Hue is often used as a color filter and is measured in degrees from 0 to 360. A value of 0 is red, 120 is green, and 240 is blue.
	SATURATION	Saturation is often used as a color filter and is measured in floating-point values that range from 0 to 1.0.
	INTENSITY	Intensity often provides a better measure of brightness than using the AVGBAND_x spectral attribute. Intensity is measured in floating-point values from 0 to 1.0.
SPECTRAL	MINBAND_X	Minimum value of the pixels comprising the region in band x.
	MAXBAND_X	Maximum value of the pixels comprising the region in band x.
	AVGBAND_X	Average value of the pixels comprising the region in band x.
	STDBAND_X	Standard deviation value of the pixels comprising the region in band x.

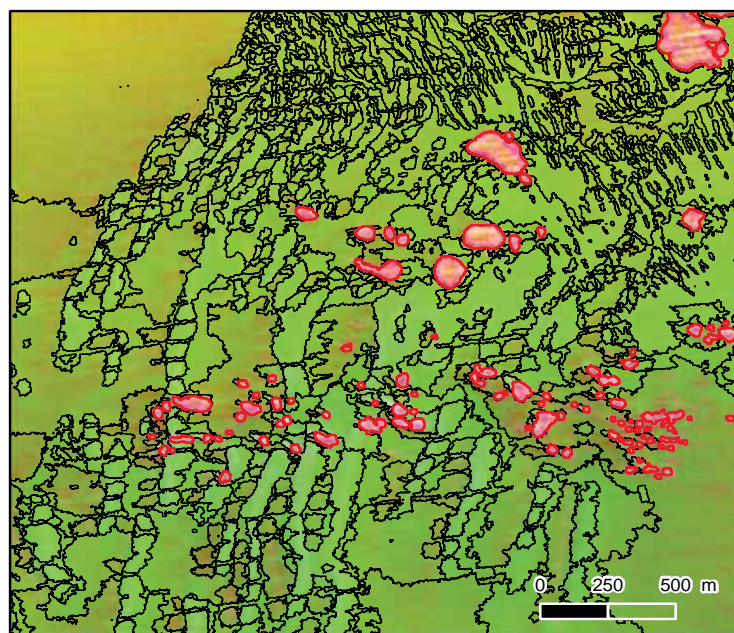


Figure 2.7. This map depicts a subset of habitat objects that were exported from ENVI Fx as a single ESRI shapefile. The pink/red objects are coral reef habitats features, while the green/brown objects are soft bottom and rhodoliths habitats features.

Figure 2.8. This series of screenshots depicts (step-by-step) the ENVI Fx 4.6 feature extraction process used to identify and delineate visually distinct habitat features. ENVI Fx is an add-on module that is nested within ENVI Zoom.

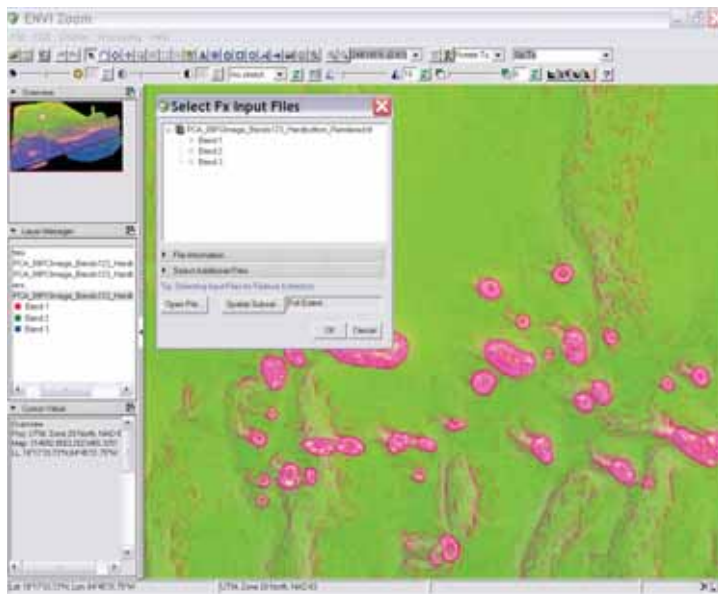


Figure 2.8a. Screenshot depicting the first step (i.e., choosing the input or source image) in the ENVI Fx feature extraction process. Specifically, this screenshot shows the source image (i.e., PCA image) from which coral reef habitat features were extracted. Bands 1, 2 and 3 in the PCA image correspond to the image's first, second and third principal components, respectively.

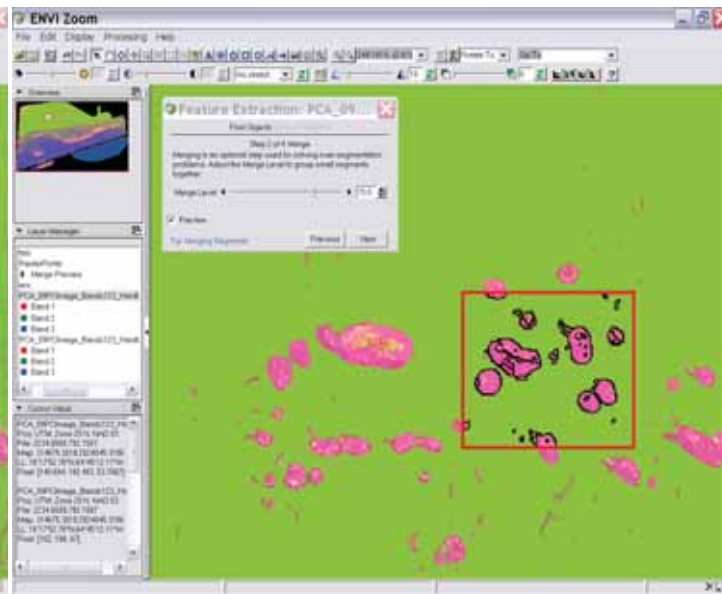


Figure 2.8b. Screenshot depicting the second step (i.e., choosing a scale level) in the ENVI Fx feature extraction process. Specifically, this screenshot shows the scale level (i.e., 0.0) used to identify coral reef habitat features. The preliminary results from choosing this scale level are seen in the red box in the lower right corner of the screenshot.

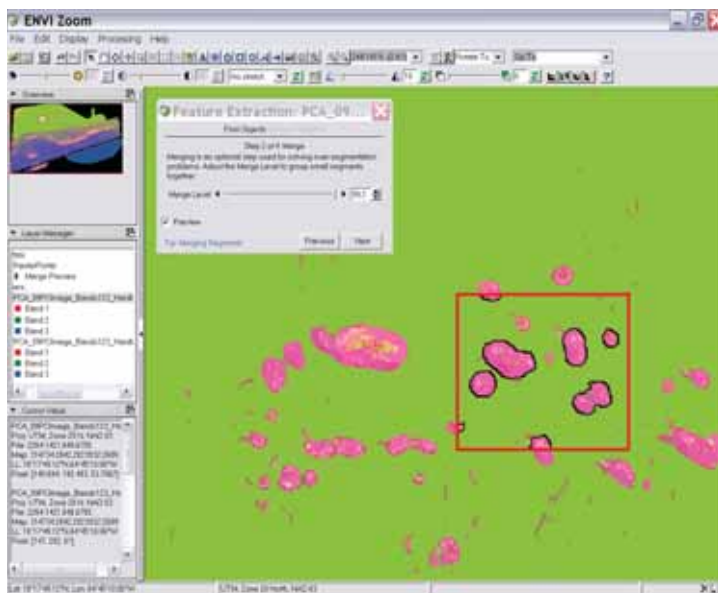


Figure 2.8c. Screenshot depicting the third step (i.e., choosing a merge level) in the ENVI Fx feature extraction process. Specifically, this screenshot shows the merge level (i.e., 99.2) used to aggregate coral reef habitat features into larger objects. The preliminary results from choosing this merge level are seen in the red box in the lower right corner of the screenshot.

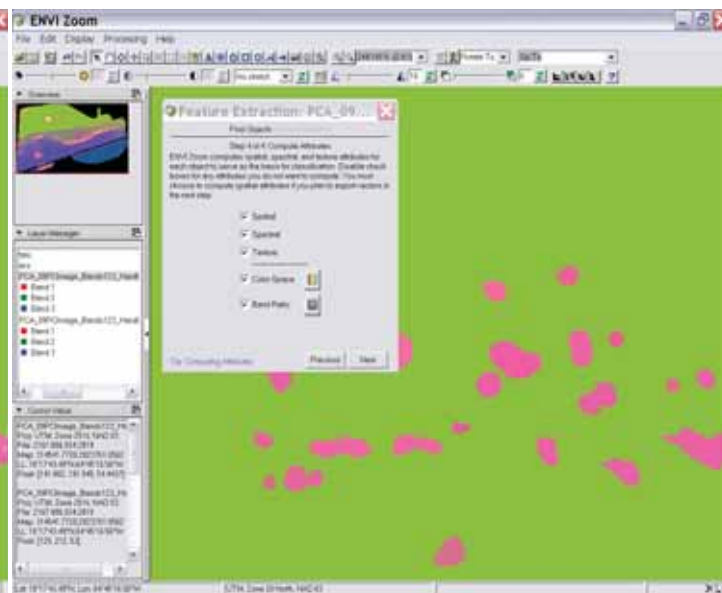


Figure 2.8d. Screenshot depicting the fourth and final step (i.e., calculating polygon attributes) in the ENVI Fx feature extraction process. Specifically, this screenshot shows that spatial, textual, HSI, ratio and spectral metrics were calculated for each of the coral reef habitat polygons identified by the feature extraction process. After these attributes were calculated, the final coral reef polygons (and their associated attributes) were exported as a single ESRI shapefile.

Ground Validation

Extensive field work is needed to create high-quality benthic habitat maps because it enhances the accuracy of habitat attribution and (to a lesser degree) habitat delineation. Given the importance of field work, a team of NOAA scientists visited predetermined locations to explore and verify existing habitat information on the seafloor. These “ground validation” (GV) locations were targeted by the cartographer to satisfy the following objectives:

1. Explore features in the imagery with unknown or confusing acoustic signatures
2. Confirm that the habitat type correlated with a particular acoustic signature remained consistent throughout the entire study area.

To achieve this first objective, the cartographer manually placed GV points in, or transects that intersected, features with unknown habitat types. These points and transects were important for understanding the habitat class associated with these distinct, but unknown acoustic signatures. To achieve the second objective, the cartographer manually placed GV points in, or transects that intersected, features with known habitat types distributed throughout the entire spatial extent of the mapped area. These points and transects were important to the GV process because the same habitat type may exhibit slightly different signatures in different parts of the study area. A single habitat type may exhibit slightly different acoustic signatures because polygons contain some structural and biological cover heterogeneity within them (e.g., polygons attributed as “rhodoliths” contain varying amounts of sand and algae).

Two different GV sampling methods (i.e., points and transects) were used because the GV data were collected during two different years (2005 and 2009) using two different pieces of equipment. In 2005, GV data were collected along 13 transects using a remotely operated vehicle or ROV (Figure 2.10) from 2/1 to 2/12 onboard the

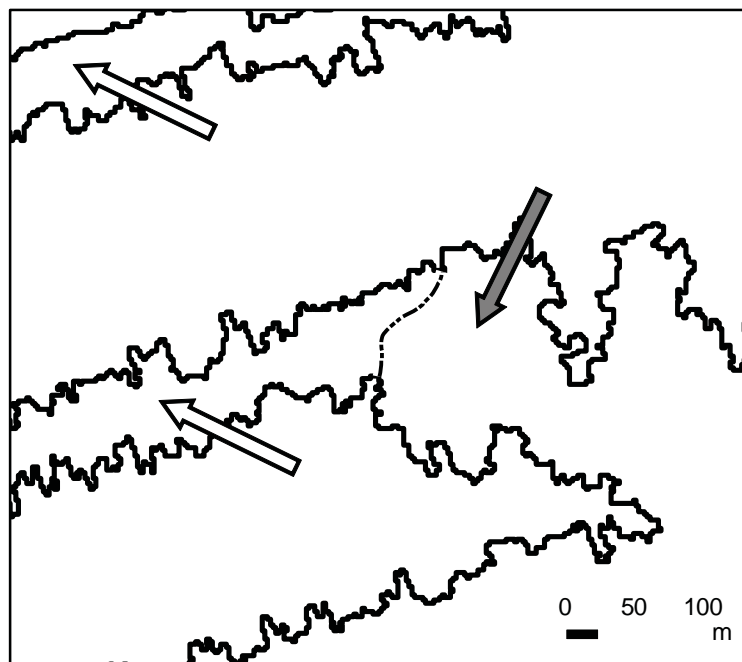


Figure 2.9. This graphic depicts how artifacts in the acoustic imagery were manually removed from the benthic habitat map. Some habitat polygons (denoted by the black lines) were manually deleted or edited because they included acoustic noise within their boundaries. The white arrows point to artifacts in the PCA image that were falsely identified as discrete habitat features. The gray arrow points to real habitat features in the PCA image. The white and black dotted line denotes where this polygon was manually split to remove the artifacts from the habitat polygon.

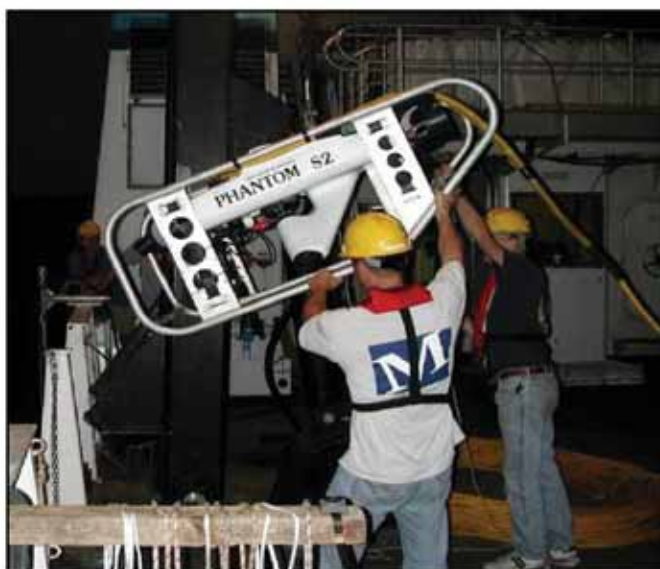
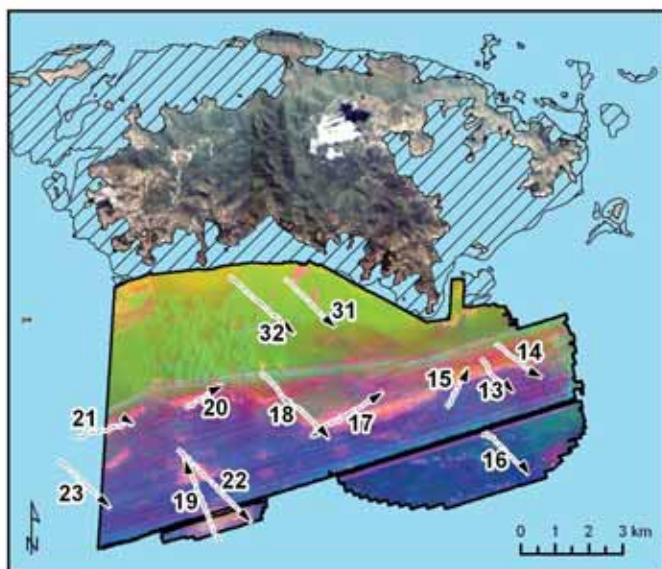


Figure 2.10. In 2005, the Spectrum Phantom S2 ROV (right) collected underwater video and high resolution photographs of the seafloor along 13 transects. These datasets were used for ground validation purposes. The map (left) depicts these 13 transects (and their orientation) overlaid on the PCA image. The thin black, hatched polygons denote the extent of the shallow-water maps developed using optical imagery. The thick black polygon denotes the spatial extent of the acoustic imagery.

