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Interpretation of Seabed Geomorphology Based on Spatial Analysis of High-Density Airborne Laser Bathymetry

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ABSTRACT

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Airborne laser bathymetric (ALB) systems rapidly acquire large, high-quality datasets via variable swath widths that are independent of water depth. Laser bathymetric survey tools have applicability in clear coastal (Case II) waters down to −70 meters depth. Deployed along the southeast Florida (Palm Beach, Broward, and Miami-Dade Counties) coast, an advanced ALB system provided a continuous dataset for 160 kilometers of coast from onshore to 6 kilometers offshore. Digital terrain models developed from this high-density bathymetric data permitted recognition of numerous seafloor features and bathymetric patterns from different image formats. Bathymetric analysis of the 600-km^2 survey area on the narrow continental shelf shows inherited lithologic features that are partly covered by surficial sediments. Primary parabathic provinces include: (1) nearshore rocky zones dominated by the Anastasia Formation, (2) coral-algal reef systems (Florida Reef Tract [FRT]), and (3) marine terraces. Secondary sedimentary subprovinces include shoreface sands, inter-reefal sedimentary infills (coral rubble in basal sequences and near reef gaps), and finer-grained materials seaward of the FRT. Tertiary topographic features include: (1) longshore bar and trough systems, shoals, sand sheets, and diabathic channels; (2) reef crests and ledges, forereef spurs and grooves, sediment ramps in large reef gaps, and incised paleo-river channels; and (3) drowned karst topography. Hierarchical organization of these bathymetric features is now possible for the first time because of the increased accuracy and density of bathymetric data obtained by ALB systems.

ADDITIONAL INDEX WORDS: *Bathymetric mapping, airborne bathymetric surveying, remote sensing, seafloor sediments, coastal geomorphology, beach nourishment, marine sand resources, inter-reefal sand deposits, karst topography.*

INTRODUCTION

Detection of shallow-water bottom features along the southeast coast of Florida, using remotely sensed methods, traditionally focused on sidescan sonar (SSS) and subbottom seismic survey. Both methods provide useful information to sand searches (ANDREWS, 2001) and environmental studies (HORGAN, ANDREWS, and BENEDET, 2003), because they show depth of sediments in inter-reefal troughs and the nature of the seabed surface (hardgrounds *vs.* sedimentary cover). With the advent of modern spaceborne platforms, it became possible to acquire bottom information from Thematic Mapper (Landsat 7) images and SPOT (SPOT Image Corporation, Chantilly, Virginia). Seminal work in this regard, for the southeast Florida coastal zone, was reported by FINKL and DAPRATO (1993) and DAPRATO and FINKL (1994), who used various image-enhancement techniques to broadly characterize the seafloor from the surf zone to about 30 meters depth.

Usefulness of aerial photography depends on clarity of the water column. Some of the early oblique photography from the 1920s occasionally showed nearshore submarine features when turbidity was low, but the images were most useful for onshore work (FINKL, 1993). In the 1940s, coverage in vertical stereo-paired images along the shore was complete, but the scale was inappropriate (>1:40,000) for most coastal applications, and practically no bottom information was provided. In the 1970s, Kodak experimented with a special water-penetrating film that provided remarkably clear and detailed images of the seafloor. These experimental runs from Miami to northern Broward County provided some of the first areally continuous clear panchromatic pictures of seafloor geomorphic units, marking a real breakthrough in seafloor mapping from aerial photography. The new experimental film was largely ignored until the Challenger space shuttle accident (28 January 1986), when it was used to search for fragments on the seabed. Realizing the strategic value of this remarkable film, the government clamped security restrictions on water-penetrating films and suspended production of this product for public use. The water-penetrating film was depth limited to about 15 meters, and although extremely useful for nearshore work, it was of little use farther offshore. Of all remote-sensing techniques, the Kodak water-penetrating film for a long time provided the best imagery for characterization of nearshore seafloor features. Nearshore seafloor mapping was recently advanced by georeferenced color

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digital aerial photography that could be imported directly into ArcView (ESRI, Redlands, California) for bottom characterization along the southeast coast (*e.g.,* BENEDET, 2002; BENEDET and FINKL, 2003; BROWN, 1998; WARNER, 1999). This application is ancillary, however, because the purpose of these aerial surveys is to document shoreline (beach) conditions, and any seafloor included in the images is incidental.

With the advent of laser technology that could sense bottom configuration, several systems became commercially available. The SHOALS Lidar system is now widely deployed for inlet and nearshore surveys of bathymetry. Optech's SHOALS airborne Lidar bathometers (Optech, Toronto, Ontario, Canada) are based on the same principle as sonar, but they use light instead of sound to survey clear water to depths around 50 meters. The Laser Airborne Depth Sounder (LADS; Tenix LADS Corporation, Mawson Lakes, South Australia, Australia) is a similar digital system that is used to sense water depth. These new optical (passive) sensors, like aerial photography, are depth limited, but the depth of penetration is much greater, often approaching 60 meters depending on the optical behavior of what remote-sensing researchers call Case II (coastal) waters (BUKATA *et al.*, 1995; FINKL, BENEDET, and ANDREWS, 2004). Turbidity is due to a combination of factors that include colored dissolved organic matter (CDOM), phytoplanktons, and nonchlorophyllous particulate matter (including the suspended sediment concentration [SSC]) (BUKATA *et al.*, 1995). These materials limit depth penetration by optical sensors because of scattering and absorption, which greatly attenuate signals from passive systems. The general rule thus follows the principal that the higher the turbidity (due to CDOM, SSC, and phytoplankton), the less penetration of water depth; ALB systems are no exception. Depth-sounding surveys are thus well adapted to the clear Case II waters found along the southeast coast of Florida.

Purpose

The collection of depth information for a small pixel size (2-meter by 4-meter grid) is one of the great advantages of ALB systems. This information is then presented at a map scale that produces the impression of continuous bottom. These digital bathymetric maps look like shaded topographic maps that assume an artificial light source, which helps make bathymetric patterns and topographic forms more recognizable. This article discusses the interpretation of high-density bathymetric data (4-meter by 4-meter grids) obtained with an ALB system in terms of morphological organization, demonstrates some common image-enhancement techniques, and gives an example of practical application to coastal engineering and management.

METHODS

Acquired along the Florida southeast coast in 2001 (Broward County) and in 2003 (Palm Beach and Miami-Dade Counties), the bathymetric data used in this article were obtained using and ALB system known as LADS developed by Tenix LADS Corporation. Surveys in southeast Florida were conducted by Tenix in collaboration with Coastal Planning & Engineering, Inc. (CPE, 1994, 1997). The dataset comprises millions of points in a bathymetric database for a coastal segment that spans 160 kilometers alongshore and up to 6 kilometers offshore, to cover nearly 600 square kilometers of seabed (Figure 1). When this detailed coverage is printed at a nominal map scale of about 1:800, it provides convenient handling capabilities for sheets laid end to end that stretch 16 meters in a long continuous map sheet. Continuous map sheets have an advantage, because patterns become recognizable for the first time, namely the extent and continuity of rock outcrop, reef tracts, sand flats, *etc.* Where there is rapid change in depth, well-defined dark shadows emphasize closely spaced isobaths. Shadows are especially useful for subtle features, because they may otherwise go unnoticed. Shaded relief bathymetric maps with about a 10-fold exaggeration of vertical scale produce discrete sounding patterns that can be interpreted in terms of topographic units. 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. Validation of typologies is achieved by seatruthing, which is supported by SSS and subbottom profiler geophysical surveys, by geotechnical (vibracore) surveys, and by bottom samples and videos retrieved by divers.

