Chapter 2
Advanced Techniques for Mapping Biophysical Environments on Carbonate Banks Using Laser Airborne Depth Sounding (LADS) and IKONOS Satellite Imagery

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Abstract Mapping seafloor environments on the continental shelf, over the past several decades, has undergone rapid transitions from early, relatively low-resolution techniques, such as echo sounding in deeper waters and digital aerial photography in shallower waters, to modern advancements like high-density airborne laser bathymetry and multi-spectral satellite imagery that can now detect seafloor reflectance at depths ranging to 50–60 m. Passive imaging systems require clear waters that typically exist on carbonate banks in many regions of the world ocean. Carbonate banks in the south Florida region provide nearly ideal conditions for mapping submarine topography and interpreting geomorphological and biophysical environments. A hierarchical open-ended classification system was developed for both open-ocean and key (low carbonate islands) environments. These classification systems, which are based on cognitive recognition of seafloor features interpreted from LADS and IKONOS imagery, are directly applied in GIS cartography programs to create comprehensive, informative, and interactive products. Examples from the open ocean southeast coast and Marquesa Islands illustrate the applicability and usefulness of advanced remote sensing techniques intercalated with GIS programs and classificatory schema for organizing seafloor typologies. This new technology and its associated classification systems permit major advancements in the detailed mapping of seafloors that have never before been achieved for margins of regional seas.

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2.1 Introduction

This chapter considers recent advances in the mapping of seafloor environments on carbonate shelves of southern Florida where water clarity is not an issue because turbidity is very low. These shallow coastal waters thus provide ample opportunity to determine a range of seafloor typologies, within which there are topological variations, using remote sensing techniques. Two different platforms were selected to determine their applicability and appropriateness in several carbonate submarine environments, using two study areas (Fig. 2.1). By reference to other methodologies such as side scan sonar and aerial photography, modern LADS (open ocean mainland coast) and IKONOS (Florida Keys) products are contrasted and compared as optimum imageries for cognitive recognition of seafloor typologies based on LADS bathymetry and IKONOS spectral reflectance. This section includes a brief review of remote sensing of carbonate shelves off distal south Florida and indicates the advantages of coupling classified remotely sensed imagery with GIS.

2.1.1 Remote Sensing of Seafloor Features

Over the past several decades, characterization of seafloor environments has made several important advancements. Early trends were based on side scan sonar imagery and seismic reflection profiling in shallower waters. Shallow water carbonate banks were further characterized with the advent of aerial photography, which continues to be a useful tool today but has limited application in regional (small scale) studies. The wider availability of airborne laser techniques in the past couple of decades provided opportunity for production of high-density bathymetric maps. LADS images, for example, have been used to advantage for small-scale mapping projects on the southeast Florida continental shelf. Although IKONOS satellite images do not provide bathymetric data, they are an excellent means of obtaining seafloor environmental (habitat) data based on processing spectral reflectance to produce near photographic-quality images.

2.1.1.1 Three-Dimensional Hachure Maps

Seafloor topography on the continental shelf was traditionally determined using soundings that were contoured into isobaths. These early bathymetric charts of shelf topography provided rudimentary insight into seafloor morphology, but horizontal positional accuracy and imprecise leadline depth sounding resulted in mapping errors and low-resolution interpretations of morphology. The advent of acoustic remote sensing techniques developed around WWII produced higher resolution maps of seafloor topography. An early landmark achievement in remote sensing during the twentieth century was Marie Tharp’s construction of a physiographic

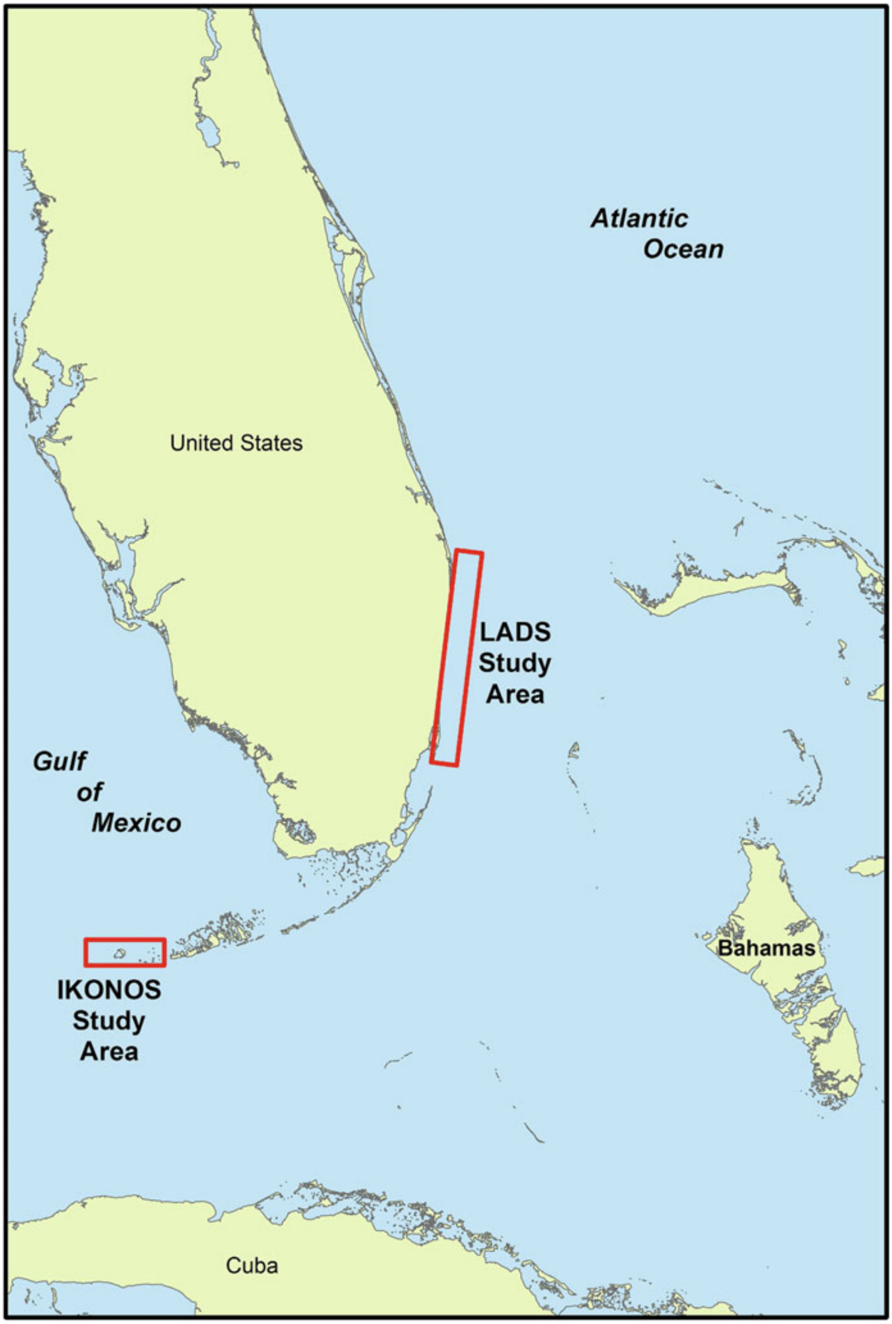

Fig. 2.1 Study areas in tropical and subtropical southern Florida. The LADS (Laser Airborne Depth Sounding) survey covers an area of about 600 km^2 on the southeast open ocean coast where there are shelf-edge coral reefs, carbonate rock reefs, and sediment flats on the narrow continental shelf. The IKONOS survey covers an area of about 422 km^2 on platform coral reefs and carbonate sediment banks in the Florida Keys

map of ocean basins. Working alongside Bruce Heezen, Tharp combined a hachuring cartographic technique with an assumed light source to depict topographic features that were related to the underlying geology (*e.g.*, Barton 2002; Doel et al. 2006; Heezen and Tharp 1965, 1966, 1977; Moody 2007). The first map showing the entire ocean basin was published in 1977 as the *World Ocean Floor* (Barton 2002; Heezen and Tharp 1977), and variations are still used today in modern geographic software applications (*e.g.*, Google™ Earth).

2.1.1.2 Coastal Aerial Photography

The advent of coastal aerial imagery introduced visual records of shallow marine environments, providing greater detail than what could be achieved by acoustic sounding. After WWII, the U.S. Coast and Geodetic Survey (C&GS) worked with the U.S. Army Air Service to acquire coastal aerial photographs. Some of the first coastal aerial imagery projects used oblique photography with single-lens cameras. While occasional nearshore bottom features were detected, these photographs provided very narrow fields of view that covered moderately-sized coastal areas.

By the 1930s and 1940s, multi-lens cameras improved surveying capabilities by allowing the photographer to acquire imagery of the coast at different angles. While vertical stereo-paired images of the coastline were available at this time, extensive sub-bottom feature information was still unobtainable because the effectiveness of aerial photography was, and still currently is, largely dependent on the clarity of the water column, which is generally limited to about 10 m in clear water (Moore 2000; Richards 1980; Thieler and Danforth 1994).

The introduction of color film with appropriate filters in the 1950s visually captured coral reefs, submerged rock outcrops, and sand flat areas. Color photography was further enhanced by Specht et al. (1973) in the 1970s when they developed experimental water-penetrating film by manipulating the blue wavelength region of the spectrum that is transmitted through the water column. Because these aerials provided remarkably clear images of the seafloor, the technology was restricted for military and government use, denying access by the public or research community.

Today, high-resolution digital orthoimagery is the preferred format for coastal aerial photographs. By incorporating visible and infrared wavelengths, digital orthoimagery is widely deployed for interpretation of shorelines and nearshore benthic environments. The digital format of the images, versus analog processing, allows for faster processing turnaround times. An additional advantage of digital aerials is that they can be georeferenced in a geographic information system (GIS) interface. Sheppard et al. (1991) showed that modern aerial photography was effective for mapping shallow marine habitats in the Caribbean. Mumby et al. (1999) and Thieler and Danforth (1994) confirmed the deduction that interpretation of color aerial photography is one of the most effective methods to conduct detailed coastal habitat mapping. Many other researchers lend credence to that postulation (*e.g.*, Anders and Byrnes 1991; Ekeborn and Erkkila 2002;

Gorman et al. 1998; Kenny et al. 2003; Lewis 2002; Moore 2000; Mount 2003; Mumby and Harborne 1999; O'Regan 1996; Ramsey and Laine 1997; Shoshany and Degani 1992; Smith and Rumohr 2005; Smith and Zarillo 1990). That being said, today's coastal aerial photographs are still limited by water clarity and depth.

2.1.1.3 Airborne Laser Imagery (LIDAR and LADS)

One advanced approach to mapping seafloor typology features high-density airborne laser bathymetry (ALB). First developed in the 1960s and 1970s, ALB is a light detection and ranging (LIDAR) technique that uses visible, ultraviolet, and near infrared light to optically sense a contour target through active and passive systems (Brock and Purkis 2009; Guenther et al. 2000; Irish and Lillycrop 1999; Irish et al. 2000). A laser pulse is usually emitted from the underbelly of a low-flying (~200–500 m elevation) aircraft (*e.g.*, helicopter, small plane) and a receiver records two back reflections: one from the water's surface (*i.e.* a passive system reliant upon surface reflectance) and one from the seafloor (*i.e.* an active system reliant upon penetration of the water column) (Guenther et al. 2000; Irish and Lillycrop 1999). In this way, researchers were able to interpret bathymetric configurations in coastal regions from airborne laser reflectance (*e.g.*, Brock and Purkis 2009; Deronde et al. 2008; Finkl et al. 2004, 2005a, b; Gesch 2009; Irish and Lillycrop 1997; Irish et al. 2000; Kempeneers et al. 2009; Klemas 2011a, b, c; Long et al. 2011; Stockdon et al. 2002, 2009; Stoker et al. 2009).