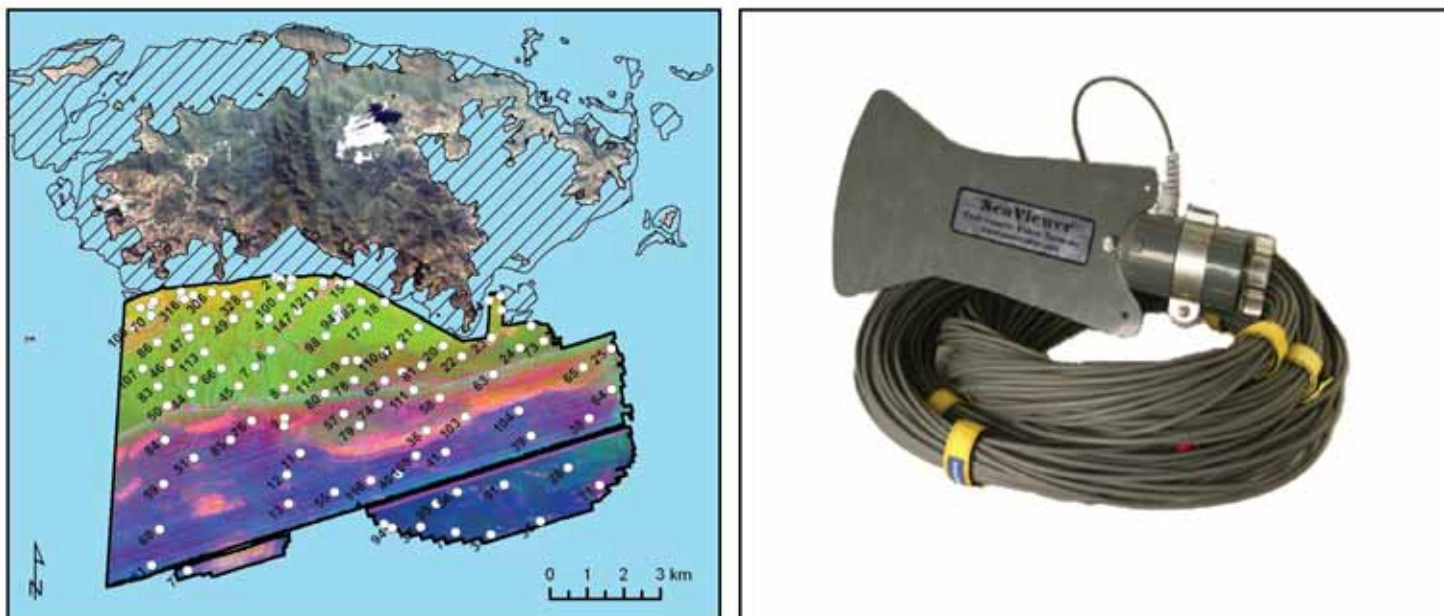


Figure 2.11. In 2009, the SeaViewer Sea-Drop 950 camera (right) collected underwater video of the seafloor at 117 discrete locations. This dataset was used for ground validation purposes. The map (left) depicts these 117 points as white dots overlayed on the PCA image. The thin black, hatched polygons denote the extent of the shallow-water maps developed using optical imagery. The thick black polygon denotes the spatial extent of the acoustic imagery.

NOAA ship, *Nancy Foster*. In 2009, GV data were collected at 117 GV sites using an underwater drop camera (Figure 2.11) from 1/5 to 1/16, 2/9 to 2/20 and 5/31 to 6/7 onboard small research vessels provided by the National Park Service (Figure 2.12).

For the 2005 mission, the GV transects were systematically placed over the study area to include as many benthic habitat features and transition zones as possible. Distinct features and transitional areas were identified by visual examination of fine-scale multibeam bathymetry data collected in 2004 and moderate-scale GEODAS bathymetry data (GEODAS, 2005). The bathymetry data were divided into distinct benthic habitats using variations in depth, roughness and spatial patterning (ridges, bumps, troughs, regular undulations, etc.). Georeferenced underwater video and photographs were acquired using a video camera and high-resolution digital still camera mounted on a Spectrum Phantom S2 ROV. High powered strobe lights mounted on the ROV were used to supplement ambient light levels during the day and served as the only source of light during night operations.

Data from the cameras were transmitted and immediately recorded to a computer's hard drive. Video data were collected during an entire transect, and still photos were collected every 30 seconds. The forward-facing video camera was pointed at a 45 degree downward angle to give ROV pilots a view of upcoming obstacles and researchers a view of the benthic habitat. The ROV's height above the substrate and speed were approximately 2 m and 1 m/s, respectively. The ROV pilot attempted to keep the ROV height and speed as constant to standardize the field of view and spatial resolution of interpretations. Two downward pointing parallel lasers separated by 5 cm and the scale of habitat features and organisms were used to estimate height off the bottom. Still photo images were acquired using a downward pointed camera. A transducer attached to the ROV and an acoustic receiver (suspended off the side of the ship) were used to determine the ROV's relative position to the ship. The ROV's absolute geographic position was estimated using this relative position and the shipboard GPS. The positional accuracy was estimated to be within ± 5 m.



Figure 2.12. A U.S. National Park Service vessel was used to collect underwater video in support of habitat map development.

For the 2009 missions, GV sites were systematically placed in features with unknown acoustic signatures, and in parts of the study area that were not explored using the ROV in 2005. These GV sites were prioritized as high, medium and low in case there was not enough time to visit all of them during the field mission. Geographic coordinates for these sites were uploaded to a hand-held Garmin 76 CS WAAS-enabled GPS unit (Figure 2.13). At the beginning of every morning, a specific region was selected (depending on the weather) to work in during that day. Often, this meant working in areas with more challenging sea conditions first, and then moving inshore or to more protected areas as the day progressed. GV sites were navigated to using the hand-held Garmin 76 CS GPS unit. The vessel was

maneuvered to within 5 m of the target location. Once in position, NOAA scientists would concurrently deploy a SeaViewer Sea-Drop 950 camera (attached to a down weight and 300 feet of line), as well as begin logging a waypoint on a Trimble GeoXT GPS receiver. The drop camera reached the bottom in approximately 60 - 90 seconds. While on site, the vessel's position was captured as an epic (i.e., point) approximately every 5-10 seconds depending on the number of satellites detected by the GPS antennae. The underwater video was recorded onto mini-video tapes using a Sony Walkman video recorder. The camera operator adjusted the camera lens to get a downward view of the seafloor approximately 2 m from the bottom, and a side view of the seafloor. This allowed for accurate measurements of percent biological cover and a broader scale understanding of the structure at each site. No attempt was made to standardize the amount of time the camera was on the seafloor. In fact, it was often advantageous to drift across habitat transitions, as it allowed the cartographer to understand the ecotone at many locations (Figure 2.14). While the camera was recording video of the seafloor, an observer viewed the video real-time on a Panasonic Toughbook, and classified the major/detailed geomorphological structure, major/detailed biological cover, and percent coral for each site. Water-proof field maps (depicting the draft habitat map and source imagery) were used to visually link signatures in the imagery with the *in situ* habitats as seen in the video (Figure 2.1). In many cases, suggestions on boundary delineation and habitat classifications were made directly on the field maps with permanent marker.

Once back in the office, Trimble Pathfinder Office software was used to post process and differentially correct the raw GPS data to the Continually Operating Reference System (CORS) station at St. Thomas, U.S. Virgin Islands (VITH). The underwater video was converted from the mini-tapes to softcopy form using Final Cut Pro software. The classification of each GPS location (completed in the field) was then reviewed in conjunction with the acoustic imagery and the associated underwater video, to develop a final classified set of GV points (Figure 2.15). Next, the final classified GV points were separated into multiple shapefiles (i.e., one file for each unique habitat class combining structure, cover, percent cover



Figure 2.13. The equipment used in the field to collect georeferenced underwater video. The Panasonic Toughbook (left) was used to view the video in real-time. The Trimble GeoXT GPS receiver (middle) was used to record the location of the drop-camera. The Garmin 76 WAAS-enabled GPS unit (right) was used to navigate to each GV site.

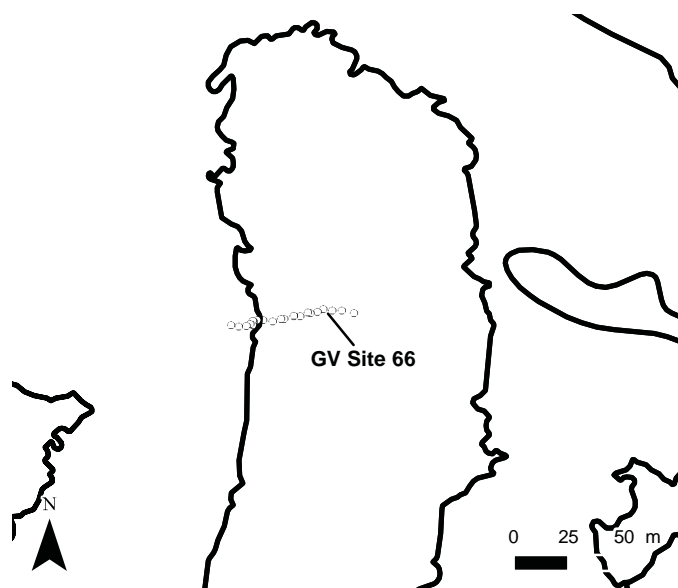


Figure 2.14. This map illustrates how the drop camera (denoted by the white points) drifted over a habitat transition (denoted by the black line) at GV site 66, allowing the cartographer to understand both habitat types.

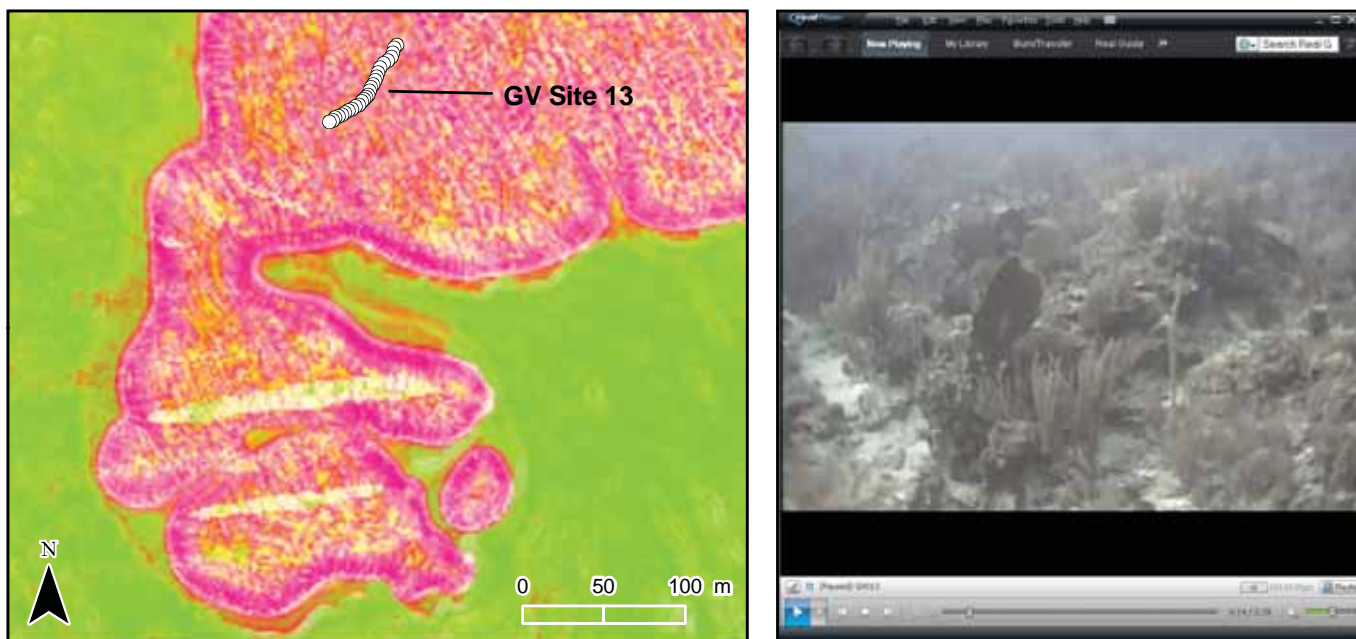


Figure 2.15. A final classified set of GV points was developed by concurrently viewing the acoustic imagery and underwater video for a specific location. The map (left) depicts the drop camera location (denoted by the white points) for GV site 13 overlaid on the PCA image. The screenshot (right) depicts the underwater video associated with GV site 13.

and live coral cover) using the “Split Layer by Attribute” toolbox in ArcGIS 9.3 (Patterson 2008). Each shapefile was subsequently imported into ENVI 4.6, and converted to ROIs (Regions of Interest) using the “Import Vector Files” and “Export Active Layer to ROIs” functions (Figure 2.16). These ROIs were needed to create a second draft habitat map.

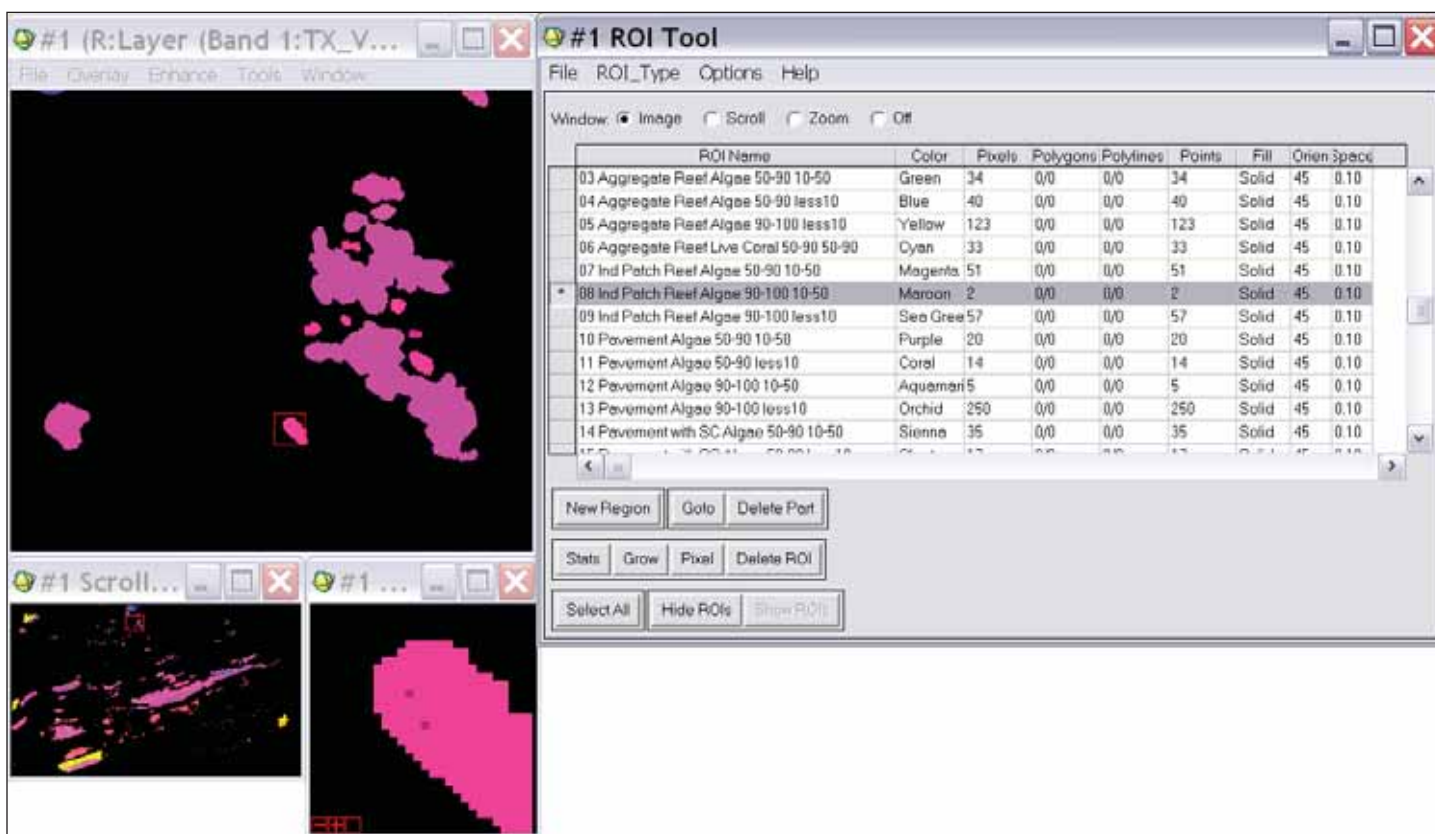


Figure 2.16. The classified GV points were converted from ESRI shapefiles to ENVI 4.6 ROIs. The table (right) shows these converted ROIs. The map (left) depicts the coral reef features extracted by ENVI Fx at three different scales. The location of the ROI highlighted in the table (i.e., 08 Ind Patch Reef Algae 90-100 10-50) is denoted by two maroon pixels overlaid on a coral reef feature in the finest scale window (bottom right).