Image Enhancement

Printed three-dimensional representations of the seabed (digital terrain models, digital elevation models [DEM]) constructed based on the dense bathymetric data produce patterns and shapes that are identifiable as discrete landform units. The bathymetric data can thus be interpreted by pattern recognition and shape detection (CAMPBELL, 1996; SCHOWENGERDT, 1997), important tools for analyzing seafloor topography. Another advantage of the digital terrain models is that digital image-enhancement techniques can be applied using specialized processing modules in programs such as ArcGIS Image Analyst (Leica Geosystems GIS & Mapping, Heerbrugg, Switzerland), Idrisi (Clark Labs, Worcester, Massachusetts), ERDAS Imagine (Leica Geosystems GIS & Mapping), PCI (PCI Geometrics, Richmond Hill, Ontario, Canada), Surfer (Golden Software, Inc., Golden, Colorado), *etc.*

Images of practical interest include DEM that are generated by data interpolation and grid generation represented in three-dimensional surfaces by triangular irregular networks. These kinds of images consist of several dominant spatial frequencies. Finer detail in an image involves a larger number of changes per unit distance than the gross image features. Fourier analysis is one of the most common mathematical techniques for separating an image into its various spatial frequency components. After an image is separated into its components (accomplished as a "Fourier Transform"), it is possible to emphasize certain groups (or "bands") of frequencies relative to others and to recombine the spatial frequencies into an enhanced image (CAMPBELL, 1996; SCHOWENGERDT, 1997). Algorithms for this purpose are called "filters" because they suppress (de-emphasize) certain frequencies and pass (emphasize) others. Filters that pass high

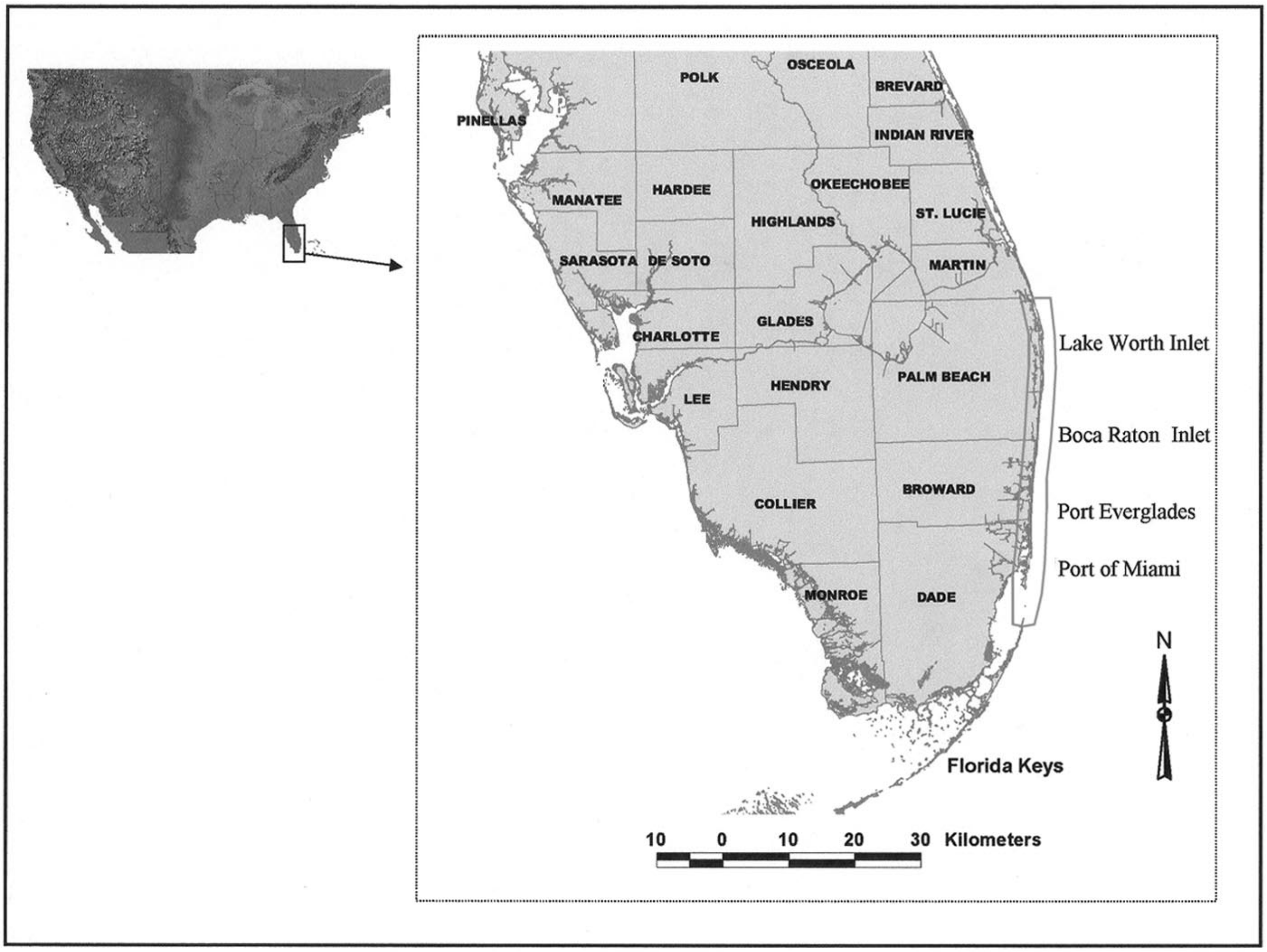

Figure 1. Location of LADS bathymetric survey area along the inner continental shelf off southeast Florida from the Martin/Palm Beach county line to the Monroe/Miami-Dade county line. The survey area covers about 600 km², extending from the shore to about 6 km offshore and into water depths of about 55 m.

frequencies, thus emphasizing fine detail and edges, are called highpass filters. Lowpass filters, which suppress high frequencies, are useful in smoothing an image and may reduce or eliminate "salt-and-pepper" noise. A lowpass (mean) filter tends to generalize the image (Figure 2).

A common mathematical method of implementing spatial filters is convolution filtering. In this procedure, each pixel value is replaced by the average over a square area centered on that pixel. Square sizes typically are 3×3, 5×5, or 9×9 pixels, but other values are acceptable. As applied in lowpass filtering, this tends to reduce deviations from local averages and thus smoothes the image (Figure 2). The difference between the input image and the lowpass image is the highpass-filtered output. Generally, spatially filtered images must be contrast-stretched to use the full range of image display. Nevertheless, filtered images tend to appear flat.

In the example of the Boca Raton area (Figure 2), a highpass filtering technique enhances deviations from local averages to emphasize relative relief for nearshore bars and troughs, diabathic channels in sand, and reef morphologies that include both large-scale parabathic trends and small-scale diabathic patterns. Although visible in the highpass filtered imagery (top image, Figure 2), an edge detection filtering technique superimposed on a smoothed background (bottom image, Figure 2) delineates boundaries between averaged trends. The boundaries (shown as white lines) separate nearshore, midshore, and offshore zones and define forereef spur-and-groove topography and backreef rubble fields. Water depths at major geomorphic boundaries are shown in Figure 2 (upper image) to define bathymorphometric units from the seaward margin of the active sand transport zone (-7 meters) to a deepwater reef (-45 meters).

