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Shelf Geomorphology along the Southeast Florida Atlantic Continental Platform: Barrier Coral Reefs, Nearshore Bedrock, and Morphosedimentary Features

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ABSTRACT

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Differentiation of continental shelf morphology along the southeast Florida Atlantic coast was based on interpretation of airborne laser bathymetry. The 600-km^2 shelf study area, which had a shoreline extent of about 160 km and extended up to 10 km offshore, displayed a diverse range of seafloor morphologies that were characteristic of four main alongshore reaches. Reach I (sand flats and karst topography) in the northern part of the study area is terminated southward by the Bahamas Fracture Zone, a major morphotectonic feature. Reach II (sand flats and coral reefs) is characterized by sand flats with diabathic channel fields leeward or shoreward of the Florida Reef Tract, the seaward margin of which occurs along the shelf break on the upper part of the continental slope. Reach III (sand flats, hardgrounds, and coral reefs) is characterized by extensive nearshore rock outcrops that are exposed as bare rock surfaces on the seafloor or are variously mantled by thin veneers of sand that are not thick enough to disguise the underlying rock structure. Reach IV (tidal sand flats and ridges, hardgrounds, and coral reefs) is dominated by tidal features that notably include fields of tidal sand ridges in the lee of the Florida Reef Tract. The barrier reef on the southeast Florida Atlantic coast, which transitions to Florida Keys shelf environments southward, grades northward to drowned karst topography that is overlain by sand sheets and sand waves. Tidal channels and associated bars, deltas, and shoals occur on the interface between Biscayne Bay and the Atlantic Ocean. This reconnaissance-level characterization of continental shelf environments into morphological reaches in a geographic information system platform provides a basis for quantifying spatial distribution patterns of discrete landform units.

ADDITIONAL INDEX WORDS: *Coastal geomorphology, beach, tidal inlet, sand bar, tidal delta, sand wave, marine terrace, light detection and ranging, hardground.*

INTRODUCTION

The continental shelf along the southeast coast of Florida has been widely studied, in relation to biological resources associated with the barrier coral reef system (Florida Reef Tract, FRT), offshore sand sources, and littoral sediment budgets. Aside from the general presence of coral reefs, hardgrounds (exposure of bedrock on the seafloor), and extensive sandy bottom areas, there is a dearth of information concerning the spatial distribution patterns (continuity, connectivity, or disjunctiveness) of geomorphic features.

Seminal studies *e.g.,* by Agassiz (1852), Hoffmeister (1974), Duane and Meisburger (1969), Lighty (1977), and Lovejoy (1983), considered salient features of the continental shelf, mainly the presence of barrier coral reefs, intervening sand flats, and nearshore exposure of bedrock. Information pertaining to morphosedimentary features in this region provided by Finkl, Benedet, and Andrews (2005a, 2005b; Finkl *et al.,* 2007) stimulated interest in a more comprehensive focus on the identification, description, and delineation of unconsolidated sedimentary deposits. This paper reports the results of detailed mapping (2001–07) on the continental shelf based on interpretation of airborne laser bathymetry (*i.e.,* bathymetric light detection and ranging) in the form of laser airborne depth sounding (LADS) in the tricounty offshore area of southeast Florida.

The initial purpose of seafloor characterization was to determine the presence of potential sand resources for beach nourishment. Eroded beaches, as defined by Clark (1993), require remediation in the form of beachfill that provides habitat and protects shoreline infrastructure. In this context, all major seafloor features had to be determined because the distribution patterns of sedimentary bodies in southeast Florida are complicated by rock outcrops and the presence of coral reefs. Because nearshore rock outcrops and offshore coral reefs frame sedimentary deposits, they were identified as spatial placeholders. The regional context of the southeastern coastal segment of the Florida peninsula is briefly described here in terms of morphological expression from the shore to the seaward margin of the offshore barrier reef system.

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Study Area and Coastal Geological Framework

From a physiographic point of view for the southeastern-most quadrant of North America, the southeast part of the Florida peninsula belongs to the Atlantic and Gulf Coastal Province (WALKER and COLEMAN, 1987). The subaerial portion is referred to as the coastal plain, whereas the suboceanic portion encompasses part of the North American continental shelf. Most of the subocean portion of the province was subaerial as recently as 18,000 years ago during the last glacial maximum, but the interface between the two divisions has been near its present elevational position for the last 5000 to 6000 years when initial phases of rapid Holocene sea-level rise decelerated. The eastern Florida shelf is extremely narrow and merges southward with the FRT, which is most extensive and best developed offshore the Florida Keys (LIDZ, 2006; LIDZ and SHINN, 1991; LIDZ, HINE, and SHINN, 1991; LIDZ, ROBBIN, and SHINN, 1985; LIDZ *et al.,* 1991; LIGHTY, 1977). The FRT is flanked on its seaward margin by the shelf break, a rather steep and abrupt slope that forms the western edge of the Straits of Florida. The active reef tract is composed of a series of complex reefal facies. During the last glacial maximum, when sea level was lowered by about 120 m (*e.g.,* BLOOM, 1983; SHENNAN, 1993), many of the reef facies were exposed and dissolution of carbonate lithologies under subaerial conditions resulted in the formation of an irregular topography upon which many modern reefal facies became established. There is much debate as to just how many times and at what rates sea level rose and fell during the Quaternary Period, but it is clear from subaerial karst topography (now drowned) that the continental shelf was exposed to subaerial weathering at different intervals (BANKS *et al.*, 2007). Since the beginning of the most recent deglaciation, episodic rises in sea level sequentially drowned the subaerial landscape and approximated the position of the present shoreline about 3000 years ago.

The study area is a 160-km-long coastal strip along the southeast coast of Florida from the Martin County–Palm Beach County line to 13 km south of the Port of Miami navigational entrance (Figure 1). Widths of the study area reach a maximum of 10 and 8.5 km offshore in northern Palm Beach County and southern Miami-Dade County, respectively. The LADS survey generally extends to about 55 m water depth seaward of the FRT at the shelf break. Portions of the Florida east coast differ markedly in shoreline configuration and are influenced by the tectonic setting of the continental margin, regional bedrock geology, nearshore sediment supply, paleoshorelines, and relative sea-level fluctuations during the Quaternary Period (*e.g.,* BANKS *et al.*, 2007; BROWN, 1998; DAVIS, HINE, and SHINN, 1992; DUANE and MEISBURGER, 1969; HOFFMEISTER, 1974; LIDZ and SHINN, 1991; PARKINSON, 1989; PERKINS, 1977). Mainland rock-cored coastal segments characterize the southeastern Florida coast, stretching from approximately northern Palm Beach County to Key West. This stretch of coast is often mistaken for a natural barrier island chain, but many of the barriers are former barrier spits that were beheaded by the cutting of inlets. The beheaded spits were destabilized and migrated landward, eventually becoming welded to the mainland (FINKL, 1993). Because the present coastal barriers are cored by the Anastasia Formation (LOVEJOY, 1983), they do not migrate as most sandy barrier islands do in response to changes in relative sea level (FINKL, 1993).

An important characteristic of the southeast Florida coast is the way in which morphology is affected by underlying bedrock. The bedrock control is related to exposures of the Anastasia Formation and Miami Limestone (formed during the Sangamon high sea-level stand) and to Pleistocene coral reefs. The pre-Holocene bedrock structure strongly influences morphological evolution of the shore (as described by BROWN, 1998; EVANS *et al.,* 1985; RIGGS, CLEARY, and SNYDER, 1995; and ROBERTSON, 2007), because these structures not only provided a base for sediment accumulation but also created topographic lows between lithified paleoshorelines (FINKL, 1993). Sands accumulate (to thicknesses of 15 m) between the shore-parallel submerged paleoshorelines to form interreefal sands (*e.g.,* DUANE and MEISBURGER, 1969; FINKL and WARNER, 2004; FINKL, ANDREWS, and BENEDET, 2003). Paleomarine abrasion surfaces are variably covered by sand, where the depth of cover is insufficient to mask bedrock structure (FINKL and WARNER, 2004).

Prior Differentiation of Seafloor Morphological Types

Recognition of salient seafloor morphologies along the southeast Florida coast goes back to early studies of the barrier coral reefs (*e.g.,* AGASSIZ, 1852), the extent of which was appreciated at that time. Subsequent studies of the coral reef system (*e.g.,* LIDZ, HINE, and SHINN, 1991; LIDZ *et al.,* 1991; LIGHTY, 1977) eventually resulted in the formalization of a complex reef system referred to as the FRT and its recognition as the third-largest barrier reef chain in the world. Although the descending staircase model of deeper reefs lying farther offshore was well known to the research community, modest progress was made in the characterization of bottom types across the Johnson (upper) shoreface (*i.e.,* less than 20 m depth), as discussed by WRIGHT and SHORT (1984) and SHORT (1999), on the inner shelf until DUANE and MEISBURGER (1969) clearly identified (using seismic survey techniques) the boundaries of reef tracts and interreefal sand flats. The same broad-scale features were also remotely sensed using the Thematic Mapper (Landsat 7) satellite platform (FINKL and DAPRATO, 1993) and integrated into a geographic information system (GIS) framework. Much previous work was brought together by FINKL, BENSON, and YUHR (1997) in their development of a comprehensive geomorphological model that incorporated a wide range of bottom types, including coral reefs, hardgrounds (rock reefs), and various types of sedimentary features. Overviews by HOFFMEISTER (1974) provided a general coastal geological framework, whereas more recent studies by LIDZ *et al.* (1991) and LIDZ (2006) on the southern portion of the FRT offered descriptions of reef and backreef environments. Coastal morphologies along the Broward County coast were interpreted in terms of morphodynamic zones (FINKL and KHALIL, 2000) that were based on the classification and distribution of seafloor typologies and coastal process zones. The present study extends and intensifies study of seafloor features (*e.g.,* FINKL and

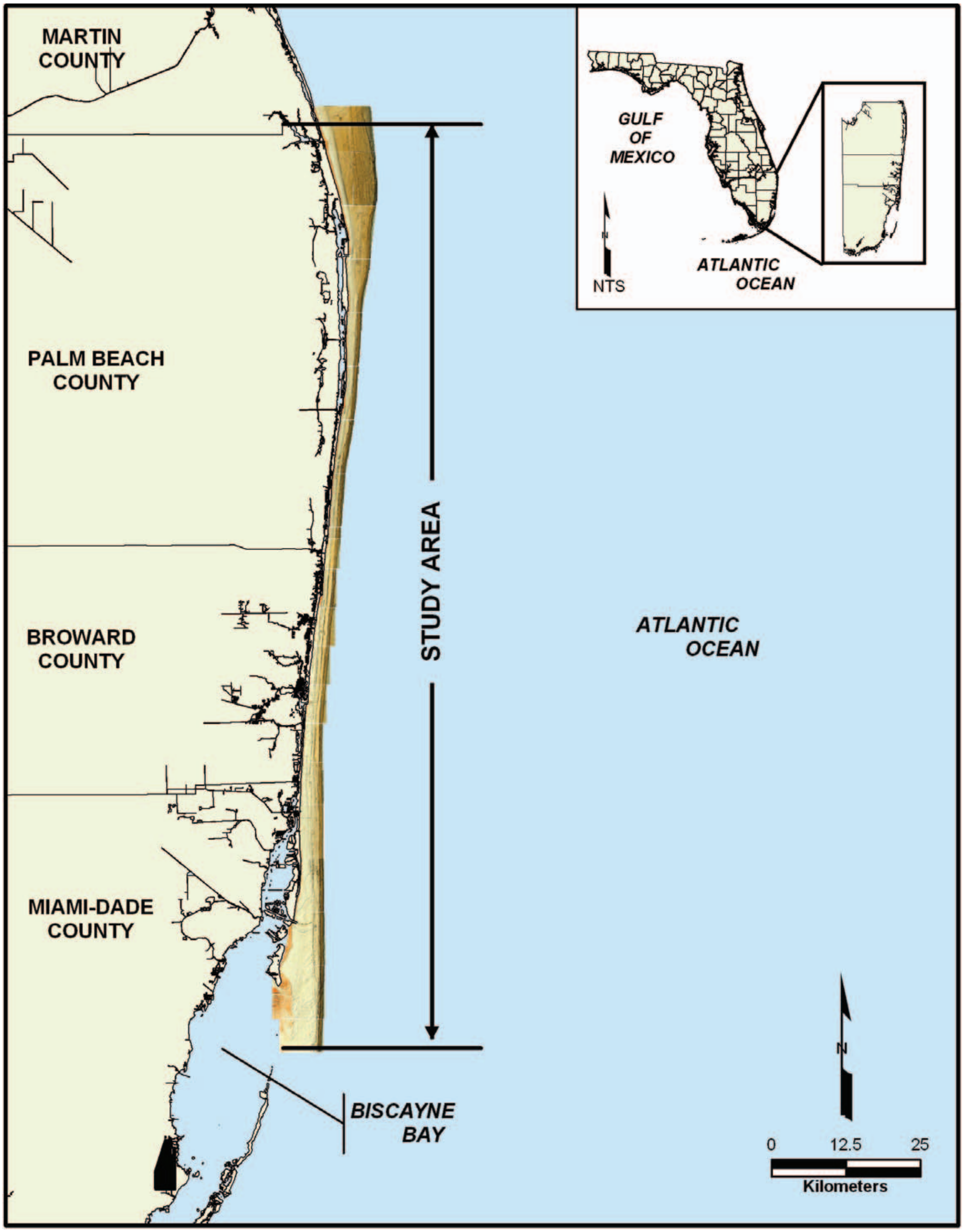

Figure 1. Location of the 600-km² study area on the southeast Florida Atlantic continental shelf. This composite image shows land areas merged with color-shaded relief airborne laser bathymetry. The brownish and tan-colored tones mark the actual area of the LADS imagery between the northern (Martin County line) and the southern (offshore in central Miami-Dade County) limits of the study area.

