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Interpretation of Seafloor Topologies Based on IKONOS Satellite Imagery of a Shallow-Marine Carbonate Platform: Florida Bay to the Florida Reef Tract

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ABSTRACT

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The shallow low-energy waters of the extensive coastal zone in sub-tropical south Florida permits the discrimination of seabed features and benthic covers acquired from remotely sensed data. A benthic environments classification system is devised from digital interpretations of multi-spectral IKONOS satellite imagery for 1,360 km^2 of the carbonate platform and presented in a comprehensive digitized map. The classification scheme is designed as a 7th order hierarchical structure that integrates 5 Physiographic Realms, 17 Morphodynamic Zones, 11 Geoforms, 38 Landforms, 6 dominant surface sediment types, 9 dominant biological covers and 3 densities of biological covers for the description of benthic environments. Digital analysis of the high-resolution (4 m) IKONOS imagery employed ESRI's ArcMap to manually digitize 412 mapping units at a scale of 1:6,000. Digital classification of environments is executed by the analyst contingent with the grouping of relative spectral reflectance, color tone variations, and the texture and pattern of the benthic unit. The mapping area incorporates a large diversity of geomorphic forms that range from coastal plains in the southern Florida Peninsula to coral reef formations along the Florida Reef Tract (FRT). The context of each Morphodynamic Zone is characterized by the content and areal distribution (in km^2) of geomorphic forms and biological covers. Florida Bay is the most widely distributed Realm and is largely characterized by polygonal lattices of salient sediment banks and sediment flats. Over 58% of the mapping area is occupied by sediment flats, and seagrasses are colonized in almost 80% of the topologies.

ADDITIONAL INDEX WORDS: *Remote Sensing, coastal geomorphology, benthic environments, GIS, digital analysis, morphodynamic zones, landforms, surface sediments, biological cover, coral reefs, Florida Keys, Hawk Channel, spectral reflectance.*

INTRODUCTION

Degradation to vulnerable shallow sub-tropical marine ecosystems from natural and anthropogenic disturbances in south Florida have acute repercussions to the resource base. Habitat modification, pollution, and resource overexploitation from human interventions continues to affect the ecological conditions and biodiversity of south Florida's dynamic estuary (Diaz, Solan, and Valente, 2004). The term *benthic* is a division of the classification of marine environments that includes the areas on or in the floor of an ocean that is distinguished by its physical, chemical, and biological facets (modified from IHO). The natural benthic environments serve as a multi-niche component in the sustainability of the coastal zone and support a large diversity of marine life that use the area for spawning and nursing, refuge, and foraging, sustain tolerable water quality and cycling nutrients, and even influence the depositional environment of sediments (*i.e.* Ginsburg and Lowenstam, 1958) and tidal ranges.

Preserving south Florida's natural ecosystem involves qualitative and quantitative investigation of the system's components, how they are distributed, and how they change over

The spectral reflectance of marine substrates in shallow waters that are registered by satellite sensors are commonly employed today to delineate and map various benthic environments of valuable coastal ecosystems. Delineation of benthic facets can assist management groups with using informed decisions concerning the areal extent of marine environments and their associated benthos. This study is in accordance with the distinction between benthic mapping and benthic habitat mapping. According to Andrews (2003), benthic mapping is defined as general seafloor mapping for identification of regional geologic features and morphology. The purpose of this research is to use 4 m resolution multispectral satellite data (IKONOS) to interpret, delineate, and map various shallow-marine benthic environments in south Florida's carbonate platform.

Study Area

The 1360 km^2 of the study area is bounded in the north by the south-central Florida Peninsula, progressing southward into the interior section of Florida Bay, through the High and Low Coral

Keys (White, 1970) of the Florida Keys and nearshore environments, into Hawk Channel, and terminates after the FRT (Figure 1). Along the southern peninsula of Florida, the bays and bights located in the boundaries of the study from west to east include; Snake Bight, Garfield Bight, Rankin Bight, Santini Bight, Terrapin Bay, Madeira Bay, Little Madeira Bay, Alligator Bay, and part of Joe Bay and David Cove. The islands of the Florida Keys included in the study from the southwest to northeast are; Long Key, Matacumbe Keys, Indian Key, Lignumvitae Key, Shell Key, Islamorada, and Windley Key. The study area was chosen because of its richness in seafloor diversity and variations from both an east-west and north-south cross-section. Using 1,360 km^2 for this study is the result of three overlapping and contiguous north-south oriented IKONOS satellite images of good quality and generally cloud free coverage.

