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Geoform and Landform Classification of Continental Shelves using Geospatially Integrated IKONOS Satellite Imagery

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ABSTRACT


Geomorphological characterization of coastal environments along continental shelves depends on accurate interpretation of mesoscale lithic and clastic benthic geoforms and landforms. Using the Geospatially Integrated Seafloor Classification Scheme (G-ISCS), cognitive visual interpretations of seafloor geoforms and their associated landforms were conducted along a diverse segment of the southeast (SE) Florida continental shelf. GeoEye IKONOS-2 satellite imagery provided the remotely sensed visual medium on which interpretations were based. With ESRI ArcGIS® ArcMap software, classification maps were created from the cognitive interpretations to show spatial distribution results of geoform and landform features throughout the study area. Additionally, smaller-scale “call-out figures” documented specific geomorphological associations among the classified units. Analysis attribute tables compared and contrasted the abundance (i.e., number of classifying vector polygons) and calculated areas for each geoform and landform classified. It was determined that classification of geoform and landform benthic features along continental shelves can be achieved where water clarity conditions allow for the cognitive visual interpretation of such seafloor formations. Future studies may build upon the classification of continental shelf geoforms and landforms to integrate more transient biogeomorphological features of the marine environment (e.g., sediment distribution, biological species identification, density of flora and fauna present), thus creating a more detailed and inclusive classification of a selected coastal region.

ADDITIONAL INDEX WORDS: Remote sensing, seafloor mapping, submarine geomorphology, benthic interpretation, Florida Reef Tract, IKONOS, Florida Bay, Florida Keys, geographic information systems, ESRI ArcGIS®.

INTRODUCTION

One of the standard components of classifying continental shelf coastal environments is the demarcation of spatially distributed geomorphological signatures along the seafloor, commonly known as geoforms and landforms. The interpretation of these general-to-specific benthic features provides a “structural framework” of the seascape topology by which a hierarchical census of biophysical units can be compiled for a given shelf region (see, for example, Fairbridge, 2004; Finkl, 2004); the ultimate result then allowing for hierarchical classifications to be extrapolated over large coastal areas and applied to corresponding mapping units. This, in return, would potentially elucidate spatial relationships between geoforms and landforms of a given area by showing how exposed lithic structures, unconsolidated clastic materials, and other geomorphological substrates available to sessile biological communities are universally distributed and interconnected. By accurately interpreting geoform and landform-based formations over a select region of continental shelf, the delineation of coastal environments and creation of a comprehensive geospatially referenced classification map can be achieved (e.g., Achatz, Finkl, and Paulus, 2009; Finkl and Banks, 2010; Finkl, Benedet, and Andrews, 2004, 2005a,b; Finkl and Vollmer, 2011; Lidz, Reich, and Shinn, 2003; Lidz et al., 2006; Makowski, 2014; Makowski, Finkl, and Vollmer, 2015, 2016; Steimle and Finkl, 2011).

In the past few decades, multispectral satellite sensor images have been among the most preferred mediums by which visual interpretation of coastal environments are carried out (e.g., Andréfouët et al., 2001, 2003; Bouvet, Ferraris, and Andréfouët, 2003; Dial et al., 2003; Dobson and Dustan, 2000; Finkl, Makowski, and Vollmer, 2014; Finkl and Vollmer, 2011; Hochberg, Andréfouët, and Tyler, 2003; Klemas, 2011; Klemas and Yan, 2014; Makowski and Finkl, 2016; Makowski, Finkl, and Vollmer, 2015, 2016; Manson et al., 2001; Mumb and Edwards, 2002; Palandro et al., 2003; Steimle and Finkl, 2011). Specifically, GeoEye IKONOS-2 satellite images can offer an enhanced view of benthic geomorphological features along those continental shelf regions where optimal water clarity permits it. In conjunction with specialized spatial analysis software applications, such as ESRI’s ArcGIS® 10.3 ArcMap program, IKONOS-2 images provide the visual means to cognitively identify, delineate, and classify seafloor geoforms and landforms along coastal shelf environments.