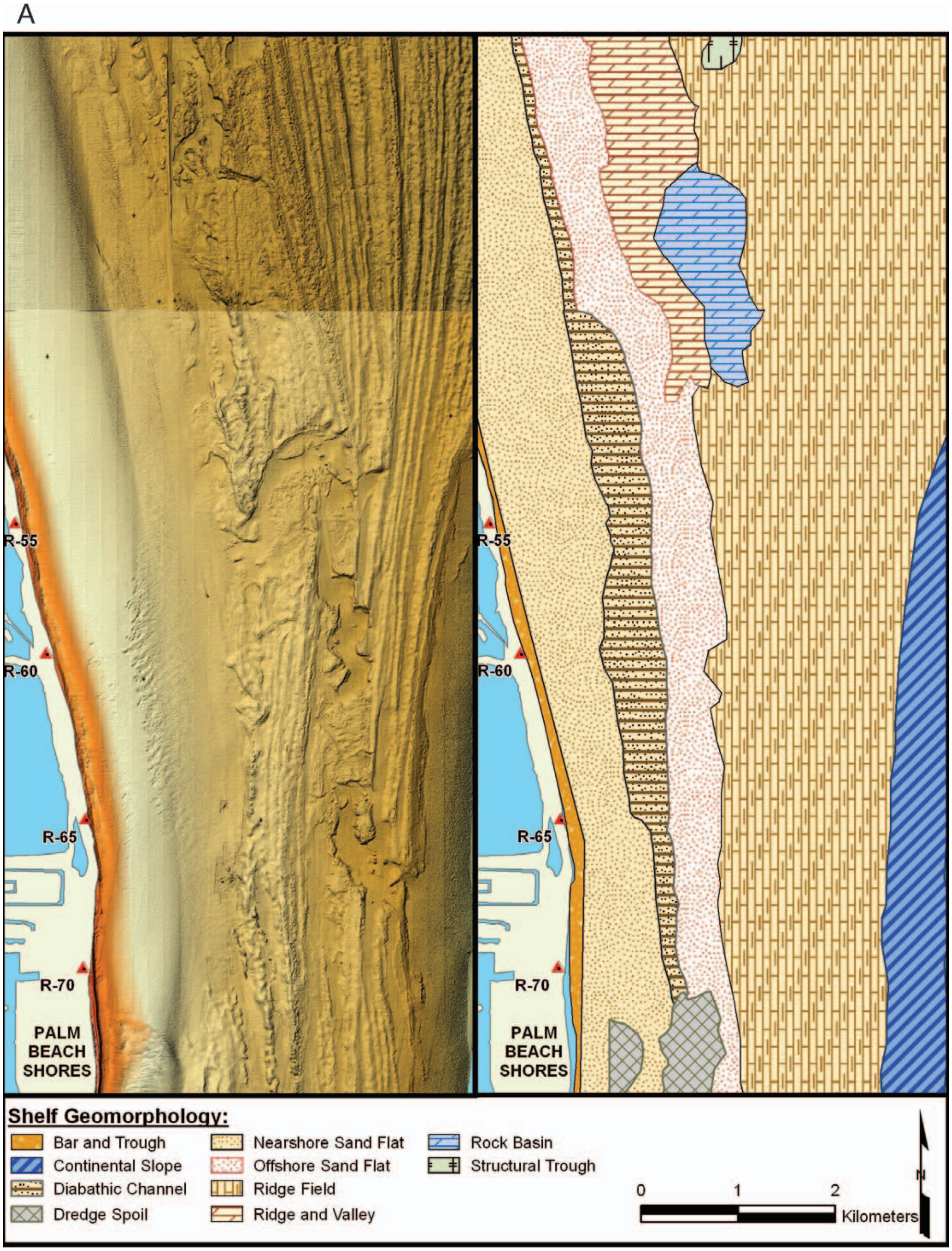

Figure 2 (see map insert). Interpretation of LADS bathymetry in terms of shelf geomorphology, where each panel matches the preceding one from north to south. The 42 map units are grouped by anthropogenic features, bar and trough, continental slope, coral reef, hardbottom, sandy bottom features, and tidal features to produce a coherent differentiation of the continental shelf into parabathic Reaches I through IV. Each of the four panels (1–4) contains detailed callouts that are identified as Figures 2A–F.

Figure 2A. Detailed composite image of submarine geomorphic units in Reach I (Figure 2, Panel 1) on the continental shelf off northern Palm Beach County, Florida, showing uninterpreted LADS bathymetry (left panel) and spatial distribution patterns of bottom types (right panel). Note the extensive occurrence of the Nearshore Sand Flat and Offshore Sand Flat mapping units shoreward of the Ridge Field, Rock Basin, and Ridge and Valley mapping units. See Figure 2 (Panel 1) for location of Figure 2A.

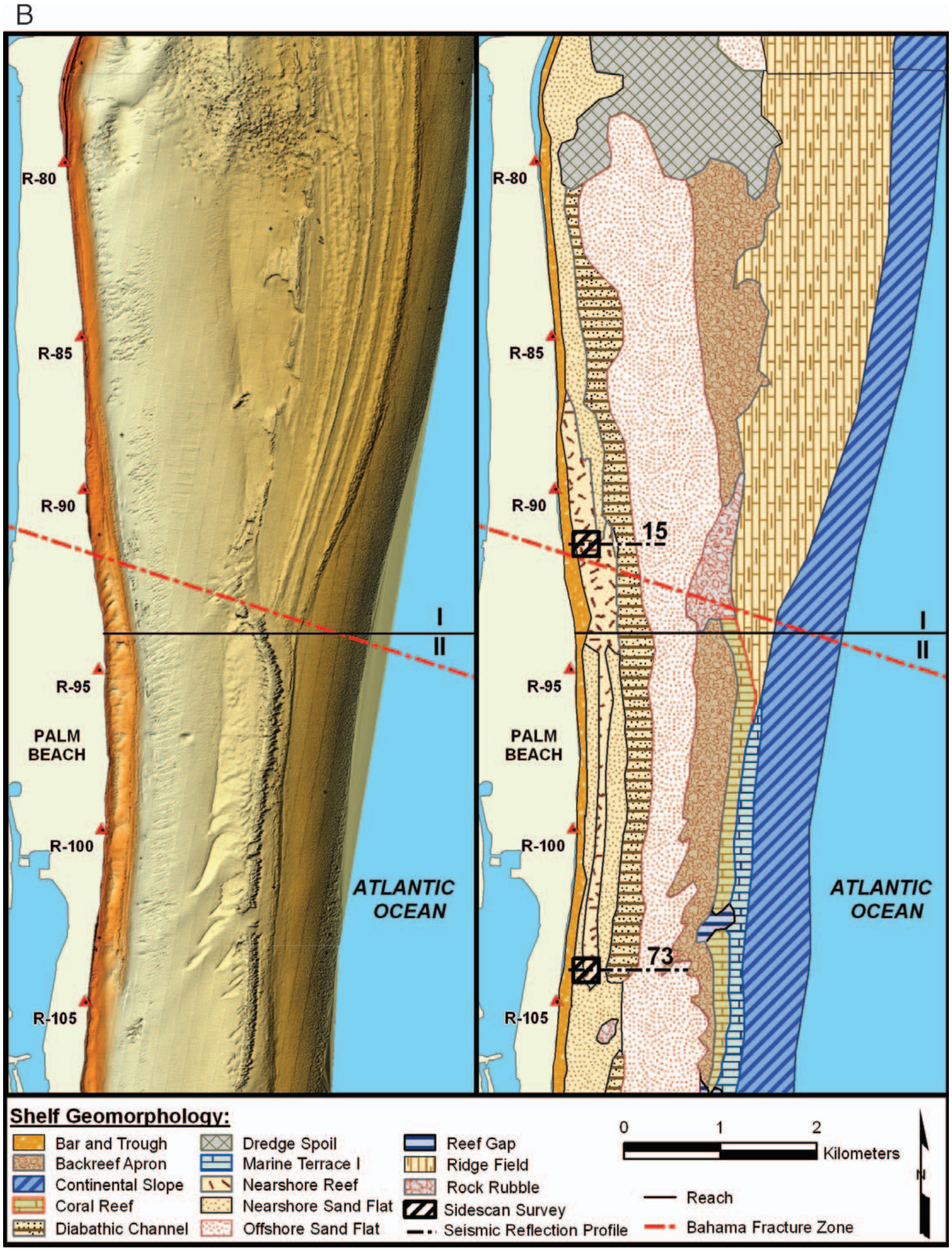

Figure 2B. Detailed composite image of submarine geomorphic units in Reaches I and II (Figure 2, Panel 1) on the continental shelf off central Palm Beach County, Florida, showing uninterpreted LADS bathymetry (left panel) and spatial distribution patterns of bottom types (right panel). Grouped shelf geomorphic distribution patterns are discriminated by the Bahamas Fracture Zone that separates sand flats and karst topography (Reach I) to the north from sand flats and coral reefs (Reach II) to the south. Nearshore and offshore sand flats are separated by nearshore reefs and diabathic channel fields.

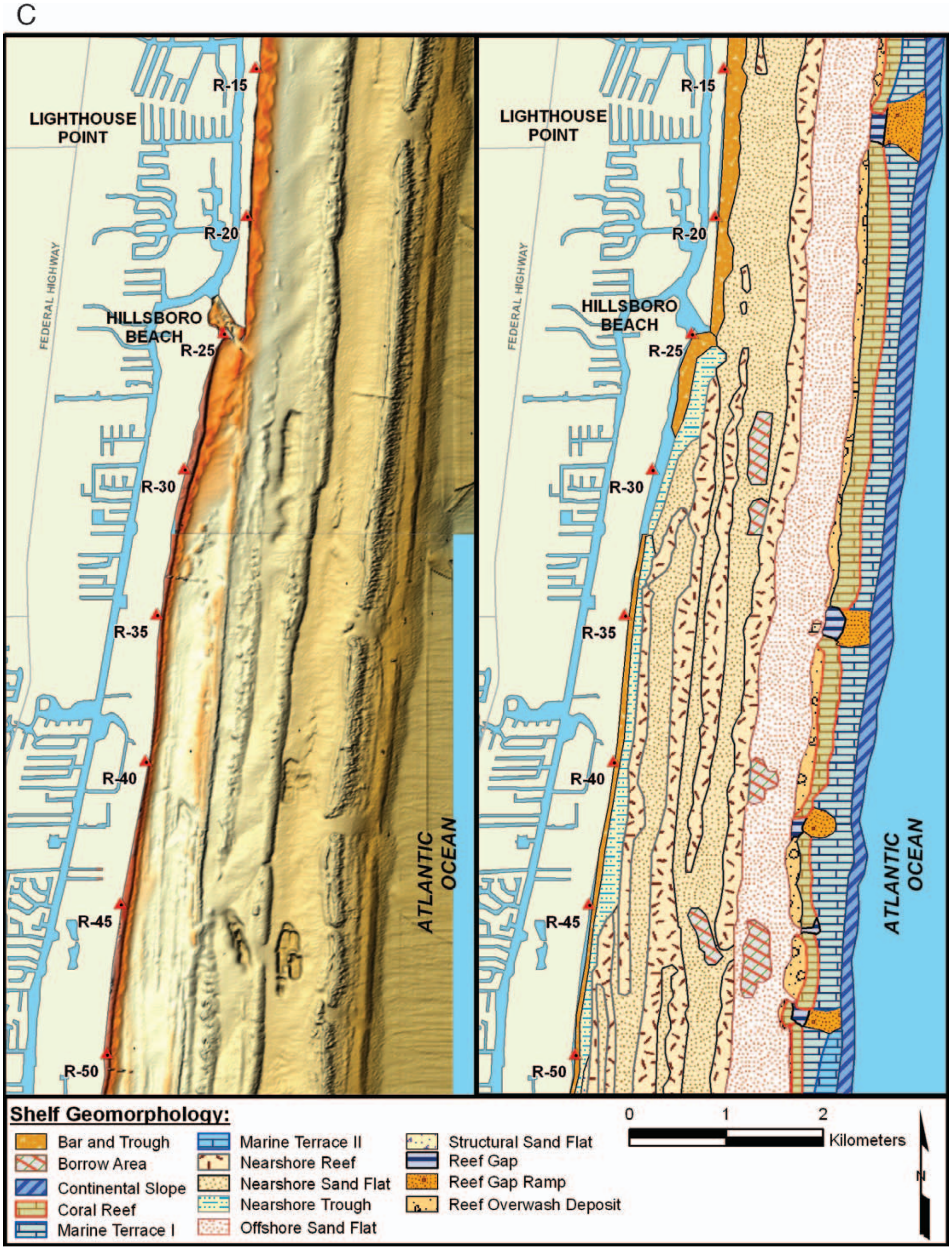

Figure 2C. Detailed composite image of submarine geomorphic units in Reach III (sand flats, hardgrounds, and coral reefs; Figure 2, Panel 2) on the continental shelf off northern Broward County, Florida, showing uninterpreted LADS bathymetry (left panel) and spatial distribution patterns of bottom types (right panel). The FRT is bounded seaward by marine terraces and shoreward by paleolagoons that are now infilled to form sand flats. Rocky outcrops on the shelf, in the form of the Anastasia Formation, become commonplace south of R025 (Hillsboro Inlet).