Habitat Classification

QUEST (Quick, Unbiased, Efficient Statistical Tree)

The ROIs created from the classified GV locations and video (above) were used to train the classification algorithm and to develop a second draft habitat map. These tasks were performed using ENVI 4.6's RuleGen 1.02 add-on (Figure 2.17; Jengo 2004). This add-on contains the Quick, Unbiased, Efficient Statistical Tree (QUEST) algorithm (Loh and Shih, 1997), which is implemented via ENVI's native Decision Tree Tool. QUEST is a type of Classification and Regression Tree (CART) (Breiman et al., 1984) that: (1) is non-parametric and nonlinear, (2) has negligible variable selection bias, (3) is computationally simplistic, and (4) yields binary splits for categorical predictor variables, ordinal predictor variables, or a mix of both types of predictors.

Unlike CART however, the QUEST algorithm separates objects in an image into classes using univariate (axis-orthogonal) discriminant-based splits. This type of analysis separates the classification process into two parts at each split (or node) in the decision tree (Figure 2.19). The first step in this analysis, *independent variable selection*, finds the independent variable (i.e., input band) that is significantly different from the other variables in order to create the most efficient split. The second step in this analysis, *binary split identification*, identifies the threshold at which to split the previously selected input band into two classes that are as homogenous as possible.

More specifically, during *independent variable selection* stage, QUEST uses the Pearson contingency table Chi-squared test of independence to approximate the statistical significance (p -value) of each input band. If the smallest p -value for these input bands is less than a predefined threshold (as determined by the Bonferroni method for multiple comparisons), then the corresponding input band is selected to be included in the classification. If not, then Levene's F -test for unequal variances is

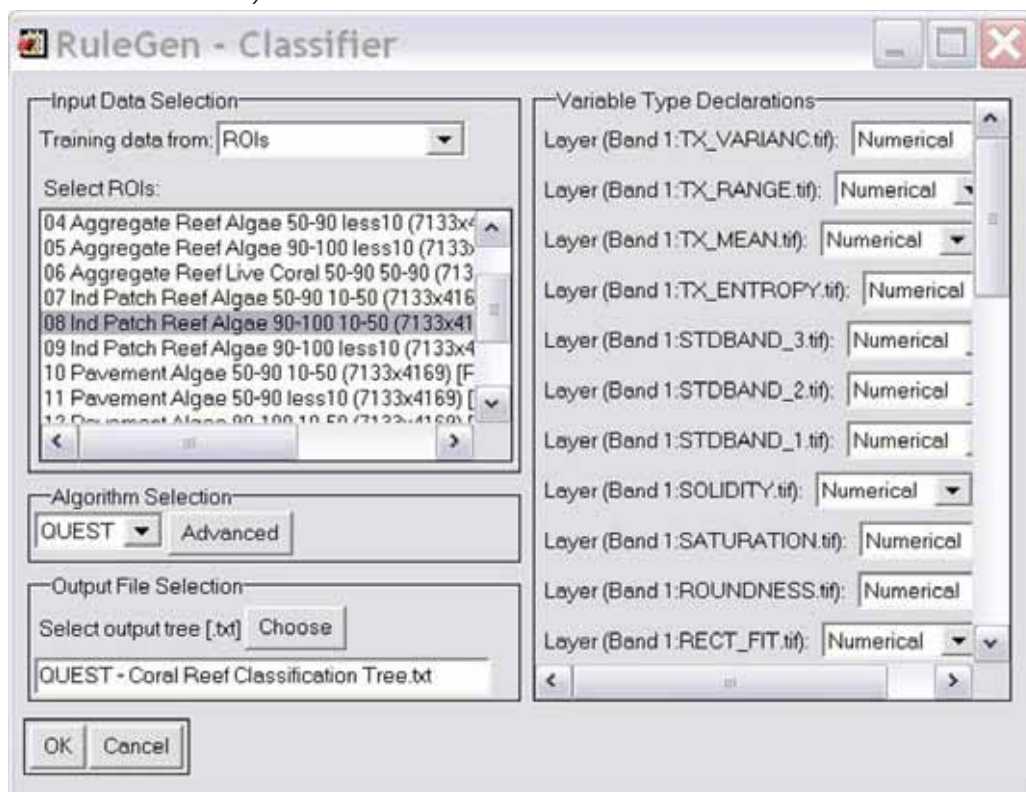


Figure 2.17. The converted ROIs were used to create a QUEST classification tree using ENVI 4.6's RuleGen 1.02 add-on. The variable type declarations included all of the spatial, textual, ratio, HSI and spectral metrics calculated for each polygon by ENVI's Fx module.

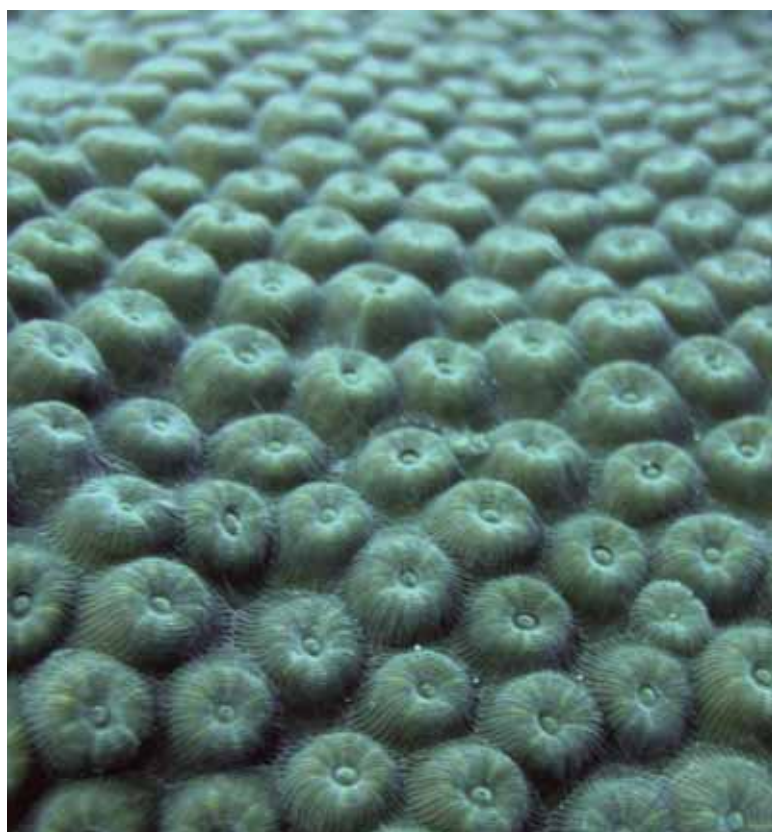


Figure 2.18. Underwater photograph of the Great Star Coral (*Montastraea cavernosa*).

calculated for each input band. If the smallest p -value from this F -test is less than another predefined threshold (again, as determined by the Bonferroni method), then the corresponding input band is selected to be included in the classification. If not, then the input band with the smallest p -value from the first Chi-squared test is selected to be included in the classification (Loh and Shih, 1997). Thus, if all the input bands are uninformative with respect to partitioning an image, then each band has approximately the same chance of being selected to split a node.

Once the statistically significant input band has been selected, this input band is then used during the *binary split identification* step to partition objects in the image into different classes. To determine the location of these splits, QUEST uses a 2-means clustering algorithm (Hartigan and Wong, 1979), which minimizes the within-cluster sum of squares, to preliminarily group objects in the image into two super classes clustered around the two most extreme sample means. If the two super class means are identical, then the class with the largest number of samples becomes one superclass, while the remaining classes are grouped into the second superclass. The ideal split between these two classes is then identified using a modified version of quadratic discriminant analysis. This modified analytical technique accounts for unequal variances by only using the quadratic root closest to the sample mean of each class. This quadratic root is then used to find the ideal split between the two super classes at the intersection of their density curves (Figure 2.20). Once the split is made, the entire process of variable selection and partitioning starts over, and continues iteratively until no more useful splits are found in the data, or until pruning or a predefined rule or tells the algorithm to stop (Loh and Shih, 1997).

Classifying Objects on the Seafloor

The QUEST algorithm was used to classify each habitat object delineated by ENVI Fx. To simplify this classification process, coral reef habitats as well as soft bottom and rhodolith habitats were classified separately. This means that ROIs for coral reef features and ROIs for soft bottom and rhodoliths features were used to train the QUEST algorithm separately to develop two different classification trees. These trees were built using the same input parameters (Table 2.5), but different combinations of the spatial, spectral, textual, HSI and band ratio attributes. In total, the algorithm found 91 and

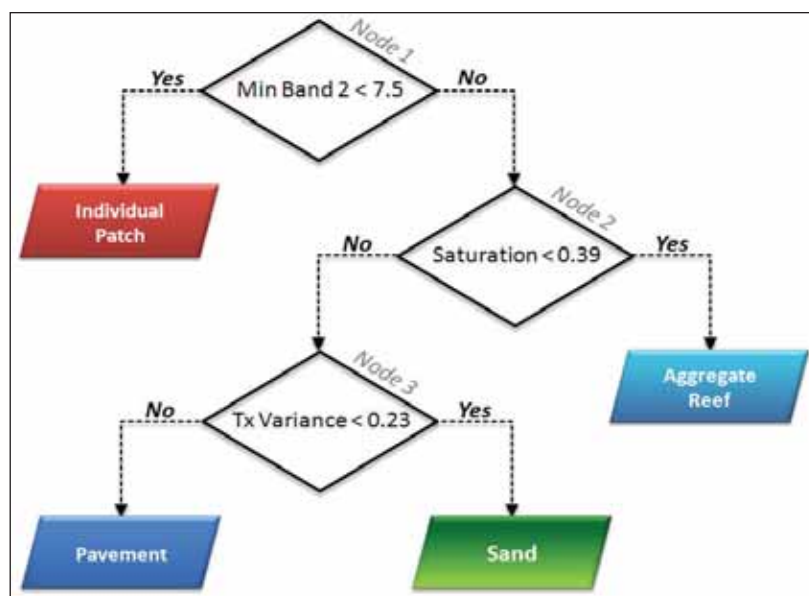


Figure 2.19. This diagram illustrates how QUEST uses binary decisions to split an image into different classes. For example at node 1, if a habitat object's Minimum Band value is < 7.5 , then it is attributed with the Individual Patch Reef detailed structure type. However, if a habitat object's Minimum Band value is ≥ 7.5 , then QUEST moves on to node 2 and so on down the line. While this sample decision tree only has three nodes, the final coral reef and soft bottom/rhodoliths decision trees had 91 and 71 nodes, respectively.

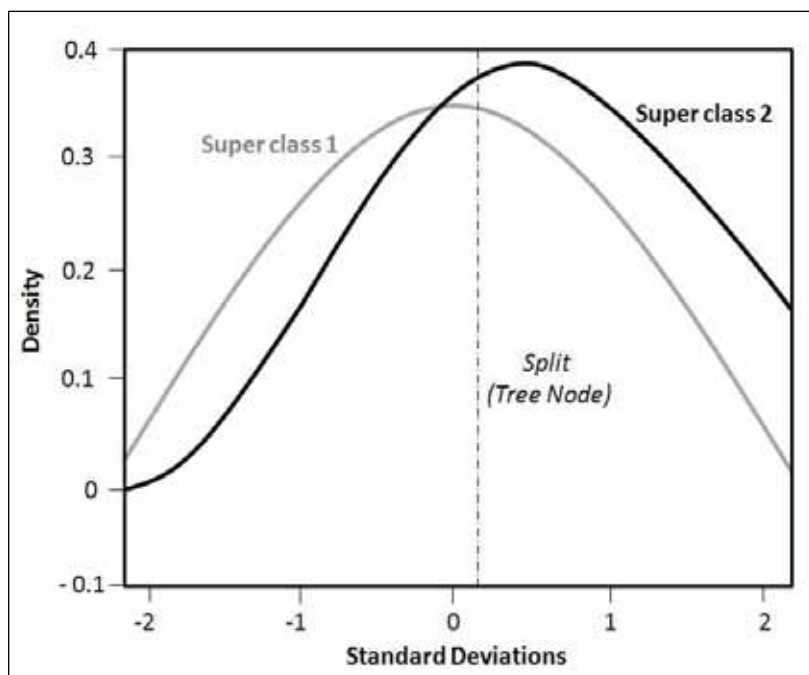


Figure 2.20. This graph describes how QUEST determines where to split super classes into two groups. The density curves of Superclass 1 and 2 are depicted in gray and black, respectively. The ideal split between the 2 super classes (denoted by the vertical dashed line) is determined by using the quadratic root closest to the sample mean of each class near the intersection of their density curves. This split becomes a binary node in the decision tree.

71 useful splits when grouping coral reef features and soft bottom/rhodoliths features, respectively. For coral reef habitats in particular, the algorithm found 19 (of the 34) ENVI Fx object attributes useful when splitting these objects into 20 distinct classes. For soft bottom and rhodoliths habitats, the algorithm found 14 (of the 22) ENVI Fx object attributes useful when splitting these objects into 11 distinct classes (Table 2.6). The distinct classes for both coral reef habitats as well as soft bottom and rhodoliths habitats were based on unique combinations of major structure, detailed structure, major biological cover, percent major biological cover and percent live coral cover classes. The final coral reef and soft bottom and rhodoliths classifications were exported from ENVI 4.6 as separate ESRI shapefiles.

Table 2.5. Descriptions of the input parameters used when building the QUEST classification trees.