Linear features, a trademark of a highpass-filtered image, commonly appear as bright lines with a dark border (Figure

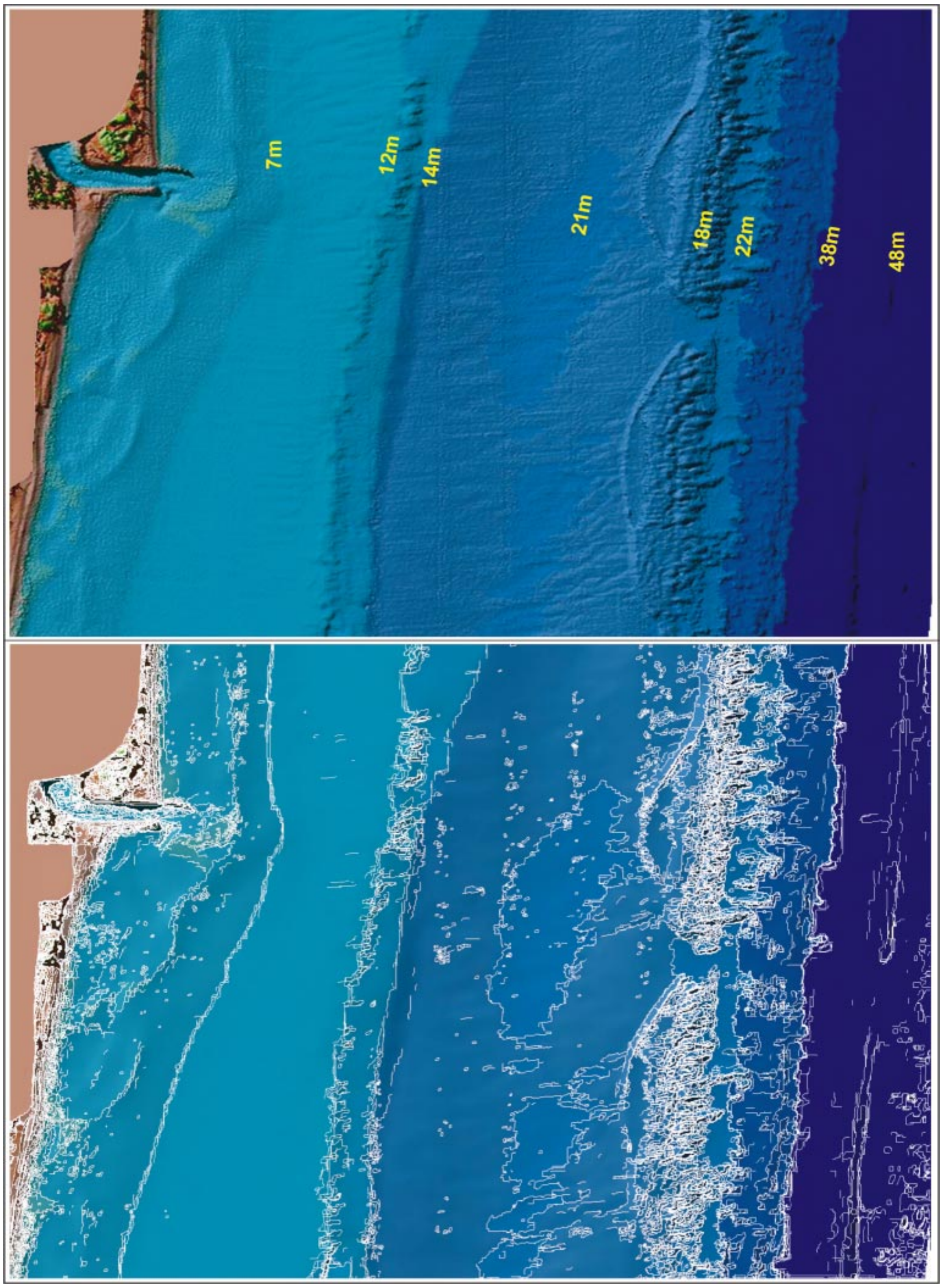

Figure 2. Area offshore the Boca Raton Inlet, Palm Beach County, comparing a filtered (highpass) color image (upper image) and smoothed (lowpass-filtered) color image (lower). The filtering merges low-relief features with surrounding areas, which in effect highlights high-relief features (upper image). General trends are, however, more clearly evident from lowpass filtering (lower image). The white lines on the right image result from a filtering technique that detects rapid changes in DN values for relief to define "edges" or boundaries between bathymetric units.

3). Edge-enhancement filters highlight abrupt discontinuities and delineate edges surrounding objects (*e.g.,* Sobel Edge Enhancement algorithm). Just as contrast stretching strives to broaden the image expression of differences in spectral reflectance by manipulating digital number (DN) values, spatial filtering is concerned with expanding contrasts locally in the spatial domain. In the real world, where there are boundaries between features on either side of which reflectances (or emissions) are quite different (notable as sharp or abrupt changes in DN values), these boundaries can be emphasized

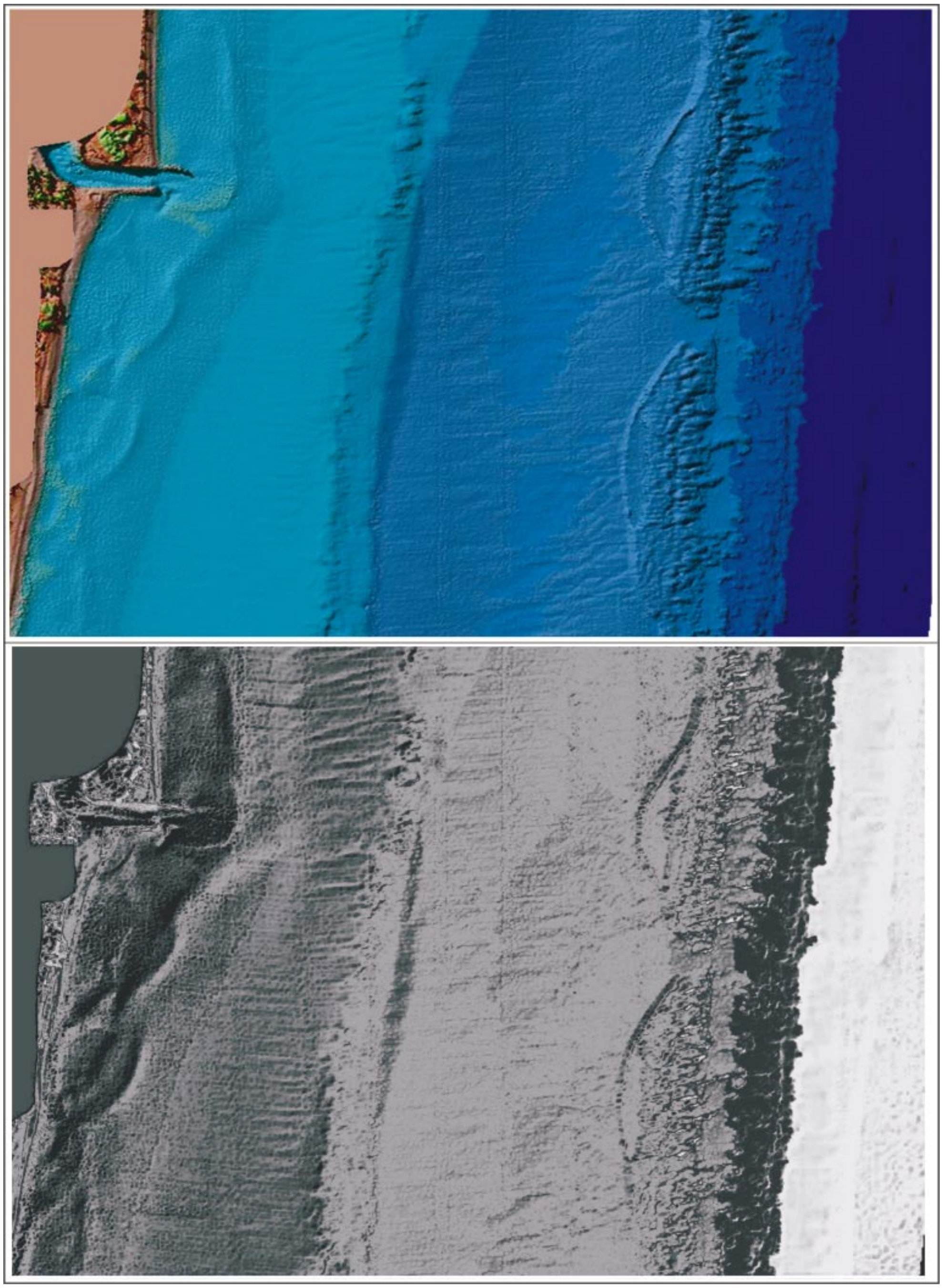

Figure 3. Enhanced bathymetric images of seafloor features offshore the Boca Raton Inlet. Highpass filtering (upper image) emphasizes linear and broadly curvilinear features as seen in the nearshore crenulate bar-and-trough bathymetric pattern; diabathic channels, reefs, and reef aprons are also emphasized. Spatial filtering (lower image) of this grayscale image produces a more maplike appearance by combining similar DN values in a specified spatial dimension. Note the emphasis of nearshore troughs (dark crenulated tones), diabathic channels on the sand flats, and separation (by grayscale tonal quality) of the major geomorphological units (beach, nearshore bars and troughs, hardgrounds, inter-reefal sand flats, and the FRT).