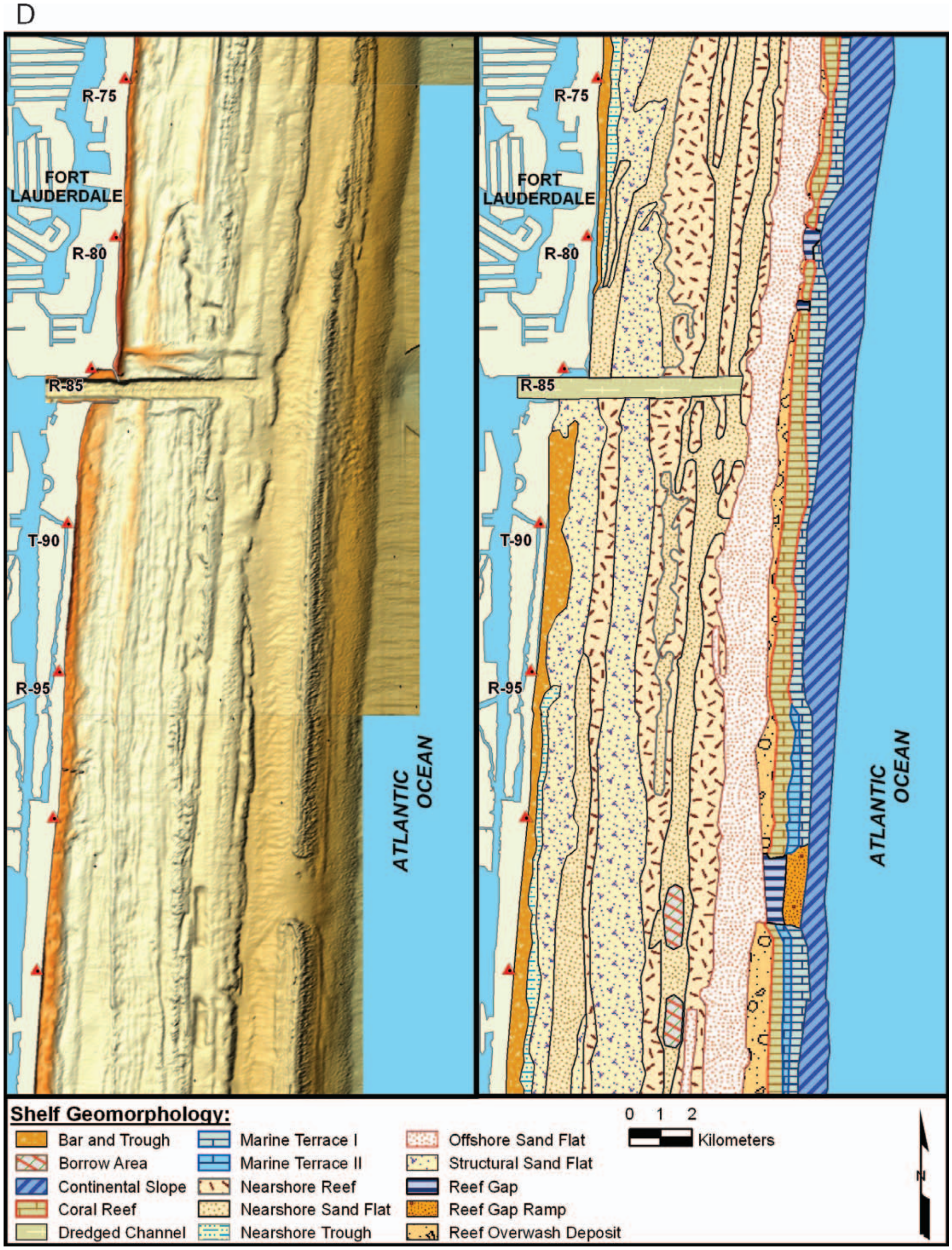

Figure 2D. Detailed composite image of submarine geomorphic units in Reach III (sand flats, hardgrounds, and coral reefs; Figure 2, Panel 3) on the continental shelf off central Broward County, Florida, showing uninterpreted LADS bathymetry (left panel) and spatial distribution patterns of bottom types (right panel). Shown here, in addition to geomorphic units previously discussed, is the extensive occurrence of structural sand flats, limestone bedrock covered by a veneer of sand so thin that rock structure is evident in the LADS imagery. The extent of nearshore sand flats is restricted by the occurrence of structural sand flats and nearshore (rock and coral) reefs.

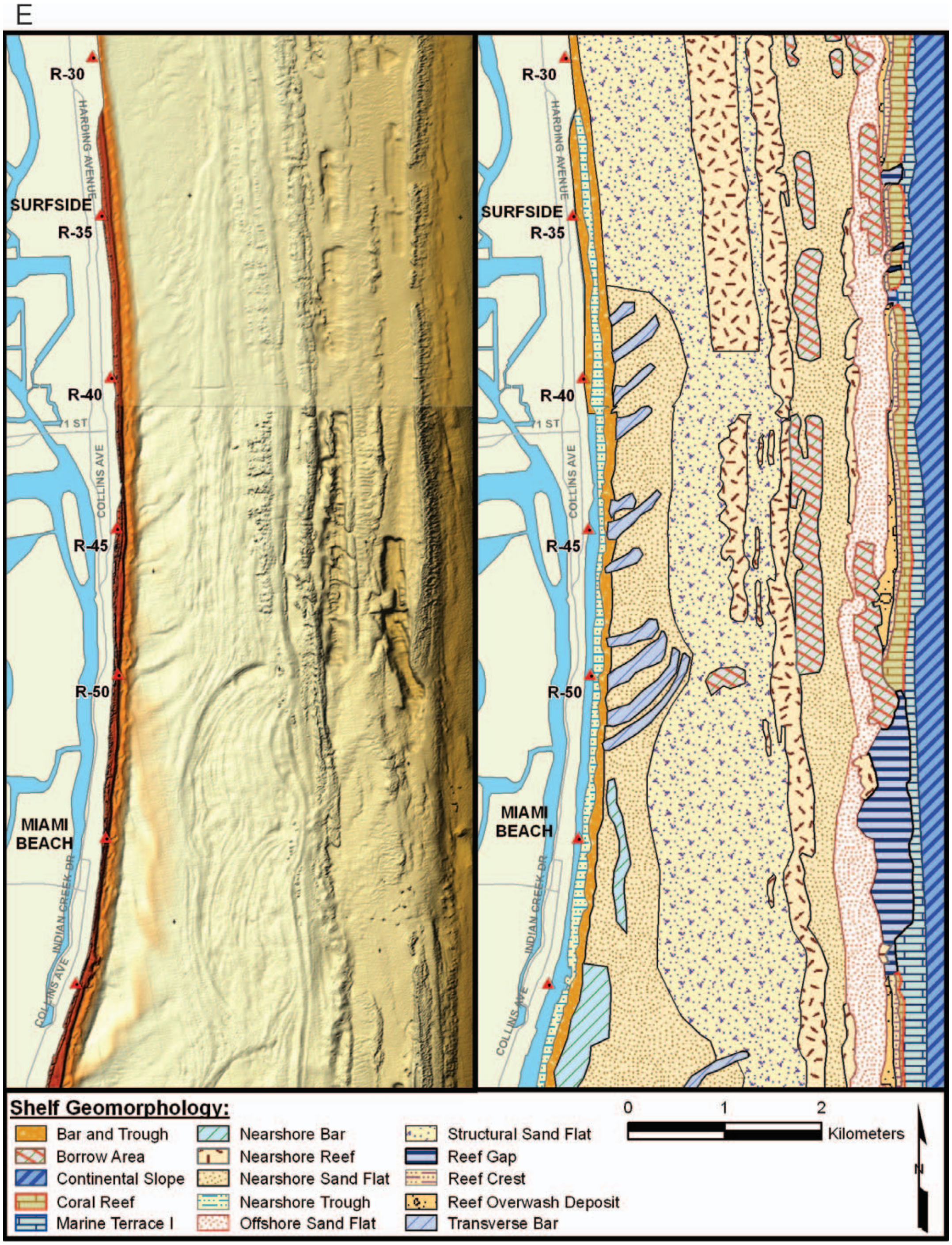

Figure 2E. Detailed composite image of submarine geomorphic units in Reach III (sand flats, hardgrounds, and coral reefs; Figure 2, Panel 3) on the continental shelf off northern Miami-Dade County, Florida, showing uninterpreted LADS bathymetry (left panel) and spatial distribution patterns of bottom types (right panel). Although the continental shelf widens here, structural sand flats are the areally dominant geomorphic unit. A transverse bar field occurs from R037 to R052 on the nearshore sand flat.

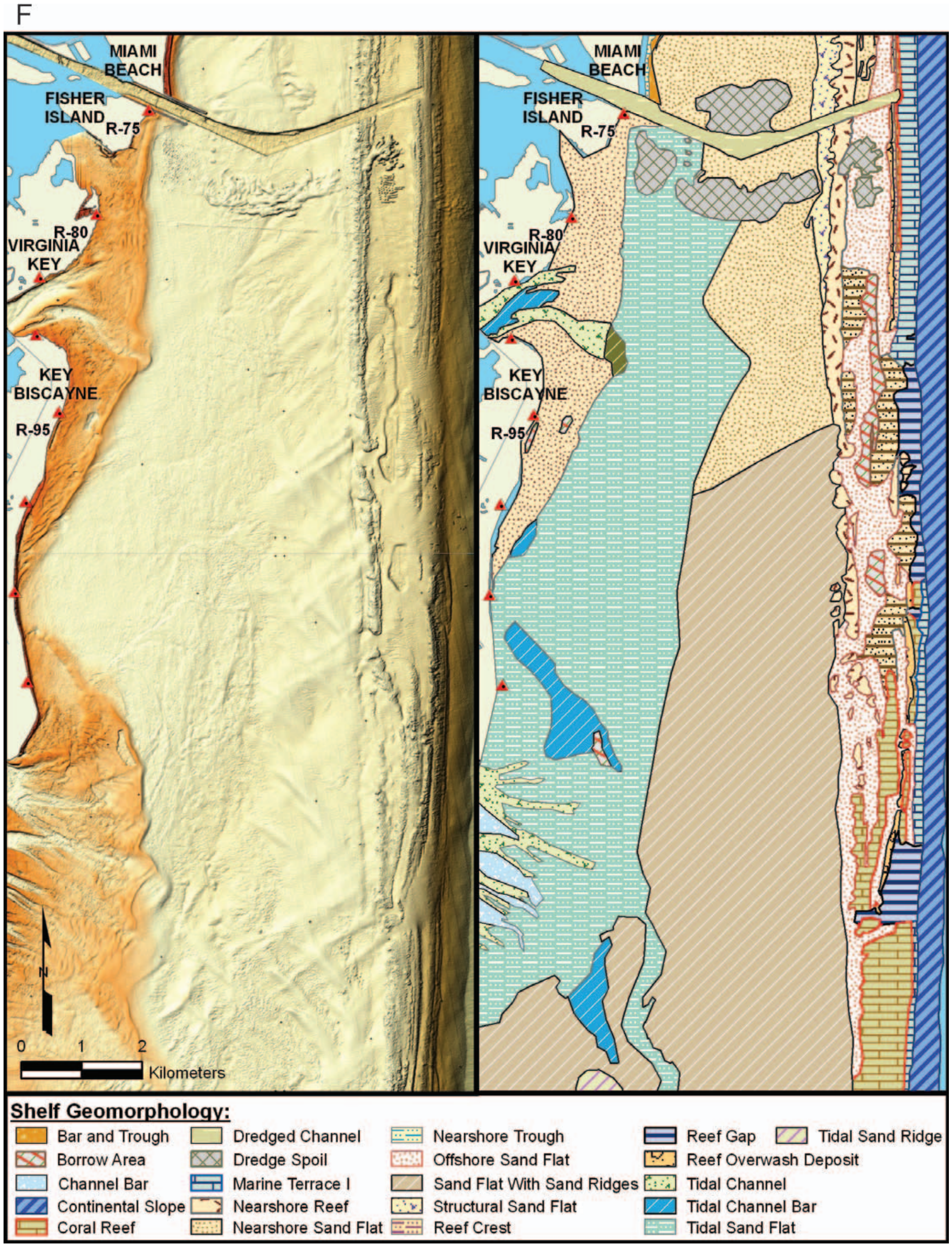

Figure 2F. Detailed composite image of submarine geomorphic units in Reaches III (sand flats, hardgrounds, and coral reefs) and IV (tidal sand flat and ridges, hardgrounds, and coral reefs; Figure 2, Panel 4) on the continental shelf off central Miami-Dade County, Florida, showing uninterpreted LADS bathymetry (left panel) and spatial distribution patterns of bottom types (right panel). Now in the realm of the Florida Keys, tidal influences become evident on the wide sand flats across which currents flow in and out of Biscayne Bay to the west. Notable here are better development of the barrier reef system, development of sand ridges, and presence of tidal sand flats.

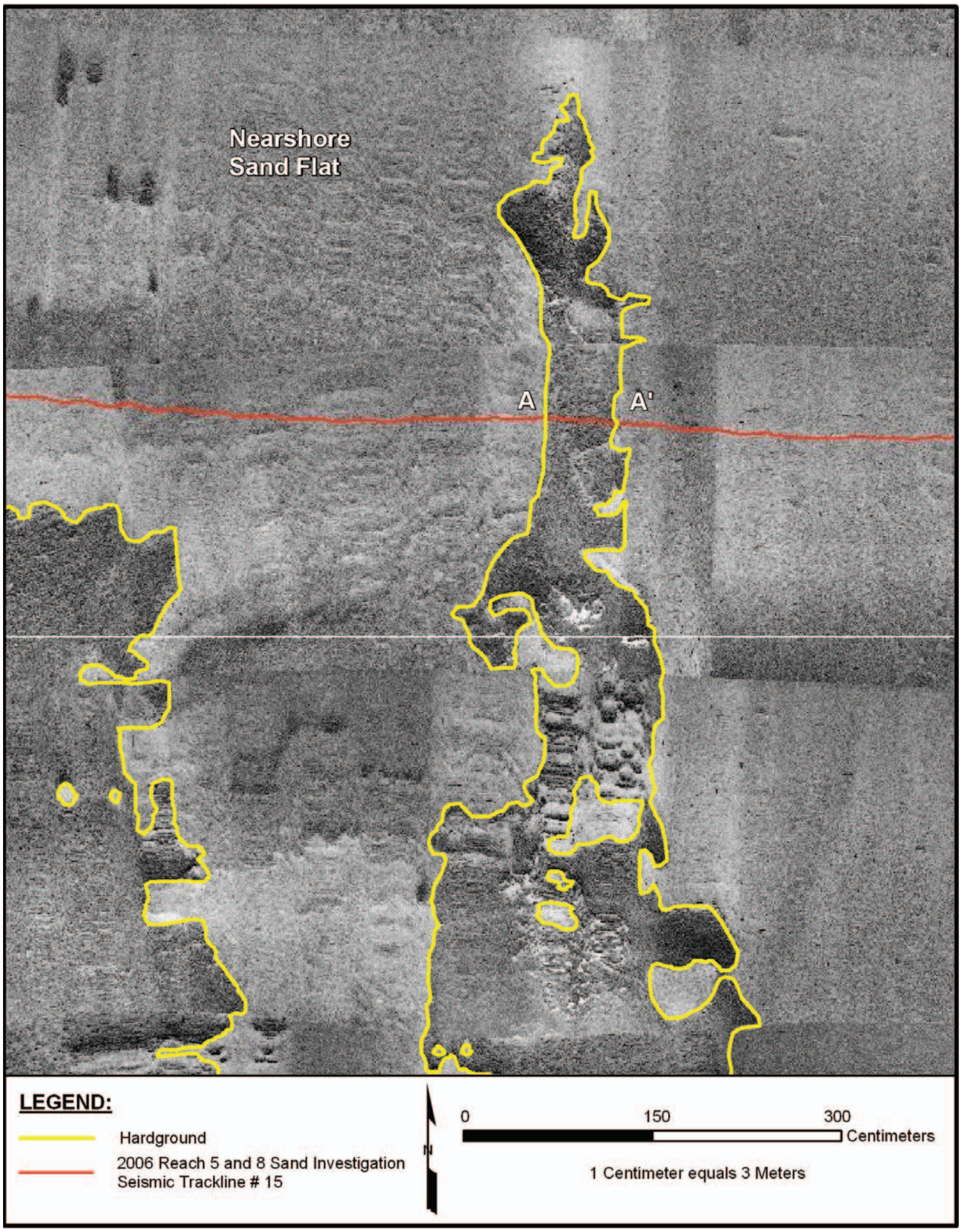

Figure 3. Sidescan sonar image showing detailed distribution of hardground (outcrop of Anastasia Formation) and nearshore sand flat in about 5 to 6 m water depth along Track 15W in Palm Beach County offshore from R092 (see Figures 2 and 2B for location) in Reach I. The darker shades represent rock outcrop on the seafloor (the hardground was mapped as Nearshore Reef), and the lighter shades are sand cover (mapped as Nearshore Sand Flat). This mosaic shows variable cover of limestone bedrock with bottom sands. Ripple marks are evident on the nearshore sand flat. The A–A′ section of the seismic reflection profile (see Figure 4) marks the rock outcrop. (Data abstracted from 2006 Reach 5 and 8 sand investigation, Town of Palm Beach, Florida. Acquisition scale: 1 cm = 3 m.)