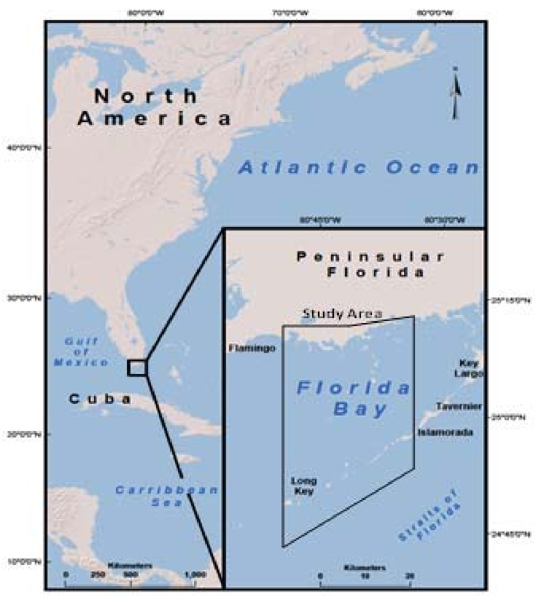

Figure 1. Index map showing location of mapping area in the south Florida carbonate platform, U.S.A.

BENTHIC ENVIRONMENT MAP: METHODS

The methodology used to delineate and produce a classified benthic environments map for south Florida's shallow-marine carbonate platform is a 7 step process: (1) acquire satellite imagery to create mapping area and process images, (2) develop a classification system of the seafloor environments for the scale and resolution of the imagery, (3) delineate and digitize boundaries to produce a draft map, (4) make *in situ* observations of indiscriminate benthic environments from digital interpretations, (5) make corrections to attribute table according to *in situ* observations, (6) edit and create topology rules for 0% overlap and gaps, and lastly (7) formulate a legend (modified from Andrews, 2003).

Image Selection and Display

A total of 16 IKONOS images were downloaded from the National Oceanic and Atmospheric Administration's (NOAA) Center for Coastal Monitoring and Assessment (CCMA) website using 8 swaths. For each IKONOS swath, both multispectral and true color images were downloaded for interpretation and provide 4 m and 1 m spatial resolutions, respectively. Albeit the IKONOS sensor has internal processing software during image collection (Dial *et al*., 2003), subsequent to image acquisition the contrast and brightness of pixels for each satellite image varied and needed to be adjusted for each image in order to display a continuous and similar tone for homogenous seafloor environments that merge into adjacent images. This step, yet important, is continuously adjusted during large-scale delineation processes of environments, to better display the contrast between their boundaries. In addition to the continuous contrast adjustments, the IKONOS images were stretched and filtered with Idirisi. Isolating the green (2) and red (3) bands of the images, using linear saturation and Gaussian stretches, and 3X3 and 5X5 filters augmented the contrast between deeper water environments on the Atlantic side of the Florida Keys.

Classification of Benthic Environmnents

The development of an explicit classification to south Florida's carbonate platform environments requires the definition, interpretation (from the IKONOS images), and inventory of both small and large-scale bottom types. A preliminary 'shopping-list' of benthic materials was interpreted from the images to determine the detail and complexity of environments to be classified. From the broad and general division of the study area to a more detailed description, this classification defines benthic environments according to 5 Physiographic Realms and 17 Morphodynamic Zones, 11 Geoforms and 38 Landforms, 6 types of surface sediment cover, and a combination of 9 biological covers (Table 1). The classification synthesizes site-specific with previously used mapping units in which some have been partially modified according to the context and scale.

When mapping units are aggregated and the dominant class of the aggregate is assigned as the attribute, the precision and efficacy for monitoring and conservation groups to use the product diminishes (Finkl, 1994). In efforts to avoid this problem, the classification of benthic environments was modified from Finkl (1994) who incorporated land systems, landforms, and land facets for the Broward Coastal Zone (BCZ). The land systems are similar to the Morphodynamic Zones, in which there is a recurring pattern of landforms and vegetation throughout. Adopting this method to benthic mapping of south Florida enhances the thematic detail of the overall system and provides a more relevant depiction (closer to reality) and representation of the complex nature of the real world.