The objective of this study was to cognitively interpret, classify, and map geoforms and associated landforms along a segment of the southeast (SE) Florida continental shelf (Figure 1) using IKONOS-2 satellite imagery and the Geospatially
Integrated Seafloor Classification Scheme (G-ISCS) method (Makowski, Finkl, and Vollmer, 2015). By doing so, analysis of geomorphological attributes can aid in determining how the “structural framework” over a given shelf area is spatially distributed and interrelated. Overall, the goal is to potentially expand upon the results presented in this paper, as well as other studies (e.g., Makowski, Finkl, and Vollmer, 2016), in an effort to create an inclusive classification of this continental shelf segment by integrating more transient biogeomorphological features of the marine environment (e.g., sediment distribution, biological species identification, density of flora and fauna present) with larger-scale physiographic realms and morphodynamic process zones.

**METHODS**

GeoEye IKONOS-2 (i.e., IKONOS-2) multispectral satellite images were acquired, processed, and visually interpreted using the study methods derived from the Geospatially Integrated Seafloor Classification Scheme (G-ISCS), as developed by Makowski, Finkl, and Vollmer (2015). Specialized processing software (IDRISI® Taiga, Clark Labs, Worcester, Massachusetts, U.S.A.; Environmental Systems Research Institute’s [ESRI] ArcGIS 10.3 ArcMap geographical information system program, Redlands, California, U.S.A.) allowed for appropriate digital enhancement techniques to the IKONOS-2 images, which then provided the required raster-based GIS and image processing modules for cognitive interpretation.

Using the G-ISCS method, each geoform and associated landforms were interpreted in tandem to describe the benthic substrate framework by which surface sediments accumulate upon and biological communities grow (Table 1). For example, in the case of the Coral Reef Geoform, which contains ridge-like structures throughout the Florida Reef Tract (FRT) Physiographic Realm built from living coral, coral skeletons, calcareous algae, mollusks, and protozoans, the corresponding landforms of Barrier Reef, Patch Reef, Aggregated Reef, Coral Apron, and Reef Gap were found (Banks et al., 2007; Cronin et al., 1981; Finkl, 2004; Finkl and Andrews, 2008; Finkl, Benedet, and Andrews, 2005a; Finkl et al., 2008; Hoffmeister, 1974; Jaap, 1984; Lidz, 2004, 2006; Lidz, Hine, and Shinn, 1991; Lidz et al., 1997). Hardbottom Geoforms, conversely, are exposed Pleistocene limestone (e.g., bedrock, boulders, rubble), including reef debris and dredged spoil piles, that are found intermittently in the Atlantic Ocean Morphodynamic Zones, Hawk Channel Physiographic Realm, Biscayne Bay Physiographic Realm, and along the leeward and windward sides of the Florida Keys Physiographic Realm (Chiappone and Sullivan, 1994; Finkl, 2004; Finkl et al., 2008; Lidz et al., 2006). Associated Hardbottom landforms include flat, generally featureless, continuous platforms in the form of Subtidal Pavement and conically shaped Rubble Fields and Dredged Spoil Piles (Buddemeier, Smith, and Kinzie, 1975; Finkl et al., 2008; Lidz et al., 2006; Lirman and Fong, 1997; Selkoe et al., 2009).