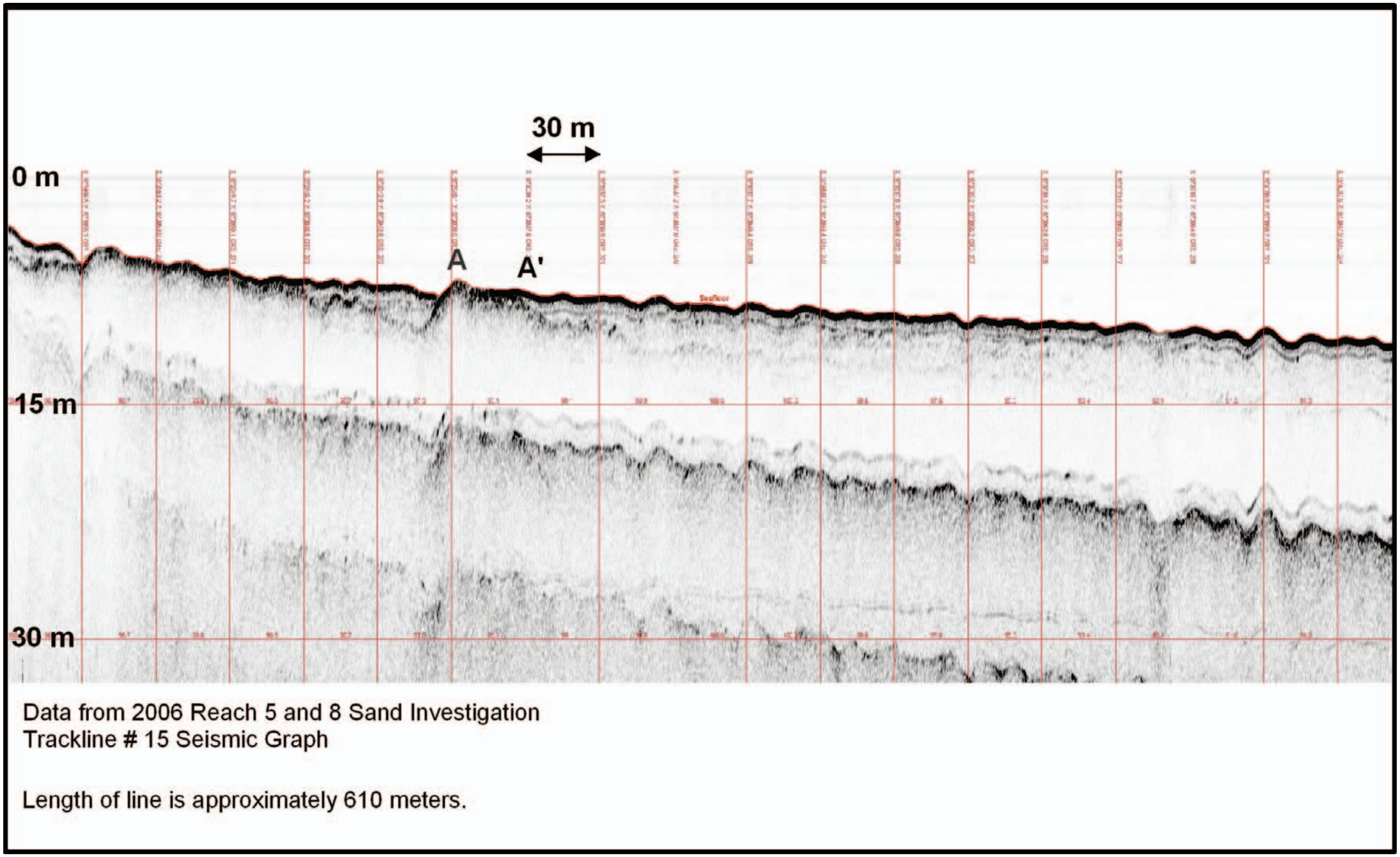

Figure 4. Cross-shore seismic reflection profile showing sand overlying limestone bedrock in water depths ranging from 5 to 15 m along Track 15W in Palm Beach County offshore from R092 (see Figures 2 and 2B for general location and Figure 3 for position of the trackline) in Reach I. Bedrock outcrops on the seafloor are marked as the A–A′ section of the seismic trace to form a nearshore hardground (mapped as Nearshore Reef, *cf.* Figure 3). Sand seaward of the rock outcrop ranges up to 3 or 4 m in thickness. The surface of the sand deposit forms the Nearshore Sand Flat mapping unit. The length of the seismic transect shown here is about 610 m. The vertical grid marks a distance of about 30 m horizontally between lines. The vertical scale, thickness of the profile, is about 15 m between the horizontal lines.

Figure 5. Sidescan sonar image showing detailed distribution of hardground (outcrop of Anastasia Formation) and nearshore sand flat in about 5 to 6 m water depth along Track 73W in Palm Beach County offshore from R104 (see Figures 2 and 2B for location) in Reach II. The darker shades represent rock outcrop on the seafloor, *e.g.,* along the section B–B′ (the hardground was mapped as Nearshore Reef), and the lighter shades are sand cover (mapped as Nearshore Sand Flat). This mosaic contains shows variable cover of limestone bedrock with bottom sands. Ripple marks in the sandy bottom of the nearshore sand flat are evident in the right side and lower half of the mosaic. (Data abstracted from 2006 Reach 5 and 8 sand investigation, Town of Palm Beach, Florida. Acquisition scale: 1 cm = 2.5 m.)

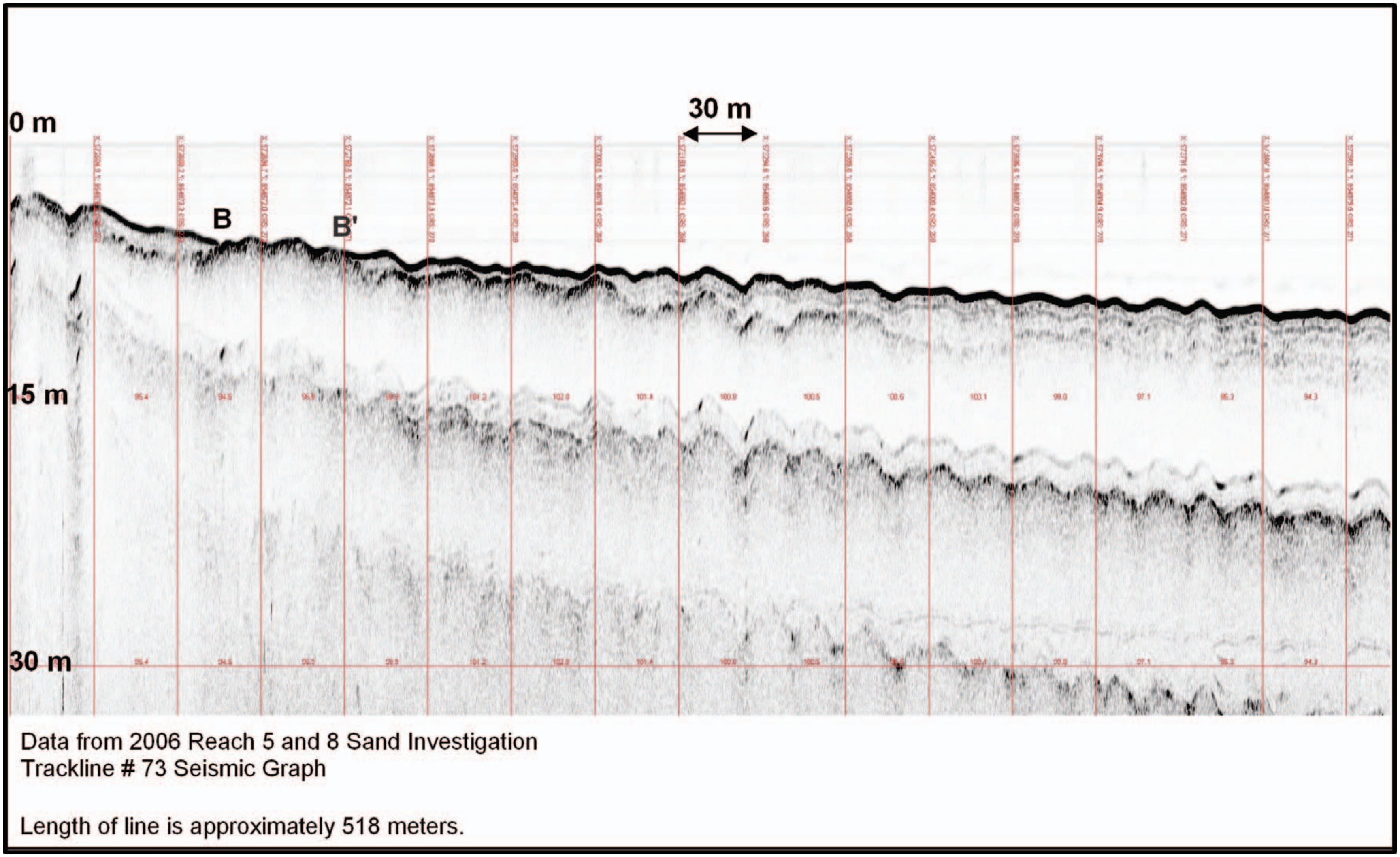

Figure 6. Cross-shore seismic reflection profile showing sand overlying limestone bedrock along Track 73 in Palm Beach County offshore from R104 (see Figures 2 and 2B for general location and Figure 5 for position of the trackline) in Reach II. Bedrock outcrops on the seafloor are marked as the B–B′ section of the seismic trace to form a nearshore hardground (mapped as Nearshore Reef, *cf.* Figure 5). Sand seaward of the rock outcrop ranges up to 3 or 4 m in thickness. The surface of the sand deposit forms the Nearshore Sand Flat mapping unit. The length of the seismic transect shown here is about 518 m. The vertical grid marks a distance of about 30 m horizontally between lines. The vertical scale, thickness of the profile, is about 15 m between the horizontal lines.

Khalil, 2000; Finkl and Warner, 2004; Finkl, Benedet, and Andrews, 2004, 2005a, 2005b) from the beachface to the shelf break.

CONCEPTUAL GEOLOGICAL MODEL

The coastal geological framework along the southeast coast of Florida is based on interpretation of seafloor topography as displayed in LADS imagery. The detailed LADS imagery provided a basis for mapping the seafloor surficial units in terms of landforms that were in turn interpreted in terms of geomorphological units. Each geomorphological unit is an assemblage of individual landforms that together represent a cohesive mapping unit. The geomorphological mapping units make up a topology for the continental shelf off the southeast coast of Florida. The basic rationale for the topological development is provided in Finkl and Warner (2004). Geomorphological maps of the seafloor in the study area were prepared by county (*i.e.,* Palm Beach, Broward, and Miami-Dade). Figure 2 (see map insert) shows the interpreted geomorphological units in four panels (1–4). Most of the sedimentary features are framed by exposure of bedrock on the seafloor or barrier coral reefs.

Methodology

Acquired along the southeast Florida coast in 2001 (Broward County) and 2003 (Palm Beach and Miami-Dade counties), the LADS data comprise millions of points in a bathymetric database for a coastal segment that spans 160 km alongshore and up to 10 km offshore to cover nearly 600 km^2 of seabed. When this detailed coverage is printed at a nominal map scale of about 1:800, it provides convenient handling capabilities in continuous map sheets. Continuous map sheets are advantageous because patterns become recognizable for the first time, *viz.,* 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, as they may otherwise go unnoticed. Shaded relief bathymetric maps with about a tenfold exaggeration of vertical scale produce discrete sounding patterns that can be interpreted in terms of bathymetric units. The LADS 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 from geophysical surveys (*i.e.,* sidescan sonar and seismic reflection profiling), by geotechnical (vibracore) surveys, and by bottom samples retrieved by divers.

Characterization of Seafloor Mapping Units

Morphological units defined by combinations of depth, shape, and arrangement of soundings and shadow patterns were drawn on the paper charts (at a scale of 1:800) by freehand and then digitized on screen. This dual procedure was followed because it was 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 ArcGIS®. The final digital product was compiled in a spatial context that facilitated analysis and computation of selected parameters, such as areas for sand flats, FRT, hardbottom, bars and troughs, or tidal features.

Before commencement of 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 in the study area (Finkl, Benedet, and Andrews, 2004, 2005a, 2005b). A list of features present on each chart was compiled. This list was used to create a master list to make a comprehensive legend. The 42 major mapping units identified in the airborne laser bathymetry survey area are similar to those described by Finkl and Warner (2004). These features are organized in terms of a simple geomorphological classification scheme (see legend in Figure 2). There are many possibilities for interpretation of features, and the orientation depends on the purpose, which in this case was production of a map showing major seafloor features on the continental shelf. The natural spatial heterogeneity of morphological units on the seafloor determines to a large extent what should be mapped. Most natural units are predetermined and build on classifications by other researchers working elsewhere.

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 to become karst noyé (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 FRT) except for some coastal channels. The main morphological features occurring in the study area are summarized by Finkl and Warner (2004) in terms of sandy bottom types, rock hardgrounds (exposed bedrock, usually as karst noyé), coral reefs, and related features.

Rock and Unconsolidated Sediments

Seafloor mapping units are described by county, from north to south. The study area shows a diverse range of bedrock morphological features, from drowned karst features (*e.g.,* beach ridges and sink holes) and submerged paleoinlets in Palm Beach and Broward counties to extensive unconsolidated sedimentary features such as tidal sand flats and sand ridges (referred to as linear shoals by Duane *et al.,* 1972) in Miami-Dade County. Each county is thus generally characterized by distinct submarine physiographic units.