INPUT PARAMETER	INPUT VALUES USED	IMPACT OF PARAMETER	DEFINITION
Minimum Node Size	5	When to stop the tree from growing	The smallest number of samples in a node during tree construction. The node will not be split if it contains fewer cases than this number. The smaller this value is, the larger the initial tree will be prior to pruning. The default value is $\max(5, n/100)$, where n is the total number of observations (Shih, 2004).
Split Method	Univariate	How to split input bands	The user can choose to create discriminant-based splits using a single variable (to examine the effects of predictor variables one at a time) or a linear combination of variables (Shih, 2004; StatSoft, 2007).
Variable Selection Method	Unbiased	How to select important input bands	The user can choose between the unbiased variable selection method described in Loh and Shih (1997) or the biased exhaustive search method which is used in CART described in Breiman et al. (1984) (Shih, 2004). The unbiased method uses discriminant-based split methods to prevent biased in variable selection. Thus, if all the attributes are uninformative with respect to the class attribute, then each has approximately the same chance of being selected to split a node (Lim et al., 2000).
Alpha Value (α)	0.05	When to consider a variable as significant	Alpha value is a number $0 \leq \alpha \leq 1$ at which point a p -value is considered significant. If the unbiased variable selection method is used, then an alpha value is needed to conduct the tests (Shih, 2004).
Number of SEs for pruning	1	How much of the tree to prune	The number of SEs (standard errors) controls the size of the pruned tree. $SE = 0$ gives the tree with the smallest cross validation estimate of misclassification cost or error (Shih, 2004).
Number of Folds (V)	10	How to calculate SE for the tree	The user can choose the value of V in V -fold cross-validation. 10-fold is usually recommended and is the default in CART (Shih, 2004). This means that when $V = 10$, the dataset is randomly divided into 10 roughly equal parts. One part is left out while a regression estimate is constructed using the 9 remaining parts. The left-out part is then used to estimate the prediction mean standard error for the tree (Loh, 2002).
CV Tree Details	No	N/A	The user can choose whether the details of the cross validation tree are reported (Shih, 2004).
Output PStricks tree?	No	N/A	The user can choose whether to use the PStricks package (to access PostScript features that are otherwise not directly accessible from LaTeX) to draw the QUEST tree. LaTeX is a document preparation system for the TeX typesetting program, offering desktop publishing features for automating aspects of typesetting and desktop publishing.

Classification Post Processing and Evaluation

These ESRI shapefiles were then brought into ArcGIS 9.3 for additional post processing and visual quality assurance and control. In particular, these steps included: (1) removing polygons smaller than the minimum mapping unit and filling gaps in the shapefiles, (2) merging the coral reef as well as soft bottom and rhodoliths maps, (3) visually evaluating and editing this merged map, and (4) smoothing the final habitat polygon boundaries. In step 1, habitat polygons, which were smaller than the 1,000 m² MMU, were merged with adjacent polygons using ET Geowizards “Eliminate” function (Tchoukanski 2008). This function removed these polygons by merging them into neighboring polygons with which they shared their longest common border (Figure 2.21). In total, this function merged 2,717 soft bottom and rhodoliths polygons into 638 soft bottom and rhodoliths polygons, and 698 coral reef polygons into 290 coral reef polygons. After these polygons with < 1,000 m² area were removed, gaps in the soft bottom and rhodoliths shapefile were filled using ET Geowizards “Clean Gaps” function (Tchoukanski 2008). This function added 360 unattributed polygons into the soft bottom and rhodoliths shapefile.

In step 2, the coral reef and soft bottom and rhodoliths shapefiles were integrated (during an active Editing session) to produce one shapefile. To do so, all 290 of the coral reef polygons were selected, copied and pasted into the soft bottom and rhodoliths shapefile. These polygons were then merged and used to collectively clip the soft bottom and rhodoliths polygons, discarding the area that intersected. Clipping the soft bottom and rhodoliths polygons with the coral reef polygons ensured that there was no overlap between habitat types. After clipping, all of the coral reef polygons were then selected, copied and pasted again into the soft bottom and rhodoliths shapefile to create a continuous map. The ET Geowizards “Eliminate” function was then run again on this continuous map to remove any polygon slivers < 1,000 m² created during the merge process.

Table 2.6. The polygon metrics (calculated by ENVI Fx) that were identified by QUEST as being significant for classifying coral reef habitats and soft bottom/rhodolith habitats. In total, 19 metrics were used to classify coral reef habitats, and 14 metrics were used to classify the soft bottom and rhodolith habitats.

# of BANDS	FX ATTRIBUTE (Coral Reef)	FX ATTRIBUTE (Soft bottom & Rhodoliths)
1	AVGBAND_1	AREA
2	BANDRATIO	AVGBAND_1
3	COMPACT	CONVEXITY
4	FORMFACTOR	HOLESOLRAT
5	HUE	MAINDIR
6	INTENSITY	MAJAXISLEN
7	MAINDIR	MAX_BAND_1
8	MAXBAND	MINBAND_1
9	MAXBAND_2	NUMHOLES
10	MAXBAND_3	ROUNDNESS
11	MINAXISLEN	STDBAND_1
12	MINBAND_2	TX_ENTROPY
13	MINBAND_3	TX_MEAN
14	RECT_FIT	TX_VARIANC
15	SATURATION	
16	SOLIDITY	
17	TX_ENTROPY	
18	TX_MEAN	
19	TX_VARIANC	

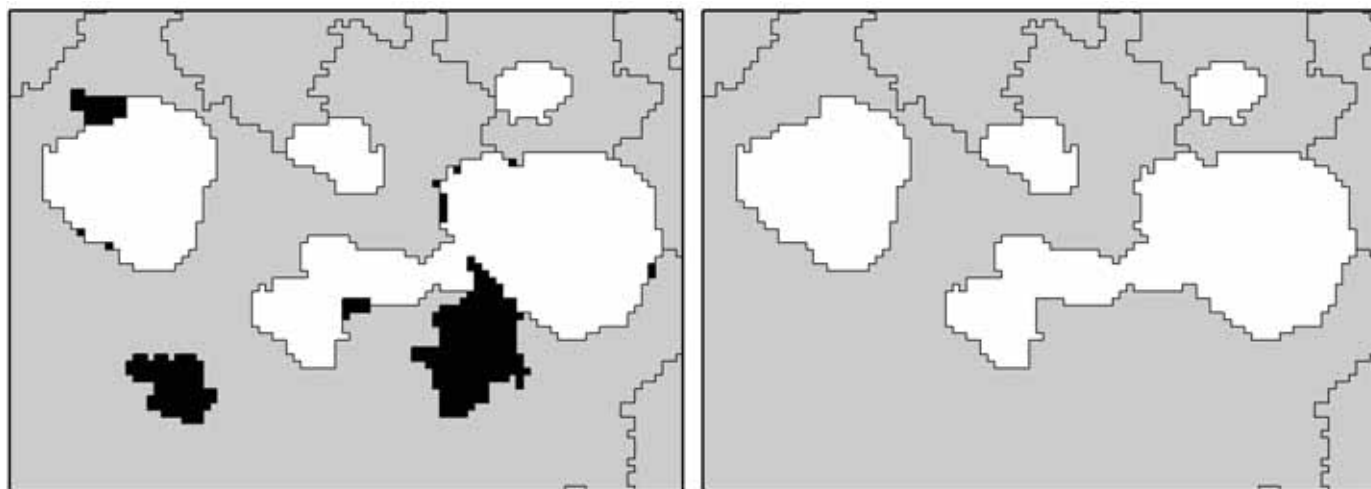


Figure 2.21. The ET Geowizard’s “Eliminate” function was used to merge polygons < 1,000 m² with neighboring polygons with which they shared their longest common border. The map on the left shows the habitat map before these polygons were merged, and the map on the right shows the habitat map after these polygons were merged. Polygons smaller than the map’s MMU are black. Coral reef features are white, and soft bottom and rhodoliths features are gray.

In step 3, the merged map was visually evaluated, and polygons were manually edited if necessary. These edits included reclassifying, merging or deleting polygons where the cartographer disagreed with the algorithm's interpretation. They also included manually digitizing habitat features (>1,000 m² at a scale of 1:2,000) that were overlooked during the feature extraction process (Table 2.7). During this QA/QC process, approximately 40% of the total number of polygons were manually deleted or merged and approximately 37% of the total number of polygons were manually added (Table 2.8). In the final step, (step 4), ET Geowizard's "Smooth Polygons" function was used to smooth the pixilated appearance of the polygon lines (Figure 2.22). The B-spline smoothing algorithm was used with the input parameters "smooth" and "freedom" set to 10 and 5, respectively. The end result was a seamless habitat map of the seafloor area between 14 to 55 m deep within and around the VICRNM.

Table 2.7. Estimated number of polygons that were manually deleted, added or merged.

	TOTAL # POLYGONS	% OF POLYGONS
Unedited Map	1,324*	-
Final Map	1,283	-
Deleted/Merged	514	$(514/1,283)*100 = 40\%$
Added	473	$(473/1,283)*100 = 37\%$

Note: * = 7,221 polygon slivers < 1,000 m² were subtracted from the total number of polygons (8,545) in the unedited map to derive this number.

Table 2.8. Estimated number of polygons that were manually reattributed because they were deleted, added and/or reclassified. These numbers are based on a randomly distributed sample of 1,000 points stratified by detailed structure type and weighted by area. Habitat classifications contained in the original map (i.e., the unedited map produced by QUEST) and the final map (i.e., the map that was manually edited and delivered to the NPS) were extracted at each of these 1,000 points, and compared to determine whether they had been changed.

POLYGON ATTRIBUTE	TOTAL # UNEDITED POLYGONS	% UNEDITED POLYGONS	TOTAL # EDITED POLYGONS	% EDITED POLYGONS
Major Structure	1,149	90%	134	10%
Detailed Structure	1,106	86%	177	14%
Major Cover	1,137	89%	146	11%
% Cover	888	69%	395	31%
Major + % Cover	844	66%	439	34%
% Live Coral Cover	1,239	97%	44	3%

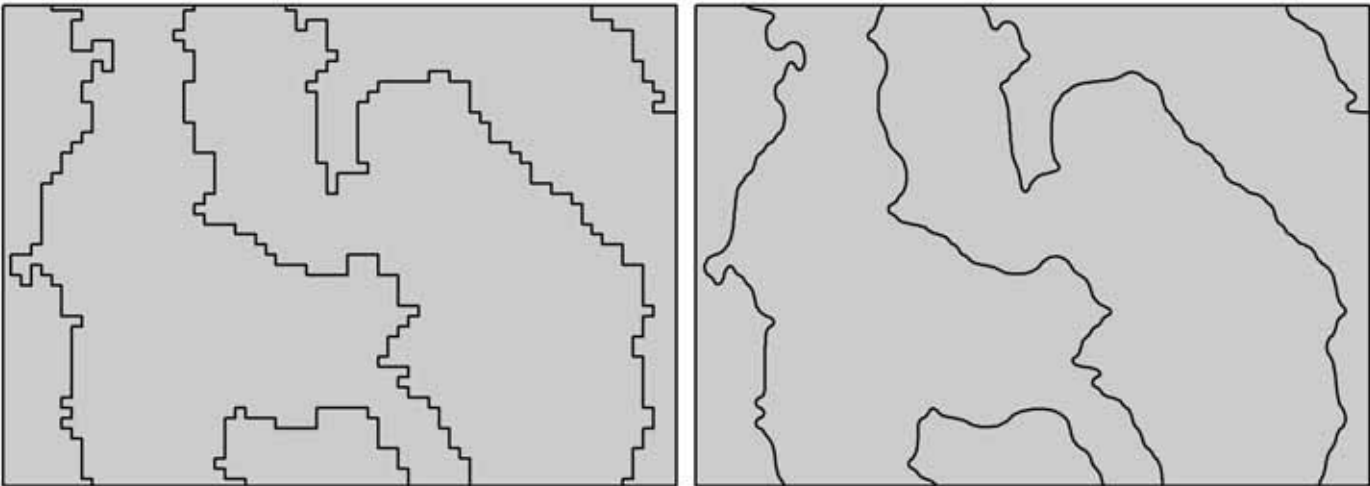


Figure 2.22. ET Geowizard's "Smooth Polygons" function was used to smooth the pixilated appearance of the polygon lines. The map on the left shows the habitat map before the polygon lines were smoothed, and the map on the right shows the habitat map after the polygon lines were smoothed.

2.4 GIS QUALITY CONTROL

All GIS deliverable products generated throughout the mapping process were examined for attribution and topological errors. Particular attention was given to polygon geometry and attribution of the benthic habitat map, as well as to the attribution of each GV point. Multipart, sliver and void polygons were all removed using standard ArcGIS Spatial Analyst tools. Two custom ArcGIS extensions were employed to identify the following conditions:

1. Adjacency – polygons that shared a common boundary and exact attribute combination that were delineated separately (Buja, 2008^a)
2. Overlap – polygons sharing the same geographic space, thus violating mutual exclusion (Buja, 2008^b)

Errors resulting from either of these GIS routines were corrected in the draft maps and eliminated from the final product. A visual inspection of attributes on a feature-by-feature basis was conducted to correct for any misspellings or illogical attribute combinations. These quality assessments and controls ensured that the GIS data from this work were topologically clean and free of attribution errors. In addition, metadata summaries were prepared in an FGDC-compliant format for all GIS products that were supplied during final delivery.

LITERATURE CITED

- Battista, T. A., and J.V. Lazar. 2005. MBES data acquisition and processing report: Project NF-05-05-USVI, NOAA Data Acquisition and Processing Report, NOS NCCOS CCMA (Online).
- Battista, T. A., B.M. Costa and S.M. Anderson. 2007^a. Shallow-water benthic habitats of the main eight Hawaiian islands. NOAA Technical Memorandum NOS NCCOS 61(Online).
- Battista, T.A., B.M. Costa and S.M. Anderson. (2007)^b. Shallow-Water Benthic Habitats of the Republic of Palau. NOAA Technical Memorandum NOS NCCOS 59 (Online).
- Breiman, L., J.H. Friedman, R.A. Olshend and C.J. Stone. 1984. Classification and regression trees. Belmont, California: Wadsworth International Group. p 324.
- Buja, K. 2008^a. Find adjacent features. ESRI Support Center. Online: <http://arcscrips.esri.com/details.asp?dbid=15805>. Accessed March 2009.
- Buja, K. 2008^b. Find overlapping polygons. ESRI Support Center. Online: <http://arcscrips.esri.com/details.asp?dbid=15198>. Accessed March 2009.
- Fonseca, L., and B. Calder. 2005. Geocoder: an efficient backscatter map constructor. Proceedings of the U.S. Hydrographic Conference 2005, San Diego, CA.
- GEODAS. 2005. NOAA's GEOphysical DATA System (GEODAS). Online: <http://www.ngdc.noaa.gov/mgg/geodas/geodas.html>. Accessed September, 2005.
- Hartigan, J. A. and M.A. Wong. 1979. Algorithm AS 136: A k-means Clustering Algorithm. Applied Statistics. 28, 100-108.
- ITT VIS (Visual Information Solutions). 2008^a. Chapter 1: Introduction. ENVI Feature Extraction Module 4.6 User's Guide. pp. 1-78.
- ITT VIS (Visual Information Solutions). 2008^b. Chapter 3: Finding Objects. ENVI Feature Extraction Module 4.6 User's Guide. pp. 1-78.
- Jengo, C. 2004. RuleGen 1.02. ITT VIS (Visual Information Solutions), Online: <http://www.ittvis.com/UserCommunity/CodeLibrary.aspx>. Accessed November, 2007.
- Jenness, J. 2002. ArcView 3.x extension: Surface Areas and Ratios from Elevation Grid v1.2. Online: http://www.jennessent.com/arcview/surface_areas.htm. Accessed September, 2009.
- Jenness, J. 2004. Calculating landscape surface area from digital elevation models. Wildlife Society Bulletin, 32, 829-839.
- Kendall, M.S., M.E. Monaco, K.R. Buja, J.D. Christensen, C.R. Kruer, M. Finkbeiner and R.A. Warner. 2001. Methods used to map the benthic habitats of Puerto Rico and the U.S. Virgin Islands. NOAA Technical Report (Online).
- Kendall, M.S., O.P. Jensen, C. Alexander, D. Field, G. McFall, R. Bohne and M.E. Monaco. 2005. Benthic Mapping Using Sonar, Video Transects, and an Innovative Approach to Accuracy Assessment: A Characterization of Bottom Features in the Georgia Bight. Journal of Coastal Research. 21:6, 1154-1165.
- Kostylev, V.E., B.J. Todd, G.B.J. Fader, R.C. Courtney, G.D.M. Cameron and R.A. Pickrill. 2001. Benthic habitat mapping on the Scotian Shelf based on multibeam bathymetry, surficial geology and sea floor photographs. Marine Ecology Progress Series. 219, 121-137.