LADS was developed by Australia's Defense, Science, and Technology Organization (DSTO) for the Royal Australian Navy in order to provide an expedited means to survey and chart coastal regions. Flying at an altitude of approximately 500 m with an average speed of 75 m/s, LADS surveys can detect submarine geomorphological features to a depth of 70 m, with a swath width up to 288 m and a sounding horizontal spot density of 6 m. The LADS infrared laser emits a vertical beam pulse that reflects off the sea surface, while a visible green wavelength beam (~532 nm) propagates through the water column to reflect benthic topography. As the infrared pulses provide an initial sea-surface reference, the returning green wavelength pulses are collected and processed by a receiving telescope that contains spectral, spatial, and polarizing filters. The resulting read-out image produces an accurate waveform bottom reflection representation of the benthic topography in relation to the sea-surface reflectance signature. However, as with the SHOALS surveys, the effectiveness of LADS data is limited by turbidity in the water column. Suspended particulate matter, dissolved organic matter, phytoplankton, and dinoflagellate blooms contribute to the scattering and absorption of optical sensors from LIDAR surveys. Only in those regions that have been classified as suitable Case I or Case II coastal waters (*e.g.*, southeast Florida) is the water column visibility clear enough to effectively run these depth-sounding laser surveys (Bukata et al. 1995; Finkl et al. 2004, 2005a, b; Irish and Lillycrop 1997; Klemas 2011a).

2.1.1.4 Satellite Imagery (IKONOS)

As the space program was born in the second half of the twentieth century, so was a new coastal imaging acquisition technology with the use of orbiting satellites. Through the utilization of hyperspectral and multi-spectral sensors, satellites provide a continuous stream of coastal photographs without the logistical hardships of deploying a vessel or aircraft. Instead of an acoustic or light reflectance, satellite sensors create an image-based visual approach to discerning physical and biological bottom features of the ocean floor. Typically, hyperspectral sensor datasets constitute a range of 100–200 spectral bands of relatively narrow bandwidths (5–10 nm). On the other hand, multi-spectral sensor datasets are only composed of a few spectral bands (5–10), but have a relatively large range of bandwidths (70–400 nm). The visual detection of submarine features is dependent upon on the spectral coverage of the spectrometer and the overall spectral resolution (*i.e.* the pixel size of the satellite image covering the earth's surface) of the acquired images. There are many satellite sensors currently in orbit around the Earth today, some with a high spatial resolution (*i.e.* 0.6–4 m) and others with a medium spatial resolution (*i.e.* 4–30 m).

The IKONOS satellite was launched in 1999 and is a good example of a high spatial resolution satellite sensor. Achieving a 0.8 m panachromatic resolution and a 3.2 m multi-spectral resolution, IKONOS uses five spectral bands that include blue, green, red, near infrared, and panachromatic.

2.2 Incorporating Classification Schemes with Advanced Remote Sensing Images

LADS and IKONOS images are used as examples of platform products that can serve as base maps for interpretation of seafloor bathymetric features and environments. The following section summarizes some of the salient steps in the preparation of image attributes that are incorporated into GIS for further analysis. Essential procedures include image enhancement, on-screen digitizing, determination of the range of seafloor features to be mapped, preparation of mapping units in legend format, creation of a hierarchical classification system, and development of new map unit symbolization. Although these are the generic procedures, explanations are separated into development of new hierarchical classification schemes for bathymetric (LADS images) and spectral data (IKONOS images).

2.2.1 Development of a Geomorphological Typology Based on LADS Imagery

Because the bathymetric data is so dense, onscreen and printed products produce patterns and shapes that are identifiable in terms of landform units. Pattern recognition and shape detection (Campbell 1996; Schowengerdt 1997) thus become relevant and important tools for interpreting the LADS bathymetry. Digital image enhancement techniques can be applied using specialized processing modules in programs like Arc GIS Image Analyst®, Idrisi® (Clark University), ERDAS Imagine®, PCI®, Surfer®, *etc*.

Images of practical interest include digital terrain models (DEM) that are generated by data interpolation (Kriging) and grid-generation represented in 3D surfaces by triangular irregular networks (TIN). Fourier analysis is a common mathematical technique for separating an image into its various spatial frequency components. On the basis of a Fourier Transform, it is possible to emphasize certain frequency groups and recombine them into an enhanced image (Campbell 1996). Such filters de-emphasize certain frequencies and pass (emphasize) others. High pass filters emphasize fine detail and edges whereas lowpass filters, which suppress high frequencies, smooth an image and reduce "salt and pepper" noise. Lowpass (mean) filters generalize an image. After an image is enhanced, it is prepared for on-screen digitizing using, for example, a large format smart board (interactive whiteboard). This procedure is possible because morphological units are comprised by combinations of depth, shape, and arrangement of soundings, and shadow patterns. The final digital product is thus compiled in a spatial context that facilitates analysis and computation of selected parameters.

Prior to embarking on image interpretation, the study area should be visually inspected to ascertain the range of features that can be identified (see discussions in Finkl et al. 2004, 2005a, b). A list of features that occur should be compiled to make a comprehensive legend. There are many possibilities for interpretation of features and the orientation depends on the purpose. Because the development of a classification scheme can be an endless task, it is necessary to focus on the purpose of the survey and to rationalize procedures for consistently recognizing features that are identifiable at specific scales of observation. A useful nominal scale of observation for regional LADS bathymetry is about 1:800. Consideration should be the balance between what can be seen, what can be mapped, and what is useful or practical to delineate. The natural spatial heterogeneity of morphological units on the seafloor determines to a large extent what should be mapped. In a sense, then, most natural units are predetermined and they reflect the units that have been mapped and described by other researchers. Table 2.1 is an example of the kind of classification that can be developed from study of LADS imageries. The typology that is presented here shows how seafloor features can be rationally organized and defined. These classificatory units are then merged into mapping units (*cf*. Fig. 2.3a, b).

The LADS high-density bathymetric data sets provide good discrimination of geomorphological units, and this cognitive recognition of various geomorphological units leads to the development of a seafloor typology (*e.g*., Banks et al. 2007; Finkl 2005; Finkl and Banks 2010). Validation of typologies is achieved by seatruthing that is supported by geophysical surveys (*e.g*., sidescan sonar and seismic reflection profiling), by geotechnical (*e.g*., vibracore, jet probe, and grab sample) surveys, and by bottom samples retrieved by divers (*e.g*., Finkl and Benedet 2005; Finkl and Khalil 2005).

Table 2.1 Typology of morphological features on the southeast Florida continental shelf, based on interpretation of laser airborne depth sounding (LADS) for water depths to 55 m

Province	Subprovince	Comments
A. Sandy (soft) bottom types	1. Shoreface sand flats (−10–25 m depth)	Sand bodies that are shore-attached, between the beachface and offshore rock outcrops
	(a) Sand waves (parabathic)	Shore-parallel waves, large-scale ripple fields
	(b) Smooth seafloor topography	No sand waves with planar bedforms or small-scale ripples
	2. Hummocky (pock-marked) shoreface sands (−20–25 m)	Seafloor surface expression of irregular patterns of low-relief dimples, scour holes
	3. Inner shoreface slope (diabathic channels)	Cross-shore rectilinear channel fields, individual channels up to 120 m wide by 3 m deep
	(a) High relief	>1.5 m with approximate 300 m lateral spacing
	(b) Low relief	<0.5 m with approximate 100 m lateral spacing
	4. Inter-reefal sand flats (north of Biscayne Bay)	Sand bodies, up to 15–20 m thick, between nearshore rock outcrops of the Anastasia
		Formation or reefs of the Florida Reef Tract (FRT)
	5. Intertidal mud flats with mangroves	Shallow-water fine-grained, unconsolidated carbonate accumulations
	6. Banks	Shallow-water backreef flats with skeletal sand overlying limestone and coral
B. Limestone rock[a]	1. Ridge flats (−25–27 m) and depressions (−27–37 m) (ridge and valley, ridge field)	Elongated basins separated by flat-topped ridges, karstified limestone
	2. Fore-basin parabathic ridge system (21–25 m depth)	Shore-parallel ridge crests seaward of basins
	3. Beach ridge plain (lithified ridge systems)	Fossilized ridge and swale topography, northward topographic extension of FRT
	4. Offshore ramp [marine terraces] (−34–37 m)	Terraces seaward of reefs
	a. False crest (top of ramp, −34–37 m)	Seaward inflection of upper slope below the crest to form a lower summit
	b. Shelf break (bottom of ramp, −52–55+ m)	Transition from the continental shelf to the slope
	5. Inshore marine terrace [−1.5–6 m, Anastasia Fm.]	Multiple ridges, partly covered by thin veneer of sand with discernable rock structure

(continued)

Table 2.1 (continued)

Province	Subprovince	Comments
	6. Key (emergent carbonate sand cover over limestone)	Fossilized reef environments, small coral and limestone islands and reefs
C. Channels, paleochannels and related features	1. Structurally controlled meander belt	Structurally controlled meanders entrenched in limestone, nominal sedimentary infilling
	2. Trace channel cuts	Vestige of paleo-valleys, largely buried by sedimentary cover
	3. Infilled valleys	Paleo-valleys filled with sand but crests of valley side slopes clearly visible
	4. Tidal channels	Inlets, drowned paleo-inlets
	5. Ebb-tidal deltas	Sediment accumulations on the seaward side of tidal inlets
D. Florida reef tract (coral-algal reef system)	1. Coral reef	Coral and algal reefs extending from the Dry Tortugas to Martin County
	(a) Barrier (1st, −7–9 m; 2nd, −10–14 m; 3rd, −15–25 m)	Parabathic series of reefs that are near to the shore but separated from it
	(b) Patch	Small isolated reef nearly equant in shape, barrier reef fragments
	(c) Backreef ledge	Shore-facing ledge up to 2 m or more in height
	(d) Backreef rubble slope	Overwashed rubble that accumulates on the backside of a barrier reef
	(e) Forereef rubble slope	Spur and groove topography with coral ridges separated by sand channels
	(f) Platform	Relatively flat-lying bench along the forereef of the FRT
	2. Reef gap (incl. rubble fans)	Break in line of barrier reefs produced by corridors that link inter-reefal troughs with forereef slope on seaward margin of the FRT
	(a) Ramp	Seaward-sloping sedimentary accumulations in reef gaps
	(b) Apron (landward rubble mound)	Arcuate overwash deposits on the backside of barrier reefs that surmount the seaward-most portions of the inter-reefal sand flats
	3. Deepwater reef	Coral reefs occurring below the shelf break in water depths generally greater than 50 m

(continued)

Table 2.1 (continued)

Province	Subprovince	Comments
E. Structural and chemical limestone (karst) bedrock features	1. Karst noye (drowned solution pits, dolines, sink holes)	Drowned limestone terrain
	2. Lineaments, faults, fissures	Linear features characteristic of limestone terrains
	3. Ridge crests	Continuous seabed elevations flanked by side slopes
	4. Trough axis	Approximate center of elongated depression or trough in drowned limestone terrain
F. Continental slope (undifferentiated)		

The classificatory units are based on cognitive interpretation of bottom morphology (bathymetry), depth, exposed and shallowly buried geological structures, and composition of sedimentary materials

[a]Anastasia Fm., Biscayne Aquifer, Tamiami Fm. – Hawthorne Group, Upper Floridan Aquifer System exposed as hardgrounds to form bottom types (Modified from Finkl et al. 2005a)

2.2.2 Geomorphological Symbolization

There are many examples of specialized geomorphological symbols (*e.g.*, Demek 1972; Gardiner and Dackombe 1979; Ollier 1977). Application of geomorphological symbols should focus on detailed geomorphological field mapping and suggestions by Gellert (1988) for coastal mapping. Other sources (*e.g.*, Butler et al. 1986; Elvhage 1980; Gierloff-Emden 1985) may be consulted to select the most useful types of symbols that could be adapted for depiction of shelf environments. Also useful are standards provided by the Federal Geographic Data Committee, Geologic Data Subcommittee (FGDC 2006). The stock symbol set in ArcGIS features topographic symbolization that is partly useful, but additional features are required to adequately depict the range of marine features on the continental shelf.