Geomorphological Zonation of the Southeast Florida Continental Shelf

Because the southeast Florida Atlantic continental shelf contains distinctive geomorphological features, it is possible to regionalize the survey area into alongshore reaches or compartments. These reaches are based on spatial interrelationships between interpreted seafloor mapping units, where dominant patterns are discernable in Figure 2. Four reaches are identified from north to south and are so noted in Figure 2. Although all reaches contain sand flats and barrier coral reefs of the FRT, they are differentiated by frequency of occurrence, spatial pattern, and presence of hardgrounds.

Reach I (sand flats and karst topography) extends from the Martin County line to 6.5 km south of Palm Beach Inlet (Figure 2, Panel 1), spanning a total alongshore distance of about 28 km. This section of the shelf is notable for its expansive drowned beach-ridge plain (mapped as Ridge Fields), drowned paleoinlets, karst basins (mapped as Structural Troughs, Rock Basins, Ridge and Valley, and Arcuate Features), and extensive sand flats separated by diabathic channel fields and sand wave fields. Reach I terminates where the Bahamas Fracture Zone (*e.g.,* Ball, 1991; Dolan, Mullins, and Wald, 1998; Pindell, Kennan, and Barrett, 2000; Rogers and Santosh, 2004; Sheridan *et al.,* 1988), locally known as the Jay Fault (Smith, 1993), crosses the shore near R095 (Florida range monument number) and extends across the Florida peninsula into the Gulf of Mexico. This boundary marks the northern terminus of the FRT and southern extent of drowned beach ridges.

Reach II (sand flats and coral reefs) extends for about 42 km alongshore to about 0.15 km north of the Hillsboro Inlet (Figure 2, Panel 2). This narrowing shelf zone, compared to a wider shelf to the north (northern Palm Beach County) and south (central Miami-Dade County), is characterized by sand flats with diabathic (normal to isobaths, *i.e.,* cross-shore) channel fields leeward or shoreward of the FRT. The seawardmost barrier reef occurs along the shelf break on the upper part of the slope. This reach terminates at the Hillsboro Inlet, where the shelf widens, diabathic channel fields disappear, and nearshore rock exposure increases.

Reach III (sand flats, hardgrounds, and coral reefs) occurs throughout the Broward County shelf area and into the northern Miami-Dade County shelf area, terminating at the entrance channel to the Port of Miami (Figure 2, Panel 3). This reach, about 64 km in alongshore length, is characterized by extensive nearshore rock outcrops (mapped as Nearshore (Rock/Coral) Reef, a combination of nearshore rock and coral reefs) that are exposed as bare rock surfaces on the seafloor or variously mantled by thin veneers of sand that are not thick enough to disguise the underlying rock structure (mapped as Structural and Sand Flats). Rock exposure and thin nearshore sedimentary veneers become more extensive southward through Broward County and into Miami-Dade County.

Reach IV (tidal sand flats and ridges, hardgrounds, and coral reefs) extends southward from the navigational entrance of the Port of Miami past Key Biscayne, which separates Biscayne Bay from the eastern shelf and FRT (Figure 2, Panel 4). The morphology of the continental shelf lying east (seaward) of Key Biscayne, the northernmost key in the chain of Florida Keys, is dominated by tidal features that notably include fields of tidal sand ridges in the lee of the FRT. Tidal channels and associated bars, deltas, and shoals occur on the interface between Biscayne Bay and the Atlantic Ocean.

Distinctive zonation of the study area into morphological reaches provides a natural base for discussion of barrier reef environments, backreef bottom types, and shelf geomorphology considered by county administrative units. Statistics are thus generated by county for comparative purposes of shelf types. This approach is consistent with the way the Florida Department of Environmental Protection collates data (by county). The following discussion begins with shelf morphologies offshore Palm Beach County and extends southward into Miami-Dade County.

Table 1. *Hardbottom features in Reaches I and II of Palm Beach County based on percentage of Anastasia Formation outcrops and coral reefs.*

Feature	Area (m^2)	% Hardbottom	% Total Area
Arcuate structural feature	1,655,503	1.2%	0.6%
Structural basin	1,382,271	1.0%	0.5%
Continental slope	40,663,357	30.1%	14.3%
Coral reef (FRT)	4,236,229	3.1%	1.5%
Marine terraces (deepwater)	5,164,588	3.8%	1.8%
Forereef platform	174,116	0.1%	0.1%
Nearshore reef	1,101,384	0.8%	0.4%
Nearshore rock	200,458	0.1%	0.1%
Patch reef	281,587	0.2%	0.1%
Ridge and valley	4,351,019	3.2%	1.5%
Ridge field	65,834,775	48.7%	23.1%
Rock ridge	5,130,592	3.8%	1.8%
Structural trough	4,973,126	3.7%	1.7%
Total	135,149,004	100%	47%

FRT = Florida Reef Tract.

Shelf Morphological Features

Seafloor features along the southeast Florida Atlantic coast are shown diagrammatically in Figure 2 (Panels 1 and 2), where 1 cm on the map equals 1500 m on the ground. More detailed, larger-scale maps (Figures 2A–F) are enlarged sections of the base map, where 1 cm on the map equals 1180 m on the seafloor. The more detailed callout maps (Arabic-lettered red boxes in Figure 2) each contain two panels, the left panel showing the color-shaded relief LADS bathymetry and the right panel showing the interpreted shelf geomorphic units. The purpose of the two-panel detailed figures is to show the details in the LADS imagery and generalization of that detail into interpretive mapping units. These maps can be used to show general along- and cross-shore trends and details of landform assemblages.

MORPHOLOGICAL FEATURES OF THE CONTINENTAL SHELF OFFSHORE PALM BEACH COUNTY

The continental shelf offshore Palm Beach County ranges up to 10 km in width in the northern part of the county but narrows to about 2 km near the Broward County line (Figure 2, Panels 1 and 2). For Reach I (sand flats and karst topography) and Reach II (sand flats and coral reefs) sectors of the overall study area in Palm Beach County, 269 km^2 were mapped with continental slope, ridge fields, and sand flats, making up about 15, 27, and 31%, respectively, of the total area (Table 1; Finkl, Benedet, and Andrews, 2007). Diabathic channel fields comprising about 19 km^2 accounted for 7% 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% of the area.

Hardbottom features collectively make up about 47% of the mapped area (284 km²) and the Ridge Field mapping unit, an exposed bedrock structure of the outcropping limestone, occupies nearly half of the hardbottom area (48.7%; Table 1). Other bedrock features include rock ridges (3.8%), structural troughs (3.7%; developed along paleolineaments), ridge and valley (3%), and arcuate structures (1.2%) in hardbottom areas. Although not defined here (see FINKL, 1993, and FINKL and WARNER, 2004, for descriptions), suffice it to say that these bedrock features are defined on the basis of the shape and arrangement of topographic expression on the seafloor and represent nonsediment areas. The Coral Reef mapping unit (Figure 2, Panels 1 and 2), although environmentally important, takes up a small part of the total survey area (1.6% composed of the FRT); however, among hardbottom features, coral reefs occupy about 3% of the area.

The contrasting nature of near- and offshore sand flats with bedrock seafloor is clearly evident in Figure 2A (left panel). The bedrock seafloor is composed of karstified terrains that have been drowned. The drowned beach-ridge plain is cut through by a paleochannel, the seawardmost portion of which must have been an inlet and/or estuary as sea level rose during the last deglaciation cycle. The paleochannel, which contains two structurally controlled right-angle bends, is about 400 m wide by about 3 km long. The channel continues shoreward beneath the Offshore Sand Flat mapping unit, as confirmed by seismic reflection profiling that shows about 8 m of sand cover (SCIENTIFIC ENVIRONMENTAL APPLICATIONS INC., 2005). The northern semicircular curve in the paleochannel may be a reflection of a collapsed doline, the rim of which forms the northern bank of the channel. Other karst features adjacent to the paleochannel include ridge and valley features and rock basins. Characteristic of subaerial limestone landscapes, these features are now drowned by relative sea-level rise. The topographic sequence in the Ridge and Valley mapping unit is about 0.5 to 1 km across by about 3.5 km in length. The dissolution basin, mapped as a Rock Basin, is about 1 km across by 2.5 km in length. There is about 2 to 4 m of local relief in both mapping units. A small portion of a Structural Trough mapping unit occurs near the top of Figure 2A. The edge of the shelf is marked by the seawardmost beach ridge about 5.8 km from shore.

These karstified surfaces of the Anastasia Formation are overlapped shoreward by sandy deposits. The littoral sand deposits are separated in two distinct units, nearshore sand flats and offshore sand flats, which are separated by diabathic channel fields. The diabathic channels mark a slope change on the shoreface, separating the nearshore from the offshore sand deposits. The diabathic channels range up to 700 m in cross-shore length. The channels average about 1 m in depth, with an alongshore (parabathic) wavelength of up to 150 m (FINKL, BENEDET, and ANDREWS, 2006).

The location of detailed callout in Figure 2B is shown in Figure 2 (Panel 1). This callout was selected because it illustrates the dynamic change in seafloor morphological patterns—specifically, the termination of the northern extension of the FRT, where the barrier coral reef is deflected shoreward and the beach-ridge plain starts. The interface between these shelf environments is marked by the westward extension of the Bahamas Fracture Zone (*e.g.,* BALL, 1991; DOLAN, MULLINS, and WALD, 1998). Surficial expression of the Bahamas Fracture Zone, a major tectonic boundary, is manifest in the shelf morphology and marks the boundary between Reaches I and II. The configuration of the continental shelf north of the Bahamas Fracture Zone is as described for Figure 2A, except for the outcrop of limestone bedrock nearshore in the Nearshore Reef mapping unit. A sidescan sonar image off the Town of Palm Beach shows exposure of bedrock on the seafloor in Figure 3 (see Figure 2B for location). This cross-shore trackline in Reach I is associated with a diabathic seismic reflection profile (Figure 4) that crosses the rock outcrop. The seismic image shows the overlap of nearshore sand onto the rock outcrop, as well as the seaward thickening of the interreefal sand flat deposit. Sand veneers may cover parts of the hardground intermittently as sand migrates with littoral drift or deposits are rearranged during storms, when there are strong parabathic currents or offshore underflow.

South of the Bahamas Fracture Zone lies shelf morphology that is characteristic of Reach II geomorphology, mostly characterized seaward by barrier reef environments and shoreward by sand flat features. The barrier reef is a complicated environment that retains most of the types of features that are typical of coral reefs, but they are too small to show at the mapped scale. Reef crest, flats, knobs, spur-and-groove topography, *etc.,* are grouped into the single Coral Reef mapping unit. Adjacent to this unit are distinctive degradational units that contain reef detritus that has accumulated in response to storms both in front of the barrier and in the lee. The seaward flanks of the coral reef beyond the spur-and-groove topography are mantled by coarse forereef rubble deposits that contain reef fragments that have broken off under high-energy conditions and tumbled down the steep forereef slope (mapped as deepwater Marine Terrace I). Deepwater reefs lie underneath the rubble layers, as occur more continuously 0.8 km south of this callout (Figure 2B) offshore from R110 (see Marine Terrace I mapping unit in Figure 2, Panel 1). Shoreward of the barrier coral reef lie extensive overwash deposits that are mapped as the Backreef Apron. These aprons can extend 750 m shoreward and can be continuous for long distances on the former lagoon side of the barrier reef. The materials making up the overwash aprons range from fine-grained scree to large coral fragments that were probably broken off during hurricanes. These materials tumbled or slid down leeward of the barrier and accumulated on the seaward margin of the former lagoon. They may range up to several meters in thickness along the base of the barrier but thin out shoreward, where they interfinger with interreefal sands. The chain of barrier reefs is broken by reef gaps, as shown in the Reef Gap mapping unit in Figure 2B, offshore from R103. Similar to overwash aprons leeward of the coral reefs, overwash deposits occur shoreward of the beach-ridge plain, as shown in the Rock Rubble mapping unit that extends northward from R094.

Littoral sand flats, which occur between the barrier coral reef and the shore, are separated by diabathic channel fields into nearshore and offshore sand flats. Extending alongshore between R086 and R104 is the Nearshore Reef mapping unit that is composed of exposure of the Anastasia Formation as a hardbottom habitat. The sidescan sonar image in Figure 5 shows bedrock on the seafloor in Reach II. The sandy bottom is evident (based on tonal differences) in the sonar image and is shown in a seismic reflection profile (Figure 6). Sand overlays the Anastasia Formation to variable depths as a thin veneer but accumulates to several meters in thickness in interreefal sand flats (mapped as Nearshore or Offshore Sand Flats) shoreward and seaward of the hardground. A Bar and Trough mapping unit extends as a continuous unit alongshore on the inner shoreface.

Bedrock Features Exposed on the Seafloor

Part of the continental shelf is sediment covered, but significant portions lack sedimentary cover and limestone bedrock is exposed on the seafloor. From central Broward County northward along the nearshore zone, bedrock outcrops are facies of the Anastasia Formation, a 100,000- to 120,000-year-old coquinoid bank deposit that formed when sea level was higher than present (Khalil, 1999; Lovejoy, 1983). The limestone outcrops are formed by a wide range of structural features that have variable topographic expression. Resistant layers in the limestone deposits formed positive relief under subaerial weathering when sea level was lower. The drowned karst topography is interpreted in general terms, as the purpose of this report is to focus on landform patterns and assemblages that form discrete regions of shelf.

Rock Ridge

The Rock Ridge mapping unit occurs in the northern part of the county about 3 km offshore from R005 to R039. The unit occupies about 5 km^2 (3.8% of hardbottoms and 1.8% of the total area mapped; Table 1) and is bounded by the Structural Trough mapping unit on its seaward margin and by the Offshore Sand Flat mapping unit landward. The distinctive topography of this drowned karst topography defines the unit in terms of numerous linear shore-parallel ridges with transverse gaps.

Ridge and Valley

A complicated series of low-relief ridges and valleys occurs south of the Ridge Field mapping unit. The small area occupies about 4.3 km^2 and is bounded in a landward direction by the Offshore Sand Flat mapping unit and seaward by the Ridge Field mapping unit. The unit contains broad valleys with a sand cover. The ridges are karstified limestone facies of the Anastasia Formation.

Ridge Field

The large Ridge Field mapping unit makes up the outer portion of the continental shelf. Covering an area of about 66 km^2, the ridge fields extend from Martin County to offshore from R095 in Palm Beach County. The unit comprises about 49% of the hardbottom area and about 23% of the total area mapped (Table 1). The ridge field is buried by sand designated as the Sand Wave mapping unit on the Martin County–Palm Beach County border. To the south, the ridge fields pinch out at the northernmost extension of the FRT about 1.4 km offshore from R095. These ridge fields are interpreted as drowned beach-ridge systems, where the ridges were lithified during subaerial exposure. The paleoswales contain unconsolidated sediments.