When Islands associated with the coral and mud-based Florida Keys Physiographic Realm archipelago are classified as the predominant geoform, the resultant landforms include Bay Key, Karst Island, and Salina (Finkl, 2004; Hoffmeister, 1974; Lidz, Hine, and Shinn, 1991; Lidz et al., 1997, 2004). Sediment Flat Geoforms, which constitute extensive, unconsolidated seafloor sediments composed of sand and mud combinations, are divided among the landforms of Intertidal Sand Flat and Planar Bed Forms and Ripples (Davis, Hine, and Shinn, 1992; Duane and Meisburger, 1969; Finkl, 2004; Finkl and Andrews, 2008; Finkl and Warner, 2005; Finkl, Benedet, and Andrews, 2005b; Finkl et al., 2008; Hoffmeister, 1974; Lidz, Hine, and Shinn, 1991; Lidz, Robbin, and Shinn, 1985). The geoform of Dune and Beach is a geomorphologically coupled coastal system consisting of Holocene dune fields, foredunes, and beach berms. The associated landforms include Bay Beach and Ocean Beach (Finkl, 1993, 2004; Finkl and Restrepo-Coupe, 2007; Finkl, Benedet, and Andrews, 2006; Hoffmeister, 1974; Wright and Short, 1984). Ridge Fields are geoforms where continental shelf sand waves display parallel long-axis alignment on sandy seafloors and contain landforms that are designated as either Discrete Ridges or Complex Ridges (Ashley, 1990; Duane and Meisburger, 1969; Finkl, 2004; Finkl and Andrews, 2008; Finkl, Andrews, and Benedet, 2006; Finkl, Benedet, and Andrews, 2005b; Finkl et al., 2007, 2008; Stapor, 1982). Channel Geoforms are low relief, elongated tidal conduits cut into seafloor bank sediments or karst bedrock. The associated landforms are Neochannel, Paleochannel, and Seafloor Channel (Davis and Fitzgerald, 2004; Finkl, 2004; Finkl et al., 2008; Hoffmeister, 1974; Jaap, 1984; Lidz, 2004, 2006; Lidz et al., 2006; Lirman and Fong, 1997; Selkoe et al., 2009).
Figure 2. Exported view of cognitive delineation results from interpreting enhanced IKONOS-2 satellite imagery. Of the 3888 vector polygons digitally created in the study area (outlined in magenta), note the increase in complexity of benthic features with the westward distance offshore of the Florida Keys and toward the Florida Reef Tract (FRT). Conversely, nearshore rock shelves, sediment flats, and offshore banks display more monotypic patterns of benthic habitats. A nominal scale of 1:230,000 was set for this image export out of ArcMap.
<table>
<thead>
<tr>
<th>Geoform</th>
<th>Landform</th>
<th>Location</th>
<th>Definitions, Descriptions, and References</th>
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<tbody>
<tr>
<td>Coral Reef</td>
<td>The Florida Reef Tract (FRT), a shelf-edge barrier reef system, lies seaward of Hawk Channel and the Atlantic Ocean Littoral Zone</td>
<td>The only living coral barrier reef in the continental United States, the FRT mimics the planform are of the Florida Keys, but the rectilinear section in Biscayne National Park is oriented north–south; these reefs, which occur in a zone that is about 6–7 km wide, are ridge-like structures built from living coral, coral skeletons, calcareous algae, mollusks, and protozoa; arranged in successive layers of limestone and drowned by Quaternary sea-level fluctuations, coral reefs (i.e., barrier, aggregated, patch reefs) of the FRT (also known as the Great Florida Reef, Florida Reefs, and Florida Keys Reef) extend along the 20 m isobath into deeper water (e.g., Banks et al., 2007; Cronin et al., 1981; Finkl, 2004; Lidz, 2004, 2006; Lidz, Hine, and Shinn, 1991; Lidz et al., 1997)</td>
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<td>Barrier Reef</td>
<td>Lies parallel to the mainland and the Florida Keys, following the shelf edge above the continental slope and separated from land by Biscayne Bay, Card Sound, Hawk Channel, and the Atlantic Ocean Littoral Zone</td>
<td>A series of barrier reef segments lying offshore, separated by reef gaps, that parallel the shelf edge and mimic the general configuration of mainland and keys; also known as continental shelf or platform reefs, these barrier reefs are strongly asymmetric in cross-section, being steep-to on seaward margins and gently sloping shoreward to a sediment wedge in Hawk Channel; shoreward margins of the FRT are decorated by coral heads, patch reefs, coral aprons, and aggregate bank reefs (e.g., Banks et al., 2007; Finkl, 2004; Hoffmeister, 1974; Jaap, 1984; Lidz, 2006; Lidz, Hine, and Shinn, 1991; Lidz et al., 1991, 1997; Shinn, 1963)</td>