by any one of several computer algorithms (or analog optical filters). The resulting images often are quite distinctive in appearance. Linear features in particular, such as geologic faults, can be made to stand out. The type of filter used, high- or lowpass, depends on the spatial frequency distribution of DN values and on what the user wishes to accentuate. In Figure 3, the spatially filtered grayscale image (bottom) emphasizes areal discontinuities in the depth-sounding data matrix to highlight bars and troughs, diabathic channels, and reef complexes. Juxtaposed color and grayscale images show that under certain circumstances, there are advantages of grayscale over colorized imagery, depending on the kind of information that is extracted by enhancement techniques.

In order to show depth ranges via color groupings, three-dimensional images of the seabed are usually color-ramped (gradation of colors). Although color ramps are selected for a variety of reasons, they most commonly attempt to simulate perceptions of increasing water depth from light blue hues nearshore to darker hues with increasing depth. Useful for giving immediate impressions of depth ranges, the procedure can be distracting to feature recognition and *vice versa.* Even though colors might be selected to simulate reflectance of seafloor features, for remote-sensing purposes it is often advantageous to use false-color sequences that are not intended to represent reality.

Unrealistic color schemes have some advantage, because spatial patterns can be more clearly displayed or because specific features can be emphasized, such as the location of sand flats or hardgrounds. For the latter purpose, grayscale imaging usually produces a more useful image, one in which tonal variations and shadow effects help demarcate individual features rather than color differences. Maps preferred for feature recognition in the study area were grayscale shadow with isobaths; omission of color ramps simplified the background and did not confuse transitional bathymetric phases, that is, decreasing depths within generally deeper water and *vice versa* (*e.g.,* successive reef tracts rising above general bottom isobaths as depth increases offshore).

Grayscale imagery was analyzed on paper for the purpose of feature recognition and geomorphological mapping of the seafloor, but colorized examples here illustrate the effects of selected image-enhancement techniques. These procedures are especially useful for determining continuity of selected topological features throughout the large datasets for each county, because variations from central tendencies can be confusing when mapping. Where spur-and-groove forereef topography is well developed, for example, there is no problem identifying or characterizing the unit, but when the relief is subdued by partial sand cover or is otherwise marginalized (diminished) by natural processes, analysis of spatial distribution patterns can be very helpful. The color ramp based on blue and red hues in Figure 4 (bottom image) is used to emphasize the separation between deepwater reef environments and shallow sand flats. This blue-red contrast clearly identifies the shoreward penetration of grooves from the forereef environment to the reef crest (right side of bottom image). Application of a gradient filter in Figure 4 (bottom image) emphasizes two different coastal process zones. The diabathic channels on the left side of the upper image (A) show underflow patterns in soft, unconsolidated sands where currents move seaward, moving sediment offshore toward the inter-reefal trough. The diabathic channels landward of the reef aprons (rubble fields) (B) show shoreward sediment transport patterns that bring coarse-grained clasts from the coral reef to depocenters in the inter-reefal trough (compare with lower image). Analysis of the seabed morphology thus shows two different mechanisms that are related to inter-reefal trough infilling. When combined with collateral data (*e.g.,* geophysical and geotechnical information), this kind of morphological analysis can be a powerful tool for interpreting large-scale coastal behavior and showing the distribution of sand resources on this narrow (1.7 kilometers wide) continental shelf (FINKL, 2004).

An advantage of combining different image-enhancement techniques is shown in Figure 5, where multiple properties are combined within one image (*cf.* upper *vs.* lower images). The same (upper) image, as shown in Figures 2, 3, and 4, shows depth, but the image-enhancement procedures can group depth ranges into classes by color to display spatial organization of relief more clearly. Brighter colors at depth, for example, enhance perception of the FRT by more clearly showing reef crests, spur-and-groove topography, backreef aprons and rubble fields, reef gaps, and deeper reefs (darker-colored parabathic bands on the far right side of bottom image).

Filtering techniques for bathymetric data just north of the Lake Worth Inlet are compared in Figure 6. Smoothing of the left image by lowpass filtering eliminates variable data, thus emphasizing only the primary features of the seafloor. The drowned channel occurs along a major hinge line where orientation of the coast changes to a more northwesterly direction, whereas the FRT follows a more northeasterly track. Details of bathymetric irregularities are emphasized by high-pass filtering (right image), but both enhancements have advantages that are user dependent. The images in Figure 6 show for the first time the distinctive nature of the local seafloor in terms of sedimentary accumulations *vs.* exposure of bedrock. These domains are relevant to marine sand searches and define the limits of potentially searchable areas. Manipulation of bathymetric data, as demonstrated in the examples shown here in Figures 2 through 6, using an array of algorithms appropriate for image enhancement, improves the quality of marine sand searches and provides additional understanding of the coastal geological framework.

Determination of Seafloor Morphology

Morphological units (composed of combinations of depth, shape, and arrangement of soundings) and shadow patterns were drawn on the paper charts (at a scale of 1:800) freehand and then digitized on screen. This dual procedure was followed because it is easier to identify and follow patterns on large charts than on the computer screen. Screen resolution was better than print resolution, and patterns marked on the bathymetric charts could be modified on screen during digitizing phases in ArcView (ArcGIS). The final digital product (Figure 7) is thus compiled in a spatial context that facilitates analysis and computation of selected parameters, such as areas for inter-reefal sand flats or coral reef crests, spur-and-groove topography, backreef debris fields, *etc.*

Before initiating the actual mapping process based on image interpretation, each chart in the series was visually inspected and partially mapped in an effort to ascertain the range of features that could be identified. Features occurring on the charts were compiled to a comprehensive legend comprising 35 features, which were organized in terms of a geomorphological classification scheme. There are many possibilities for interpretation of features, and the orientation de-