Continental Slope

The Continental Slope mapping unit occurs seaward of the FRT with a depth of about 50 m and makes up about 30% of the mapped area (Table 1). It occurs throughout the study area and often contains older coral reef systems (identified as deepwater reefs) at the base of the FRT, *e.g.,* in the vicinity of R110 to R130 and intermittently southward. The slope, referred to as the Florida-Hatteras Slope, forms a transitional drop from the shallow shelf edge 50 to 60 m into the Straits of Florida (Reed *et al.,* 2005), where water depths approach 800 to 1000 m. Shelf-edge reefs occur near the top of the slope.

Nearshore Rock

The Nearshore Rock mapping unit includes exposed facies of the Anastasia Formation that generally occur landward of the surf zone. Small patches of rock occur sporadically alongshore and may be exposed or covered by moving sand, depending on the season (winter vs. summer). Some outcrops occur within the Nearshore Sand Flat mapping unit, *e.g.,* in the range R203 to R212. Small cliffs ($<$2 m) occur sporadically alongshore but are especially prominent north of Jupiter Inlet. Although minor in areal extent, comprising only 0.1% of total hardbottom occurrences (Table 1), nearshore rock has important morphodynamic implications for shoreline stability and platform configuration.

Structural Trough

Subaerial weathering of coquinoid bank deposits of the Anastasia Formation formed large linear troughs in otherwise more resistant layers. Solution of carbonate materials seems to have followed paleolineament systems to produce the distinct linearity of troughs. This mapping unit, lying 4.5 km offshore from R005 to R040, occupies an area of about 4.9 km^2 or 3.7% of the hardbottom area (Table 1). The unit lies shoreward of the drowned beach ridges and is transitional to the Rock Ridge mapping unit, from which it differs by having wider valleys between ridges.

Coral Reefs and Related Features

The FRT, the main coral reef system on the continental shelf, is composed of a series of shore-parallel barrier reefs that are separated from one another longitudinally by sand flats that are best developed in Broward County. In Palm Beach County, there is a single, wide (up to 1.5 km at R165) sand flat that lies between the shore and the barrier reef. The barrier is disjointed, with sections of the reef separated from one another by reef gaps, which often form conduits for sand transport from the sand flats offshore beyond the barrier reef (Finkl, 2004) and across the reef gap ramp. Rubble accumulates shoreward of the barrier reefs due to overwash during storms. The Backreef Apron mapping unit identifies these rubble accumulations that spill into the Nearshore Sand Flat mapping unit. The seaward margins of the barrier reefs are characterized by a series of benches that step down into deeper water. The benches are composed of undifferentiated Marine Terrace mapping units. Patch reefs occur sporadically shoreward of the barrier reefs.

Coral Reef (Florida Reef Tract)

Barrier coral reefs comprising the FRT tend to occur about 1 to 1.5 km offshore and occupy about 4.2 km² or about 3% of the total hardbottom area (Table 1). The barrier reefs in Palm Beach County are the areally constricted northern extension of the FRT, which is thoroughly described in the Florida Keys (*e.g.,* LIDZ, 2006; LIDZ, HINE, and SHINN, 1991; LIDZ, ROBBIN, and SHINN, 1985; LIDZ *et al.,* 1991, 1997). HOFFMEISTER (1974) and LIGHTY (1977) include descriptions of the more northerly portions of the FRT, as occur in Palm Beach County. Gaps between the barrier reefs are mentioned by these authors and described in terms of leaky sediment valves by FINKL (2004). The barrier reefs act as sills that retain sediments in the trough between the coral reefs and the shore. Reef gaps and reef gap ramps contain sand spillways through the FRT from offshore sand flats. Submarine deltas often occur seaward of the gap in the FRT and obscure deepwater marine terraces in the vicinity offshore from R173 and R181.

Marine Terraces

The Marine Terrace mapping unit occurs along the seaward margin of the barrier coral reefs but in deeper water, beginning at 35 m and stepping downward as marine terraces on the outermost part of the continental shelf. The terraces appear to be discontinuous but are well-developed offshore from R110 to R135 and R140 to R188, as well as from R195 to Broward County and into Miami-Dade County. They make up about 5 km² or nearly 4% of the hardbottom area offshore Palm Beach County (Table 1).

Nearshore Reef

The Nearshore (Rock/Coral) Reef mapping unit is caused by exposure of the Anastasia Formation alongshore. Normally masked by a thin sedimentary cover that is transitory in nature, moving with the seasons and energy conditions (*e.g.,* quiescent phases punctuated by storms), these rock reefs (hardbottom) are prominently displayed between R086 and R095. The units make up about 1 km² or 0.8% of the hardbottom area (Table 1). Smaller rock reefs occur sporadically throughout the nearshore zone, but they are not mapped at the scale of this reconnaissance survey. Because it is not always possible to differentiate rock reef from coral reef in the LADS imagery, this unit is predominantly rock reef but may contain inclusions of coral–algal reefs.

Patch Reef

In terms of reef geomorphology (shape, form, distribution of reef-building corals), a patch reef is defined as an isolated coral growth forming a small platform in a lagoon, barrier reef, or atoll. Patch reefs may occur as isolated features or in clusters of variable density and tend to occur inshore of the main reef line. For instance, most of the Florida Keys' main reef lies 10 km offshore. But the patch reefs are small, isolated, and scattered anywhere between dry land and deeper water. Most patch reefs in Palm Beach County occur landward of the barrier reefs as isolated features that collectively account for 0.2% of the hardground area (0.281 km²) or 0.1% of the total mapping area (Table 1). These features, although areally restricted, require environmental buffers that restrict exploitation of sand resources near them.

Sedimentary Features and Sandy Bottom Forms

Sediments make up the rest of the survey area in Palm Beach County. Sandy sediments occur alongshore but are interrupted on the beachface and shoreface by sporadic outcrops of the Anastasia Formation. In the northern part of the county where the continental shelf widens, sediments partly cover drowned beach ridges and occur in various types of basins or troughs within karstified hardbottom areas (see types described earlier). Sedimentary areas, which are more extensive in the northern part of the county, become restricted by a narrow shelf and the presence of coral reefs in the south.

Diabathic Channels

The Diabathic Channels mapping unit, a prominent feature of nearshore sand flats, extends nearly continuously for the length of the county. Diabathic channels make up about 18 km² (6.6% of the mapped area) and comprise about 15% of the sand resources in the county. They were first identified in the LADS imagery. In the Palm Beach County seabed classification system (FINKL, BENEDET, and ANDREWS, 2005a, 2005b), these cross-shore channels were mapped as "Diabathic Channel Fields" alongshore for a more or less continuous distance of 70 km. The channel fields average about 300 m in width but show variability ranging from 100 to 600 m (FINKL, BENEDET, and ANDREWS, 2006). Based on measurements of the LADS imagery, the diabathic channels occur in water depths of 7.5 to 10.5 m and have an azimuth orientation ranging from 70 to 90°. Channel lengths average about 300 m but show variation on the order of ±60 m. Alongshore wavelengths range from 75 m in the south to 150 m in the north, ±15 m in both areas, and show an average local relief of 1 ± 0.3 m. The landward boundary of the diabathic channel field lies about 400 m offshore the present shoreline. The channels are associated with interreefal sand flats (Nearshore Sand Flat mapping unit), sedimentary accumulations in backreef troughs, where sandy materials accumulate up to 10 m in thickness. The contiguous nature of the diabathic channels suggests that they are unrelated to the barrier coral reefs and reef gaps farther offshore in deeper water.

Ebb-Tidal Deltas

Small deltas are associated with Jupiter Inlet (R010), Boynton (South Palm Beach) Inlet (R150), and Boca Raton Inlet (R222). The Palm Beach Inlet is dredged as a deep draft navigation channel. The Boynton ebb-tidal delta is shown on the map because it is morphologically distinctive. It occupies an area of about 0.1 km^2 and accounts for 0.1% of the sand resource area.

Nearshore Sand Flat

Sand flats occurring in the nearshore zone occupy about 70 km^2 or about 25% of the total area mapped. Sedimentary flats, a characteristic feature of the seafloor, occur shoreward of barrier reefs in the FRT. Many sedimentological studies on the southeastern Florida continental shelf describe sedimentary infills in the nearshore zone as being composed mainly of sand-sized clastics and carbonates (DUANE and MEISBURGER, 1969). The sandy deposits in the study area are mostly sheet formations that overlie karstified bedrock depressions as basin infillings. Although wide ranges of seafloor patterns are associated with this unit, they are grouped into one category for mapping purposes. One notable variation within the Nearshore Sand Flat mapping unit is the presence of diabathic channels. Other variations include ripples and planar bedforms. Sediments within this mapping unit fill former backreef areas to depths of 7 to 10 m. Study of sediment stratigraphy in the sand flat unit indicate mostly sandy facies, but there may be lenses of fine-grained materials or coarse limestone rubble derived from storm overwash of barrier reefs (COASTAL PLANNING & ENGINEERING, 1985, 1997, 2001; FINKL, 2004).

Offshore Sand Flat

Along the northern part of the county where the shelf widens, an Offshore Sand Flat mapping unit occurs seaward of diabathic channels, which tend to occur on the seaward margin of the Nearshore Sand Flat mapping unit. This sedimentary unit is flanked on seaward margins by hardbottom mapping units, *viz.,* Ridge Field, Ridge Valley, and Rock Ridge. On the northeastern extension of the unit, it merges with Sand Waves and Sediment-Covered Ridge Field mapping units. Offshore sand flats make up about 25 km^2 or about 9% of the total area mapped.

Sand Wave

Large sand waves occur near the northern margin of the study area about 2 km offshore from R117 (Martin County) to R007 (Palm Beach County). The Sand Wave mapping unit is differentiated from the Nearshore Sand Flat mapping unit by the presence of large sand waves (800 m to 1 km wavelength and more than 3 km in length). On its seaward flank, the unit overlaps the Ridge Field mapping unit and merges with the Sediment-Covered Ridge Field mapping unit. Shoreward, the unit merges into nearshore sand flats. The Sand Wave mapping unit takes up about 5.6 km^2 or 2% of the total area mapped.

Morphosedimentary Environments

Morphosedimentary subprovinces in Palm Beach County included shoreface sands, interreefal sedimentary infillings (sandy deposits with thin intercalations of finer-grained materials overlying coral rubble in basal sequences and near reef gaps), and finer-grained materials seaward of coral reefs. The parabathic sedimentary subprovinces can be further divided into diabathic facies that include cross-shore channels in shoreface sand deposits. The channels, identified in the LADS imagery and by shore-parallel seismic reflection profiling, range up to 100 m wide by 3 m deep by 300 m long. These deposits are identified by FINKL, BENEDET, and ANDREWS (2006) as occurring in a high-energy depositional environment.

Table 2. *Hardbottom features in Reach II of Broward County based on percentage of Anastasia Formation outcrops and coral reefs.*

Feature	Area (m^2)	% Hardbottom	% Total Area
Continental slope	10,500,158	23.3%	9.4%
Coral reef	5,056,462	11.2%	4.5%
Marine Terrace I	6,948,949	15.4%	6.2%
Marine Terrace II	1,182,334	2.6%	1.1%
Nearshore (rock and coral) reef	21,370,767	47.4%	19.2%
Patch reef	14,006	0.0%	0.0%
Total	45,072,676	40%	40%

MORPHOLOGICAL FEATURES OF THE CONTINENTAL SHELF OFFSHORE BROWARD COUNTY

In contrast to Palm Beach and Miami-Dade counties, the Reach III (sand flats, hardgrounds, and coral reefs) sector offshore Broward County is characterized by a relatively narrow continental shelf (Figures 1 and 2), which measured about 2 km wide in the vicinity of the Port Everglades entrance channel. Most of the shelf area is occupied by sediment areas in the north, but there is considerably more exposure of bedrock surfaces in the southern part of the county. Of the total area mapped (112 km^2), major hardbottom features make up about 40% of the area. Exposure of the Anastasia Formation on the seafloor accounts for most of the hardgrounds. Of the hardbottom features, the Nearshore Reef mapping unit accounts for nearly half of the rock (47%) and 19% of the total area mapped. Coral Reef Marine Terrace mapping units (FRT, Marine Terrace I, Marine Terrace II) make up nearly a third (29%) of the hardbottom area and about 12% of the total area mapped (Table 2).

Figure 2C (see Figure 2, Panel 2, for location) is a double composite image, like Figures 2A and 2B, that shows cadastral features merged with LADS bathymetry and interpreted shelf geomorphic units. The essential morphological features of the northern part of Reach III entail nearshore littoral sand flats interspersed by nearshore reef map units, offshore sand flats, and coral reefs. The most prominent feature of Reach III geomorphology is the presence of the barrier coral reef system that is fronted by deepwater marine terraces (Marine Terraces I and II). Reef gaps separate segments of the FRT, but they often cut through the deepwater marine terraces, forming a long, continuous ramp from the outer continental shelf to the upper slope, as shown in the six morphological Reef Gap Ramp units in Figure 2. The Offshore Sand Flats are sedimentary corridors that are bounded seaward by the FRT and shoreward by Nearshore Reef mapping units. As shown in Figure 2, this mapping unit is mostly composed of coral reefs except immediately alongshore where the Anastasia Formation outcrops. Leeward of the FRT are overwash deposits that are similar to the Backreef Apron mapping unit except that they are more closely associated with the FRT and do not extend as far shoreward into the former lagoon (now an interreefal sand flat).

Figure 2D (see Figure 2, Panel 3, for location) shows a seafloor landform assemblage that is similar to the geomorphological patterns in Figure 2C, except for the extensive occurrence of the Structural Sand Flat mapping unit. These parabathic structural sand flats are interspersed between the shore and the offshore barrier coral reefs. The extensive nature of the structural sand flats imparts a dominant character to this part of the shelf. Reef overwash deposits flank the lee side of the barrier reefs and are intercalated with deposits making up the offshore sand flats. Deepwater marine terraces occur on the seaward margins of the FRT, marking the position of the upper continental slope.

Bedrock Features Exposed on the Seafloor

The continental shelf in Broward County contains extensive exposure of limestone bedrock (Anastasia Formation to the north and Miami Limestone to the south). Nearly half of the shelf area contains hardbottom in the form of bedrock exposure or coral reefs (barrier and patch; Table 2). The continental slope contains forereef rubble that has moved downslope by gravity flow to form talus and scree deposits that partly cover proximal portions of deeper-water marine terraces.