Raster Analysis and Vector Digitizing

Digital enhancements, seafloor interpretations, digitizing boundaries, map production, and spatial analysis were completed with ESRI's ArcMap. Effectively identifying and mapping benthic environments with high-spatial and –spectral resolution IKONOS images requires that the various environments are discriminated by there spectral reflectance characteristics (Hochberg and Atkinson, 2000). The fundamental focus of the analyst is to isolate the portion of upwelling radiance of light which penetrates the atmosphere, water column, dissolved organic material, turbidity, and is reflected from bottom features (Maritorena, Morel and Gentili, 1994; Dobson and Dustan, 2000). Raster analysis for this project incorporates the visual grouping of spectral signatures at a given scale. Digital classification of environments is defined by the ability of the

Table 1: Classification table of benthic environments for mapping units in the south Florida carbonate platform.

(I) Physiographic Realm	(II) Morphodynamic Zone	(III) Geoform	(IV) Landform	(V) Dominant Surface Sediment	(VI) Dominant Biological Cover	(VII) Percent Biological Cover
1. Distal/Southern-	1. Southern Slope	1. Coral Reefs	1. Barrier	1. No-	10. Live Coral	-
Florida	2. Marsh Prairies		2. Patch	Sediment	2. Seagrass	1. Continuous
	3. Bay Coastal-		3. Aggregate	(Exposed		(>66%)
	Lagoons		4. Apron	Rock)		2. Patchy
	4. Reticulate Coastal-	2. Hardbottom	1. Subtidal Pavement			(33-66%)
	Swamp	3. Islands	1. Bay Key	2. Mud		3. Scattered
2. Florida Bay	1. Degrading Banks/		2. Karst			(<33%)
	Low Tannic Acids		4. Isthmus	3. Sand	3. Macroalgae	1. Continuous
	2. Migrational Banks/		5. Spit		(Algal Bloom)	(>66%)
	Moderate Tannic-	4. Sediment-	1. Rippled	4. Mixed		2. Patchy
	Acids	Flat	2. Planar Bed Form	Sand and		(33-66%)
	3. Constructional-		3. Structural	Mud		3. Scattered
	Banks/High-		4. Intertidal			(<33%)
	Tannic Acids	5. Sediment-	1. Intertidal	5. Coral	40. Wetlands	-
	4. Destructional-	Bank	2. Flanking Subtidal	Rubble	5. Mangrove	1. Continuous
	Banks/Mixed-		3. Beach			(>66%)
	Waters		5. Reticulated Intertidal	6. Wrack		2. Patchy
3. Florida Keys	1. High Coral Key		6. Reticulated Subtidal	(Litter)		(33-66%)
	2. Low Coral Key	6. Ridge Field	1. Discrete			3. Scattered
	3. Fringing Bayside		2. Complex			(<33%)
	4. Fringing Atlantic	7. Channel	1. Tidal		6. Juvenile	1. Continuous
	5. Transitional		2. Distributary		Mangrove	(>66%)
	6. Nearshore Rock-		3. Paleochannel			2. Patchy
	Ledge		4. Seafloor			(33-66%)
4. Hawk Channel	1. Parabathic Shelf		5. Creek			3. Scattered
5. Florida Reef-	1. Back Reef		6. Moat			(<33%)
Tract	2. Outer Reef		7. Back Reef Trough		7. Hardwoods	1. Continuous
6. Others	1. Dredged		8. Reef Gap			(>66%)
	2. Urban	8. Delta	1. Ebb-Tidal			2. Patchy
	3. Cloud Cover		2. Flood-Tidal			(33-66%)
	4. Suspended-	9. Peninsula/	1. Intertidal Flat			3. Scattered
	Sediment	Coastal Plain	2. Supratidal Flat			(<33%)
	5. Unknown		3. Point of Land		80. Un-	-
		10. Pond/Lake	1. Circular		colonized	
			2. Oblate		9. Epiphytes	-
			3. Irregular			
		11. Bight	1. Bay			
			2. Cove			

interpreter to distinguish relative spectral reflectance, color tone variations, and the texture and pattern of the benthic unit. The tone of a pixel or pixels refers to the relative brightness or color of objects from the IKONOS data, and classified according to three conditions; light, medium, and dark (Sulong *et al.,* 2002). The analyst uses texture as an index of similarity of a connected set of pixels that is a function of the frequency or variance of brightness values (Dobson and Dustan, 2000). Texture is then the frequency of tonal changes on the data and is classified into coarse, medium, and fine (smooth) (Sulong *et al*., 2002).