Additional sources include symbolization from guides to detailed and medium-scale geomorphological mapping (*i.e.* Demek 1972; Demek and Embleton 1976) and various reports of the IGU Commission on Geomorphological Survey and Mapping (viz., Report of the 6th meeting in Canada, 1972; 7th meeting in Brno, 1973; 8th meeting in the USSR, 1974; 9th meeting in CSSR, 1975; 10th meeting in The Netherlands, 1975; 11th meeting in the USSR, 1976; and 12th meeting in Finland, 1977) including legends to the International Geomorphological Map of Europe (Bashenina et al. 1971, 1977). More complete and relevant symbolization can be adapted from Demek (1972) for detailed geomorphological mapping, especially maritime and lacustrine landforms as detailed by Bashenina et al. (1968). Other sources for symbolization and feature names in the marine environment included Milard (1996) and guidelines proposal from terminology for the *Standardization of Undersea Feature Names* (IHB 1989) and lacustrine and marine features (FGDC 2006). Although these works form a basis for mapping, symbolization (*i.e.* symbols, colors, and patterns) can be devised for specific study areas. In the example cited here, geomorphological symbolization was specifically

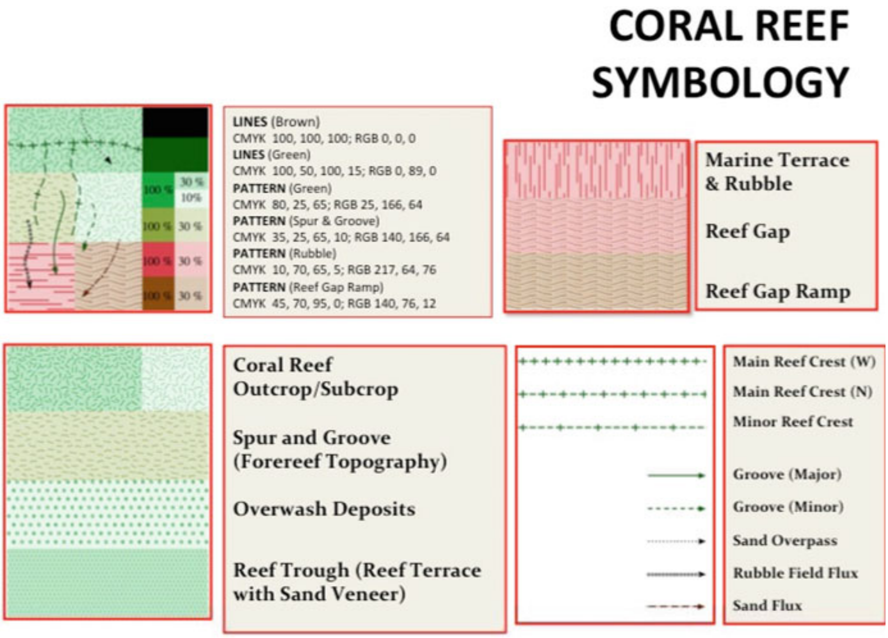

Fig. 2.2 Example of coral reef symbology developed for geomorphological mapping of the seafloor based on cognitive interpretation of LADS imagery. *Lines*, *colors*, *patterns*, and *shading* were assembled in a representative manner to depict the types of features mapped. This kind of symbology was used to construct the map shown in Fig. 2.3a. This symbolization was added as a complimentary layer extension in the standard ESRI ArcGIS® palate (symbol library)

developed for the southeast Florida continental shelf that is broadly characterized by carbonate bedrock exposure (hardgrounds), drowned karst features, barrier and shelf-edge coral reef systems, and unconsolidated carbonate and siliciclastic deposits (see Finkl and Andrews 2008; Finkl et al. 2008). Brief explanations of the legend, symbols, and signs follows.

2.2.2.1 Color Tints and Shades

Maps of seafloor topography interpreted from LADS bathymetric imagery were designed so that symbols were scale independent. The example provided in Fig. 2.2 for coral reefs shows how to build a set of map symbols. The box in the upper left-hand corner of Fig. 2.2 contains the complete symbol set for coral reef mapping units. Line colors are green and brown. The CMYK and RGB notations are supplied so the color can be duplicated. The shade in each tint is denoted by a percentage compared to 100 %. Pattern colors are indicated in the same way and identified in boxes in the lower left-hand corner and upper right-hand corner of Fig. 2.2. The boxes in the lower right-hand corner show line symbols. Within this symbol group, reef crests are denoted by green-colored crosses or crosses with dashes. Solid or dashed green lines with arrowheads indicate forereef grooves. Sand overpass, rubble field flux areas, and sand flux (movement) areas are indicated by brown-colored solid or dashed lines with arrowheads. Color tints, shades, and lines may be combined to produce a wide range of symbols that represent seafloor features.

2.2.2.2 Symbols, Signs, and Ciphers

Map symbols may be derived from a variety of sources (see preceding discussion) or specifically created in a graphics program. The potential combinations of lines, arrows, hachures, and closed polygons (regular and irregular shapes) is almost limitless but most realistic possibilities have already been achieved, as noted in mapping guides, and symbol standards. Representationally, the graphic symbols stand for seafloor geomorphic features that are depicted in simplistic form.

2.2.2.3 Legend Patterns

The map legends should contain all symbology on the maps and include cadastral information, survey area boundaries, sampling locations, and anthropogenic features in addition to the geomorphological units they portray. The mapping units within and between categories collectively combine to produce legend patterns that define similar or dissimilar seafloor features. Cognizance of mapping unit patterns and choice of mapping symbolization normally requires several iterations to achieve compatibility of resulting patterns while maintaining interpretability.

2.2.3 Interpretation and Classification of IKONOS Imagery

IKONOS satellite imagery is increasingly used as a basis for mapping marine habitats (*e.g.*, Dial et al. 2003; Finkl and Vollmer 2011; Hochberg et al. 2003; Maeder et al. 2002; Mumby and Edwards 2002; Palandro et al. 2003; Steimle and Finkl 2011). Andrefouet et al. (2003), for example, incorporated multiple IKONOS satellite images of the Arabian Gulf, Indian Ocean, Indo-Pacific, Pacific, and Caribbean biogeographic zones in order to map geomorphologic zones (*e.g.*, reef flats, forereef, patch reef, lagoon) and biological communities (*e.g.*, seagrass beds, macroalgae coverage, coral overgrowth). Their mapping results help justify the use of IKONOS satellite supplied images as a means to appropriately interpret and classify marine carbonate environments.

Once IKONOS satellite images are enhanced, they can be imported into ArcGIS® ArcMap for onscreen cognitive interpretation of seafloor features and incorporation of classification schemes. Effective interpretation of coastal and benthic marine environments require that the various features are cognitively discriminated by their spectral reflectance characteristics (Hochberg and Atkinson 2000). The fundamental focus of cognitive interpretation is to isolate the portion of upwelling light radiance that penetrates the atmosphere, water column, dissolved

Table 2.2 Typology of morphological features on the Marquesas carbonate bank, based on cognitive interpretation of IKONOS satellite imagery

Bottom type	Material	Geomorphic unit	Type of cover	Coverage
(1) Unconsolidated sediment	(1) Sand	(1) Shoreline intertidal	(1) Live Coral	(1) Continuous
	(2) Mud			(2) Patchy
(2) Coral reef and hardbottom	(1) Spur and groove	(2) Lagoon		(3) Sparse
	(2) Individual or aggregated patch reef		(2) Seagrass	(1) Continuous
		(3) Bank/Shelf		(2) Patchy
	(3) Aggregate reef			(3) Sparse
	(4) Scattered coral/rock in Unconsolidated sediment	(4) Back reef	(3) Macroalgae	(1) Continuous
				(2) Patchy
		(5) Ridge and swale		(3) Sparse
	(5) Pavement		(4) Encrusting/coralline algae	(1) Continuous
	(6) Rock/boulder	(6) Reef crest		(2) Patchy
	(7) Reef rubble			(3) Sparse
	(8) Pavement with sand channels	(7) Forereef	(5) Turf algae	(1) Continuous
		(8) Channel		(2) Patchy
(3) Man-made and terrestrial	(1) Engineering works	(9) Dredged		(3) Sparse
		(10) Vertical wall	(6) Emergent vegetation	(1) Marsh
	(2) Land	(*) Bank/shelf escarpment		(2) Mangrove
			(7) Uncolonized	(1) Uncolonized
(4) Unknown	(1) Unknown	(#) Unknown	(8) Unknown	(1) Unknown

The *color-coded* classificatory units include platform reef environments (*e.g.*, coral reef and hardbottom, unconsolidated sediment), biological overlays, and terrestrial and sub-terrestrial realms. The *numerical codes* are grouped by color, where bottom types and materials go together as a couplet and the other categories are independent

organic material, and turbidity, thereby ultimately, reflecting the specific interpreted features from the seafloor (Dobson and Dustan 2000; Maritorena et al. 1994). However, contrast and brightness of the reflected light can vary amongst different IKONOS images, therefore, color, the main variable in autoclassification algorithms, should be disqualified as the sole conclusive factor for seafloor bottom interpretation. Rather, cognitive interpretation of seafloor environments is contingent upon the ability to collectively distinguish between different color, tone, texture, pattern, and relative spectral reflectance variations.

Just as with the LADS images, local working knowledge of a study area, referred to as contextual editing by Green et al. (2000), becomes a necessary requirement when interpreting seafloor boundaries from IKONOS images. By applying prerequisite knowledge (collateral data) of the geomorphology and biological coverages in tandem with the elements of color, tone, texture, pattern, and relative spectral reflectance, a comprehensive cognitive interpretation of ecological zonations and physical gradients can be accomplished. The process first involves determining the relative brightness, color, and tone of a pixel, or set of pixels, in the IKONOS imagery as light, medium, or dark. The frequency of color and tone variations can then be identified as coarse, medium, or fine texture and pattern. Cognitive knowledge of the study area should also be applied to the repetition and amalgamation of textural patterns, as well as, the relative spectral reflectance of visual cues, to differentiate seafloor features along the various carbonate banks. This is especially important when variable water depths cause seafloor signatures to spectrally appear lighter or darker, which can produce false-positives in autoclassification schemes.