- Lillesand, T.M. and R.W. Kiefer. 2000. Remote sensing and image interpretation, 4th ed. New York, U.S.A.: John Wiley and Sons Ltd. p 724.
- Lim, T-S., W-Y. Loh and Y-S. Shih 2000. A Comparison of Prediction Accuracy, Complexity, and Training Time of Thirty-three Old and New Classification Algorithms. *Machine Learning*, 40, 203-229.
- Loh, W-Y. 2002. Regression Trees with Unbiased Variable Selection and Interaction Detection. *Statistica Sinica*, 12, 361-386.
- Loh, W-Y. and Y-S. Shih. 1997. Split Selection Methods for Classification Trees. *Statistica Sinica*, 7, 815-840.
- Mather, P.M. 2004. Computer processing of remotely-sensed images, 3rd ed. West Sussex, England: John Wiley and Sons Ltd. pp. 1-324.
- Monaco, M.E. and S.C. Rooney. 2004. MBES data acquisition and processing report: Project NF-04-06-VI, NOAA Data Acquisition and Processing Report, NOS NCCOS CCMA (On-line).
- Patterson, D. 2008. Split Layer by Attributes. ESRI Support Center. Online: <http://arcscripts.esri.com/details.asp?dbid=14127>. Accessed August, 2009.
- Prada, M.C., R.S. Appeldoorn and J.A. Rivera. 2008. Improving Coral Reef Habitat Mapping of the Puerto Rico Insular Shelf Using Side Scan Sonar. *Marine Geodesy*. 31, 49-73.
- Robinson, D.J., N.J. Redding and D.J. Crisp. 2002. Implementation of a fast algorithm for segmenting SAR imagery, Scientific and Technical Report, 01 January 2002. Australia: Defense Science and Technology Organization.
- Shih, Y-S. 2004. QUEST User's Manual. National Chung Cheng University, Taiwan. p 28. Online: <http://www.stat.wisc.edu/~loh/treeprogs/quest/questman.pdf>. Accessed September 2009.
- StatSoft, Inc. 2007. Electronic Statistics Textbook (Classification Trees). Tulsa, OK. Online: <http://www.statsoft.com/textbook/stclatre.html#computation2>. Accessed September, 2009.
- Tchoukanski, I. 2008. ET Geo Wizards 9.8 for ArcGIS 9.2. ET Spatial Techniques. Pretoria, South Africa. Online: <http://www.ian-ko.com/>. Accessed September, 2009.
- Wright, D.J., E.R. Lundblad, E.M. Larkin, R.W. Rinehart, J. Murphy, L. Cary-Kothera and K. Draganov. 2005. ArcGIS Benthic Terrain Modeler (BTM). Corvallis, Oregon. Oregon State University, Davey Jones Locker Seafloor Mapping/Marine GIS Laboratory and NOAA Coastal Services Center. Online: <http://www.csc.noaa.gov/products/btm/>. Accessed September, 2009.

This page intentionally left blank.

CHAPTER 3: ASSESSMENT OF CLASSIFICATION ACCURACY

A comprehensive assessment was conducted to evaluate the thematic accuracy of the St. John benthic habitat map. Thematic accuracy was characterized for major and detailed geomorphological structure, major and detailed biological cover, and percent coral cover classifications (see Chapter 1 for classification scheme description).

3.1. FIELD DATA COLLECTION

Target locations for the accuracy assessment (AA) procedure were determined by an iterative, GIS-based, stratified random sampling technique to ensure that all bottom classifications would be assessed. Points were randomly placed within each geomorphological structure class of the draft habitat map using Hawth's Analysis Tools (Beyer, 2004). No buffer from polygon edges was used. A minimum of 25 points were randomly distributed within each detailed structure class. Classes occupying larger areas were often allocated more than 25 points. A total of 325 sample locations were targeted, of which 299 were sufficiently surveyed to be included in the accuracy assessment.

Data were collected over a field mission from 5/31/09 to 6/7/09. Sample locations were navigated to using a hand-held Garmin 76 CS WAAS-enabled GPS unit. Underwater video from a SeaViewer Sea-Drop 950 camera was taken at each site. A weight was tied to the bottom of the camera to help lower the camera to the bottom, and the camera operator adjusted the camera position to get a downward and side view of the habitat at each location. Video length depended on the habitat type and vessel drift, ranging from approximately 30 seconds to two minutes. Videos of large, homogeneous sand habitats were generally short while heterogeneous coral reef habitats (especially edges) were typically longer. While the video was being recorded, GPS waypoints were recorded on board the vessel using a Trimble GeoXT GPS receivers. This resulted in a string of epics that tracked boat position at each site. An observer categorized each site according to the video for each level of the map classification scheme: major/detailed geomorphological structure, major/detailed biological cover, and percent coral. Data was entered into a custom data dictionary on the Trimble data logger and recorded on waterproof data sheets. Videos were recorded to tape using a Sony Walkman video recorder, and converted to digital video clips using Final Cut Pro software.

3.2. EVALUATION OF ASSESSMENT DATA

The GPS data were processed using Trimble Pathfinder software. GPS data, which were originally recorded as code phase signals, were differentially post-processed to the Continually Operating Reference System (CORS) station at St. Thomas, U.S. Virgin Islands (VITH). For each survey site, individual epics were averaged to generate an "average" GPS point. The GPS data were then exported and plotted in ArcGIS along with the corresponding field notes. In most cases, the average point was a sufficient representation of the survey site; however in cases where the survey was conducted along or crossed a polygon edge, the average GPS point did not always fall into the polygon that was assessed. In these cases, the survey point was shifted to the portion of the transect and polygon that was classified.

Prior to analysis, each video clip was re-analyzed and viewed in concert with the benthic habitat map overlaid on the acoustic imagery. It should be noted that all analysis at this stage was made by a scientist independent of the cartographer who created the map. Density of the biological cover was assessed at the video level and patchiness of the biological cover polygon level. As a result, it was often necessary to adjust the classifications that were initially recorded in the field to reconcile the differences between the video and map scales. Similar adjustments were sometimes necessary to correctly characterize detailed structure. For example, heterogeneous hardbottom classes, such as pavement with sand channels, could not always be correctly classified from the video alone. In other cases, additional information on the position, size and shape of hardbottom features was needed to determine whether the structure should be classified as aggregate reef or a patch reef (either individual or part of an aggregated patch reef feature, if below the MMU).

Following these adjustments, data were then spatially joined to the benthic habitat layer to extract the map classification for each point. Sites that differed between field notes and map classification were evaluated both in GIS and from video to determine possible source of disagreement. At this stage, a couple of map-wide issues were identified resulting from a difference in general interpretation between the cartographer and the scientist conducting the accuracy assessment. For example, patch reefs and aggregate reef were not always classified

in the same way. In addition, there were certain areas of the map that could not be sufficiently classified under the current scheme. Following discussion, it was decided that an additional habitat class be created called: *Rhodoliths with Scattered Coral and Rock*. The map was edited to resolve these differences before the accuracy assessment was conducted.

3.3. ANALYSIS OF THEMATIC ACCURACY

The thematic accuracy of the St. John benthic habitat map was characterized in several ways from these data. Error matrices were computed for the attributes major and detailed geomorphological structure, major and detailed biological cover, and percent coral cover. Overall accuracy, producer's accuracy, and user's accuracy were computed directly from the error matrices (Story and Congalton, 1986). The error matrices were constructed as a square array of numbers arranged in rows (map classification) and columns (accuracy assessment, or ground-truthed classification). The overall accuracy (P_o) was calculated as the sum of the major diagonal (i.e. correct classifications, divided by the total number of accuracy assessment samples).

The producer's and user's accuracies were calculated to characterize the classification accuracy of individual map categories. The producer's accuracy (omission/exclusion error) is a measure of how well the cartographer classified a particular habitat (e.g., the percentage of times that substrate ground-truthed as sand was correctly mapped as sand). The user's accuracy (commission/inclusion error) is a measure of how often map polygons of a certain habitat type were classified correctly (e.g., the percentage of times that a polygon classified as sand was actually ground-truthed as sand). Each diagonal element was divided by the column total to yield a producer's accuracy and by the row total to yield a user's accuracy.

In addition, the Tau coefficient (T_e), a measure of the improvement of classification accuracy over a random assignment of map units to map categories (Ma and Redmond, 1995), was calculated. As the number of categories increases, the probability of random agreement (P_r) diminishes, and T_e approaches P_o . Values of T_e were calculated as follows:

$$\text{Tau coefficient} = T_e = (P_o - P_r) / (1 - P_r),$$

where $P_r = 1/r$. The variance of Tau (Ma and Redmond 1995) was calculated as:

$$\text{Variance of Tau coefficient} = \sigma_r^2 = P_o(1 - P_o) / n(1 - P_r)^2$$

Confidence intervals were then calculated for each Tau coefficient at the 95% confidence level ($1-\alpha$), using the following generalized form:

$$95\% \text{ CI} = T_e \pm Z_{\alpha/2}(\sigma_r^2)^{0.5}$$

While stratification ensures adequate evaluation of all map categories, it has the undesired effect of introducing bias into the error matrix (Hay 1979; Card 1982). A minimum number of sites were targeted within each mapping category, which caused rare map categories to be sampled at a greater rate than common map categories. For example, although *Rhodoliths* habitat comprised 77% of the map area, only 44% of the target points were allocated for this habitat. Conversely, *Aggregated Patch Reefs* comprised only 3% of the map area, but received 13% of the allocated target sample points. The bias introduced by differential sampling rates was removed using the method of Card (1982), which utilizes the known map marginal proportions (i.e. the proportional areas of map categories relative to the total map area). The map marginal proportions were calculated as the area of each map category divided by the total mapped area of the St. John benthic habitat map. The map marginal proportions were also utilized in the computation of confidence intervals for the overall, producer's, and user's accuracies (Card 1982; Congalton and Green, 1999). This method was also used in the recent accuracy assessment of the NOAA Florida Keys benthic habitat map (Walker and Foster, 2009) and the NOAA shallow-water St. John habitat map (Zitello et al., 2009).

The known map marginal proportions (π_j) were computed from the GIS layer of the draft benthic habitat map for each of the four error matrices (major and detailed geomorphological structure, major and detailed biological cover), by dividing the area of each category by the total map area. Marginal proportions were not computed for the percent coral cover matrix, as this would have required an estimate of the percent hardbottom within each

polygon to truly estimate the area of live coral. The map areas were exclusive to categories present in the error matrix. For the example of detailed structure category *Rhodoliths*, π_i was 0.77 (69.9 km²/90.2 km²). The individual cell probabilities, i.e. the product of the original error matrix cell values and π_j , divided by the row marginal (total map classifications per category), were computed for the off-diagonal elements using the following equation:

$$\text{Individual cell probabilities} = \hat{P}_{ij} = \pi_j n_{ij} / n_{-j}$$

The relative proportions of the cell values within a row of the error matrix were unaffected by this operation, but the row marginals were forced to the known map marginal proportions (i.e. the row total of a particular habitat now equaled the fraction of map area occupied by that habitat, instead of the total number of accuracy assessment points). The estimated true marginal proportions (p_i) were computed as the sum of individual cell probabilities down each column of the error matrix.

The π_j -adjusted overall, producer's, and user's accuracies were then computed from the new error matrix, now populated by individual cell probabilities. The values of the π_j -adjusted overall and producer's accuracies differ by design from those of the original error matrix, as they have been corrected for the areal bias introduced by the stratified random sampling protocol. The user's accuracy, in contrast, is not affected. The variances and confidence intervals of the overall, producer's, and user's accuracies were then computed from the following set of equations (Card 1982; Walker and Foster, 2009):

$$\text{Overall Variance} = V(\hat{P}_c) = \sum_{i=1}^r p_{ii} (\pi_i - p_{ii}) / n_i$$

$$\text{Overall Confidence Interval} = \text{CI} = \hat{P}_c \pm 2[V(\hat{P}_c)]^{1/2}$$

$$\text{Producer's Variance} = V(\hat{\theta}_{ii}) = p_{ii} p_i^{-4} [p_{ii} \sum_{j \neq i} p_{ij} (\pi_j - p_{ij}) / n_{-j} + (\pi_i - p_{ii})(p_i - p_{ii})^2 / n_{i-j}]$$

$$\text{Producer's Confidence Interval} = \text{CI} = \hat{\theta}_{ii} \pm 2[V(\hat{\theta}_{ii})]^{1/2}$$

$$\text{User's Variance} = V(\hat{\lambda}_{ii}) = p_{ii} (\pi_i - p_{ii}) / \pi_i^2 n_i$$

$$\text{User's Confidence Interval} = \text{CI} = \hat{\lambda}_{ii} \pm 2[V(\hat{\lambda}_{ii})]^{1/2}$$

3.4 ACCURACY ASSESSMENT RESULTS AND DISCUSSION

Major Geomorphological Structure

Error matrices for major geomorphological structure are displayed in Tables 3.1 and 3.2. The overall accuracy (P_o) at the major geomorphological structure level was 96% (Table 3.1). The Tau coefficient for equal probability of group membership is 0.913 ± 0.046 ($\alpha=0.05$). The error matrix in Table 3.2 is populated by the individual cell probabilities (p_{ij}), which in review are the product of the original error matrix cell values (Table 3.1) and the map marginal proportions, divided by the row marginal of the original matrix (i.e., total map classifications per category). The adjusted overall accuracy, corrected for bias using the true map marginal proportions, was virtually identical at 95.7 (± 2.3)% ($\alpha=0.05$). The user's

Table 3.1. Error matrix for major geomorphological structure.

		Accuracy Assessment (i)		
Map data (j)		Hard	Soft	n_j
	Hard	264	11	275
	Soft	2	22	24
	n_i	266	33	n=299
	Producer's Accuracy (%)	99.2%	66.7%	$P_o = 95.7\%$
				$T_e = 0.913 \pm 0.046$

accuracies were similarly high for both hard and softbottom habitats, while producer's accuracy was markedly lower for softbottom than hardbottom (Table 3.2). Eleven sites located in polygons that were mapped as hardbottom were determined to be softbottom in the accuracy assessment. This was primarily due to confusion between *Sand* and *Rhodoliths* (Section 1.3 Geomorphological Structure Types (pg. 4)).

Detailed Geomorphological Structure

Error matrices for detailed geomorphological structure are displayed in Tables 3.3 and 3.4. The overall accuracy (P_o) at the detailed geomorphological structure level was 88.3%, with a Tau coefficient (T_e) of 0.868 ± 0.041 ($\alpha=0.05$) (Table 3.3). The adjusted overall accuracy, corrected for bias using the true map marginal proportions, was similar at 88.7 (± 4.4)% ($\alpha=0.05$), which indicated that the classes that covered the most area were also the most correctly interpreted.