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<tr>
<td>Patch Reef</td>
<td>Isolated reef patches scattered in backreef, intra-reefal, inner reef, and outer reef zones</td>
<td>Isolated patches or equant platforms scattered throughout the FRT; patch reefs, commonly found in sheltered environments that are unattached to other major reef structures, are typically surrounded by sand or seagrass halos; they occur in open ocean and high-energy reef gap areas, as well as sheltered backreef zones and range in size from a few square meters to larger reef forms (e.g., Banks et al., 2007; Finkl, 2004; Jaap, 1984; Lidz, 2006; Lidz, Hine, and Shinn, 1991; Lind et al., 1991, 1997; Shinn, 1963)</td>
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<tr>
<td>Aggregated Reef</td>
<td>Occupies the backreef zone between the seaward margins of Hawk Channel and the intra-reefal sediment flats</td>
<td>Isolated groups of coalesced patch reefs, occurring in variable shapes without major sand channels (e.g., Banks et al., 2007; Finkl, 2004; Jaap, 1984; Lidz, 2006; Lidz, Hine, and Shinn, 1991; Lidz et al., 1991, 1997; Mummy and Harborne, 1999; Shinn, 1963)</td>
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<td>Coral Apron</td>
<td>Deltoideal shaped accumulations of coral scree and finer-grained carbonate sediments along the lee side of aggregated and barrier reefs</td>
<td>Overwash storm deposits containing fine-grain comminuted carbonates and larger coral fragments derived from storm waves and surge; apron materials migrate down the leeward side of aggregated and barrier reefs and accumulate in backreef troughs adjacent to intra-reefal sediment flats (e.g., Finkl, 2004; Finkl and Andrews, 2008; Finkl, Benedet, and Andrews, 2005b; Finkl et al., 2008)</td>
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<td>Reef Gap</td>
<td>Perpendicular to shore-parallel and shelf-parallel barrier reefs separating them into tracts or segments</td>
<td>Sedimentary spillways composed of erosional relicts of paleo-inlets or river channels cut into the underlying substrate; reef gaps, which segment barrier reefs into tracts, form variable-width corridors that link the open ocean with lagoonal waters of Hawk Channel and Biscayne Bay (e.g., Banks et al., 2007; Finkl, 2004; Finkl and Andrews, 2008; Finkl, Benedet, and Andrews, 2005b)</td>
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<td>Hardbottom</td>
<td>Isolated outcrops of limestone bedrock, debris fields, and dredge spoil dispersed intermittently throughout the Atlantic Ocean zones, Hawk Channel, Biscayne Bay, and along the leeward and windward sides of the Florida Keys</td>
<td>Exposed Pleistocene limestone (e.g., bedrock, boulders, rubble) including reef debris and dredged spoil piles; these features have low relief with smooth or rough surfaces and typically carry a thin veneer (a few centimeters) of surface sediment with macroalgae (e.g., Chiappe and Sullivan, 1994; Finkl, 2004; Finkl et al., 2008; Lidz et al., 2006)</td>
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<td>Geoform</td>
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<td>Subtidal Pavement</td>
<td>On the continental shelf, shoreward of the FRT in the Atlantic Ocean zones, extensively in the northern parts of Hawk Channel, and along the flanks of the Florida Keys</td>
<td>Flat, generally featureless continuous hardbottom that is typically partially mantled with a thin sand veneer and macroalgae that partially obscure the nature of the underlying surface; pavements may occur as isolated rock outcrops offshore or as nearshore platforms along the landward and seaward margins of the Florida Keys (e.g., Buddemeier, Smith, and Kinzie, 1975; Lidz et al., 2006; Selkoe et al., 2009)</td>
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<td>Rubble Fields and Dredged</td>
<td>Deposits in the Atlantic Ocean Littoral Zone, offshore of Fisher Island, and in northern Biscayne Bay</td>
<td>Conically shaped rubble fields and dredged spoil piles derived from the dredging of Biscayne Bay, Port of Miami, and Bear Cut; spoil piles occur in designated depositional zones and provide substrates for macroalgae (e.g., Finkl et al., 2008; Lirman and Peng, 1997)</td>