The vector data model was employed to represent an area of similar seafloor composition with a closed polygon that defines the boundary of that particular environment (Andrews, 2003). Creating polygons promotes the development of an attribute table that lists each environment's component of the classification for that digitized polygon, along with its areal extent (m^2). This also enables a spatial query of benthic distribution to be completed. There was no minimum mapping unit (MMU) used for benthic delineation, however, digitizing polygons at a scale of 1:6,000 provided sufficient resolution to reduce map generalization and still yield great thematic detail.

Thematic Editing

Subsequent to the completion of a draft map in which the entire study area is covered by thouroughly attributed discrete polygons, *in situ* observations of unknown seafloor types from digital interpretations are used to confine and correct misinterpreted environments. Polygons that were digitized for the draft map delineate the boundaries between contrasting environments. Therefore, reclassification of incorrect environments only requires changing the polygon's attribute for the landform, sediment cover, and biological cover. Each of the components in the attribute table represent thematic layers (facets) of benthic environments that are synthesized into a comprehensive map yielding 7th order hierarchical mapping units.

RESULTS

This research employs the south-Florida-specific classification of benthic environments to digitally delineate and analyze the areal distribution of seafloor bottom types. The focus of this study is to emphasize the different morphostructures in unique realms and zones with respect to the hydrographic and geologic conditions that largely regulate the construction and destruction of geomorphic forms, sedimentation, and biologic colonization of the benthic environment. The delineation of mapping units is described by the digital analysis (interpretation) of texture and color tones for various benthic materials. The results yield an amalgamatation of the thematic layers of the classification of benthic environments into a comprehensive map product.

Delineation of Benthic Facets

The most generalized element of the classification of benthic environments that geographically defines the unique domain under which prominent geomorphic forms and controlling processes are distinguishable from adjacent domains, are the Physiographic Realms (White, 1970). The Morphodynamic Zones are larger-scale subdivisions within a Realm that are distinguished by a more detailed content of processes that host either distinct forms, or distinct areal distribution of forms. The realms and zones refer to only the benthic environment's location and does not imply the type of form, surface sediment, or biological cover of the detailed environment. The organization and delineation of realms and zones are completed with local knowledge of the spatial distribution of endemic forms, and modified from previous delineations of regional studies.

The context of a Physiographic Realm and Morphodynamic Zone consists of a unique landscape that is characterized by the spatial distribution and abundance of certain geologic forms. The Geoform is delineated as the generalized structure of the benthic environment that varies in composition and areal distribution. Landforms are larger-scale variations of the Geoforms that are defined by their geometry (planform shape and size), composition (*i.e*. indurated rock vs. unconsolidated sediments), and location with respect to sea-level (brightness values due to water depth, *i.e.* subtidal, intertidal, supratidal). Therefore the detailed Landforms were delineated as a group of similar pixel patterns in regards to brightness values and color tones that were interpreted as a field of homogeneous composition and elevation/bathymetry. Boundaries of the Landforms were digitized where a sharp contrast in pixel patterns occurred.

The delineation of the different types of biological covers is completed in the same manner as the Geoforms and Landforms. Each of the biological types digitally display inherent textural patterns and color-tone variations that are interpreted from the IKONOS images. The biological covers included in the classification of benthic environments incorporate emergent vegetation as well as submerged aquatic vegetation (SAV). Topologies with seagrass, macroalgae (and algal blooms), mangroves and juvenile mangroves, and hardwoods are further classified according to their percentage or density of the area they have colonized (continuous, patchy, scattered).