An established scheme of mapping and classificatory units (Tables 2.2 and 2.3) can be applied directly to completed cognitive vector delineation. An individual

Table 2.3 Typology of morphological features on the Marquesas carbonate bank, based on cognitive interpretation of IKONOS satellite imagery

Platform reef environment
Coral reef and hardbottom
Aggregated reef
Patchy[a] live coral (23312[b])
Sparse live coral (23313)
Scattered coral/rock in unconsolidated sediment
Patchy live coral (24312)
Sparse live coral (24313)
Patchy seagrass (24322)
Sparse seagrass (24323)
Sparse macroalgae (24333)
Back reef (rubble)
Patchy macroalgae (27432)
Sparse macroalgae (27433)
Unconsolidated sediment
Bank/shelf seagrass
Continuous (11321)
With patchy soft coral (11321, 72[c])
With patchy macroalgae and soft coral (11321, 82)
Patchy (11322)
With continuous macroalgae (bloom) (11322, 11)
With patchy macroalgae (bloom) (11322, 12)
With sparse macroalgae (bloom) (11322, 13)
With sparse epiphytes (11322, 22)
With spare epiphytes and sparse lugworms (11322, 33)
With continuous epiphytes and macroalgae (11322, 51)
With patchy epiphytes and macroalgae (11322, 52)
With sparse epiphytes and macroalgae (11322, 53)
With continuous lugworm field (11322, 61)
With patchy lugworm field (11322, 62)
With sparse lugworm field (11322, 61)
With continuous soft coral (11322, 71)
With patchy soft coral (11322, 72)
With sparse soft coral (11322, 73)
With patchy macroalgae and soft coral (11322, 82)
With continuous macroalgae mats (11322, 91)
With patchy macroalgae mats (11322, 92)
With sparse macroalgae mats (11322, 93)
Sparse (11323)
With patchy macroalgae (bloom) (11323, 12)
With sparse macroalgae (bloom) (11323, 13)
With patchy epiphytes and sparse lugworms (11323, 32)
With sparse epiphytes and sparse lugworms (11323, 33)
With sparse epiphytes and macroalgae (11323, 53)
With patchy lugworm field (11323, 62)
With sparse lugworm field (11323, 63)

(continued)

Table 2.3 (continued)

With patchy soft coral (11323, 72)
With sparse soft coral (11323, 73)
With sparse macroalgae and soft coral (11323, 83)
With patchy macroalgae mats (11323, 92)
Lagoon seagrass
Patchy (11222)
With continuous macroalgae (bloom) (11222, 11)
With patchy macroalgae (bloom) (11222, 12)
With sparse macroalgae (bloom) (11222, 13)
With patchy epiphytes (11222, 22)
With sparse epiphytes (11222, 23)
With continuous epiphytes and sparse lugworms (11222, 31)
With patchy epiphytes and sparse lugworms (11222, 32)
With sparse epiphytes and sparse lugworms (11222, 33)
With continuous epiphytes and sparse mangroves (11222, 41)
With patchy epiphytes and sparse mangroves (11222, 42)
With sparse epiphytes and sparse mangroves (11222, 43)
With continuous epiphytes and macroalgae (11222, 51)
With patchy epiphytes and macroalgae (11222, 52)
With sparse epiphytes and macroalgae (11222, 53)
With patchy lugworm field (11222, 62)
With sparse lugworm field (11222, 63)
Sparse (11223)
With patchy epiphytes and sparse lugworms (11223, 32)
With sparse epiphytes and sparse lugworms (11223, 33)
With sparse epiphytes and lugworms (11223, 53)
With patchy lugworm field (11223, 62)
With sparse lugworm field (11223, 63)
Macroalgae
Patchy (11332)
Sparse (11333)
Shoreline intertidal (emergent vegetation)
With continuous mangrove (121621)
With patchy mangrove (121622)
With sparse mangrove (121623)
Saline lake (1118, 11)
Shoreline supertidal
Sand dune (vegetated/unvegetated) (111a, 10)
Upland vegetation (111a, 12)
Channel
With continuous seagrass (11821)
With patchy seagrass (11822)
With sparse seagrass (11823)
Uncolonized
Shoreline intertidal (1117)
Channel (1187)

(continued)

Table 2.3 (continued)

Lagoon (1127)
Bank/shelf (1137)
Unknown
Barrier reef environment
Coral reef and hardbottom
Aggregated reef
With patchy live coral (23312
With sparse live coral (23313)
Individual or aggregate patch reef
With patchy live coral (22312)
With sparse live coral (22313)
Scattered coral/rock in unconsolidated sediment
With patchy seagrass (24322)
With sparse seagrass (24323)
Back reef (reef rubble)
With patchy seagrass (27422)
With sparse seagrass (27423)
Unconsolidated sediment
Seagrass
Patchy (11322)
Sparse (11323)
Uncolonized
Bank/shelf (1137)
Unknown

The classificatory units include platform reef and barrier environments (*e.g.*, coral reef and hardbottom, unconsolidated sediment), biological overlays, and terrestrial and sub-terrestrial realms. The numeric code following a mapping unit is the designator that was entered into the GIS attribute table

[a]Dominant biological coverages: continuous = >90 %, patchy = 50–90 %, sparse = 10–50 %

[b]Mapping units are based on a numeric system that was devised for this project so that each polygon received a coded identifier

[c]Some numeric codes carry a suffix following a comma. The suffix codes are: (1) macroalgae bloom, (2) epiphytes, (3) epiphytes and sparse lugworms, (4) epiphytes and sparse mangroves, (5) epiphytes and macroalgae, (6) lugworm field, (7) soft coral, (8) macroalgae and soft coral, (9) macroalgae mats. The percentage cover is as follows: (1) continuous (>90 %), (2) patchy (50–90 %), and (3) sparse (10–50 %)

thematic layered display, and associated legend, is created for each category heading in the classification scheme, with a specific color being assigned to each classifying interpretation unit. Vector polygons may then be filled with a specific classifying color that corresponds to the cognitive interpretation.

Creation of comprehensive attribute tables relates directly to the classification of cognitive digitized polygons. By doing so, a database of spatial query information, including areal extents of classified units, is compiled for analysis. Attribute tables for given imagers are created in ESRI's ArcGIS® 10.1 ArcMap program. The spatial integrity of attributes can be confirmed through a series of topology checks in ArcMap. When errors are detected, the error inspector table can be used to zoom to specific attributes that spatially broke the parameters set forth in the topological rules layer. Once all the errors have been identified and corrected, the topology is validated and attribute data can be exported for analysis.

2.3 Remote Sensing of Carbonate Banks in Southern Florida

Multiple studies have focused on the classification of seafloor types on southeast Florida carbonate banks (*e.g*., Banks et al. 2007; DaPrato and Finkl 1994; Finkl 2004; Finkl and Warner 2005; Finkl et al. 2005a, b; Finkl and Vollmer 2011; Lidz 2004; Lidz et al. 1997, 2003, 2006; Madden et al. 2008; Madley et al. 2002; Moyer et al. 2003; Palandro et al. 2005; Rohmann and Monaco 2005; Steimle and Finkl 2011; Walker et al. 2008; Warner 1999; Zieman et al. 1989). One of the earlier modern classification studies was conducted by Duane and Meisburger (1969) in their investigation of geomorphology and unconsolidated sediments offshore Palm Beach and Miami-Dade counties. They surveyed 365 km^2 with seismic reflection interpretation of ridges and sandy areas in water depths ranging from 3 to 33 m. Finkl and Warner (2005), using stereo-paired aerial photographs, mapped submarine morphological features offshore Palm Beach County. Using an acquisition scale of 1:3,900, seafloor features were mapped to an approximate water depth of 15 m (about 500 m seaward of the shoreline).

Using LADS bathymetric data, Finkl et al. (2005a, b) developed a hierarchal classification that defined submarine provinces and subprovinces based on bottom topography, water depth, exposed and shallowly buried geological structures, and composition of sediments. The main provinces included: sedimentary (soft) seafloor units; limestone rock; channels, paleochannels, and related features; Florida Reef Tract and the coral-algal system; structural and chemical limestone (karst) bedrock features; and continental slope. Individual mapping units were then extrapolated and applied to the final maps based on the pre-interpreted submarine provinces.

Lidz et al. (2006) used aerial photomosiacs to map 3,140 km^2 of the Florida Keys National Marine Sanctuary (FKNMS). Instead of specific bottom feature interpretations, Lidz et al. (2006) applied a more general approach to mapping such a large area and derived 19 submarine units. Benthic habitat mapping units with the largest contributions to the overall study area included seagrasses on lime mud (864.70 km^2; 27.5 %), seagrasses on carbonate sand (587.63 km^2; 18.7 %), bare carbonate sand (542.80 km^2; 17.3 %), bare lime mud and/or seagrass-covered muddy carbonate sand (302.87 km^2; 9.6 %), bare Pleistocene oolitic limestone (250.35 km^2; 8.0 %), and senile coral reef (70.19 km^2; 2.2 %). By using this general approach to mapping large areas, Lidz et al. (2006) were able to provide new information on previously undetermined seabed morphologies in the FKNMS.

This type of seafloor mapping was expanded by Madden et al. (2008) with the introduction of a classification scheme that was amenable to mapping carbonate bank ecosystems in shallow water. The Madden et al. (2008) system is based on a rigid hierarchical approach that starts with general coral ecosystem geomorphological structures and ends with specific biological covers. Steimle and Finkl (2011) mapped 1,360 km^2 of Florida Bay using a comprehensive hierarchical classification scheme that they developed to included five physiographic realms, 17 morphodynamic zones, 11 geoforms, 38 landforms, six types of surface sediment cover, and a combination of nine biological covers. They produced a new type of map that amalgamated geological properties and biological communities on a carbonate bank.

2.4 Examples of Seafloor Mapping on Carbonate Banks

The following two examples serve as vignettes of seafloor mapping on carbonate banks based on interpretation of bathymetry (LADS surveys) and environments and habitats (IKONOS surveys). These studies draw on prior mapping efforts in the area but provide new classifications of seafloor typologies that advance application of modern technologies. The first case study deals with a LADS survey along an open ocean coast with shelf-edge coral reefs, shelf hardgrounds (exposure of carbonate bedrock), and sedimentary deposits. The second case study focuses on biophysical environments in the Marquesa Keys and features carbonate bank typologies in the distal Florida Keys. Classification schemes were developed for both areas by cognitive interpretation of bathymetric or spectral data. General hierarchical schema were devised in such a way that they are open ended and can be modified according to local typologies. This procedure avoids compiling massive all-inclusive systems that would need to be uploaded into GIS for further analysis.

2.4.1 LADS Survey of Carbonate Shelf

Bathymetric data, derived from LADS (Laser Airborne Depth Sounding Survey) developed by Tenix LADS Corporation (Mawson Lakes, South Australia), was acquired along the Florida southeast coast in 2001 (Broward County) and 2003 (Palm Beach and Miami-Dade counties). The dataset comprised millions of bathymetric data points along a 160-km coastal segment that extends up to 6 km offshore to cover nearly 600 km^2 of seabed (see Fig. 2.1). The high-density bathymetric datasets provide good discrimination of geomorphological units and this cognitive recognition of various geomorphological units leads to the development of a seafloor typology (Table 2.1). Validation of typologies is achieved by seatruthing that is supported by side scan sonar and sub-bottom profiler geophysical surveys, by geotechnical (vibracore) surveys, and by bottom samples and videos retrieved by divers (Finkl et al. 2005a, b).

Some of the morphological units in the study area originated as terrestrial features (*e.g.*, karst nu) that were subsequently drowned by sea-level rise viz. to become karst noye (drowned karst) of which there is ample evidence throughout the study area in the form of solution pits, dolines, and sink holes. Most other features are, however, marine in origin (*e.g.*, the Florida Reef Tract) except for the coastal channels. The main morphological features occurring in the study area, summarized in Table 2.1, include sandy bottom types, rock hardgrounds (exposed bedrock, usually as karst noye), coral reefs and related features. For the Palm Beach County sector of the overall study area, 269 km^2 were mapped with continental slope, ridge fields, and sand flats respectively making up 15.6 %, 27.4 % and 30.6 % of the total area. Diabathic channel fields comprising 19.2 km^2 accounted for 7.1 % of the survey area. Other units of lesser extent individually accounted for less than 2 % of the survey area except for deepwater reefs, forereef rubble slopes, backreef overwash deposits, and sand waves each of which accounted for about 2 %.