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<td>Island</td>
<td>Coral and mud-based Florida Key archipelago that separates Biscayne Bay from Hawk Channel</td>
<td>Land that is completely surrounded by water and identified as Florida Keys (limestone-cored karst keys, with mangroves, marshes, and salinas) and muddy-sandy islands (Bay Keys) (e.g., Finkl, 2004; Hoffmeister, 1974; Lidz, Hine, and Shinn, 1991; Lidz et al., 1997; Nunn, 1994)</td>
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<td>Bay Key</td>
<td>Small, compacted mud islands between karst islands or as solitary subaerial landforms (exposed banks) in Biscayne Bay</td>
<td>A low-lying, compacted mud island (emerged bank) in the Florida Keys archipelago or as isolated structural banks in Biscayne Bay and Card Sound; developed from coarser sediment accumulations transported above mean high tide during storms, bay keys contain organic-rich muddy surficial materials stabilized by mangroves (e.g., Enos, 1989; Halley, Vacher, and Shinn, 1997; Swart and Kramer, 1997)</td>
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<td>Karst Island</td>
<td>Limestone-cored keys that separate Biscayne Bay and Card Sound from Hawk Channel</td>
<td>Islands in the Florida Keys composed of oolitic grainstone (i.e. Miami Limestone), fossil coral reef rock (i.e. Key Large Limestone), and coquina shell bedrock (i.e. Anastasia Formation); karst islands are typically colonized by mangroves and wetlands but may have areas of exposed bedrock in higher elevations with little vegetative cover (e.g., Finkl, 2004; Halley, Vacher, and Shinn, 1997; Hine, 2013; Hoffmeister, 1974; Lidz, Reich, and Shinn, 2003; Multer et al., 2002; Wanless et al., 1988)</td>
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<td>Salina</td>
<td>Low-lying depressions in karst islands or bay keys</td>
<td>Enclosed or semi-enclosed depressions in karst islands with no major source of fresh groundwater or surficial freshwater input so that evaporation exceeds rainfall, allowing for brines and other evaporites to form; these shallow, inland depressions are filled with saltwater directly from the sea or from salty groundwater (e.g., Hoffmeister, 1974; Wanless et al., 1988; Wanless et al., 1989)</td>
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<td>Sediment Flat</td>
<td>Unconsolidated seafloor extensively found throughout Biscayne Bay, Card Sound, Hawk Channel, the Atlantic Ocean Littoral Zone, and in intra-reefal pockets of the FRT</td>
<td>Extensive, unconsolidated seafloor sediments composed of sand and mud that are usually submerged, except on intertidal sand flats; sediments that are subject to transport from waves and currents occur in variable thickness over karstified bedrock; sediment flat landforms are characterized by planar bed forms, ripples, and intertidal sand flats (e.g., Banks et al., 2007; Davis, Hine, and Shinn, 1992; Duane and Meisburger, 1969; Finkl, 2004; Finkl and Andrews, 2008; Finkl, Benedet, and Andrews, 2005b; Finkl and Warner, 2005; Finkl et al., 2008; Hoffmeister, 1974; Lidz, Bobbin, and Shinn, 1985; Lidz, Hine, and Shinn, 1991)</td>
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<td>Intertidal Sand Flat</td>
<td>Periodically exposed sediment flats found in Biscayne Bay</td>
<td>Intertidal flats associated with structural banks in Biscayne Bay; these flats may have bare surfaces or be colonized with seagrass or macroalgae (e.g., Davis, Hine, and Shinn, 1992; Duane and Meisburger, 1969; Finkl, 2004; Finkl and Andrews, 2008; Finkl, Benedet, and Andrews, 2005b)</td>
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<td>Planar Bed Forms and Ripples</td>
<td>Flat, smooth, or rippled sand and mud sheets occurring in Biscayne Bay, Card Sound, Hawk Channel, the Atlantic Ocean Littoral Zone, and in intra-reefal pockets of the FRT</td>
<td>Carbonatic and silici-clastic seafloor sedimentary deposits ranging in grain size from sand to mud, with admixtures of organic matter; these sediment flats may be uncolonized or colonized with seagrass meadows; although seafloor surface sediments are typically featureless, sediment thickness varies with the irregular karstified bedrock topography (e.g., Davis, Hine, and Shinn, 1992; Duane and Meisburger, 1969; Finkl, 2004; Finkl and Andrews, 2008; Finkl and Warner, 2005; Hoffmeister, 1974; Lidz, Robbin, and Shinn, 1985; Lidz, Hine, and Shinn, 1991)</td>