Continental Slope

The continental slope occupies an area of about 10 km^2 or 23% of the hardbottom area and 9.4% of the total mapped area (Table 2). Forereef rubble accumulates near the base of the seaward margin of the FRT and partly mantles the upper (shallower) marine terrace, identified here as Marine Terrace I (Figure 2). This terrace, which tends to occur in water depths of about 29 to 37 m, occupies an area of about 0.69 km^2. Marine Terrace II occurs in about 38 to 46 m of water and occupies about 1.18 km^2. Identification of the marine terraces was problematic in some areas because they occur near the instrumental depth limit of the LADS technology. Nevertheless, their distribution was very clear in some areas, and here they were mapped with confidence. It is not known whether the marine terraces are rock-cut surfaces or whether they contain Pleistocene coral reefs under a surficial cover of sedimentary debris derived from the FRT or sandy deposits. More investigation is required to ascertain the true nature of these deposits.

Nearshore (Rock and Coral) Reef

The Nearshore Reef mapping unit (Figure 2) is composed of limestone bedrock and coral reef. Because there were numerous thin shore-parallel stringers that appeared to have undifferentiated surface expression in the LADS imagery, it was not possible to consistently distinguish one unit from the other. They were thus mapped as a complex unit containing both types of hardground. This complexed mapping unit accounts for about 47% of the hardbottom occurrence on the Broward County continental shelf.

Spatial distribution patterns of the Nearshore Reef mapping unit become complex south of Port Everglades, where they tend to break the Nearshore Sand Flat mapping unit into long, narrow segments of both units. That is, the nearshore reefs (rock plus coral reef) and the sand flats tend to become long, narrow stringers.

Coral Reefs and Related Features

The FRT, the main coral reef system on the continental shelf, is composed of a series of shore-parallel barrier reefs that are separated from one another longitudinally by sand flats, a sequence that is best developed in Broward County (Figure 2). Between R020 and R030, the crest of the barrier reef ranges between 153 and 255 m in width and lies in about 18 to 24 m water depth. The seaward margins of the barrier reefs are characterized by a series of benches that step down into deeper water. The benches are composed of undifferentiated Marine Terrace mapping units. Marine terraces occur seaward of the barrier reef system, where the Marine Terrace I mapping unit is continuous along the FRT seaward margin. Discontinuous segments of the Marine Terrace I mapping unit occur seaward of R049 to R059, R096 to R101, and R104 to R108.

The barrier coral reef is disjointed, with sections of the reef separated from one another by reef gaps, which often form conduits for sand transport from the sand flats offshore beyond the barrier reef (FINKL, 2004). Reef gap ramps descend seaward across the shelf break, cutting through the marine terraces to the upper margins of the continental slope (see examples in Figures 2C and 2D). The ramps comprise the deep portions of reef gaps. The barrier reefs act as a sill or lip that retains sediments in the trough between the coral reefs and the shore. Reef gaps and reef gap ramps funnel sand leaking from the offshore sand flats. Submarine deltas often occur seaward of the gap in the FRT and obscure deepwater marine terraces in the vicinity offshore from R003, R017, R035, R043, R057, R103, and R124.

Rubble accumulates shoreward of the barrier reefs due to overwash during storms. The Backreef Apron mapping unit identifies these rubble accumulations that spill shoreward into the Nearshore Sand Flat mapping unit. Patch reefs occur sporadically shoreward of the barrier reefs.

Coral Reef

Barrier coral reefs comprising the FRT tend to occur about 2 to 3 km offshore and occupy about 5 km^2 or about 11.2% of the total hardbottom area and 4.5% of the total mapping area (Table 2). The barrier reefs in Broward County are the areally constricted northern extension of the FRT, which is thoroughly described in the Florida Keys (*e.g.,* LIDZ, 2006; LIDZ, HINE, and SHINN, 1991; LIDZ, ROBBIN, and SHINN, 1985; LIDZ *et al.,* 1991, 1997). HOFFMEISTER (1974) and LIGHTY (1977) include descriptions of the more northerly portions of the FRT, as they occur in Broward County. Gaps between the barrier reefs, mentioned by these authors and described in terms of leaky sediment valves by FINKL (2004), are identified here as Reef Gap and Reef Gap Ramp mapping units. The barrier reefs act as a sill or lip that retains sediments in the trough between the coral reefs and the shore.

Marine Terraces

The Marine Terrace I and Marine Terrace II mapping units occur along the seaward margin of the barrier coral reefs but in deeper water, beginning at 35 m and stepping downward as marine terraces along the shelf break (Figure 2). Marine terraces make up about 7 km^2 or nearly 15% of the hardbottom area (6% of the total mapped area) and 1 km^2 or about 48% of the hardbottom area (about 1% of the total mapped area) for Marine Terrace I and Marine Terrace II, respectively (Table 2). There are typically more than two marine terraces, four being a common occurrence. The Marine Terrace I and Marine Terrace II mapping units are wider and more contiguous than the other deeper terraces. A good example of multiple terraces centers offshore from the reef gap at R120.

Nearshore Reef

Nearshore coral–algal reefs are not easily interpreted in the LADS imagery, and they are consequently mapped together with rock outcrops, mostly Anastasia Formation from central Broward northward and Miami Limestone from central Broward southward. The Nearshore Reef mapping unit is thus composed of rock reef and coral reef. This complex unit accounts for about 21 km^2 of mapped shelf area, about 47% of the hardbottom and 19% of the total area mapped (Table 2). The nearshore reefs tend to occur as elongated stringers that trend parallel to the shore. They are surrounded by sand flats in the northern part of offshore Broward County but become progressively and spatially involved with the Structural Sand Flat mapping unit south of Port Everglades (see detail in Figure 2D). The seawardmost occurrence of the Nearshore Reef mapping unit rests in about 12 to 18 m water depth and separates nearshore sand flats from offshore sand flats. Sand flat corridors occurring between nearshore reefs and/or structural sand flats are of variable widths ranging up to 375 m wide but commonly narrow to several tens of meters in width.

Patch Reef

A patch reef is an isolated coral growth forming a small platform in a lagoon, barrier reef, or atoll. Patch reefs may occur as isolated features or in clusters of variable density. Most patch reefs in Broward County occur landward of the barrier reefs as isolated features that together collectively account for about 14,000 m^2 (Table 2). Because of their small size and scalar considerations in the production of maps showing submarine geomorphological features, most patch reefs are not shown. They are mentioned because of their environmental significance. Because of their small size, they are normally precluded from the mapping. Some of the more prominent strings of patch reefs occurring in offshore sand flats are shown offshore from R003, R012 to R016, R025 to R028, R030 to R032, R033, R038 to R039, R052 to R054, R067, and R117 to R122. Mapping more detailed than this reconnaissance survey (*e.g.,* sidescan sonar or multibeam with bottom reflection) is required to show the positions of patch reefs.

Sedimentary Features and Sandy Bottom Forms

The wide range of sedimentary deposits mapped in Reach III of Broward County includes nearshore bar and trough systems, nearshore troughs, nearshore sand flats, offshore sand flats, structural sand flats, and coral reef overwash deposits. Sand resources for beach renourishment are associated with nearshore and offshore sand flats. The other types of sedimentary deposits occur too close to shore (*e.g.,* sand bars), are too thin (*e.g.,* structural sand flats), or contain rock fragments (overwash deposits) that are unsuitable for placement on the shore.

Nearshore Sand Flat

Extending seaward from the Bar and Trough, Nearshore Trough, Structural Sand Flat, and Nearshore Reef mapping units, the nearshore sand flats occupy an area of about 22 km^2 or about 54% of the sand resource area (about 20% of the total mapped area; FINKL, BENEDET, and ANDREWS, 2007). The sand flats range in width from about 800 m along the northern portion of the county to about 1 km or so in the south (Figure 2). Along the northern segment of the county shore, the nearshore sand flats lie about 200 m offshore but become progressively displaced seaward by intervening structural sand flats that may range up to 1.5 km in width. Beginning at the Hillsboro Inlet (R025), the nearshore sand flats become fragmented from contiguous belts up to about 1 km wide (near R024) to narrower sand corridors that are flanked by rock, coral reef, or structural sand flats (Figure 2C). Some of these corridors eventually pinch out to form complex distribution patterns between R045 and R100. The Nearshore Sand Flat mapping unit is separated from the Offshore Sand Flat mapping unit by coral reefs. Gaps in the so-called third reef occur from R087 to R088, R089 to R090, R108 to R113, and R124 to R125. At these reef gaps, the two sand flats merge and morphodynamically interact, but they are cartographically separated to provide closed polygons in the GIS.

Offshore Sand Flat

Lying seaward of the Nearshore Sand Flat and Nearshore Reef mapping units, offshore sand flats take up about 17 km^2 of the sand resource area in Broward County (FINKL, BENEDET, and ANDREWS, 2007). Although more contiguous and less fragmented by rock outcrops and coral reefs, the offshore sand flats make up about 41% of the sand resource area and about 15% of the total mapped area. The offshore sand flats are slightly more than 1 km wide in the northern part of the offshore area but narrow to about 0.5 km in width starting at R057 and extending to about R090 south of the Port Ev-

Table 3. *Hardbottom features in Reaches III and IV of Miami-Dade County based on bedrock exposure on the seafloor and coral reefs (FRT).*

Feature	Area (m²)	% Hardbottom	% Total Area
Continental slope	19,839,568	38.3%	7.6%
Coral reef	8,564,472	16.5%	3.3%
Marine terraces	6,409,339	12.4%	2.4%
Forereef rubble	267,056	0.5%	0.1%
Nearshore reef	15,396,396	29.7%	5.9%
Patch reef	208,620	0.4%	0.1%
Reef crest	1,139,580	2.2%	0.4%
Total	51,825,030	100%	20%

FRT = Florida Reef Tract.

erglades entrance channel. Southward, the offshore sand flats average between 0.50 and 1 km in width.

Morphologically, the offshore sand flats are flanked on their seaward margins by the barrier coral reefs (Figure 2). The FRT acts as a physical barrier that retains sand deposits on the continental shelf, except at reef gaps. The general morphology of reef gaps is described by Finkl (2005), who reports that they function as leaky sediment valves that control the level of sand behind the barrier coral reefs. Reef gaps offshore Broward County are often associated with Reef Gap Ramps, which form a mapping unit that extends the reef gap through the shelf break to the continental slope. Examples occur at R017, R035, R042, R049, R056, R103, and R125 (Figure 2, Panels 1 and 2). Sometimes there are wide reef gaps that are open for 5 km or more, such as occurs between R107 and R128. In this location, there is no reef gap ramp and the gap is closed at depth by a marine terrace (Marine Terrace I mapping unit). The seaward margin of the Offshore Sand Flat mapping unit is mostly bounded by reef overwash deposits that stratigraphically interdigitate with sediments in the flats. The overwash deposits (see previous descriptions) contain coarse-grained clasts, mostly coral fragments, that are unsuitable as beach fill materials.

MORPHOLOGICAL FEATURES OF THE CONTINENTAL SHELF OFFSHORE MIAMI-DADE COUNTY

About one-third (29.7%) of the hardbottom shelf area in Reaches III and IV (Miami-Dade County offshore area) is composed of the Nearshore Reef mapping unit, with about another third (32%) being taken up by the FRT (Coral Reef, Deepwater Reef, Forereef Rubble, Patch Reef, and Reef Crest mapping units; Table 3). The continental slope takes up the remainder, but it lies seaward of the FRT (Figure 2, Panels 3 and 4). Seafloor exposure of bedrock is significant in the northern part of the county but decreases southward and is largely replaced by sediments south of the Port of Miami navigational entrance. Overall, hardbottom features make up 20% of the total area mapped.

Sedimentary features cover about 63% of the total area mapped (see examples in Figures 2E and F). The Sand Flat with Sand Ridges mapping unit occupies the largest area of sediment cover (about 40%) followed by Tidal Sand Flat (19%) and Nearshore Sand Flat and Nearshore Sand Sheet (22%) mapping units. Offshore sand flats make up about 10% of the sediment area and 6% of the total area mapped. Assuming a 3 m thickness for all sand bodies, there is a potential sand resource of about 470×10^6 m³ that will no doubt be reduced by proximity to environmentally sensitive areas and other types of hazards to dredging. In the mapped sediment area, about 2.4% has been exploited by dredging for beach nourishment.

Figure 2E (for location see Figure 2, Panel 3) illustrates the transition from Reach III to Reach IV shelf environments, where sand flats become more tidally influenced, structural sand flats become more thickly covered with sand, and exposure of nearshore bedrock units disappears. The Reach IV environment is additionally notable for the occurrence of tidal sand ridges, as illustrated in the detailed callout in Figure 2F (for location see Figure 2, Panel 4).

Bedrock Features Exposed on the Seafloor

Limestone outcrops on the continental shelf in Miami-Dade County are contained with the Structural Sand Flat and Sand Flat with Sand Ridges mapping units (Figure 2). Sand cover is generally only a few centimeters thick over the limestone bedrock, permitting linear structural features to be seen in the LADS imagery. Placement of the Structural Sand Flat mapping unit in a hierarchical classification is problematic because it is transitional from bedrock features to sedimentary seafloor features. When structures are clearly evident in the bathymetric imagery, the unit characterizes rocky seafloor with a thin sediment cover. In any case, the unit eventually becomes obscured by thicker sediment accumulations as occur, *e.g.,* in the Nearshore Sand Flat (R037 southward) and Nearshore Sand Sheet (R075 to R090) mapping units (Figure 2). Bedrock is sporadically exposed in the Tidal Sand Flat and the Sand Flat with Sand Ridges mapping units, depending on the thickness of sediment cover. Sand ridges are typically separated by sediment troughs that may contain patches of exposed limestone bedrock.

Continental Slope

The continental slope occurs about 5 km offshore in the northern part of the county but lies nearly 10 km offshore in southern Miami-Dade County (Figure 2, Panels 3 and 4). It accounts for about 38% of the hardbottom area and about 8% of the total area mapped. The slope lies seaward of marine terraces fronting the FRT and occurs in about 50 m water depth.

Nearshore Reef

The Nearshore Reef mapping unit (Figures 2 and 2E), which includes both rock and coral reef, separates structural sand flats from nearshore sand flats in the nearshore zone and separates nearshore sand flats from offshore sand flats in the offshore zone. There are, however, gaps in the latter separation, *e.g.,* as occur offshore from R002 to R004, R009, R027 to R036, R038, R045 to R060, and southward (Figures 2 and 2E). Nearshore reefs take up about 15 km² and account for about 30% of hardbottom occurrences, or 6% of the total area mapped (Table 3).