User's accuracy was above 80% for all categories (Table 3.3). No systematic errors were evident. The user's accuracy of the *Sand with Scattered Coral and Rock* class could not be assessed as no points were located in mapped areas of this structure type. Other categories with relatively low sampling effort include *Aggregate Reef*, *Individual Patch Reef*, and *Rhodoliths with Scattered Coral and Rock*, classes that also comprise a small percentage of the total map. These categories were likely undersampled due to changes in the draft map and classification scheme following collection of the ground-truth and accuracy assessment data.

Table 3.2. Error matrix for major geomorphological structure using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the true map marginal proportions.

		Accuracy Assessment (i)			
		hard	soft	π_j	User's Accuracy (%)
Map data (j)	hard	0.8872	0.0370	0.9242	96.0%
	soft	0.0063	0.0695	0.0758	91.7%
	p_i	0.8935	0.1065	$\pi=1$	
	Producer's Accuracy (%)	99.3%	65.3%	$P_o = 95.7\%$	
	Producer's CI ($\pm\%$)	1.0%	13.7%	$CI(\pm) = 2.3\%$	

Table 3.3. Error matrix for detailed geomorphological structure.

		Accuracy Assessment (i)										
		Aggregate Reef	Aggregated Patch Reefs	Individual Patch Reef	Pavement	Pavement with Sand Channels	Rhodoliths	Rhodoliths w/ SCR	Sand	Sand w/ SCR	n _j	User's Accuracy (%)
Map data (j)	Aggregate Reef	10		1							11	90.9%
	Aggregated Patch Reefs		32	1	1		2	2			38	84.2%
	Individual Patch Reef			9							9	100.0%
	Pavement	3	1	1	49		3		1		58	84.5%
	Pavement with Sand Channels	2			0	17					19	89.5%
	Rhodoliths				4		117	1	7	3	132	88.6%
	Rhodoliths w/ SCR							8			8	100.0%
	Sand						2		22		24	91.7%
	Sand w/ SCR									0	0	n/a
n _i		15	33	12	54	17	124	11	30	3	n=299	
Producer's Accuracy (%)		66.7%	97.0%	75.0%	90.7%	100.0%	94.4%	72.7%	73.3%	0	P _o = 88.3%	
T _e = 0.868 ± 0.041												

Table 3.4. Error matrix for detailed geomorphological structure using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the true map marginal proportions.

Accuracy Assessment (i)													
	Aggregate Reef	Aggregated Patch Reefs	Individual Patch Reef	Pavement	Pavement with Sand Channels	Rhodoliths	Rhodoliths w/ SCR	Sand	Sand w/ SCR	π_j	User's Accuracy (%)	User's CI ($\pm\%$)	
Map data (j)	Aggregate Reef	0.0206		0.0021						0.0226	90.9%	17.3%	
	Aggregated Patch Reefs		0.0313	0.0010	0.0010		0.0020	0.0020		0.0372	84.2%	11.8%	
	Individual Patch Reef			0.0036						0.0036	100.0%	0.0%	
	Pavement	0.0032	0.0011	0.0011	0.0527		0.0032		0.0011	0.0624	84.5%	9.5%	
	Pavement with Sand Channels	0.0006				0.0048				0.0054	89.5%	14.1%	
	Rhodoliths				0.0235		0.6868	0.0059	0.0411	0.0176	0.7748	88.6%	5.5%
	Rhodoliths w/ SCR							0.0183			0.0183	100.0%	0.0%
	Sand						0.0063		0.0692		0.0755	91.7%	11.3%
	Sand w/ SCR										0.0003	n/a	n/a
π_i	0.0244	0.0324	0.0077	0.0772	0.0048	0.6982	0.0261	0.1114	0.0176	$\pi=1$			
Producer's Accuracy (%)	84.4%	96.7%	46.5%	68.3%	100.0%	98.4%	70.0%	62.1%	n/a	$P_o = 88.7\%$			
Producer's CI ($\pm\%$)	13.1%	12.4%	29.4%	20.7%	0.0%	1.4%	32.2%	17.2%	n/a	$CI(\pm) = 4.4\%$			

Adjusted and un-adjusted producer's accuracy was very high (>95%) for several classes, including *Rhodoliths*, *Pavement with Sand Channels*, and *Aggregated Patch Reefs* Categories with the lowest adjusted producer's accuracy include *Individual Patch Reef*, *Pavement*, *Rhodoliths with Scattered Coral and Rock*, and *Sand* (Table 3.4). In all cases, there was a high degree of variance. Several points ground-truthed as *Sand* or *Sand with Scattered Coral and Rock* were mapped as *Rhodoliths*. These errors were the primary reason for the lower producer's accuracy for unconsolidated sediment at the major structure level.

Major Biological Cover

Error matrices for major biological cover are displayed in Tables 3.5 and 3.6. The overall accuracy (P_o) at the major biological cover level was 95.3%, with a Tau coefficient (T_e) of 0.930 ± 0.036 ($\alpha=0.05$). The adjusted overall accuracy, corrected for bias using the true map marginal proportions, was similar at 95.0 (± 2.3)% ($\alpha=0.05$).

Both producer's and user's accuracy were high for *Algae*. The primary source of confusion was between *Algae* and *No Cover*, which resulted in slightly lower accuracy for the *No Cover* category. The number of accuracy assessment points for *Live Coral* was too few to robustly assess this category. The low sample size was due to the rarity of polygons mapped where coral was mapped as the dominant cover. However, a better assessment of the accuracy of mapped coral cover will be discussed in the subsection Percent Coral Cover (pg. 46).

Table 3.5. Error matrix for major biological cover.

Map data (i)	Accuracy Assessment (i)				User's Accuracy (%)
	No Cover	Live Coral	Algae	n_j	
	No Cover	15	7	22	68.2%
	Live Coral		1	1	100.0%
	Algae	7	269	276	97.5%
n_i	22	1	276	$n=299$	
Producer's Accuracy (%)	68.2%	100.0%	97.5%	$P_o = 95.3\%$	
					$T_e = 0.930 \pm 0.036$

Detailed Biological Cover

Error matrices for detailed biological cover are displayed in Tables 3.7 and 3.8. The overall accuracy (P_o) at the detailed biological cover level was 74.2%, with a Tau coefficient (T_e) of 0.678 ± 0.062 ($\alpha=0.05$). The adjusted overall accuracy, corrected for bias using the true map marginal proportions, was similar at 74.0 (± 5.2)% ($\alpha=0.05$).

The greatest source of confusion at the detailed biological cover level was degrees of density/patchiness within *Algae* categories. For example, the adjusted user's and producer's accuracy of the *Algae* 10% - <50% were 68.2% and 31.1%, respectively (Table 3.8). Of the 21 sites interpreted to have 10% - <50% patchiness in the accuracy assessment, only three had been mapped as that category. The remaining 18 points were had been mapped as *No Cover*, *Algae* 50% - <90%, and *Algae* 90% - 100%. Producer's accuracy was also low (62.2% adjusted) for *Algae* 50-90%, primarily due to confusion with *Algae* 90%-100%.

Percent Coral Cover

The error matrix for percent coral cover is displayed in Table 3.9. The overall accuracy (P_o) at the detailed biological cover level was 88.3%, with a Tau coefficient (T_e) of 0.844 ± 0.049 ($\alpha=0.05$). As mentioned previously, a second matrix using the true map marginal proportions, was not computed for percent coral cover.

Two of the possible coral categories were primarily present in the map and accuracy assessment data (<10% and 10% - <50%) Only one location had coral cover of 50% - <90%. Accuracy was very high for the softbottom habitats, where a low amount of coral is to be expected. There was lower accuracy for percent coral on hardbottom habitats. The decision between <10% and 10% - <50% is often difficult to determine, especially if there is a mix of octocorals and sclerectinians. As such, user's accuracy of 10% - <50% coral on hardbottom was only 56.4%. Since percent coral cover was recorded at all sites regardless of whether it was the dominant cover type, this is a better measure of coral accuracy than is found under Major Cover (pg. 13).

3.5 CONCLUSIONS

Accuracy for detailed geomorphological structure and biological cover were both high, although accuracy was better for structure than cover. There are several possible reasons for this result. The first is that the poor quality of the intensity imagery in some areas prevented the cartographer from accurately mapping biological cover on the seafloor. Second, it is possible that the semi-automated technique may be better at picking out signatures for

Table 3.6. Error matrix for major biological cover using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the true map marginal proportions.

		Accuracy Assessment (i)					
Map data (j)		No Cover	Live Coral	Algae	$\pi_{.j}$	User's Accuracy (%)	User's CI (\pm)
	No Cover	0.0456		0.0213	0.0669	68.2%	19.9%
	Live Coral		0.0028		0.0028	100.0%	0.0%
	Algae	0.0284		0.9019	0.9303	96.9%	2.1%
	$p_{i.}$	0.0740	0.0028	0.9232	$\pi=1$		
	Producer's Accuracy (%)	61.6%	100.0%	97.7%	$P_o = 95.0\%$		
	Producer's CI (\pm)	17.5%	0.0%	1.4%	$CI(\pm) = 2.3\%$		

Table 3.7. Error matrix for detailed biological cover.

		Accuracy Assessment (i)						
		No Cover 90% - 100%	Live Coral 50% - <90%	Algae 90% - 100%	Algae 50% - <90%	Algae 10% - <50%	n _j	User's Accuracy (%)
Map data (j)	No Cover 90% - 100%	15				7	22	68.2%
	Live Coral 50% - <90%	0	1				1	100.0%
	Algae 90% - 100%	3		127	45	6	181	70.2%
	Algae 50% - <90%	3		6	76	5	90	84.4%
	Algae 10% - <50%	1			1	3	5	60.0%
	n _i	22	1	133	122	21	n=299	
Producer's Accuracy (%)		68.2%	100.0%	95.5%	62.3%	14.3%	P _o = 74.2%	
								T _e = 0.678 ± 0.062

Table 3.8. Error matrix for detailed biological cover using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the true map marginal proportions.

Accuracy Assessment (i)									
		No Cover 90% - 100%	Live Coral 50% - <90%	Algae 90% - 100%	Algae 50% - <90%	Algae 10% - <50%	π_j	User's Accuracy (%)	User's CI (\pm)
Map data (j)	No Cover 90% - 100%	0.0456				0.0213	0.0669	68.2%	19.9%
	Live Coral 50% - <90%		0.0028				0.0028	100.0%	0.0%
	Algae 90% - 100%	0.0097		0.4113	0.1457	0.0194	0.5862	70.2%	1.9%
	Algae 50% - <90%	0.0100		0.0201	0.2541	0.0167	0.3010	84.4%	3.8%
	Algae 10% - <50%	0.0086			0.0086	0.0259	0.0432	60.0%	35.8%
π_i		0.0740	0.0028	0.4314	0.4085	0.0833	$\pi=1$		
Producer's Accuracy (%)		61.6%	100.0%	95.3%	62.2%	31.1%	$P_o = 74.0\%$		
Producer's CI (\pm)		19.7%	0.0%	3.5%	6.6%	18.2%	$CI(\pm) = 5.2\%$		

structure than for cover. In addition, the way cover was classified (i.e., as a combination of both density and polygon-wide distribution) could have influenced this outcome as well.

Although the classification schemes are not directly comparable due to region-specific categories, the level of accuracy for detailed structure was similar to that of recent NOAA shallow-water benthic habitat maps in St. John (85.7% [88.8% adjusted], Zitello et al., 2009), the Florida Keys (86.2% [91.5% adjusted], Walker and Foster, 2009), Palau (90.0%, Battista et al., 2007b), and the Main Hawaiian Islands (90.0%, Battista et al., 2007^a).

Table 3.9. Error matrix for major geomorphological structure and percent live coral cover.

Accuracy Assessment (i)							
Map data (j)	Softbottom, Coral <10%	Hardbottom, Coral <10%	Hardbottom, Coral 10% - <50%	Hardbottom, Coral 50% - <90%	n _j	User's Accuracy (%)	
	Softbottom, Coral <10%	22	2	0	0	24	91.7%
	Hardbottom, Coral <10%	11	219	5	0	235	93.2%
	Hardbottom, Coral 10% - <50%	0	17	22	0	39	56.4%
	Hardbottom, Coral 50% - <90%	0	0	0	1	1	100.0%
	n _i	33	238	27	1	n=299	
Producer's Accuracy (%)		66.7%	92.0%	81.5%	100.0%	P _o = 88.3%	
							T _e = 0.844 ± 0.049

Comparisons with other accuracy assessments at the biological cover level are difficult due to the differences in the classification scheme and how cover was assessed. With the exception of the new shallow-water map for St. John, previous mapping efforts utilized a hierarchical classification scheme to characterize biological cover, in comparison to the dominance based scheme used here. In addition, due to inherent differences in the structure and biological cover types present in shallow vs. moderate-depth environments, the classification schemes vary accordingly. For instance, several classes that were present in the shallow-water map (e.g., *Rock Outcrop*, *Boulder*, *Spur and Groove*) were not present in the deep environment. In contrast, rhodoliths dominated the deep shelf environment, and were often interdispersed with patch reefs or scattered coral and rock. Further, biological cover levels were a product of both density and polygon-wide patchiness in the deep shelf map.

LITERATURE CITED

- Battista, T.A., B.M. Costa, and S.M. Anderson. 2007^a. Shallow-Water Benthic Habitats of the Main Eight Hawaiian Islands. NOAA Technical Memorandum NOS NCCOS 61, Biogeography Branch. Silver Spring, MD.
- Battista, T.A., B.M. Costa and S.M. Anderson. 2007^b. Shallow-Water Benthic Habitats of the Republic of Palau. NOAA Technical Memorandum NOS NCCOS 59, Biogeography Branch. Silver Spring, MD.
- Beyer, H.L. 2004. Hawth's Analysis Tools for ArcGIS. Online: <http://www.spatialecology.com/htools>. Accessed September 2009.
- Card, D.H. 1982. Using known map categorical marginal frequencies to improve estimates of thematic map accuracy. *Photogrammetric Engineering and Remote Sensing*, 48, 431-439.
- Congalton, R.G. and K. Green. 1999. *Assessing the Accuracy of Remotely Sensed Data: Principles and Practices*. CRC/Lewis Press, Boca Raton, FL. 137 pp.
- Hay, A.M. 1979. Sampling designs to test land use map accuracy. *Photogrammetric Engineering and Remote Sensing*, 45, 529-533.
- Ma, Z. and R.L. Redmond. 1995. Tau coefficients for accuracy assessment of classification of remote sensing data. *Photogrammetric Engineering and Remote Sensing*, 61, 435-439.
- Story, M. and R. Congalton. 1986. Accuracy assessment: A user's perspective. *Photogrammetric Engineering and Remote Sensing*, 52, 397-399.
- Walker, B.K. and G. Foster. 2009. Final Report: Accuracy Assessment and Monitoring for NOAA Florida Keys mapping: AA ROI-1 (near American Shoal). National Coral Reef Institute, Nova Southeastern University, Dania Beach, FL. 32 pp.
- Zitello, A.G., L.J. Bauer, T.A. Battista, P.W. Mueller, M.S. Kendall and M.E. Monaco. 2009. Benthic Habitats of St. John, U.S. Virgin Islands. NOAA Technical Memorandum NOS NCCOS 96, Biogeography Branch. Silver Spring, MD.