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<td>Dune and Beach</td>
<td>Coupled dune and beach system fronting Hawk Channel, the bay sides of Fisher Island, Virginia Key, and Key Biscayne, and the oceanic side of the SE Florida Coastal Zone north of Bear Cut</td>
<td>A geomorphologically coupled system containing Holocene dune fields, foredunes, and beach berms; salt-tolerant trees, shrubs, grasses, and other vegetation characterize dune and back-beach geoforms; soils are thin, weakly developed, coarse to fine textured, and excessively drained carbonate sands; ocean beaches are frequently reworked by wind and waves, while bay beaches are relatively undisturbed and contain a higher silt content (e.g., Finkl, 1993, 2004; Finkl and Restrepo-Coupe, 2007; Finkl, Benedet, and Andrews, 2006; Hoffmeister, 1974; Wright and Short, 1984)</td>
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<td>Bay Beach</td>
<td>Low energy beach systems along the bay side of Fisher Island, Virginia Key, and Key Biscayne</td>
<td>Carbonate beach sediments ramped up along the bay side of Fisher Island, Virginia Key, and Key Biscayne; low energy conditions, alongshore rocky substrates, and low-elevation karst headlands help protect these beaches; dune development is incipient or absent (e.g., Finkl, 2004; da Fontoura Klein, Benedet, and Schumacher, 2002)</td>
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<td>Ocean Beach</td>
<td>High-energy dune and beach system along the ocean side of Fisher Island, Virginia Key, Key Biscayne, and the SE Florida Coastal Zone north of Bear Cut</td>
<td>Natural and renourished ocean beaches, which front the northern sections of Hawk Channel and the shore north of Bear Cut, contain incipient foredunes behind beach berms that help protect the backshore from storm surge and overwash; the dune-beach configuration dissipates wave energy (e.g., Finkl, 2004; Finkl and Andrews, 2008; Ginsburg and James, 1974; Hine, 2013; Hoffmeister, 1974; Short, 1999; Wright and Short, 1984)</td>
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<td>Ridge Field</td>
<td>Offshore linear sand ridges (waves) occurring in Hawk Channel and the Atlantic Ocean Littoral Zone, between the Florida Keys and the FRT, in SW Biscayne Bay, and within the SE portion of the FRT</td>
<td>Shelf sand ridges (waves) show parallel long-axis alignment on sandy seafloors in Hawk Channel; these ridges are characteristic of tide- and storm-dominated shelves where there is sufficient sediment supply to accumulate in mounds several meters thick; the ridges are oriented in distinct patterns: NW by SE, NE by SW, and N-NW by S-SE; the dune fields rest on sand flats lying over limestone bedrock; these sand ridges are confined to the Hawk Channel morphodynamic zone, where tidal and storm currents produce the different ridge field orientations; seagrass meadows may occur in the swales between sand ridges (e.g., Ashley, 1990; Duane and Meisburger, 1969; Finkl, 2004; Finkl and Andrews, 2008; Finkl, Andrews, and Benedet, 2006; Finkl, Benedet, and Andrews, 2005b; Finkl et al., 2007, 2008; Stapor, 1982)</td>
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<td>Discrete Ridges</td>
<td>Isolated, single sand ridges orientated in the same direction within the field in Biscayne Bay, Hawk Channel, and the FRT</td>
<td>Outliers of the complex ridge field where individual ridges are isolated on the seafloor in Hawk Channel and the FRT; discrete ridges modified by tidal currents also occur in Biscayne Bay and in reef gaps of the FRT (e.g., Ashley, 1990; Finkl, 1999; Finkl and Andrews, 2008; Finkl, Andrews, and Benedet, 2006; Finkl et al., 2007, 2008; Stapor, 1982)</td>
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<td>Complex Ridges</td>
<td>Field of crisscrossing sand ridges in Hawk Channel and the Atlantic Ocean Littoral Zone</td>
<td>An area where multiple subparallel ridges are formed along more than one axis to create a complex crisscross pattern of ridge and swale topography on the seafloor (e.g., Ashley, 1990; Finkl, 2004; Finkl and Andrews, 2008; Finkl, Andrews, and Benedet, 2006; Finkl et al., 2007, 2008; Stapor, 1982)</td>
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Table 1. Continued.