Figure 2.3a is a diptych showing seafloor morphology, based on cognitive interpretation of LADS bathymetry, on the narrow continental shelf offshore the Hillsboro Inlet. The LADS bathymetry extends from the beach to about 55 m depth on the upper reaches of the continental slope. The raw LADS bathymetry (left panel) was deliberately color ramped to emphasize depth relations as demarcated by rock reef and coral reef parabathic (shore-parallel) tracts. Interpretation of seafloor geomorphology is shown in the right panel. The key to the symbols used here is laid out in Fig. 2.3b. The amount of detail provided by LADS bathymetry offers a high level of interpretability for sections of the seafloor that was previously not possible. Study of Fig. 2.3a, b in a GIS format emphasizes the usefulness of airborne remote sensing of the seafloor where applications of the acquired and interpreted data are only beginning to be appreciated.

It is hoped that this example provides insight into the advantages of using ALB data to interpret a range of submarine geomorphological features that can be grouped into general mapping units. The mapping units were determined at a scale of 1:25,000 for the project as a whole, zooming to greater detail as required. It is evident that these mapping units generalize what can be interpreted from the ALB data. Detailed mapping is thus possible and even required in many areas to better ascertain relationship between morphologic features and mapping units. One advantage of having the imagery in GIS format is that scales can be easily manipulated for viewing and analysis.

2.4.2 IKONOS Survey of the Marquesas

Imagery was acquired in 2006 over several months and different frames were used for the same geographic area in order to map different seafloor features that were obscured by cloud cover, waves, glint, turbidity in the water column, or seasonal algal blooms.

Shallow water features were interpreted from pan sharpened and color images but near the seaward margin of the shelf, deepwater features (in about 60 m of water) associated with the FRT could only be interpreted from digitally enhanced images. Image enhancement followed procedures outlined by Finkl and DePrato (1993) and Chauvaud et al. (1998) and was conducted using IDRISI Taiga

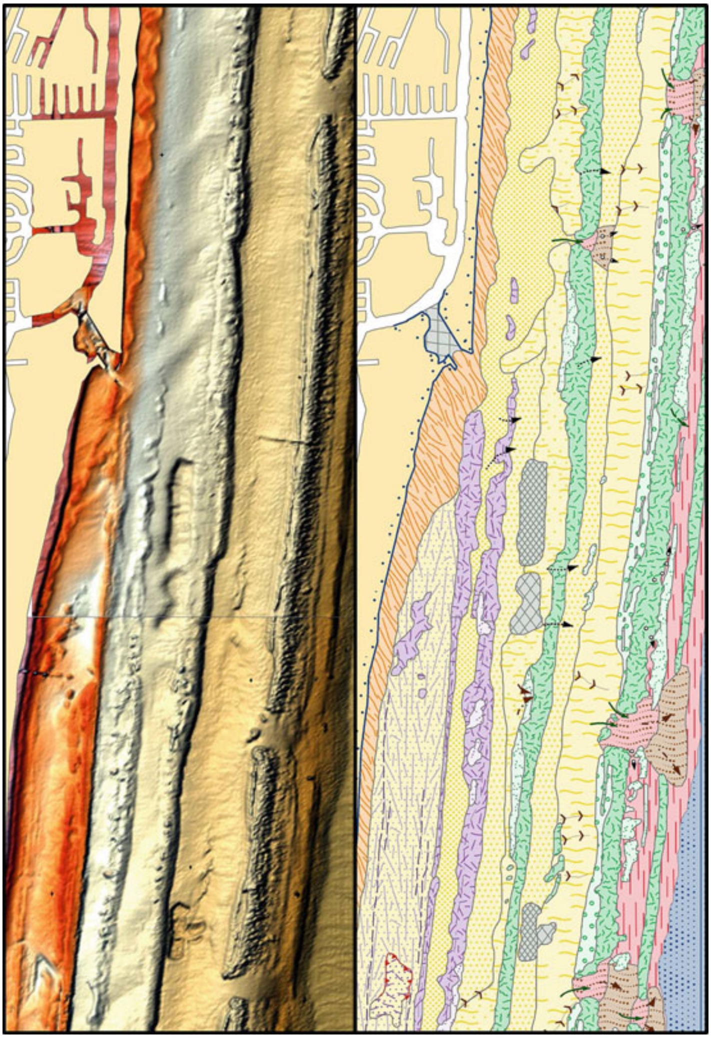

Fig. 2.3 (**a**) Diptych showing an uninterpreted enhanced LADS image in the *left panel* and the cognitively interpreted geomorphological units based on bathymetry in the *right panel* for the southeast Florida continental shelf (see Fig. 2.1 for overall survey location). The raw LADS image was enhanced, vertically exaggerated, and bathymetrically colorized for easier interpretation. *Symbols* explained in Fig. 2.2 are used to depict the coral reef systems of the Florida Reef Tract and displayed in GIS format using IDRISI. (**b**) Legend to accompany (**a**), showing mapping units displayed in the right panel of the diptych in (**a**). Although this example of mapping units is incomplete as it only refers to the field of view in (**a**), it demonstrates an ability to interpret LADS bathymetry with symbols specifically developed for depicting submarine topographic units in a GIS format

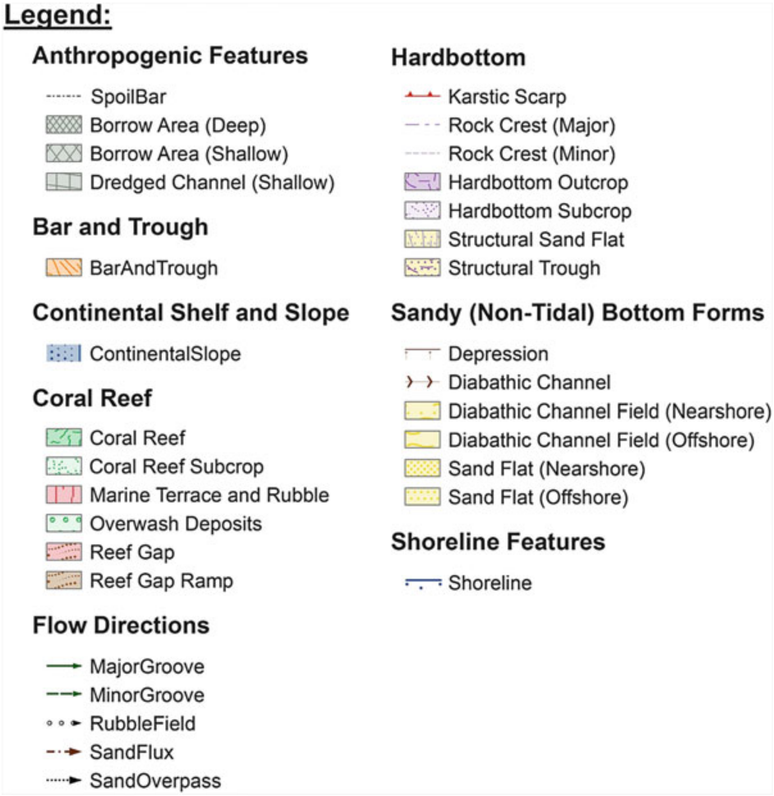

Fig. 2.3 (continued)

integrated GIS and image processing software (Clark University, http://www.clarklabs.org/), which includes nearly 300 modules for the analysis and display of digital spatial information, and involved the following basic steps for enhancing images: (1) import images, (2) determine bands that allow for deepwater features, (3) overlay images (band ratioing), (4) stretch image, and (5) filter image. The linear contrast stretch of the digital data involved the identification of lower and upper bounds from the histogram (minimum and maximum brightness values in the image) and applying a transformation to stretch this range to fill the full spectral range. The data was then filtered using Gaussian and mean filters with filter sizes ranging from 3×3 to 7×7. High-pass and low-pass filters were used to determine the best image quality, which varied from scene to scene.

Figure 2.4 shows the advantages of image enhancement that compares an RGB 8-bit color image (top panel) with a pan-sharpened image (middle panel) with an enhanced image (bottom panel) that shows more detail of deepwater shelf features. Details of the image enhancement procedures are as follows. The IKONOS image was first imported into the software and each band was individually analyzed for its ability to enhance deepwater features. Bands two and three best represented

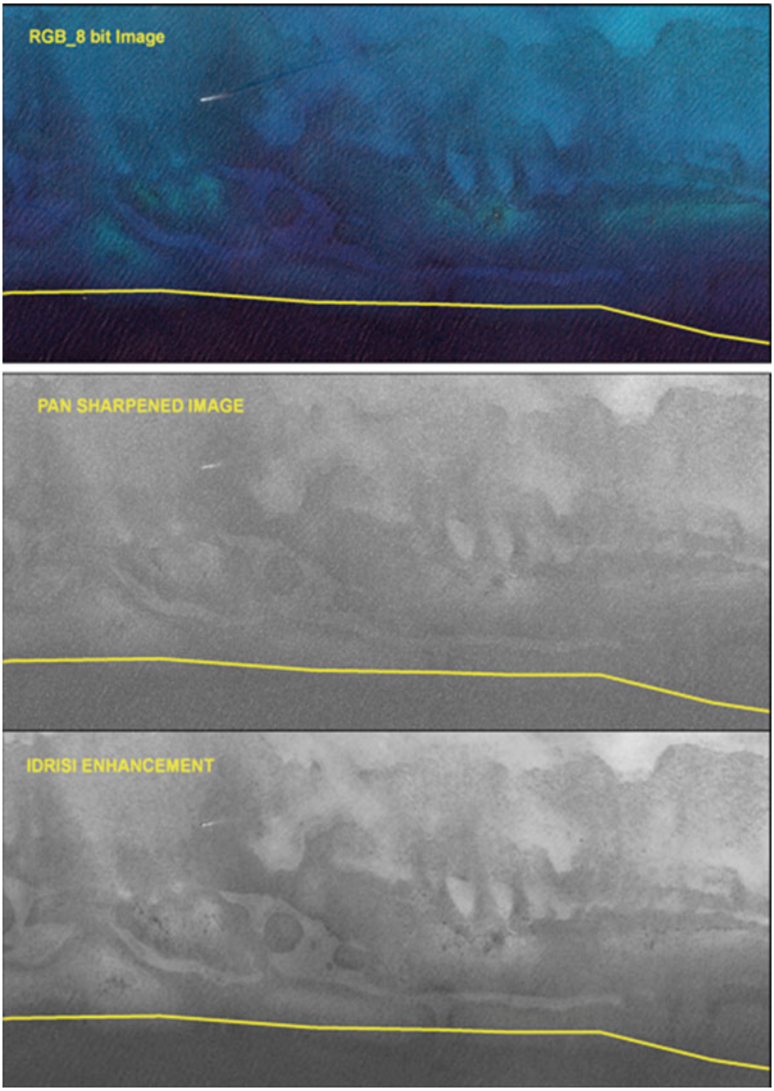

Fig. 2.4 Comparison of image enhancement techniques for deep water coral reef environments that are near the detection limits of the IKONOS radiometer. The spectrally enhanced bottom two images (pan sharpened vs. the IDRISI enhancement) show progressively more detail of bottom features. The yellow line marks the boundary between interpretable and uninterpretable data

deepwater geomorphic features. The overlay module was combined with the maximize option to produce a single image from multiple bands, providing the most detail possible. The maximize option outputs pixels that represent the maximum digital number for those in corresponding positions on the first and second image. A data stretch was then performed on the overlaid image to increase contrast. A linear stretch was found to be the best methodology to further enhance