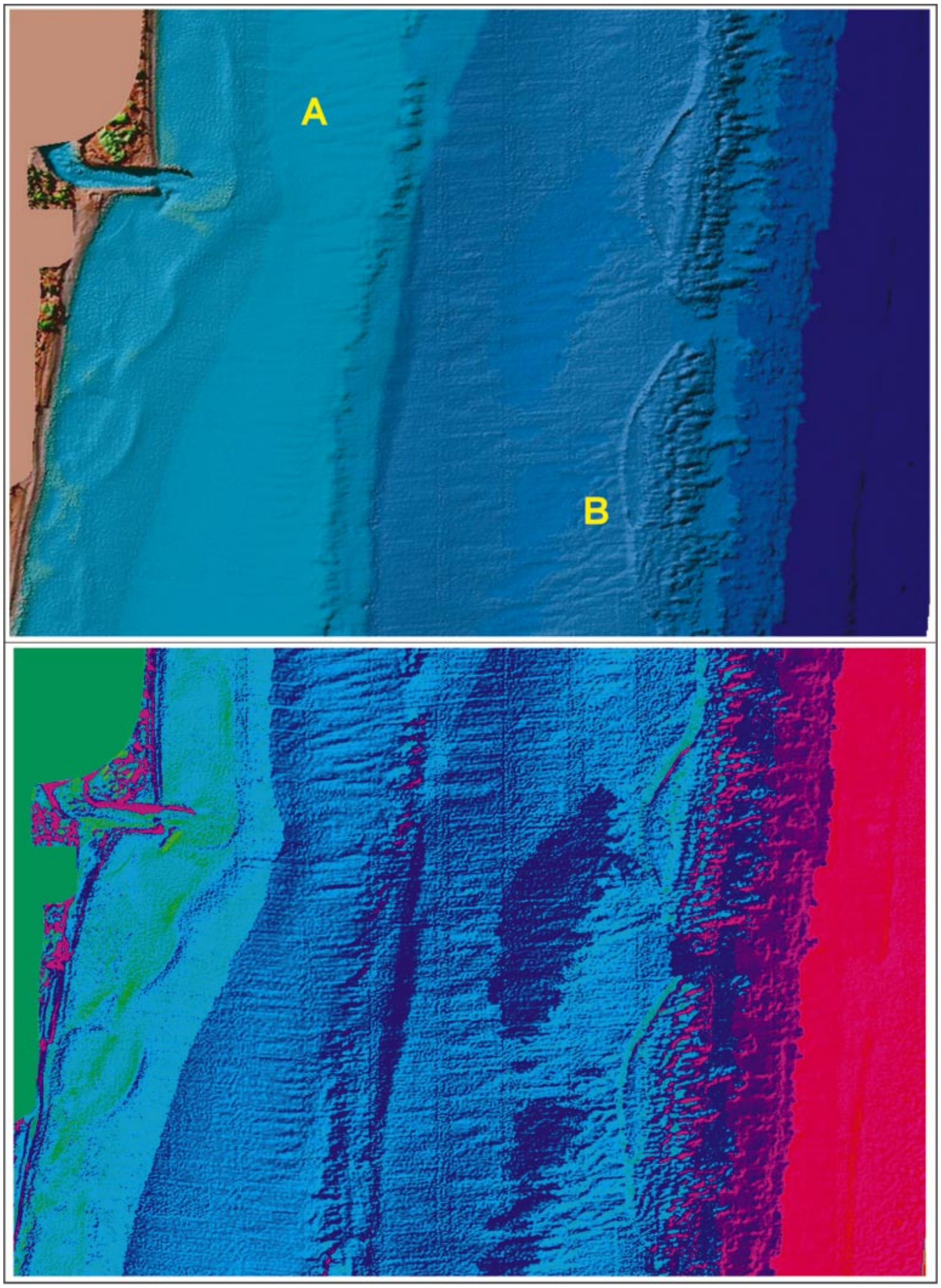

Figure 4. Enhanced false-color imagery of seafloor features offshore the Boca Raton Inlet. The highpass-filtered (upper) image was subjected to a gradient filter technique that emphasizes changes in DN numbers over a specified number of pixels. This kind of "change in slope" image combines some classes separated in previous images but discerns bathymetric change. Note in particular how close-order depth differences are highlighted in the forereef spur-and-groove topography (right side of lower image, where reddish hues for deeper water transect bluish hues for shallower water) and how clearly diabathic ridges and troughs stand out for nearshore and inter-reefal sands.

pends on the purpose, which was production of a geomorphological map of the seafloor. The classification scheme is summarized in Table 1, along with mapping units.

The development of a morphological classification scheme can be an endless task. It is thus 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. More detail can be observed on computer monitors, to the point where the image disintegrates by pixelation. For large-scale mapping, the printed map

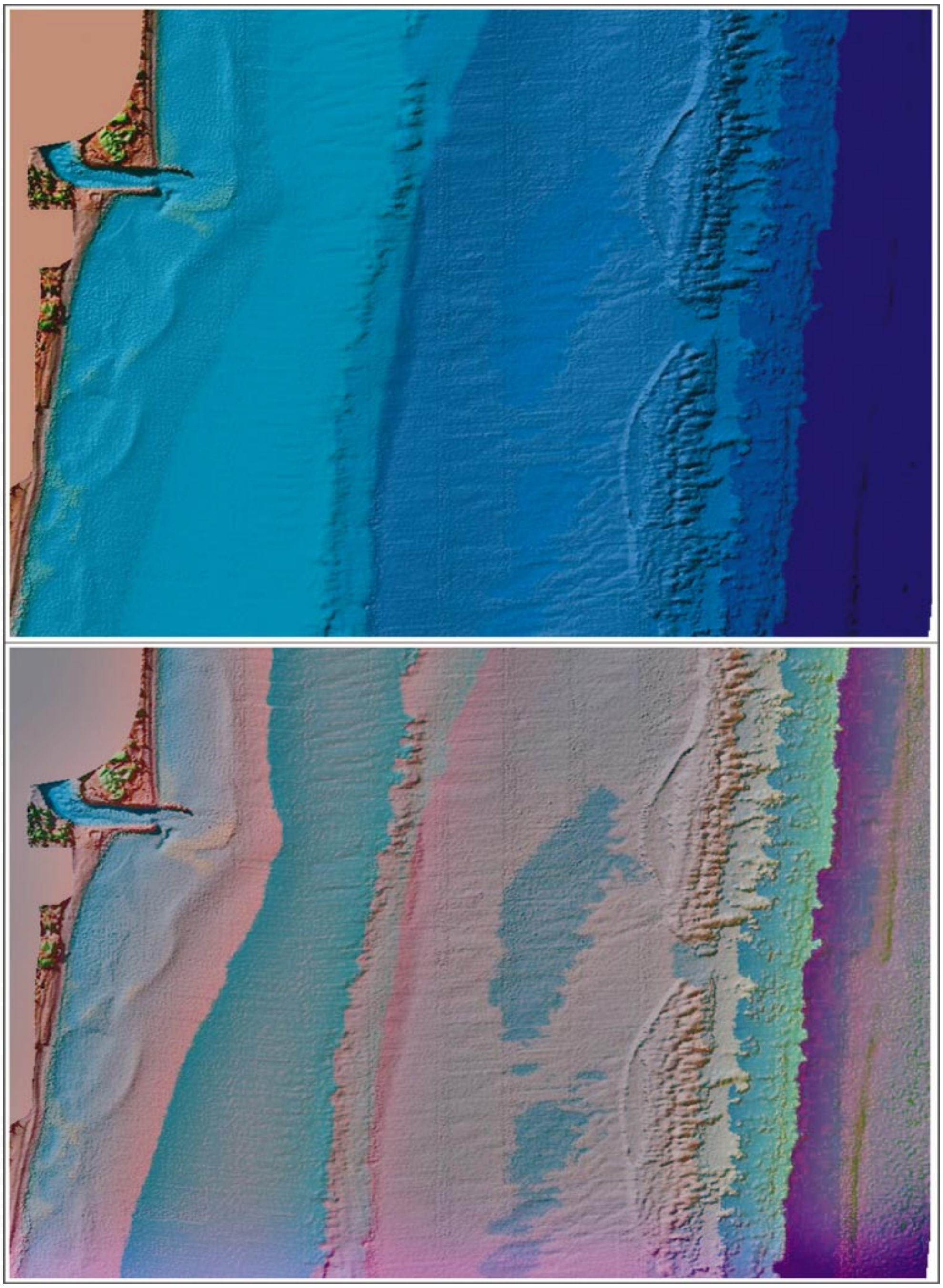

Figure 5. Enhanced false-color imagery of seafloor features offshore the Boca Raton Inlet. The upper image is the same highpass-enhanced image shown in Figures 2, 3, and 4. The lower image was enhanced by combining filters for diffusion (deconvolution) and highpassing. The result is a clear delineation of bathymetric classes by color, emphasis of relief, and distinction of spatial distribution patterns for relief types (landforms).

sheets provided sufficient detail for feature recognition but still showed general spatial trends (Figure 7). It was thus possible to identify a range of features without distraction by too much detail. Also relevant is the balance between what can be seen, what can be mapped, and what is useful or practical to delineate. That is, the natural spatial heterogeneity of morphological units on the seafloor determines what should be mapped. Most natural units are thus predetermined, and they reflect units that have been mapped and described by other researchers working elsewhere.