The digital interpretation of Landforms and biologic covers incorporates the textural grouping of similar brightness values and color tones, however, the delineation of surface sediments from 1 m and 4 m resolution data can only be differentiated between fine sediments (mud and sand) and larger coral rubble. The spectral difference between mud and sand does not provide sufficient spectral differentiation for the delineation of the two different carbonaceous grain sizes. Therefore, the distinction between carbonate mud and carbonate sand spatial associations within zones that are influenced by currents and waves that fractionates grain sizes through the depositional process. Grain size analyses (based on percent weight) of benthic sediments at selected locations correlate with results of previous studies that differentiated mud from sand in the mapping area (Ginsburg, 1956; Lynts, 1966; Enos, 1977; Enos and Perkins, 1979; Bosence, 1989). Because the grain size distribution patterns are highly variable within the study area (see Bosence 1989), surface sediment attributes for benthic environments lists the **dominant** grain size.

Comprehensive Benthic Enviroment Map

The final benthic environment map (Figure 2) characterizes mapping units that integrate 5 Physiographic Realms and 17 Morphodynamic Zones, 11 Geoforms and 38 Landforms, 6 types of surface sediment, and 9 biological covers in a 1360 km^2 study are of the south Florida carbonate platform. Subsequent to digitizing a benthic environment, each polygon is assigned a code in the attribute table for the shapefile according to the classification. Each number of the code is hierarchical and reflects one of the components in each of the columns of the classification table (Table 1). Interpreting and delineating benthic environments at a scale of 1:6,000 resulted in the classification of nearly 6,000 polygons within the boundaries of the study area. The synthesis of the seven thematic layers of the benthic environment classification produced 412 mapping units. The entire mapping area is visible at a scale of 1:335,000, and therefore not all of the large-scale polygons can be seen at such a small-scale.

Legend Acquisition

Given the complexity and diversity of environments in the study area, color cannot be used alone to symbolize each unit. Each of the Landforms in the classification is attributed a specific symbol that in planform, and theoretically, reflect the true shape or pattern of that unit. Biological covers are assigned a specific family of colors that vary in brightness according to their densities interpreted from the satellite images. The same combination of

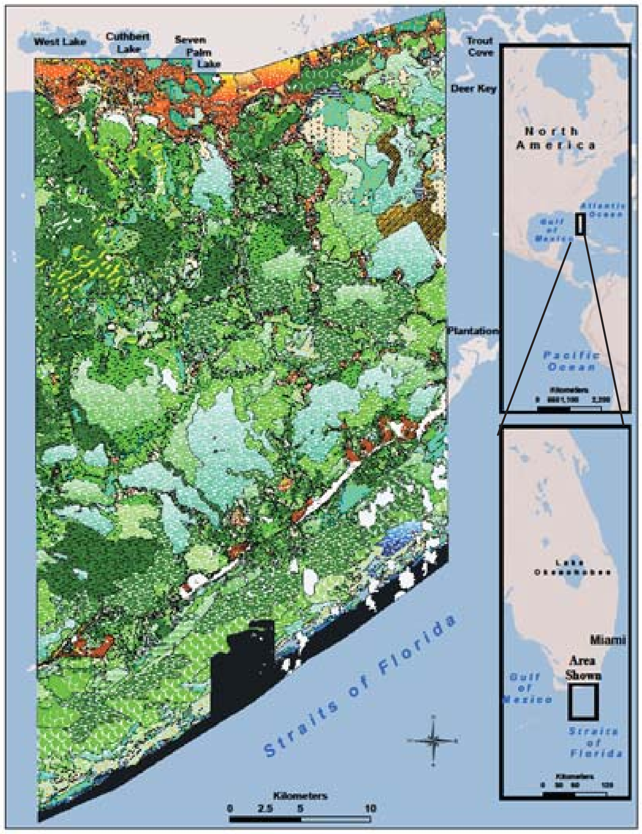

Figure 2. Amalgamation of thematic layers synthesized into a comprehensive and classified benthic environments map of the south Florida carbonate platform.

landform, surface sediment, and biological cover are found in several different realms and zones. According to the constructed legend, two polygons of the same combination of form, sediment, and biology are represented by the same symbol and color. The complete classification of benthic environments of the study area produced 412 individual units, assigning that many different symbols and colors would deprive a reader of comprehension and literacy of the map. Also, one of the purposes of this project is to analyze the areal extent and spatial distribution of detailed environments within the context of the study area. Therefore having the same symbol and color in different zones visually supports the quantitative data of landforms and biologic covers.