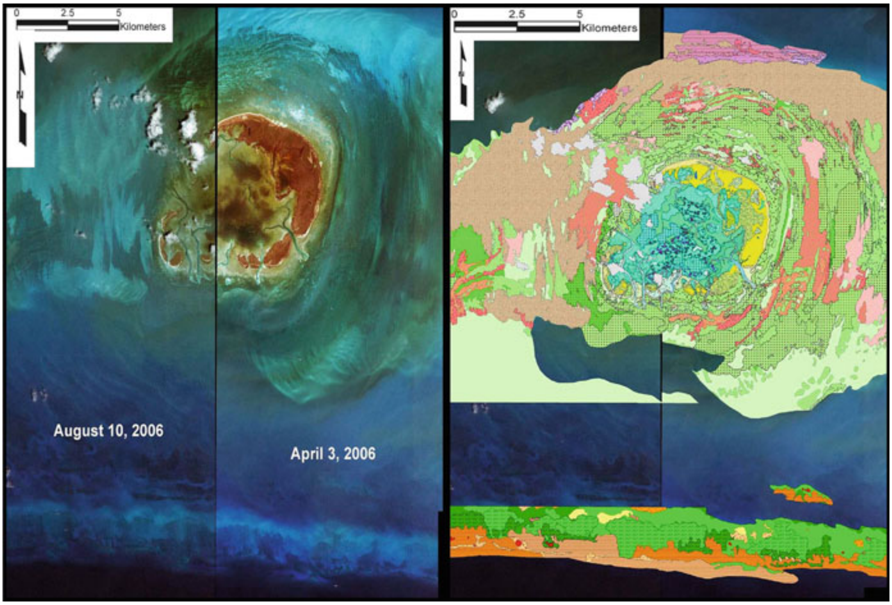

Fig. 2.5 Marquesa Islands (see Fig. 2.1 for overall survey location) diptych showing an uninterpreted enhanced IKONOS image in the *left panel* and cognitively interpreted biophysical units based on spectral reflectance of seafloor barrier and platform coral reef environments in the right panel. The *left panel* is provided for comparison with cognitively interpreted units. Some GIS layers were turned off in the *right panel* for easy comparison of interpreted vs. uninterpreted seafloor. Polygons in this map were compiled from a numerical code for seafloor environments that are summarized in Table 2.1. Application of the code to each polygon produced discrete mapping units, a partial example of which is found in Table 2.2

the underwater features. This stretch linearly scales values between a specified minimum and maximum limit. To further prepare the image for visual display, the stretch was performed in certain instances with 5 % saturation. This saturation concentrates the output values on the less extreme values. The image was then filtered to enhance the deepwater geomorphic features as much as possible. The filtering creates a new image by combining pixel values with immediate neighbors. Gaussian, mean, and median filters were found to be most effective: the Gaussian and mean filters generalized the image whereas median filters removed random noise.

Seafloor features were cognitively interpreted and mapped at a nominal scale of 1:6,000 (Fig. 2.5). They were delineated by relative spectral reflectance, color, textures and patterns of their boundaries as well as contextual inferences from previous studies and *in situ* observations. Visual identification and interpretation of seafloor environments derived from a mosaic of 4 m resolution multi-spectral IKONOS images utilized ESRI's ArcMap Geographic Information System (GIS). Polygon boundaries were digitized in shapefiles georeferenced to the North American 1983 Datum Zone 17 North, Universal Transverse Mercator (UTM) projected coordinate system. Subsequent to initial digital delineations of shallow-marine environments, obscured or irresolute seafloor types were visited in the field for direct visual observations. The *in-situ* observations either confirmed the classified polygon or reclassified incorrect cognitive interpretations.

About 422 km^2 were interpreted with 96 mapping units defined. The Platform Barrier Reef environment had 84 units and the Barrier Reef environment had 12 units. Classification units were defined by a numeric code to allow a "full picture" to the individual units (Table 2.2). These units were defined in a stepwise procedure: the first number is selected from the column for 'Bottom Type,' followed by the associated color units in the second column: 'Material.' Next comes the geomorphologic base, which is independent of the first two columns. The extent of the biological cover is grossly estimated as a percentage of the dominant type of cover. The attribute table was built with a multi-discipline interpretation in mind, by allowing the end user the flexibility of extracting the information of interest, *i.e.*, major biological cover, detailed geological cover, *etc*. Suffixes were added to further interpret the areas biological cover.

A symbology was created for each seafloor feature, providing a range of mapping units. An example of how this was set up is summarized in Table 2.3, which lists the classification but does not show the mapping unit symbolization. The typology breaks down the overall environment into two major provinces: platform reef environment and barrier reef environment. Each is further subdivided into the dominant types of features that can be cognitively interpreted from the IKONOS imagery. Geomorophological and biological units were color-coded by major type, then a pattern was applied to represent minor types and finally a gradation of colors was applied to represent changes in feature densities (frequency of occurrence) within the area. A portion of the mapped area is shown in Fig. 2.4 as an example of the level of detail that can be extracted from the satellite imagery. A legend is not provided because it is so extensive. The figure should be regarded as an illustration of what can be done using the system developed here, as summarized in Tables 2.2 and 2.3.

Interpretation of seafloor environments from IKONOS satellite imagery is possible with major geomorphological features being most easily determined. Subdivision of seafloor environments is, however, complicated by biological covers that can mask underlying geology and geomorphology. Dense seagrass can, for example, look very similar to patch reefs making differentiation problematical (*e.g*., Mumby et al. 1999). Other complicating factors include variable growth patterns of mangroves, presence of algal blooms, variable water depths and suspension of particulates that can change the appearance of the same features, and hard-bottoms with aggregate corals, sponges, and turf algae. Lugworms (sand worms) (*Arenicola cristata*) that burrow in soft sandy or muddy sediments bring substrate materials to the surface of the seafloor imparting a grayish-blue tone to some lighter colored sediment flats. Where lugworm fields were especially dense, they were identified as discrete mapping units due to tonal differences in the IKONOS imagery. Field inspection is usually required to resolve mapping units that appear similar and this is particularly so for dense circular seagrass beds with sand halos which resemble patch reefs and patchy hardgrounds with variable biological covers.

Development of a hierarchical classification and mapping units was a somewhat complicated process due to complex spatial distribution patterns (Tables 2.2 and 2.3). The Platform Reef Environment was broken down into two main units: coral reefs (aggregate reefs, individual or patch reefs, and scattered corals in unconsolidated sediment) and unconsolidated sediment (uncolonized sand, sand with seagrass, sand with macroalgae, and with turf algae, sand with emergent vegetation, mud with marsh, and mud with mangrove).

The Barrier Reef Environment was likewise broken down into two main mapping units: coral reef and hardbottom (aggregate reef, patch reefs, scattered coral in unconsolidated sediment, and backreef) and unconsolidated sediment (uncolonized or with seagrass and macroalgae). There were different combinations that could be used, but this system seemed to capture salient natural features. Inclusion of biological covers enormously complicated the range and number of mapping units, which were initially and most importantly based on geomorphological parameters. An advantage of presenting the classification and mapping efforts in a GIS framework is that very complicated marine systems can be differentially queried, broken down into component parts, subsumed within overarching units, or graphically displayed to show various types of spatial interrelationships.

2.5 Discussion

Advancements in the interpretation of seafloor biophysical environments on carbonate banks in tropical and subtropical environments, such as in southern Florida, include the use of laser airborne depth sounding (LADS) data and IKONOS satellite imagery and are facilitated by generally clear, shallow waters. Turbidity (due to algal blooms and suspension of particulate matter) and coloration of the water column by tannic acids from surface runoff of the Florida Everglades degrade data quality and under extremely adverse conditions severely limit the acquisition of usable products for interpretation from passive systems. Therefore, airborne laser bathymetric and satellite multispectral data are thus conditioned by optimum environmental conditions that characterize these areas for much of the year. As with any advanced remote sensing platform, there are pros and cons associated with acquisition and interpretation of the data.

Once usable data is acquired under near-optimal conditions, interpretation depends upon the skill set and expertise of the interpreter. Data acquisition is thus one part of the problem and its interpretation is another. Presently there is a plethora of data and a dearth of interpretations. Interpretive skills are very much dependent on formal scientific background or training in such fields as remote sensing, geomorphology, marine geology, and marine biology as well as subfield specializations within these broader disciplines. Some of the pros and cons related to interpretation of airborne high-density bathymetric data and satellite mulitspectral data are discussed in what follows.

2.5.1 Pros and Cons Associated with High Density Airborne Laser Bathymetry (ALB) Data

Numerous pitfalls are associated with the production of geomorphological maps when interpreted from ALB data without optimal geological control. Sub-bottom seismic data helps to define some units, but it may not always be available. The quality of geomorphological units interpreted from the ALB imagery depends on the expertise of researchers. In general, the greater the experience of the researcher (*i.e.* familiarity with geomorphological mapping, landform classification, and terrain analysis in different shelf settings), the more accurate the map. Nevertheless, a great deal of morphological and morphometric information can be acquired by interpretation of high density ALB data represented in three-dimensional digital terrain models, which can be interpreted in terms of bathymorphometric units. This new information provides increased insight into understanding of seafloor features on the continental shelves. Image enhancement is limited by one data band and lack of access to proprietary LADS algorithms that could assist manipulation of the data.

A primary advantage of ALB technology is laser acquisition of sounding data in digital format that provides millions of data points for nearshore seabed topography in a fraction of the time required by conventional surveys. Airborne data acquisition permits rapid day or night survey of large areas that are difficultly accessible. The digital terrain model generated from dense ALB datasets permits variation of pixel size, provides a degree of data separation or overlap, and is amenable to filtering techniques for data enhancement.

The resulting hard copy color maps provide picture-like renditions of the seabed that provide for the first time, accurate depiction of ALB as bathymorphometric images. This latter property is often taken for granted, in spite of the fact that until these bathymetric datasets and associated imagery appeared, we had no good idea of the complexity and continuity of detailed seafloor topography. More than three decades ago, Duane and Meisburger (1969) delineated the approximate positions of reefs, hardgrounds, and sand flats associated with the Florida Reef Tract (FRT). Aerial photography shows nearshore bottom features, but lacks depth information. Satellite imagery also provides limited access to nearshore bottom features, but no previous system of seafloor mapping or image analysis provides the kind of spatial resolution of bottom features over large expanses of the seabed as the newly acquired high dense bathymetric data using ALB systems. Seafloor discrimination on the basis of acoustic classes from sidescan sonar and single- or multibeam bathymetric survey shows a high-level of correlation with interpreted LADS bathymetric classes.

2.5.2 Pros and Cons Associated with Satellite Multispectral Data

Satellite multispectral data provides many advantages when interpreting biophysical environments along carbonate banks. In the tropics and subtropics, marine carbonate banks can be extremely complex to interpret because the sedimentary cover may range from meters thick to only a few centimeters over short distances. Sand waves and dunes are common, but interdunal areas can be nearly sediment-free with the underlying limestone exposed by strong currents. On the reef platform around the Marquesas atoll, for example, there were areas of carbonate sediments that covered the underlying limestone but there were also mosaics of sponges, soft corals and seagrass in areas with thin sediment cover. Even though these areas were dominated by a sedimentary cover, sediment must be restricted to a relatively thin layer (*i.e.* a few centimeters or less) so that species of soft corals and sponges could take advantage of rocky footholds in areas that become exposed by currents. The sedimentary cover in many places is so thin that the underlying rock structure (lineaments, fractures, variations in microtopography due to heterogeneity of the limestone make up) is clearly visible in the IKONOS multispectral imagery. Variations in thickness of the sedimentary cover complicate interpretation of the IKONOS imagery because very small differences on the order of a few centimeters and the velocity of bottom currents determine whether the sediment is uncolonized or is thick enough to support variable densities of seagrass.