An example of the interpretative procedure in which color-ramped bathymetry is converted into bathymorphometric

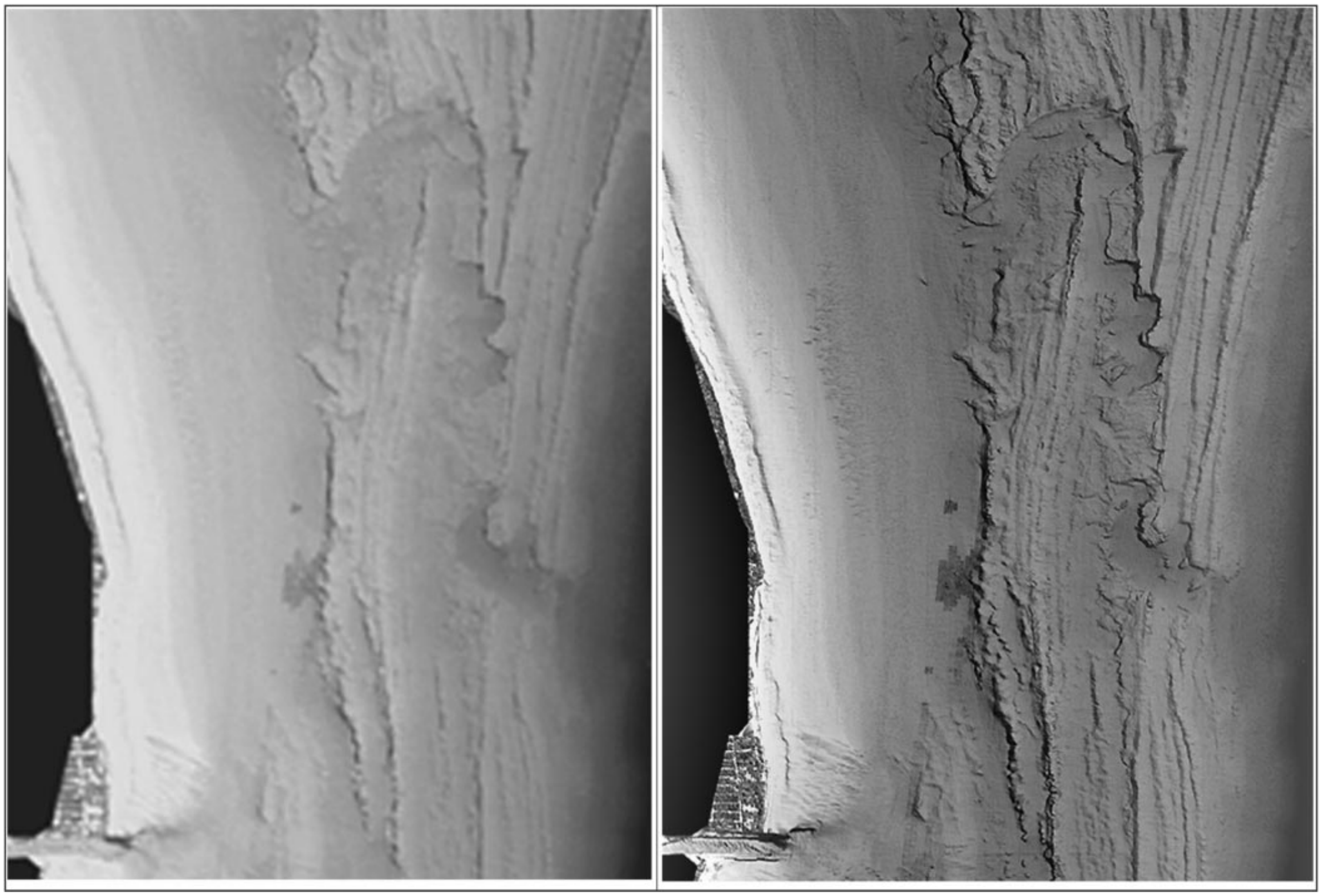

Figure 6. Grayscale ALB image in the vicinity of Lake Worth Inlet (bottom lefthand corner) showing a paleochannel cut through the northern extension of the FRT. This comparison of image-enhancement techniques contrasts lowpass filtering (left image) with highpass filtering (right image). The left image is generalized and smoothed, showing only major morphological features on the seafloor. This is useful to observe surface expression of the general geological framework. The sharpness of the right image emphasizes details and the intricacy of structural units in the limestone bedrock. Solution features are clearly evident in both images. The path of the paleochannel, probably an inlet when functioning, was influenced by structural lines of weakness and presence of solution pits. The channel thalweg is covered by sedimentary infills, and its landward and seaward margins are obscured by nearshore sand bodies.

units is shown in Figure 7, a small subsample of the regional ALB image. Image-enhancement techniques, described previously, were used to help discern various morphologic features on the seafloor. The sequence of parabathic mapping units from the shore seaward includes nearshore reef (exposure of Anastasia Formation bedrock), nearshore sand flats, reef overwash deposits, coral reef, forereef rubble, deepwater reef, and continental slope. Diabathic mapping units included reef gaps that extend across the barrier reefs from shallow-water nearshore sand flats to deep water, sometimes cutting through deepwater reefs, as seen in the upper reef gap (Figure 7, center of right image). These maps of bathymorphometric units simplify the complexity of the ALB image (Figure 7, left image), but at the same time, they provide an overview of seafloor features in terms of their spatial organization while providing an opportunity to better understand the nature of this narrow continental shelf.

Some morphological units originated as terrestrial features (*e.g.,* karst nu) that were subsequently drowned by sea-level rise to become karst noye ("drowned karst"), of which there is ample evidence throughout the study area in the form of solution pits, dolines, and sinkholes. Other features are marine, however, except for coastal channels (Figure 6). The main morphological features occurring in the study area are summarized in Table 1 in terms of sandy accumulations, rock hardgrounds (exposed bedrock, usually as karst noye), coral reefs, and related features.

These units, which are keyed to the ALB maps, represent an initial attempt to characterize the nature of the inner continental shelf along the southeast coast of Florida. This classification of seafloor morphological types is open ended and can be amended as required. Morphological features occurring at depths less than 10 meters were not included in this study because they were already mapped using aerial photography for Palm Beach and Broward Counties (Brown, 1998; Benedet, 2002; Warner, 1999).