As noted earlier, each mapping unit is assigned seven attributes that are combined together to describe the unit as a numerical code. Each number in the code indicates the unit's individual components for each column in the hierarchical classification. For example, a mapping unit with a code of '2151323' represents a seafloor topology in the Florida Bay Realm (2) and Degrading Banks/Low Tannic Acids Zone (1), sediment bank (5), intertidal bank (1), with mud surface sediments (3), and colonized with seagrass (2) in a scattered cover (3) (see Table 1).

ANALYSIS

The results of this study incorporate the synthesis of the thematic layers of the classification system, which can then be broken down into individual components that assist the spatial analyst to characterize contexts by the content of the benthic environment. The focus of this section is to examine and quantify the spatial distribution of detailed benthic environments (*i.e*. forms, surface sediment, and biological covers) that were interpreted from the IKONOS imagery (and field work), according to the Realms and Zones. Dissolving the mapping area into discrete zones facilitates the spatial querying and characterization of larger-scale landscapes within smaller-scale contexts. The sum areas of each of the classification components for mapping units are summarized in the attribute table to determine the percentage of their distribution in the context of the study area, and for each of the Morphodynamic Zones.

Characterization of a 1,360 km^2 study area is challenging because of natural diversity in the region and because the classification system must per force reflect a wide range of morphodyanmic processes and geomorphic features (*e.g*. Geoforms and Landforms). However, identifying the unique Morphodynamic Zones and site-specific geomorphic features not only implies increased thematic accuracy in representing the ecosystem, it also models how this ecosystem is differentiated from others around the world. To properly describe the context of the study area requires a multi-faceted approach that is achieved in the hierarchy of the classification system specifically devised for this study area.

DISCUSSION

Using imagery that is acquired during different periods of the year can yield a misleading representation of the system due to the unconformable coverages. Benthic environments may significantly change along the intertidal zone or low-lying islands over the course of a few months due to storm activity for example. However, Mumby and Edwards (2002) indicate that the disparities between acquisition dates and *in situ* observations are found to be negligible. They indicate that (1) the environments observed in the field do not migrate tens of meters in 4 years, (2) each waypoint was located in a single habitat patch of at least a 20 m radius, and (3) the location of each point was checked on the imagery to avoid any small misregistration between image and field coordinates. There were however, many discrepancies with overlapping IKONOS images that revealed a certain benthic environment in one coverage and was completely different in another (*e.g*. ponds/lakes on bay key islands). This discrepancy is eliminated with reconnaissance studies that use contiguous and conformable coverages. Furthermore, to the problems generated by the discrepancies of unconformable imagery for digital interpretations of benthic covers, color tones and texture is also affected. Mumby and Edwards (2002) conclude that even though the IKONOS data cannot accurately identify many benthic habitats (environments for the purpose of this study) spectrally, the boundaries of environment topologies are mapped with much greater accuracy than other satellite sensors. Therefore, the efficacy of using IKONOS imagery to map seafloor topologies is justified as a result of textural detail, and the discussion remains on the thematic accuracy of the benthic classification.

CONCLUSIONS

Four meter resolution multi-spectral IKONOS satellite images were digitally analyzed to catalogue, classify, and map various benthic environments. Digital classification of detailed environments is executed contingent with the grouping of relative spectral reflectance, color tone variations, and the texture and pattern of the benthic topology. The results of this study yield a comprehensive benthic environment map viewed entirely at a scale of 1:35,000. Albeit the transformation of two-dimensional digital data into a classified map inherently generalizes mapping units, the IKONOS images proved to provide sufficient resolution and spectral information in the classification of a complex carbonate platform. Utilizing GIS for benthic environment mapping provides a time and cost efficient approach that not only identifies discrete seafloor topology boundaries, but also facilitates in the analysis of benthic distribution over large areas. Digital analysis of the comprehensive map also provides the user to pan through the dataset at various scales in which each topology's thematic layers can be quickly identified. This advantage accommodates for a complex classification scheme that can provide more relevant and vital information about the system that facilitates management and conservation efforts with the necessary data to make informed decisions.

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