Geological and geomorphological features, which form the basis of the mapping units, are greatly expanded upon with the consideration of biological covers that imparted many different tonal combinations in the satellite images. In order to comprehend all of the variations in the IKONOS imagery based on color, texture, tone, pattern, and saturation, it is necessary to construct logical and systematic mapping procedures that first identify bedrock and unconsolidated sediments (*e.g.*, sand, mud), then biophysical features (*e.g.*, coral reefs), and finally various types of biological covers (*e.g.*, live coral, seagrass) The incorporation of all these major biological categories in the IKONOS imagery provides an interpretation advantage that ALB datasets lack. Whereas the ALB allows for a more accurate interpretation of the geomorphology, IKONOS images provide a more complete interpretation of the biological covers growing on the geologic features. Even though the increased number of mapping units in the IKONOS imagery is necessarily large, the mapping effort does not become over-complicated or convoluted. However, there are many challenges associated with the incorporation of biological units when mapping seafloor environments, as well as subtidal and supratidal zones. Beaches on the Marquesas atoll, for example, are composed of macroalgal *Halimeda* platelets and perched on limestone platforms, making it difficult to accurately delineate. Furthermore, in the IKONOS imagery, tonal differences between beaches, intertidal platforms, and lugworm fields can be very subtle and cognitive context becomes the main interpretive guide.

Even though spectral data from IKONOS satellite imagery have been used in multiple benthic interpretive efforts as an ideal platform (*e.g.*, Dial et al. 2003; Finkl and Vollmer 2011; Hochberg et al. 2003; Maeder et al. 2002; Mumby and Edwards 2002; Palandro et al. 2003; Steimle and Finkl 2011), there are some limitations associated with the IKONOS images. IKONOS satellite imagery is typically not freely available to the public; therefore, it must be purchased. In addition to availability and cost, another limitation may include color and tone variations between individual IKONOS scenes, which were acquired at different times. Disparity in the appearance of adjacent scenes making up a composite of the study area occurs due to efforts to minimize cloud cover and variable underwater clarity. While deselection of unusable scenes provides the most effective means for collating a composite image of the study area, noticeable lines of transition from one scene to another are an unwanted result. These variable transitions between scenes eliminate the possibility of using autoclassification algorithms for seafloor interpretation, which would result in false-positives (*i.e.* spurious results) by interpreting the same marine landform unit differently in multiple areas. However, even with these limitations, IKONOS satellite images provide one the most effective remote sensing platforms for the application of newly developed seafloor classification schemes.

2.6 Conclusions

The last four decades has seen remarkable progress in the advancement of remote sensing capabilities. With the advent of technological progress, there has been a corresponding increase in the levels of interpretation and mapping of coastal marine environments. Increasing perfection of LADS and IKONOS technologies now permits a level of image cognition that was heretofore not possible. Airborne digital bathymetry facilitates the mapping of large expanses of seafloor at levels of detail where topographic assemblages can be detailed. Satellite imagery is likewise capable of depicting seafloor environments based on multispectral reflectance. These technological advancements bring together the nature and character of the submarine world into better focus on shallow carbonate banks. Although the two examples discussed here represent advanced technologies that retain advantages and disadvantages, the pros far out weight the cons to produce resilient databases of value to coastal research and resource management. The main problem today is that much more remotely sensed data can be collected than analyzed.

As shown in the LADS survey of the open ocean southeast Florida coast, enhancement of digital imagery created from dense bathymetric data can be used to highlight selected features, detect previously unnoted features, or digitally select certain features from an array of seabed features for specialized study. A good example of application of the new bathymorphometric data is the realization that the Florida Reef Tract contains long continuous troughs between reef systems that have been infilled with sediments. These bathymorphometric maps also show that the classical three-reef system is more complicated than originally perceived.

The example of the Marquesa Islands in the Florida Keys shows that IKONOS satellite imagery provides a suitable platform for mapping coastal (terrestrial) marine (seafloor) environments because the pixel size and number of bands permits differentiation of seafloor environments based on geomorphological units and biological covers. The southern Florida Keys hosts a great diversity of submarine environments in the area containing the only known atoll in the Atlantic Ocean. Interpretation of seafloor features seen in the IKONOS imagery provides an opportunity to develop biogeomorphological classification systems that could be used to characterize shallow water carbonate bank environments in lagoons, sediment flats, hardbottoms, tidal channels, and coral reefs.

References

Anders FJ, Byrnes MR (1991) Accuracy of shoreline change rates as determined from maps and aerial photographs. Shore Beach 59(1):17–26

Andrefouet S, Kramer P, Torres-Pulliza D, Joyce KE, Hochberg EJ, Garza-Perez R, Mumby PJ, Riegl B, Yamano H, White WH, Zubia M, Brock JC, Phinn SR, Naseer A, Hatcher BG, Muller-Karger FE (2003) Multi-site evaluation of IKONOS data for classification of tropical coral reef environments. Remote Sens Environ 88:128–143

Banks KW, Riegl BM, Shinn EA, Piller WE, Dodge RE (2007) Geomorphology of the southeast Florida continental reef tract (Miami-Dade, Broward, and Palm Beach Counties, USA). Coral Reefs 26:617–633

Barton C (2002) Marie Tharp, oceanographic cartographer, and her contributions to the revolution in the Earth sciences. In: The earth inside and out: some major contributions to geology in the twentieth century. The Geological Society of London, Oxford, pp 215–228

Bashenina NV, Gellert J, Joly F, Klimaszewski M, Scholz E (1968) Project of the unified key to the detailed geomorphological map of the world, Folia Geographica (Krakow, Polska Akademia Nauk), Series Geographica-Physica, vol II. Uniwersytetu Jagiellońskiego, Kraków, pp 11–12, 18

Bashenina NV, Blagovolin NS, Demek J, Dumitrashko NV, Ganeshin GS, Gellert JF, Leontyev OK, Mirnova AV, Scholz E (Compilers) (1971) Legend to the international geomorphological map of Europe 1:2,500,000, 5th version. Czechoslovak Academy of Sciences, Institute of Geography, Brno, 30p

Bashenina NV, Blagovolin NS, Castiglioni CB, Demek J, Dumitrashko NV, Gams I, Embleton C, Ganeshin GS, Gellert JF, Leontyev OK, Mirnova AV, Scholz E, Starkel L (1977) Legend to the international geomorphological map of Europe 1:2,500,000. Czechoslovak Academy of Sciences, Institute of Geography, Brno, 23p

Brock JC, Purkis SJ (2009) The emerging role of Lidar remote sensing in coastal research and resource management. In: Brock JC, Purkis SJ (eds) Coastal applications of airborne Lidar, Journal of coastal research, special issue no. 53. Coastal Education and Research Foundation, West Palm Beach, pp 1–5

Bukata RP, Jerome JH, Kondratyev KY, Posdnyakov DV (1995) Optical properties and remote sensing of Inland and Coastal Waters. CRC Press, Boca Raton, p 365

Butler MJA, LeBlanc C, Belbin JA, MacNeill JL (1986) Marine resource mapping: an introductory manual, FAO fisheries technical paper 274. Food and Agriculture Organization of the United Nations, Rome, 256p

Campbell JB (1996) Introduction to remote sensing, 2nd edn. Taylor & Francis, London, 622p

Chauvaud S, Bouchon C, Maniere R (1998) Remote sensing techniques adapted to high resolution mapping of tropical coastal marine ecosystems (coral reefs, seagrass beds and mangrove). Int J Remote Sens 19(18):3625–3639

DaPrato GW, Finkl CW (1994) Applications of a layered classification approach, based on spatial primitives obtained from TM data from Southern Florida, for the analysis of turbid marine waters using fuzzy sets. Int Arch Photogramm Remote Sens 30(4):69–76

Demek J (ed) (1972) Manual of detailed geomorphological mapping. Academia (for the International Geographical Union, Commission on Geomorphological Survey and Mapping), Prague, 344p

Demek J, Embleton C (eds) (1976) Guide to medium-scale geomorphological mapping. Czechoslovakia: International Geographical Union, Brno, Commission on Geomorphological Survey and Mapping (Preliminary edition for the 11th Commission meeting, Kiev, 1976, 23rd International Geographical Union), 339p

Deronde B, Houthuys R, Henriet JP, Van Lancker V (2008) Monitoring of the sediment dynamics along a sandy shoreline by means of airborne hyperspectral remote sensing and LIDAR: a case study in Belgium. Earth Surf Process Landf 33:280–294

Dial G, Bowen H, Gerlach F, Grodecki J, Oleszczuk R (2003) IKONOS satellites, imagery, and products. Remote Sens Environ 88(1–2):23–36

Dobson EL, Dustan P (2000) The use of satellite imagery for detection of shifts in coral reef communities. In: Proceedings, American Society for Photogrammetry and Remote Sensing, Washington, DC

Doel RE, Levin TJ, Marker MK (2006) Extending modern cartography to the ocean depths: military patronage, cold war priorities, and the Heezen-Tharp mapping project, 1952–1959. J Hist Geogr 32(3):605–626

Duane DB, Meisburger EP (1969) Geomorphology and sediments of the nearshore continental shelf Miami to Palm Beach, Florida, CERC technical memorandum 29. U.S. Army Corps of Engineers, Washington, DC, 47p

Ekebom J, Erkkila A (2002) Using aerial photography for identification of marine and coastal habitats under the EU's habitats directive. Aquat Conserv 13(4):287–304

Elvhage C (1980) An experimental series of topogeomorphological maps. Geografiska Annaler Ser A 62:105–111

FGDC (Federal Geographic Data Committee) [prepared for the Federal Geographic Data Committee by the U.S. Geological Survey] (2006) FGDC Digital Cartographic Standard for Geologic Map Symbolization. Federal Geographic Data Committee, Reston, VA. Document number FGDC-STD-013-2006, 290p

Finkl CW (2004) Coastal classification: systematic approaches to consider in the development of a comprehensive scheme. J Coast Res 20(1):166–213

Finkl CW (2005) Nearshore geomorphological mapping. In: Schwartz ML (ed) The encyclopedia of coastal science. Kluwer Academic, Dordrecht, pp 849–865

Finkl CW, Andrews JL (2008) Shelf geomorphology along the southeast Florida Atlantic continental platform: barrier coral reefs, nearshore bedrock, and morphosedimentary features. J Coast Res 24(4):823–849

Finkl CW, Banks KW (2010) Mapping seafloor topography based on interpretation of airborne laser bathymetry: examples from the southeast Florida Atlantic continental shelf. In: Martorino L, Puopolo K (eds) New oceanography research developments: marine chemistry, ocean floor analyses and marine phytoplankton. Nova Science Publishers, Hauppauge, pp 163–187

Finkl CW, Benedet L (2005) Jet probes. In: Schwartz ML (ed) The encyclopedia of coastal science. Kluwer Academic, Dordrecht, pp 707–716

Finkl CW, DaPrato GW (1993) Delineation and distribution of nearshore reefs in subtropical southeast Florida coastal environments using Thematic Mapper imagery. In: MTS '93 conference proceedings (Marine Technology Society annual meeting, Long Beach, CA), pp 90–96

Finkl CW, Khalil SM (2005) Offshore exploration for sand sources: general guidelines and procedural strategies along deltaic coasts. In: Finkl CW, Khalil SM (eds) Saving America's wetland: strategies for restoration of Louisiana's coastal wetlands and barrier islands, Journal of coastal research, special issue no. 44., pp 203–233

Finkl CW, Vollmer H (2011) Interpretation of bottom types from IKONOS satellite images of the southern Key West National Wildlife Refuge, Florida, USA. J Coast Res SI (64). In: Proceedings of the 11th international coastal symposium, pp 731–735

Finkl CW, Warner MT (2005) Morphological features and morphological zones along the inner continental shelf of southeastern Florida: an example of form and process controlled by lithology. J Coast Res SI (42): 79–96

Finkl CW, Benedet L, Andrews JL (2004) Laser Airborne Depth Sounder (LADS): a new bathymetric survey technique in the service of coastal engineering environmental studies, and coastal zone management. In: Proceedings of the 17th annual national conference on Beach Preservation Technology (February 11–13, 2004, Lake Buena Vista, FL). Florida Shore and Beach Preservation Association, CD-ROM, Tallahassee, 15p