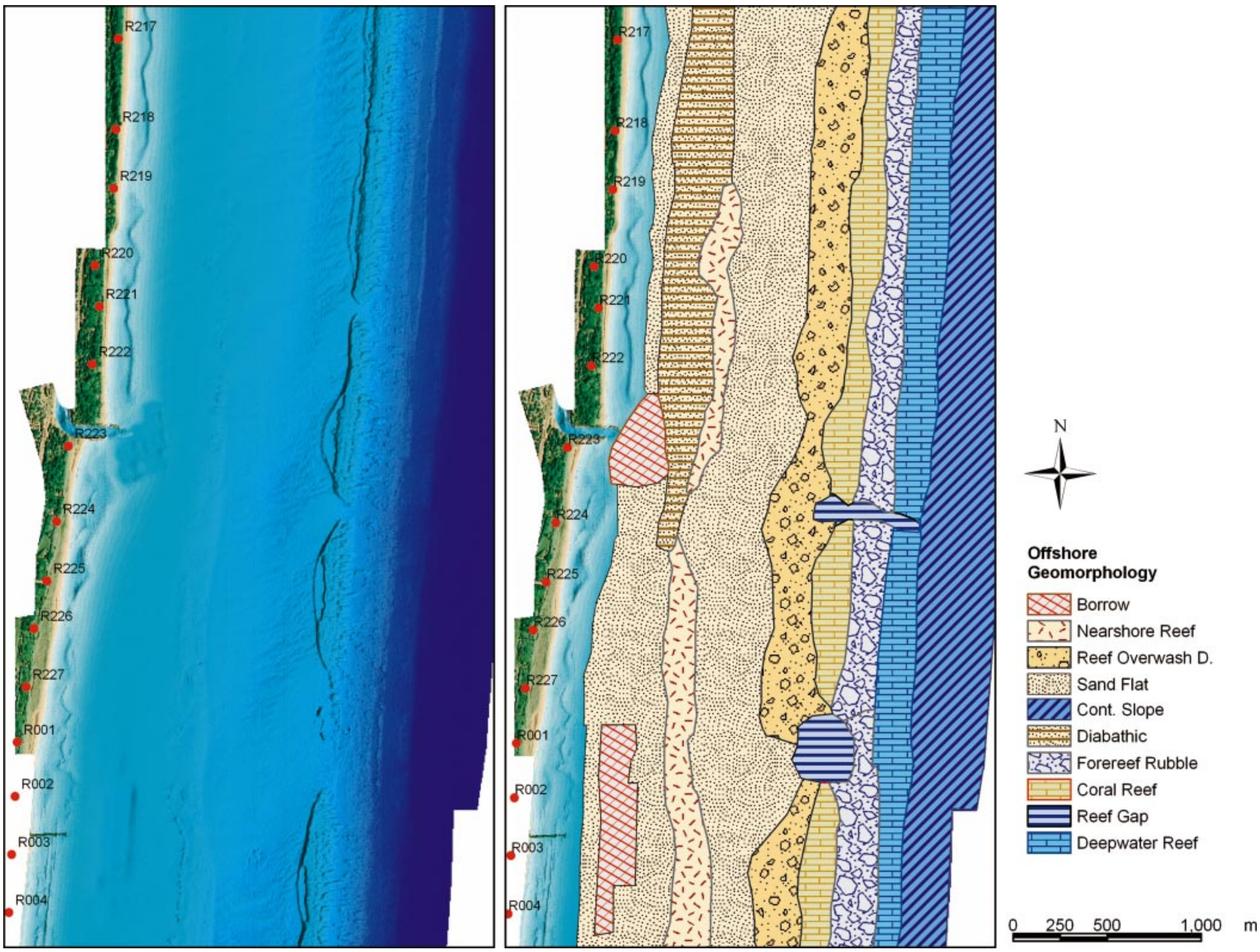

Figure 7. Interpreted ALB imagery for an 11-km² area in the vicinity of the Boca Raton Inlet, Palm Beach County, Florida. The ALB imagery (left image) shows more complexity than the interpreted offshore geomorphology (right image) that is generalized by mapping units. Nearshore features in water depths less than 10 m, mapped in detail previously from aerial photographs, are not shown here for simplicity.

Morphometric Analysis of Third Reef in Broward County

Classification and mapping of bottom types has multiple uses for coastal engineers, geologists, marine biologists, planners, and managers, among others. Some obvious applications focus on delineation of hardgrounds (exposure of bedrock as habitat), coral reefs (barrier and patch reefs for protection) (*e.g.,* STORLAZZI, LOGAN, and FIELD, 2003), and inter-reefal sand flats (for sand mining) (*e.g.,* BODGE and ROSEN, 1988; BENEDET and FINKL, 2003; FINKL, ANDREWS, and BENEDET, 2003). Bathymorphometric analysis of the third reef in Broward County, as one example, analyzed length of reef segments, crest widths within segments, length of spur-and-groove topography, widths of backreef aprons (reef overwash deposits), and gap widths (Table 2). The total length for 28 reef segments accrues to 35 kilometers (average reef length is 1,243 meters), with total gap widths amounting to 8.6 kilometers (ranging from 15 meters to 3,780 meters). The longest continuous reef segment was 5.1 kilometers long, followed by two additional segments 4.7 kilometers and 4.4 kilometers long. The smallest measured reef segment was a patch reef 76 meters long. Widths of reef gaps ranged from 15 meters to 3.8 kilometers, but they averaged about 309 meters wide.

Spur-and-groove topography along the forereef averaged 107 meters wide, but it ranged from zero where there was a cliff face replacing spurs and grooves to a maximum of a 244-meter-long spur-and-groove couplet. Storm rubble aprons decorate the backsides of many reef segments where debris has accumulated from storm overwash of forereef and reef crest materials. Aprons composed of reef overwash deposits are generally coarse grained, convex outward (facing the shore) in plan view, and range up to 244 meters wide (Table 2). All coastal segments have backreef aprons, and although

Table 1. *Preliminary classification of seafloor morphological features in the survey area, based in interpretation of ALB bathymetry for water depths 10 to 55 meters. Classification is based on bottom morphology (topography), depth, exposed and shallowly buried geological structures, and composition of sedimentary materials.*

Province and Subprovince	Mapping Unit	Comments
A. Sedimentary (soft) seafloor units		
1. Shoreface sand flats (10–25 m depth)	NA*	Sand bodies that are shore attached
a. Sand waves (parabathic)	Sand waves	Shore-parallel waves
b. Smooth seafloor topography	Sand flat	No sand waves
2. Hummocky (pock-marked) shoreface sands (−20 to −25 m)	Sand flat	Irregular paterns of low-relief dimples
3. Inner shoreface slope (diabathic ridge and runnel)	Diabathic channels	
a. High relief		> 0.5 m
b. Low relief		< 0.5 m
4. Inter-reefal sand flats (north of Biscayne Bay)	Nearshore sand flat	Sand bodies between reefs
5. Intertidal mud flats with mangroves	Mudflat	South of Bear Cut, Miami
6. Banks (backreef flats with skeletal sand)	Bank	South of Biscayne Bay
B. Limestone rock†		
1. Ridge flats (−25 to −27 m) and depressions (−27 to −37 m)	Ridge and valley	Elongated basins, probably karst
2. Forebasin parabathic ridge system (21 to −25 m depth)	Ridge and valley	Ridge crests seaward of basins
3. Beach ridge plain (lithified ridge systems)	Ridge and valley	Fossilized ridge-and-swale topography
4. Offshore Ramp (marine terraces) (−34 to −37 m)	Forereef platform	Terraces seaward of reefs
a. False crest (top of ramp, −34 to −37 m)	NA	
b. Shelf break (bottom of ramp, −52 to −55+ m)	Shelf break	
5. Inshore marine terrace (−1.5 to −6 m, Anastasia Formation)	Nearshore reef	Multiple ridges, partly covered by sand
6. Key (emergent carbonate sand cover over limestone)	Key	Northern limit of Florida Keys
C. Channels, paleochannels, and related features		
1. Structurally controlled meander belt	NA	Structurally controlled meanders
2. Trace channel cuts	NA	Vestige of paleovalleys
3. Infilled valleys	NA	Paleovalleys filled with sand
4. Tidal channels	Tidal channel	On banks and backreef sand flats
5. Ebb-tidal deltas	Ebb-tidal delta	Associated with inlets
D. Florida Reef Tract (coral-algal reef system)		
1. Coral reef		Coral and algal reefs
a. Barrier	Coral reef	Parabathic series of reefs (first, −7 to −9 m; second, −10 to −14 m; third, −15 to −25 m)
b. Patch	Coral reef	Small isolated reef
c. Backreef ledge	Coral reef	Shore-facing ledge
d. Backreef rubble slope	Reef overwash deposit	Overwashed rubble
e. Forereef slope	Forereef rubble	Spur and groove
2. Reef gap (including rubble fans)	Reef gap	Break in reef line
a. Ramp (seaward-sloping accumulations)	Reef gap ramp	Detrital outwash
b. Apron (landward rubble mound)	Reef overwash deposit	Coral debris
3. Deepwater reef	Deepwater reef	Reefs seaward of third reef tract
E. Structural and chemical limestone (karst) bedrock features		Drowned limestone
1. Karst noye	Sinkhole	Drowned solution pits, dolines, sinkholes
2. Lineaments, faults, fissures	Lineament	
3. Ridge crests	Ridge and valley, rock ridge	Drowned calcarenite dunes
4. Trough axis	Ridge and valley, structural trough	Drowned swale
F. Cultural features		
1. Dredge spoil banks	Spoil bank	
2. Artificial reefs	NA	Sunken ships, rubble mound structures
3. Beach restoration dredge pits	Borrow	
4. Submerged breakwaters (Port Everglades)	Submerged breakwater	Dredged spoil

* NA = not applicable.