CHAPTER 4: CONCLUSION

NOAA’s Biogeography Branch, with support from the U.S. National Park Service, has completed benthic habitat mapping and subsequent field validation and accuracy assessment of the moderate-depth marine environment south of St. John, U.S. Virgin Islands. An independent accuracy assessment revealed overall map accuracies to be over 95% for major structure and cover classes, and over 88% and 74% for detailed structure and cover classes, respectively. As a result, these digital map products can be used with confidence by scientists and resource managers for a multitude of different applications. The scientific and management communities have used previous NOAA benthic habitat maps to structure monitoring programs, support management decisions, and establish and manage marine conservation areas in coral reef ecosystems. The final delivery consisted of the benthic habitat maps in several formats and all ancillary data generated in support of map creation. These items are listed in Table 4.1 with a description of the format type and quantity when appropriate.

Table 4.1. Final deliverable items for NOAA’s moderate-depth benthic habitat map of St. John. Additional information is provided describing the item, its format and quantity.

ITEM	FORMAT	QUANTITY
Benthic Habitat Map	GIS	1,283 polygons
Acoustic Imagery	GIS	11 images
Interactive Map Project	Online	-
Ground Validation Dataset	GIS	117 locations & 13 transects
Accuracy Assessment Dataset	GIS	299 locations
Video of Seafloor	.mov or .wmv	432 videos
Final Report	PDF	1
FGDC-compliant Metadata for GIS Files	Text	17 files

4.1 MAP SUMMARY STATISTICS

In total, 90.2 km² of the seafloor was mapped in and around the VICRNM. Of this 90.2 km², 43.2 km² fell inside and 47.0 km² fell outside the VICRNM boundaries. Several patterns emerged when examining the summary map statistics for the total mapped area, as well as the mapped area inside and outside the park boundaries. These patterns are discussed in more detail below.

Total Mapped Area

In looking at major structure, *Coral Reef and Hardbottom* constituted the majority of the total mapped area (91.8%), while *Unconsolidated Sediment* only comprised a small fraction of this area (Table 4.2; Figure 4.1). *Coral Reef and Hardbottom* constituted the majority of the mapped area because the *Rhodoliths* habitat type dominated the entire moderate-depth region south of St. John. If the *Rhodoliths* category is excluded, the *Coral Reef and Hardbottom* category only accounted for 14.9% of the total mapped area. After *Rhodoliths*, *Sand* was

Table 4.2. Summary statistics describing the total amount (and percent) of mapped area by major and detailed geomorphological structure types. These numbers are further divided into the amount of mapped area inside and outside the VICRNM.

	GEOMORPHOLOGICAL STRUCTURE	TOTAL AREA (km ²) INSIDE VICRNM	TOTAL AREA (km ²) OUTSIDE VICRNM	TOTAL AREA (km ²) MAPPED	% OF TOTAL MAPPED AREA
Major Structure	Coral Reef and Hardbottom	39.4	43.4	82.8	91.8
	Unconsolidated Sediment	3.83	3.59	7.4	8.23
Detailed Structure	Aggregate Reef	0.24	2.31	2.6	2.83
	Aggregated Patch Reefs	2.13	1.22	3.4	3.72
	Individual Patch Reef	0.21	0.13	0.3	0.39
	Pavement	3.07	2.02	5.1	5.64
	Pavement with Sand Channels	0.11	0.37	0.5	0.53
	Rhodoliths	32.8	36.6	69.4	76.9
	Rhodoliths with Scattered Coral and Rock	0.87	0.79	1.7	1.84
	Sand	3.74	3.57	7.3	8.11
	Sand with Scattered Coral and Rock	0.09	0.02	0.1	0.12
	Total Area (km ²) Mapped	43.2	47.0	90.2	100

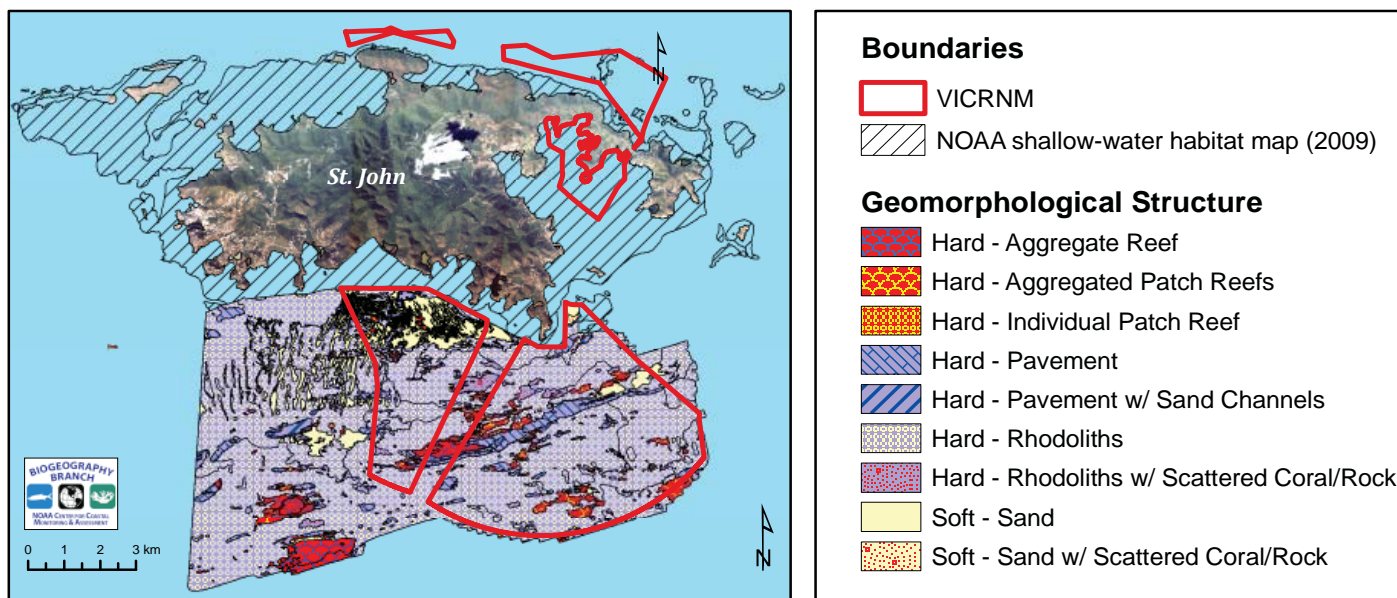


Figure 4.1. This figure depicts the major and detailed geomorphological structure of the moderate-depth area that was mapped using acoustic imagery south of St. John. The black hatched polygon denotes the area mapped using optical imagery. The red polygons show the boundaries of the VICRNM.

the second most dominant detailed structure type, followed respectively by: (3) *Pavement*, (4) *Aggregated Patch Reefs*, (5) *Aggregate Reef*, (6) *Rhodoliths with Scattered Coral and Rock*, (7) *Pavement with Sand Channels*, (8) *Individual Patch Reef*, and (9) *Sand with Scattered Coral and Rock*. Although ecologically significant, *Individual Patch Reefs* and *Aggregated Patch Reefs* comprised just over 4% of the moderate-depth habitat that was mapped south of St. John.

In looking at major biological cover, *Algae* colonized the majority of the total mapped area (92.8%) (Table 4.3; Figure 4.2). *Algae* dominated this moderate-depth region because this category included any combination of numerous types of red, green, or brown algae that were turf, fleshy, filamentous or crustose coralline species. After *Algae*, *No Cover* was the second most dominant major cover type, followed respectively by *Seagrass* and *Live Coral*. When the percent cover modifier is added to the calculations, *Algae 90% - 100%* colonized the majority of the total mapped area (54.8%), followed respectively by *Algae 50% - <90%*, *No Cover 90% - 100%*, *Algae 10% - <50%*, *Live Coral 50% - <90%* and *Seagrass 50% - <90%* and *90% - 100%*. The area colo-

Table 4.3. Summary statistics describing the total amount (and percent) of mapped area by major and detailed biological cover type as well as by amount of live coral cover. These numbers are further divided into the amount of mapped area inside and outside the VICRNM.

	BIOLOGICAL COVER	TOTAL MAPPED AREA (km ²) INSIDE VICRNM	TOTAL MAPPED AREA (km ²) OUTSIDE VICRNM	TOTAL MAPPED AREA (km ²)	% OF TOTAL MAPPED AREA
Major Cover	Algae	39.9	43.8	83.7	92.8
	Live Coral	0.00	0.25	0.25	0.28
	No Cover	3.36	2.93	6.28	6.97
	Seagrass	0.02	0.02	0.04	0.04
Detailed Cover	Algae 10% - <50%	2.03	2.29	4.32	4.79
	Algae 50% - <90%	11.7	18.2	29.9	33.2
	Algae 90% - 100%	26.1	23.3	49.4	54.8
	Live Coral 50% - <90%	0.00	0.25	0.25	0.28
	No Cover 90% - 100%	3.36	2.93	6.28	6.97
	Seagrass 50% - <90%	0.02	0.01	0.02	0.02
	Seagrass 90% - 100%	0.00	0.02	0.02	0.02
Live Coral Cover	0% - <10%	42.9	45.4	88.3	97.9
	10% - <50%	0.39	1.33	1.72	1.91
	50% - <90%	0.00	0.25	0.25	0.28
	Total Area (km²) Mapped	43.2	47.0	90.2	100

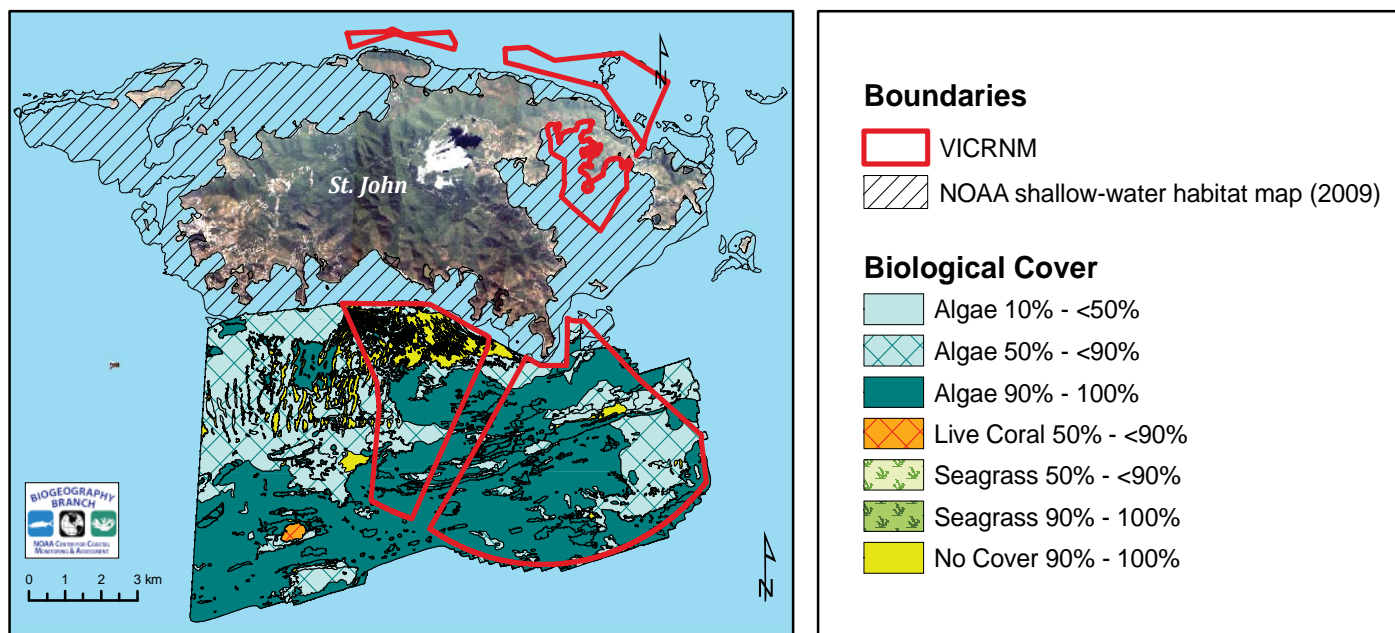


Figure 4.2. This figure depicts the major and detailed biological cover of the moderate-depth area that was mapped using acoustic imagery south of St. John. The black hatched polygon denotes the area mapped using optical imagery. The red polygons show the boundaries of the VICRNM.

nized by *Live Coral 50% - <90%* is the only polygon of its kind within the mapped area. This polygon is located in the southwestern part of the mapped area between 26 and 37 m in depth (Figure 4.3). Except for this one polygon, the majority of the mapped area (97.9%) was colonized by 0% - <10% live scleractinian and/or soft corals. Only 2 km² (or 2.2%) of the mapped area was colonized by coral covers greater than or equal to 10%.

Total Mapped Area Outside VICRNM Boundaries

In looking at major structure, *Coral Reef and Hardbottom* also constituted the majority of the mapped area inside the VICRNM boundaries (92.4%), while *Unconsolidated Sediment* only comprised a small fraction (7.6%). *Coral Reef and Hardbottom* again constituted the majority of the mapped area inside the VICRNM boundaries because *Rhodoliths* were the dominant habitat type outside the park boundaries. If the *Rhodoliths* category is excluded, *Coral Reef and Hardbottom* only accounts for 14.6% of the mapped area outside the VICRNM boundaries. After *Rhodoliths*, *Sand* was the second most dominant detailed structure type (just as it was for the total mapped

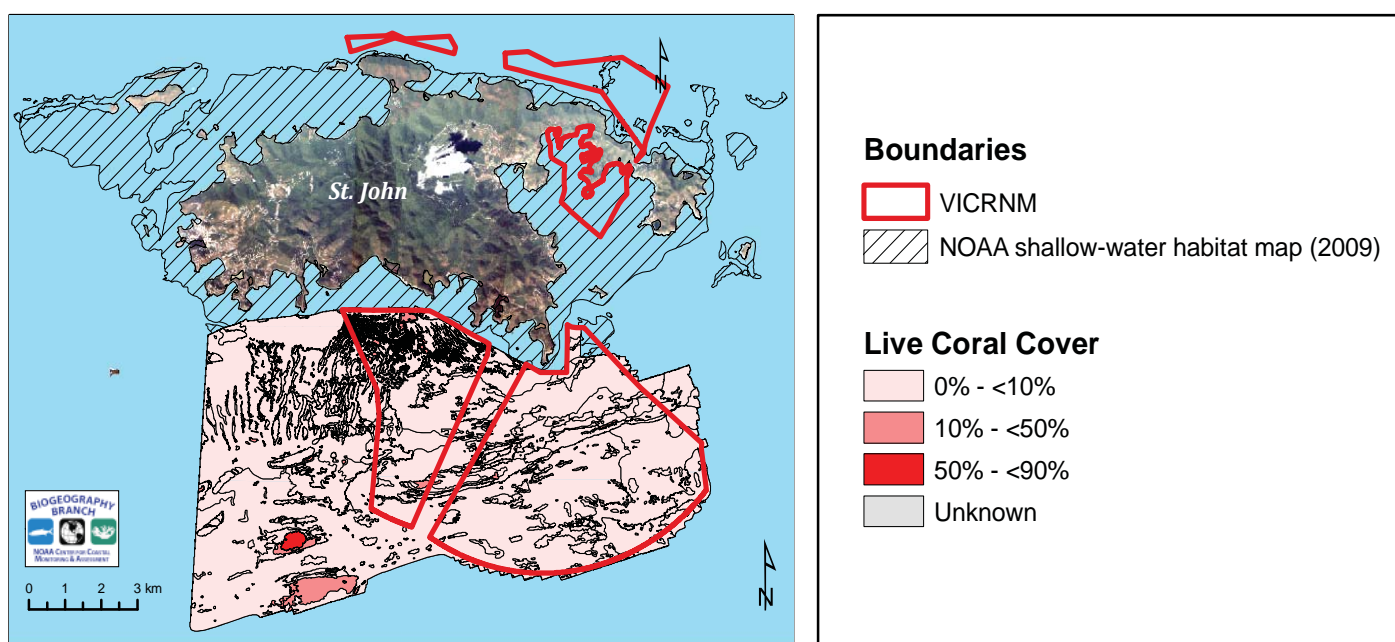


Figure 4.3. This figure depicts the amount of live coral cover present in the moderate-depth area that was mapped using acoustic imagery south of St. John. The black hatched polygon denotes the area mapped using optical imagery. The red polygons show the boundaries of the VICRNM.

area) followed respectively by: (3) *Aggregate Reef*, (4) *Pavement*, (5) *Aggregated Patch Reefs*, (6) *Rhodoliths with Scattered Coral and Rock*, (7) *Pavement with Sand Channels*, (8) *Individual Patch Reef*, and (9) *Sand with Scattered Coral and Rock*. Although ecologically significant, *Individual Patch Reefs* and *Aggregated Patch Reefs* again only comprised approximately 3% of the moderate-depth habitat mapped outside the VICRNM boundaries.