Finkl CW, Benedet L, Andrews JL (2005a) Interpretation of seabed geomorphology based on spatial analysis of high-density airborne laser bathymetry. J Coast Res 21(3):501–514

Finkl CW, Benedet L, Andrews JL (2005b) Submarine geomorphology of the continental shelf off southeast Florida based on interpretation of airborne laser bathymetry. J Coast Res 21(6):1178–1190

Finkl CW, Becerra JE, Achatz V, Andrews JL (2008) Geomorphological mapping along the upper southeast Florida Atlantic continental platform; I: mapping units, symbolization, and GIS presentation of interpreted seafloor topography. J Coast Res 24(6):1388–1417

Gardiner V, Dackombe RV (1979) Geomorphological field manual. Allen & Unwin, London, 254p

Gellert JF (1988) Applied geomorphological survey and mapping on coasts. Zeitschrift fur Geomorphologie, N.F., Supplement Band 68, 223p

Gesch DB (2009) Analysis of lidar elevation data for improved identification and delineation of lands vulnerable to sea-level rise. J Coast Res SI (53): 49–58

Gierloff-Emden HG (1985) Documentation and presentation of the relief of the sea on maps. In: Fuchs K, Soffel H (eds) Numerical data and functional relationships in science and technology. Springer, Dordrecht. (Landolt-Bornstein, Group V Geophysics. Lehrbuch d. Allgemeinen Geographie, vol 5, Subvolume B [Relief of the Seafloor)]), pp 267–271

Gorman L, Morang A, Larson R (1998) Monitoring the coastal environment; Part IV: mapping, shoreline changes, and bathymetric analysis. J Coast Res 14(1):61–92

Green EP, Mumby PJ, Edwards AJ, Clark CD (2000) Remote sensing handbook for tropical coastal management. UNESCO Publishing, Paris, p 316

Guenther GC, Cunningham AG, LaRocque PE, Reid DJ (2000) Meeting the accuracy challenge in airborne lidar bathymetry. In: Proceedings of EARSeL-SIG-workshop LIDAR, Dresden/FRG, 16–17 June 2000, 27p

Heezen BC, Tharp M (1965) Tectonic fabric of the Atlantic and Indian Oceans and continental drift. Philos Trans R Soc Lond Ser A Math Phys Sci 258(1088):90–106

Heezen BC, Tharp M (1966) Physiography of the Indian Ocean. Philos Trans R Soc Lond Ser A Math Phys Sci 259(1099):137–149

Heezen BC, Tharp M (1977) World ocean floor. U.S. Navy, Washington, DC

Hochberg EJ, Atkinson MJ (2000) Spectral discrimination of coral reef benthic communities. Coral Reefs 19:164–171

Hochberg EJ, Andrefouet S, Tyler MR (2003) Sea surface correction of high spatial resolution Ikonos images to improve bottom mapping in near-shore environments. IEEE Trans Geosci Remote Sens 41(7):1724–1729

IHB (International Hydrographic Bureau) (1989) Standardization of undersea feature names. International Hydrographic Organization and the Intergovernmental Oceanographic Commission, Monaco, 28p

Irish JL, Lillycrop WJ (1997) Monitoring new pass, Florida with high density lidar bathymetry. J Coast Res 13(4):1130–1140

Irish JL, Lillycrop WJ (1999) Scanning laser mapping of the coastal zone: the SHOALS system. ISPRS J Photogramm Remote Sens 54(2–3):123–129

Irish JL, McClung JK, Lillycrop WJ (2000) Airborne lidar bathymetry: the SHOALS system. Int Navig Assoc PIANC Bull 103:43–53

Kempeneers P, Deronde B, Provoost S, Houthuys R (2009) Synergy of airborne digital camera and Lidar data to map coastal dune vegetation. J Coast Res SI(53): 73–82

Kenny AJ, Cato I, Desprez M, Fader G, Schuttenhelm RTE, Side J (2003) An overview of seabed-mapping technologies in the context of marine habitat classification. ICES J Mar Sci 60:411–418

Klemas V (2011a) Remote sensing techniques for studying coastal ecosystems: an overview. J Coast Res 27(1):2–17

Klemas V (2011b) Remote sensing of wetlands: case studies comparing practical techniques. J Coast Res 27(3):418–427

Klemas V (2011c) Beach profiling and Lidar bathymetry: an overview with case studies. J Coast Res 27(6):1019–1028

Lewis JB (2002) Evidence from aerial photography of structural loss of coral reefs at Barbados, West Indies. Coral Reefs 21:49–56

Lidz BH (2004) Coral reef complexes at an atypical windward platform margin: late quaternary, southeast Florida. Geol Soc Am Bull 116:974–988

Lidz BH, Shinn EA, Hine AC, Locker SD (1997) Contrasts within an outlier-reef system: evidence for differential quaternary evolution, south Florida windward margin, U.S.A. J Coast Res 13(3):711–731

Lidz BH, Reich CD, Shinn EA (2003) Regional quaternary submarine geomorphology in the Florida keys. Bull Geol Soc Am 115:845–866

Lidz BH, Reich CD, Peterson RL, Shinn EA (2006) New maps, new information: coral reefs of the Florida keys. J Coast Res 22(2):260–282

Long TM, Angelo J, Weishampel JF (2011) LiDAR-derived measures of hurricane- and restoration-generated beach morphodynamics in relation to sea turtle nesting behaviour. Int J Remote Sens 32(1):231–241

Madden C, Goodin K, Allee B, Finkbeiner M, Bamford D (2008) Coastal and marine ecological classification standard. NOAA and NatureServe, Arlington, 77p

Madley KA, Sargent B, Sargent FJ (2002) Development of a System for Classification of Habitats in Estuarine and Marine Environments (SCHEME) for Florida. Unpublished report to the U.S. Environmental Protection Agency, Gulf of Mexico Program (Grant Assistance Agreement MX-97408100). Florida Marine Research Institute, Florida Fish and Wildlife Conservation Commission, St. Petersburg, 43p

Maeder J, Narumalani S, Rundquist DC, Perk RL, Schalles J, Hutchins K, Keck J (2002) Classifying and mapping general coral-reef structure using IKONOS data. Photogramm Eng Remote Sens 68(12):1297–1305

Maritorena S, Morel A, Gentili B (1994) Diffuse reflectance of oceanic shallow waters: influence of water depth and bottom albedo. Limnol Oceanogr 39(7):1689–1703

Milard F (1996) Symboles et Abre'viations figurant sur les cartes marines françaises. Service Hydrgoraphique et Oce'anographique de la Marine (SHOM), Brest, 102p (Based on Chart Specifications of the IHO. XIIth International Hydrographic conference 1982 in Monaco)

Moody R (2007) Beyond plate tectonics: 'plate' dynamics. Infinite Energy 74:1–13

Moore LJ (2000) Shoreline mapping techniques. J Coast Res 16(1):111–124

Mount R (2003) The application of digital aerial photography to shallow water seabed mapping and monitoring: how deep can you see? In: Proceedings of coastal GIS 2003, University of Wollongong, Australia, 7–8 June 2003, 10p

Moyer RP, Riegl B, Banks K, Dodge RE (2003) Spatial patterns and ecology of benthic communities on a high-latitude south Florida (Broward County, USA) reef system. Coral Reefs 22:447–464

Mumby PJ, Edwards AJ (2002) Mapping marine environments with IKONOS imagery: enhanced spatial resolution can deliver greater thematic accuracy. Remote Sens Environ 82:248–257

Mumby PJ, Harborne AR (1999) Development of a systematic classification scheme of marine habitats to facilitate regional management and mapping of Caribbean coral reefs. Biol Conserv 88:155–163

Mumby PJ, Green EP, Edwards AJ, Clark CD (1999) The cost-effectiveness of remote sensing for tropical coastal resources assessment and management. J Environ Manag 55(3):157–166

O'Regan PR (1996) The use of contemporary information technologies for coastal research and management: a review. J Coast Res 12(1):192–204

Ollier CD (1977) Terrain classification: methods, applications and principles. In: Hails JR (ed) Applied geomorphology. Elsevier, Amsterdam, pp 277–316

Palandro D, Andrefouet S, Dustan P, Muller-Karger FE (2003) Change detection in coral reef communities using IKONOS satellite sensor imagery and historical aerial photographs. Int J Remote Sens 24(4):873–878

Palandro D, Thoms K, Kristen K, Muller-Karger F, Greely T (2005) Satellite remote sensing of coral reefs: by learning about coral reefs, students gain an understanding of ecosystems and how cutting-edge technology can be used to study ecological change. Sci Teach 72(6), 51p

Ramsey EW III, Laine SC (1997) Comparison of landsat thematic mapper and high resolution photography to identify change in complex coastal wetlands. J Coast Res 13(2):281–292

Richards DG (1980) Water-penetration aerial photography. Int J Naut Archaeol Underw Explor 9(4):331–337

Rohmann SO, Monaco ME (2005) Mapping southern Florida's shallow-water coral ecosystem: an implementation plan, NOAA Technical Memorandum NOS NCCOS 19. Center for Coastal Monitoring and Assessment, Silver Spring, 45p

Schowengerdt RA (1997) Remote sensing models and methods for image processing, 2nd edn. Academic, San Diego, 560p

Sheppard CR, Matheson K, Bythel JC, Murphy P, Myers CB, Blake B (1991) Habitat mapping in the Caribbean for management and conservation: use and assessment of aerial photography. Aquat Conserv 5:277–298

Shoshany M, Degani A (1992) Shoreline detection by digital image processing of aerial photography. J Coast Res 8(1):29–34

Smith CJ, Rumohr H (2005) Imaging techniques. In: Eleftheriou A, McIntyre A (eds) Methods for the study of marine benthos. Blackwell Science, Oxford, pp 87–111

Smith GL, Zarillo GA (1990) Calculating long-term shoreline recession rates using aerial photographic and beach profiling techniques. J Coast Res 6(1):111–120

Specht MR, Needler D, Fritz NL (1973) New color film for water photography penetration. Photogramm Eng 39:359–369

Steimle JT, Finkl CW (2011) Interpretation of seafloor topologies based on IKONOS satellite imagery of a shallow-marine carbonate platform: Florida Bay to the Florida Reef Tract. J Coast Res SI 64. In: Proceedings of the 11th international coastal symposium, pp 825–830

Stockdon HF, Sallenger AH, List JH, Holman RA (2002) Estimation of shoreline position and change using airborne topographic lidar data. J Coast Res 18(3):502–513

Stockdon H, Doran KS, Sallenger AH Jr (2009) Extraction of lidar-based dune-crest elevations for use in examining the vulnerability of beaches to inundation during hurricanes. J Coast Res SI (53): 59–65

Stoker JM, Tyler DJ, Turnipseed DP, Van Wilson K Jr, Oimoen MJ (2009) Integrating disparate lidar datasets for a regional storm tide inundation analysis of Hurricane Katrina. J Coast Res SI (53): 1–13

Thieler ER, Danforth WW (1994) Historical shoreline mapping (I): improving techniques and reducing positioning errors. J Coast Res 10(3):549–563

Walker BK, Riegl B, Dodge RE (2008) Mapping coral reef habitats in southeast Florida using a combined technique approach. J Coast Res 24(5):1138–1150

Warner MT (1999) Analysis of coastal morphodynamic zones based on detailed mapping in Palm Beach County. Master's thesis, Florida Atlantic University, Boca Raton, 110p

Zieman JC, Fourqurean JW, Iverson RL (1989) Distribution, abundance and productivity of seagrasses and macroalgae in Florida Bay. Bull Mar Sci 44(1):292–311

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