Coral Reefs and Related Features

Coral reefs comprising the FRT become more spatially extensive from north to south, the variation ranging from 100 m in the north (*e.g.,* R030) to over 800 m (south of R112) in the south (Figure 2). The coral reef area covers about 8.6 km² and accounts for about 16% of the hardbottom area (about 3% of the total area mapped; Table 3). Patch reefs cover about 200,000 m² and account for about 0.4% of the hardbottom. The Reef Crest mapping unit was introduced for Miami-Dade County because the FRT increases in width compared to Palm Beach and Broward counties.

Barrier Coral Reef

The barrier coral reefs in Miami-Dade County lie nearly 4 km offshore in the northern part of the county and about 8 km offshore in the south (Figure 2). The barriers are broken by reef gaps centered on R009, R027, R034, R038, R055, R068, R090, R105, and southward from R112. In the northern and central parts of the mapping area, the barrier reefs are backed by offshore sand flats and reef overwash units, but south of R112 they are backed by the Sand Flat with Sand Ridges mapping unit. This basic change in the character of the submarine topography occurs south of the Port of Miami navigational entrance in the general offshore vicinity of R095 (Figures 2 and 2F).

Marine Terraces

The Marine Terrace mapping units occur along the seaward margin of the barrier coral reefs but in deeper water, beginning at 35 m and stepping downward as marine terraces along the shelf break. The terraces make up about 6 km² or about 12% of the hardbottom area (2% of the total mapped area; Table 3). There are typically more than two marine terraces, but they are mapped here as a complex single unit for simplicity. The Marine Terrace mapping units tend to become wider and more contiguous south of R095, where three combined terraces are nearly 800 m wide (Figure 2F).

Forereef Rubble

Scree deposits occur along the seaward base of the FRT and sometimes accumulate as coarse-grained deposits in reef gaps (*e.g.,* R003). Because the deposits tend to be narrow, elongated gravity accumulations at the base of spur-and-groove topography of the reef face, they are not extensively mapped but are noted as an important feature of reef topography.

Nearshore Reef

Complex limestone bedrock and coral reef mapping units tend to occur about 0.5 to 1 km offshore in northern and central segments of the continental shelf area, except southward from the navigational entrance to the Port of Miami, where they lie about 5 km offshore. The Nearshore Reef mapping unit separates Structural Sand Flats from Nearshore Sand Flat units. On the northern part of the shelf in Miami-Dade County (Figure 2), nearshore reefs also occur as elongated, shore-parallel hardbottoms surrounded by structural sand flats. The Nearshore Reef mapping unit takes up about 15 km² and accounts for about 30% of hardbottom occurrences (6% of the total shelf mapping area; Table 3).

Sedimentary Features

As the continental shelf area widens south of the entrance to the Port of Miami (Figure 2), topographic expression and the nature of the sedimentary cover contrast with characterizations of shelves in Broward and Palm Beach counties. With a broader shelf area and tidal influences on the shallow flats, the new mapping units include Channel Bar, Nearshore Sand Sheet, Tidal Sand Flat, Tidal Sand Ridge, Tidal Channel, Tidal Channel Bar, and Sand Flat with Sand Ridges (Figure 2). This wide range of sedimentary deposits in the southern Miami-Dade County shelf mapping segment forms spatially complex depositional environments that are described below in terms of mapping units that were interpreted from the LADS imagery.

Diabathic Channels

Shore-normal ridge and valley topography was described in this report as occurring within Nearshore Sand Flat mapping units in Palm Beach County. These features were also detailed by FINKL, BENEDET, and ANDREWS (2006) as having formed by processes associated with high-energy events affecting offshore sand transport from the beach to nearshore sand flats. In contradistinction to the cross-shore (diabathic) channels in Palm Beach County, those in Miami-Dade County occur in offshore sand flats mostly shoreward of reef gaps. Strong tidal current flows cause the channeling effect (ridge and valley topography) on the sand seafloor. This mapping unit makes up about 2 km².

Ebb-Tidal Delta

The single ebb-tidal delta in the Miami-Dade mapping area occurs at Haulover Inlet (Figure 2) and extends between R025 and R028. Sands comprising the shoal cover a small portion of the Structural Sand Flat mapping unit.

Nearshore Sand Flat, Sand Flat with Ridges, and Tidal Sand Flat

The Nearshore Sand Flat mapping unit, which is fragmented in Broward County, becomes displaced alongshore by structural sand flats. These sand flats take up about 30 km² of shelf area and account for about 19% of the sand resource base (FINKL, BENEDET, and ANDREWS, 2007). The unit occurs continuously along the seaward margin of structural sand flats and averages about 1 km in width in northern segments of the shelf but narrows offshore near R050, where it is marginal to offshore sand flats, to about 200 to 300 m wide before termination at the navigational entrance to the Port of Miami (offshore from R074; Figures 2 and 2F). Near R038, the unit occurs alongshore to about R074, where it becomes partially replaced by a distinctive rippled surface topography that reflects strong tidal currents. A series of transverse bars occurs alongshore between R038 and R053 (Figure 2E). Some of the transverse bars range up to 1 km in length, such as at R052. The transition is gradual, and the boundary between the Tidal Sand Flat mapping unit and the nearshore sand flats is diffuse. The unit is further differentiated from the more or less featureless sandy seafloor by distinct sand ridges of about 2 m or more in height and up to 2 km in length. The Sand Flat with Sand Ridges mapping unit has a northern boundary offshore from about R093 (Figure 2F). This unit takes up about 64 km^2 and accounts for about 65% of the sand resource base (25% of the mapping area) in Miami-Dade County. Tidal sand flats take up about 31 km^2 (12% of the mapped shelf area) or about 19% of the sand resource base (FINKL, BENEDET, and ANDREWS, 2007).

Nearshore Sand Sheet

From R075 on Fisher Island southward to R103 on Key Biscayne, there is a nearshore sand sheet that is topographically distinct from the tidal sand flat offshore (Figure 2). The shoreface attached sand sheet is composed of tidal sediments that have been redistributed by alongshore currents. Seafloor topography in this unit is modified by tidal currents flowing through Government Cut (R075), Norris Cut (R085), and Bear Cut (R112). The sand sheet flanks black mangrove forest on Virginia Key and Key Biscayne. The nearshore sand sheet takes up about 5 km^2 or nearly 4% of the sand resource base on the continental shelf mapping area (FINKL, BENEDET, and ANDREWS, 2007).

Offshore Sand Flat

Offshore sand flats occur as sedimentary units confined between the FRT and the Nearshore Reef and Structural Sand Flat mapping units in the northern part of the study area (Figure 2). South of the navigational entrance channel to the Port of Miami, about the latitude of R095, the offshore sand flats merge shoreward with nearshore sand flats and sand flats with tidal sand ridges (Figure 2F). Offshore from Bear Cut, which separates Virginia Key from Key Biscayne (south of R112), offshore sand flats occur on both sides of the FRT. Offshore sand flats take up about 16 km^2 or about 10% of the sand resources area (6% of the total shelf area mapped).

Structural Sand Flat

Structural sand flats exist offshore throughout the Miami-Dade County (Figure 2). In the northern part of the shelf area, the unit occurs alongshore from the Bar and Trough mapping unit to the Nearshore Reef and Nearshore Sand Flat mapping units. Structural sand flats average about 0.5 to 1 km in width from R001 to about the latitude of R035 but are interspersed with nearshore reefs. About the latitude of R035, nearshore sand flats cover the structural sand flat units up to 2 km offshore north of the entrance channel to the Port of Miami (about the latitude of R070). Limestone bedrock units making up the structural sand flat units are buried by sediment (nearshore sand sheets, tidal sand flats, nearshore sand flats, sand flats with tidal ridges) south of the latitude of Fisher Island (R075).

Tidal Channel and Bar

Tidal channels and bars, as well as ebb-tidal shoals, are mapped in Bear Cut and where they cross the Nearshore Sand Sheet mapping unit between R083 and R090 (Figures 2 and 2F). Tidal channels and bars take up about 3 km^2 and account for about 2% of the sand resource base (1% of the mapped area).

Transverse Bars

Sand bars that are oblique to the shoreline occur in the central part of the study area from R038 to R073 (Figures 2 and 2E). The bars, which can range up to 4 km in length, occupy nearly 2 km^2 of shelf area and account for about 1% of the sand resource base (Table 3). The transverse bars occur within the Nearshore Sand Flat mapping unit.

DISCUSSION

Application of airborne laser bathymetry technology to the continental shelf off southeast Florida in the form of LADS imagery permits interpretation of bathymetry as sequences of landforms. The resulting interpretive maps that depict seafloor features present a rational basis for delineating bottom types, particularly hardgrounds (bedrock and corals) and sediments. LADS provides useful imagery for interpretive purposes, and the results can be dramatic and useful, but caveats are associated with training and experience of the interpreter. The present reconnaissance mapping scale (1:800 operational scale for hard copy maps) precludes detailed investigation of many types of features but has the advantage of providing an overview of general relationships between mapping units.

These geospatial relationships combined with collateral data (*e.g.,* vibracore logs, sidescan sonar, and seismic reflection profiles) were used to build a model of the coastal surficial geological framework. The geological model is essentially composed of two overarching types of units: hardgrounds and sediments. Perusal of the LADS geomorphological units in a GIS platform showed that areal distributions of sedimentary bodies are constrained by bedrock (Anastasia Formation and Miami Limestone) and barrier coral reefs, with minor occurrences of patch reefs. Without interpretation of the LADS bathymetry, these relationships could not be established on a regional basis. Prior work identified general bottom types for localized study areas, but there was no integrated interpretation of trends or geospatial variation within and between counties along the southeast Florida coast. The gradation of bottom types from northern Palm Beach County to the general latitude of Biscayne Bay in Miami-Dade County is pronounced and heretofore generally unappreciated. Seafloor geomorphological units in northern Palm Beach County are gradational to reefless shelf areas (drowned coastal plains) that are characterized by rock outcrop and the presence of sand sheets and sand ridges, whereas the southern part of the study area in Miami-Dade County grades to Florida Keys environments. Seafloor in Broward County is transitional to both extremes and best represents the model that is most familiar in the literature: several reef tracts separated by sedimentary corridors. The interpreted LADS maps show that this well-known geological model for Broward County is only partially applicable in modified form to Palm Beach and Miami-Dade counties. The comprehensive geological model developed in this study incorporates intra-county variation in seafloor geomorphological units, as well as gradation in distal northern and southern parts of the study area to different geomorphological regimes.

Differentiation of the seafloor morphological units was initially problematic because spatial distribution patterns were not evident. As the list of morphological units was compiled in advance of actual mapping, following the lead of the FINKL and WARNER (2004) classification of seafloor units on the shelf, detection of landform assemblages, and discretization of topographies into a hierarchical framework evolved as the mapping continued. Eventually, patterns emerged and regionalization of seafloor environments was possible. The process was not without back tracking and some remapping, but the end result was satisfying because the resulting maps made sense and built upon previous work.

The present maps represent, however, an initial attempt that requires further work for clarification and verification of mapping units. Of particular note in this regard is the interpretation of parabathic ridges offshore in northern Palm Beach County as drowned beach ridges. Diver descriptions and sediment samples were used to interpret the coarse-textured ridges as representation of a drowned beach-ridge plain. Structural Sand Flat was another mapping unit that posed problems of interpretation. The unit is complex and variable, depending on the thickness of sand cover that ranges from a few centimeters of sand, which allows rock structure to remain visible in the LADS imagery, to thicker veneers, which obscure the underlying rock. Structural sand flats thus may merge into sand flats or to nearshore reefs, the distinction being made according to the thickness of the sand veneer. The differentiation of nearshore sand flat from offshore sand flat was arbitrary, the boundary occurring with abrupt changes in slope, along diabathic channel fields, or with nearshore reef. The complexity of tidal features south of the navigational entrance to the Port of Miami (seaward of Biscayne Bay, Virginia Key, and Key Biscayne) is simplified in the seafloor mapping units and shown simply as "Tidal Sand Flat" or "Sand Flat with Sand Ridges." More detailed mapping would be required to show the intricate tidal patterns.

The value of mapping seafloor topographic and sedimentological units from airborne laser bathymetry is that it is now possible to differentiate types of shelf environments at myriad scales with different levels of detail. Morphological units can be interpreted from the new digital imagery to produce maps that previously were not possible to interpret at the same level of detail from isobaths, giving such maps an advantage over conventional bathymetric charts.

CONCLUSION

Differentiation of shelf morphology along the southeast Florida Atlantic coast was based on interpretation of airborne laser bathymetry in the form of LADS for a 600-km^2 study area. Identification and mapping of discrete landform assemblages in spatial groupings regionalized shelf environments into four distinct shore parallel reaches. Reach I (sand flats and karst topography) from the Martin County–Palm Beach County line terminates southward at the Bahamas Fracture Zone, a major morphotectonic feature. Reach II (sand flats and coral reefs) is characterized by sand flats with diabathic channel fields leeward or shoreward of the FRT, the seaward margin of which occurs along the shelf break on the upper part of the slope. Reach III (sand flats, hardgrounds, and coral reefs) contains extensive nearshore rock outcrops that are exposed as bare rock surfaces on the seafloor or variously mantled by thin veneers of sand that are not thick enough to disguise the underlying rock structure. Reach IV (tidal sand flats and ridges, hardgrounds, and coral reefs) includes tidal features such as fields of tidal sand ridges in the lee of the FRT. Tidal channels and associated bars, deltas, and shoals occur at the interface between Biscayne Bay and the Atlantic Ocean. Morphological units comprising the four reaches are classified as types of bar and trough, coral reef, hardbottom, sandy bottom features, and tidal features.

Even though this study of shelf morphology was conducted at a reconnaissance scale, it provides a basic window into types of shelf environments and indicates shapes, forms, and materials that coalesce to form alongshore reaches with similar topologies. This differentiation of shelf morphologies provides baseline information for biological, geological, and environmental studies. Delineation of the present range of seafloor landform assemblages (42 mapping units) shows that this narrow shelf environment is more complex than indicated in previous studies that did not have the advantage of LADS imagery. More detailed studies of the FRT should elucidate complexities of this barrier reef system beyond the 12 mapping units identified here. Of particular interest to shore protection, and especially beach renourishment, is the presence of sandy bottom forms that include diabathic channel fields, sand flats, sediment-covered ridges and valleys, and sand waves, as well as tidal features such as ebb-tidal deltas, shoals, and tidal sand flats and ridges. This geomorphological framework provides a basis for estimating sand resource potential on the continental shelf off southeast Florida.

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