In looking at major biological cover, *Algae* colonized the majority of the mapped area outside the VICRNM boundaries (93.2%). Again, *Algae* dominated the mapped area outside the VICRNM boundaries because this category included any combination of numerous types of turf, fleshy, filamentous or crustose coralline algal species. After *Algae*, *No Cover* was the second most dominant major cover type, followed respectively by *Live Coral* and *Seagrass*. When the percent cover modifier is added to the calculations, *Algae 90% - 100%* colonized the majority of the mapped area outside the park boundaries (49.5%), followed respectively by *Algae 50% - <90%*, *No Cover 90% - 100%*, *Algae 10% - <50%*, *Live Coral 50% - <90%*, *Seagrass 90% - 100%* and *Seagrass 50% - <90%*. The area colonized by *Live Coral 50% - <90%* is the only polygon of its kind within the mapped area outside the VICRNM boundaries (and within the mapped area as a whole). Except for this one polygon, the majority (96.6%) of the mapped area outside the VICRNM boundaries was colonized by *0% - <10%* live corals. Only 1.6 km² (or 3.4%) of the mapped area outside the VICRNM was colonized by coral covers greater than or equal to 10%.

Total Mapped Area Inside VICRNM Boundaries

In looking at major structure, *Coral Reef and Hardbottom* also constituted the majority of the mapped area inside the VICRNM boundaries (91.1%), while *Unconsolidated Sediment* only comprised a small fraction (8.9%), because rhodoliths dominated the seafloor inside the park boundaries. If the *Rhodoliths* category is excluded, the *Coral Reef and Hardbottom* category only accounted for 15.3% of the mapped area within the VICRNM boundaries. After *Rhodoliths*, *Sand* was the second most dominant detailed structure type (just as it was for the total mapped area). This detailed structure type was followed respectively by: (3) *Pavement*, (4) *Aggregated Patch Reefs*, (5) *Rhodoliths with Scattered Coral and Rock*, (6) *Aggregate Reef*, (7) *Individual Patch Reef*, (8) *Pavement with Sand Channels*, and (9) *Sand with Scattered Coral and Rock*. Although ecologically significant, *Individual Patch Reefs* and *Aggregated Patch Reefs* again only comprised 5.4% of the moderate-depth habitat mapped inside the VICRNM boundaries.

In looking at major biological cover, *Algae* colonized the majority of the mapped area inside the VICRNM boundaries (92.2%). Again, *Algae* dominated the area inside the VICRNM boundaries because this category included any combination of numerous types of turf, fleshy, filamentous or crustose coralline algal species. After *Algae*, *No Cover* was the second most dominant major cover type, followed respectively by *Seagrass* and *Live Coral*. When the percent cover modifier is added to the calculations, *Algae 90% - 100%* colonized the majority of the mapped area inside the park boundaries (60.4%), followed respectively by *Algae 50% - <90%*, *No Cover 90% - 100%*, *Algae 10% - <50%*, and *Seagrass 50% - <90%*. No polygons within the VICRNM boundaries were dominated by live coral. The majority (99.1%) of the mapped area inside the VICRNM boundaries was colonized by *0% - <10%* live scleractinian and/or soft corals. Only 0.4 km² (or 0.9%) of the mapped area inside the VICRNM was colonized by coral covers greater than or equal to 10%.

Comparing Total Mapped Areas Inside and Outside VICRNM Boundaries

The mapped areas inside and outside the VICRNM followed the same general trends for major and detailed structure types. In particular, the seafloor both outside and inside the park boundaries was dominated by *Coral Reef and Hardbottom* habitat because *Rhodoliths* were ubiquitous on the shelf south of St. John. When *Rhodoliths* were removed from the calculation, roughly 15% of both areas were covered by *Coral Reef and Hardbottom*. In terms of detailed structure, both areas had the same diversity of structure types represented, although the quantity of these structure types differed slightly. In particular, the mapped area outside the VICRNM boundaries had approximately: (1) 4.3% more *Aggregate Reef*, (2) 2.0% more *Rhodoliths*, and (3) 0.5% more *Pavement with Sand Channels* than did the mapped area inside the VICRNM boundaries. The mapped area inside the VICRNM boundaries, on the other hand, had approximately: (1) 2.8% more *Pavement*, (2) 2.3% more *Aggregated Patch Reefs*, (3) 1.1% more *Sand*, (4) 0.3% more *Rhodoliths with Scattered Coral and Rock*, (5) 0.2% more *Individual Patch Reef*, and (6) 0.2% more *Sand with Scattered Coral and Rock* than did the mapped area outside the VICRNM boundaries.

The mapped areas inside and outside the VICRNM followed the same general trends for major and detailed biological cover types. In general, *Algae* colonized the majority of the mapped area both inside and outside the VICRNM boundary, with *No Cover* being the second most common cover category. Both areas were also dominated by continuous, high density algae (*Algae* 90% - 100%), followed respectively by *Algae* 50% - <90%, *No Cover* 90% - 100%, and *Algae* 10% - <50%. The mapped area outside the park boundary did, however, have 11.7% more *Algae* 50% - <90% and 10.9% less *Algae* 90% - 100% than the mapped area inside the VICRNM boundary.

In terms of coral cover, the majority (>96%) of both areas were colonized by 0% - <10% live scleractinian and/or soft corals. It is important to note, however, that the mapped area outside the VICRNM had one 0.25 km² polygon dominated by live coral (i.e., *Live Coral* 50% - <90%), whereas the mapped area inside the VICRNM did not. In addition to this one polygon, the mapped area outside the park was found to have 1.9% more *Live Coral* 10% - <50% habitat than the mapped area inside the VICRNM. This difference suggests that there is slightly more live coral outside (than inside) the current VICRNM boundaries south of St. John.

4.2 INTEGRATION WITH SHALLOW-WATER NOAA HABITAT MAPS OF ST. JOHN

In 2009, NOAA's Biogeography Branch has successfully mapped the majority of the shallow-water (< 30 m) benthic habitats and a significant portion of the moderate-depth (30 – 60 m) benthic habitats around St. John in the U.S. Virgin Islands. The moderate-depth benthic habitat map begins at the optical limit of the shallow-water map, and continues to the edge of the acoustic imagery. Integration of the shallow-water and moderate-depth maps will provide NPS with one seamless benthic habitat map, extending from the shoreline of St. John southward to the 55 m isobath.

The integration of these two maps is possible, given that the same general habitat classification schemes and MMUs were applied to both habitat maps. That being said, the differences between these two maps must be thoroughly understood, in order to recognize the limitations associated with using such an integrated map. Most notably, the important differences between the two maps include: (1) slightly different definitions of *Pavement*, (2) different definitions of *Algae*, and (3) different methods used to quantify percent biological cover. These classification differences and their potential ramifications are discussed in more detail in the following paragraph.

Pavement, first of all, is defined as an area of “flat, low-relief solid carbonate rock with little or no fine-scale rugosity” in the shallow-water scheme. In the moderate-depth scheme, *Pavement* is defined as an area of “flat, low-relief or sloping solid carbonate rock with little or no fine-scale rugosity.” Thus, in the shallow-water scheme, *Pavement* does not have relief, whereas in the moderate-depth classification scheme, *Pavement* may be sloping. These differing degrees of slope may influence the physical oceanography of an area, which in turn may affect the zonation and distribution patterns of corals (Geister, 1977; Sheppard, 1982; Done, 1983).

Algae, secondly, is defined as an area dominated by “any combination of numerous species of red, green, or brown algae that may be turf, fleshy or filamentous species” in the shallow-water scheme. In the moderate-depth scheme, *Algae* is defined as an area of “any combination of numerous species of red, green, or brown algae that may be turf, fleshy, filamentous or crustose coralline species.” Thus, in the shallow-water scheme, the *Algae* class does not include crustose coralline species, whereas in the moderate-depth classification scheme, the *Algae* class does include these algal types. As a result, the *Algae* and *Coralline Algae* classes should be merged together in the shallow-water habitat map, if it is to be integrated with the moderate-depth habitat map.

Lastly, in the shallow-water scheme, the percent biological cover modifier represents a measure of the level of patchiness of the biological cover at the scale of the $\geq 1,000$ m² habitat feature. It does not represent the density of biological cover observed by divers in the water. The moderate-depth classification scheme, on the other hand, quantified percent biological cover by accounting for both the density of biological cover at the scale of the 4 m² pixel and the patchiness of biological cover at the scale of the $\geq 1,000$ m² habitat feature. This methodological difference caused some polygons in the shallow-water map to have higher percent covers than spatially coincident polygons in the moderate-depth map. Thus, the percent biological cover modifiers are not directly comparable in both maps, and should be viewed independently.

4.3 THE NEXT GENERATION OF MAPPING

The majority of shallow-water coral reef habitats have been successfully characterized at high thematic resolutions (≤ 32 classes) by conducting heads-up digitizing and interpretation of high resolution ($\leq 4 \times 4$ m) imagery (Kendall et al., 2001; Battista et al., 2007^a; Battista et al., 2007^b). These resulting maps, however, are time-intensive to produce, limited by the size of the minimum mapping unit, and ultimately subjective and irreproducible because they depend on the accuracy and interpretation of the person that is digitizing.

Other studies have also successfully mapped marine habitats using pixel-based semi-automated classification techniques (Maeder et al., 2002; Mishra et al., 2006; Purkis et al., 2006). While these methods are more objective and reproducible than heads-up digitizing, they are not synoptic and easily scalable to coral reef areas of different sizes. Changing environmental conditions also inhibit these methods from producing maps with thematic accuracies and resolutions high enough to meet the needs of most marine resource managers.

In order to address these difficulties and increase the repeatability and efficiency with which maps are produced, the Biogeography Branch has been experimenting with alternative techniques to automate the process of delineating and attributing features on the seafloor. This moderate-depth map represents the Biogeography Branch's first attempt to create a benthic habitat map from acoustic imagery using this new semi-automated methodology. Results from this moderate-depth mapping effort suggest that this new mapping approach is 7x more time efficient (and just as thematically accurate) as heads-up habitat delineation and attribution (Table 4.4). Additionally, less than 40% of the polygons created using the semi-automated method were manually edited (Tables 2.7 and 2.8 (pg. 36)), suggesting that the majority of the moderate-depth map produced using this method is completely reproducible.

Table 4.4. Estimated time required to map St. John's shallow-water habitats using the heads-up digitizing and attribution method, and St. John's moderate-depth habitats using the semi-automated delineation and classification technique. These numbers were used to estimate of the number of square kilometers that were mapped per hour using each technique.

Mapping Method	Area Mapped (km ²)	Estimated Time (hours)*	Estimated Area Mapped (km ²) per Hour
Manual Heads-up Digitizing and Attribution	53.4	571	0.09
Semi-automated Delineation and Attribution	90.2	120	0.75
Total Difference	-36.8	451	-0.66

*This number only includes the time needed to delineate and attribute habitat features in the imagery. It does not include the time required for image processing, field work, data processing, expert reviews as well as report and product generation.

These initial results indicate that this new semi-automated approach has the potential to increase the repeatability and efficiency with which maps are produced. The ability to quickly, accurately and objectively create benthic habitat maps would transform the process of mapping from a static, resource inventory tool to a dynamic, resource monitoring tool. By doing so, resource managers would be able to more frequently assess the changing distribution (and ultimately, health) of the coral reef systems that they manage. Improving our understanding of these ecosystems is the key to identifying and mitigating the heterogeneous threats that face these important and precious resources.

LITERATURE CITED

- Battista, T. A., B.M. Costa and S.M. Anderson. 2007^a. Shallow-water benthic habitats of the main eight Hawaiian islands. NOAA Technical Memorandum NOS NCCOS 61(Online).
- Battista, T.A., B.M. Costa and S.M. Anderson. 2007^b. Shallow-Water Benthic Habitats of the Republic of Palau. NOAA Technical Memorandum NOS NCCOS 59 (Online).
- Done, T. J. 1983. Coral zonation: Its nature and significance. In D. J. Barnes (ed.), Perspectives on coral reefs. Australian Institute of Marine Science and Brian Clooston, Manuka, ACT, Australia. pp. 107-147.
- Geister, J. 1977. The influence of wave exposure on the ecological zonation of Caribbean coral reefs. Proceedings of the 3rd International Symposium on Coral Reefs, 1, 23-29.
- Kendall, M.S., M.E. Monaco, K.R. Buja, J.D. Christensen, C.R. Kruer, M. Finkbeiner and R.A. Warner. 2001. Methods used to map the benthic habitats of Puerto Rico and the U.S. Virgin Islands. NOAA Technical Report (Online).
- Maeder, J., S. Narumainai, D.C. Rundquist, R.L. Perk, J. Schalles, K. Hutchins and J. Keck. 2002. Classifying and Mapping General Coral-Reef Structure Using IKONOS Data. Photogrammetric Engineering and Remote Sensing 1297-1305.
- Mishra, D., S. Narumaiani, D. Rundquist and M. Lawson .2006. Benthic Habitat Mapping in Tropical Marine Environments Using QuickBird Multispectral Data. Photogrammetric Engineering and Remote Sensing, 1037-1048.
- Purkis, S.J., S.W. Myint and B.M. Riegl. 2006. Enhanced detection of the coral *Acropora cervicornis* from satellite imagery using a textural operator. Remote Sensing of Environment, 101: 82-94.
- Sheppard, C. R. C. 1982. Coral populations on reef slopes and their major controls. Marine Ecology Progress Series, 7, 83-115.

This page intentionally left blank.

ACKNOWLEDGEMENTS

Funding for this study was provided by NOAA's Coral Reef Conservation Program. This report would not have been possible without the numerous people who shared their data, information and time throughout this process. We appreciate the support of U.S. National Park Service staff including Rafe Boulon, Jeff Miller and Peter Laurencin. We also appreciate the support of the crew and officers onboard the NOAA ship *Nancy Foster*, as well as many scientists at NOAA's National Undersea Research Program (NURP) and National Marine Fisheries Service (NMFS). Also, many thanks to Randy Clark for helping to collect ground validation and accuracy assessment data in the field, and to Jamie Higgins for organizing the content of this report.

United States Department of Commerce

Gary Locke
Secretary

National Oceanic and Atmospheric Administration

Jane Lubchenco
Administrator

National Ocean Service

John H. Dunnigan
Assistant Administrator