† Anastasia Formation, Biscayne Aquifer, Tamiami Formation, Hawthorne Group, upper Floridan aquifer system exposed as hardgrounds to form bottom types.

Table 2. *Morphometrics of selected parameters of the third coral reef set in the FRT in Broward County, southeast Florida.*

Reef Number (north to south)*	Crest Width of Barrier Reef (m)†	Length of Spur and Groove Topography (m)‡	Width of Backreef Apron (m)§	Reef Length (m)**	Width of Reef Gap (m)††
1	61	122	61	610	61
2	61	152	61	762	61
3	91	137	15	914	366
4	76	76	15	732	305
5	61	168	30	1,768	46
6	198	213	244	5,121	15
7	183	198	122	1,890	305
8	244	137	61	975	274
9	229	107	46	244	152
10	61	122	107	732	15
11	107	168	61	1,341	30
12	46	152	30	1,006	183
13	15	122	30	1,829	61
14	46	137	122	2,316	122
15	76	152	15	1,829	15
16	15	0	15	366	792
17	15	61	15	183	46
18	15	46	8	152	91
19	15	46	8	183	15
20	15	107	76	853	61
21	61	122	15	4,389	853
22	152	244	30	4,755	671
23	15	61	122	732	3,780
24	15	30	46	122	91
25	15	15	46	91	15
26	15	30	46	76	30
27	15	30	46	366	61
28	15	30	46	457	122
Average	69	107	55	1,243	309
Standard deviation	70	64	51	1,390	719

* The barrier reefs of the FRT , in the so-called third reef set, were numbered from north to south on the ALB imagery. Patch reefs smaller that 75 m in diameter were ignored in the calculations.

† Widths of reef crests were measured from landward-facing ledges to seaward margins of the reef face or beginning of spur-and-groove topography.

‡ Length of spur-and-groove topography was measured from the forereef crest down the forereef to the seafloor where spurs or grooves were no longer discernable in the ALB imagery (*i.e.*, had no topographic expression).

§ Backreef aprons, composed of reef overwash deposits, were measured from landward-facing ledges of reef crests to the landward extent of hummocky topography or pronounced topographic break.

** Length of reefs in the so-called third reef set of barrier reefs was measured from gap to gap, where there was no reef crest, landward-facing ledge, spur-and-groove topography, or other forereef expression. Patch reefs smaller than 75 m in diameter were ignored.

†† Widths of reef gaps were measured from end of reef to beginning of reef, from north to south, in a shore-parallel direction. Widths of reef gaps less than 15 m were ignored.

some aprons are very narrow (15 meters), average widths are about 55 meters. Reef crest widths include the top parts of reef tracts with "crest depressions" that appear to be elongate solution features. Standard deviations for all features are high, indicating variability in morphometric properties.

Before the advent of ALB imagery, it was not possible to ascertain the morphometric properties of the northern extension of the FRT beyond the Florida Keys. Aerial photography in the shallower reef and backreef environments of the Florida Keys to the south provided clear images to study reef morphology. Along the narrower continental shelf in the present study area, where reefs lie in deep water (the so-called third reef lies in 15 to 25 meters of water), aerial photography or satellite imagery (Finkl and DaPrato, 1993) did not provide information as useful as the information extracted from the ALB. The examples cited here in Table 2 represent initial attempts to comprehend morphometric properties of the northernmost extensions of the FRT.

CAVEATS ASSOCIATED WITH THE INTERPRETATION OF HIGH-DENSITY BATHYMETRY DATA

Numerous pitfalls are associated with the production of geomorphological maps, and those problems are compounded when the maps are interpreted from ALB data without good geological control. Subbottom seismic data help define some units, but such data are not generally available nor is the coverage comprehensive or inclusive. The general lack of drill holes or description of trench walls from harbor deepening or inlet dredging makes it hard to interpret offshore bedrock features. The quality of the geomorphological units interpreted from the ALB imagery depends on the expertise of researchers and the extent of corporate knowledge. 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 better the map. Nevertheless, a great deal of morphological and morphometric information can be acquired from the 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 and understanding of bottom features on the continental shelf along the southeast coast of Florida. 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 accessible only with difficulty. 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 seafloor topography along this segment of the continental shelf. More than three decades ago, DUANE and MEISBURGER (1969) delineated the approximate positions of reefs, hardgrounds, and sand flats associated with the 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 has provided the kind of spatial resolution of bottom features over large expanses of the seabed as the newly acquired high-density bathymetric data using ALB systems. Seafloor discrimination on the basis of acoustic classes from SSS and single- or multibeam bathymetric survey shows a high level of correlation with interpreted LADS bathymetric classes.

Spatial properties of reef tracts and many of the morphological features associated with them are now accessible to a wide range of users. Also, for the first time, we can now see spatial relationships between stable hard rock features and mobile sedimentary forms. The spatial arrangement of seabed features permits detailed morphological analysis of coral reefs, hardground habitats, and sedimentary bodies in a contextual framework that was heretofore not possible. This kind of information is invaluable to nearshore geomorphological studies and to biological and engineering assessments of such diverse application as para(dia)bathic sediment transport patterns, burial/(re)exposure of hardgrounds, survey of inter-reefal sand depocenters in troughs (for borrow areas) (*e.g.,* FINKL, ANDREWS, and BENEDET, 2003), routes for fiber-optic cables through reef gaps, backgrounds for artificial reef (shipwreck) locations, fishing spots on reefs, *etc.*

CONCLUSION

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. From the purview of beach nourishment, detailed bathymetric data provide the best available depiction of seabed conditions along a complicated section of the seafloor on the southeast coast of Florida. A good example of application of the new bathymorphometric data is the realization that the FRT contains long, continuous troughs between reef systems that have been infilled with sediments that have potential for beach nourishment. Heretofore, it was not fully appreciated that vast quantities of sand lie offshore in trough systems that extend along the tricounty shore. Sand has been mined from inter-reefal borrows since the 1970s, but the borrows were sporadically searched and utilized without knowledge of inter-reefal continuity of sedimentary bodies, nor were there comprehensive systematic sand searches (using sidescan and subbottom profiling) that could comprehend the coral reef/hardbottom/sediment interface that is so crucial to environmental management and long-term planning of marine natural resources, including use of offshore beach-quality sand for renourishment activities. These bathymorphometric maps also show that the classical three-reef system developed for the Broward coastal sector is more complicated than originally perceived and that the system does not extend all the way to the Martin County line, as hypothesized by DUANE and MEISBURGER (1969). Steplike sequences of more than a dozen successive hardground-reef ridges are commonly observed in northern Palm Beach County, for example. Use of ALB systems will no doubt provide the impetus for public and private re-evaluation of marine resources along the southeast coast. Subsequent ALB surveys will provide unparalleled opportunity for time-dependent spatial analysis of changing seabed morphology related to sediment movement along- and cross-shore, as, for example, in the case of temporal burial and exposure of hardgrounds. Image-enhancement techniques provide an opportunity to selectively show various bathymorphometric features, which has not been possible in the past.

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