Geoform | Landform | Location | Definitions, Descriptions, and References
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Channel | Intra-key conduits connecting Biscayne Bay, Card Sound, and Hawk Channel; are modern-day tidal channels that are cut into sedimentary band deposits; these subtidal channels facilitate tidal flows between Biscayne Bay, Card Sound, and Hawk Channel (e.g., Banks et al., 2007; Davis and Fitzgerald, 2004; Finkl et al., 2008; Hoffmeister, 1974; Lidz, 2006; Lidz et al., 1997, 2006)

--- | Neochannel | Tidal sand channels in the Safety Valve and on sedimentary banks south of Key Biscayne, and transitional between Biscayne Bay, Card Sound, and Hawk Channel

--- | Paleochannel | Bedrock channels separating the Florida Keys

--- | Seafloor Channel | Tidal channels cut within the banks of Biscayne Bay

--- | Delta | A triangular tract of sediment deposited at the terminus of tidal paleochannels that contain ebb- and flood-tidal deltas (e.g., Banks et al., 2007; Davis, Hine, and Shinn, 1992; Finkl et al., 2008; Hoffmeister, 1974; Lidz, 2006; Lidz et al., 1997, 2006)

--- | Ebb-Tidal Delta | Deltaic formations in transitional paleochannels on seaward terminus in Hawk Channel

--- | Flood-Tidal Delta | Deltaic formations in transitional paleochannels on seaward terminus in Hawk Channel

--- | Delta Transition | A depositional geoform produced from the shoaling sedimentation at the seaward terminus of tidal paleochannels that are transitional between Biscayne Bay, Card Sound, and Hawk Channel (e.g., Banks et al., 2007; Davis and Fitzgerald, 2004; Davis, Hine, and Shinn, 1992; Finkl and Andrews, 2008; Finkl, Benedet, and Andrews, 2005b; Finkl et al., 2008; Hoffmeister, 1974; Lidz, 2006; Lidz et al., 1997, 2006)

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Table 1. Continued.

Geoform Landform Location Definitions, Descriptions, and References

Flat, low-lying point of land that includes the salient and central extensions of Southeast Distal Florida and the Southeast Florida Coastal Zone adjacent to Biscayne Bay and Card Sound; this geoform is dominated by anthropogenic modified uplands and overwash shoreline landform, except for areas of the coastal mangrove marshes and the Florida Everglades. Geomorphology of the Southeast Distal Florida Physiographic Realm includes the low-lying marshlands of the Everglades within the Southeast Florida Coastal Zone and the Florida Everglades (Shinn, 1991; Schwartz, 2005). The final geoform identified was categorized as the Peninsula and Coastal Plain, which includes the low-lying marshlands of the Everglades within the Southeast Distal Florida Physiographic Realm and such morphodynamic zones as Tree Island Biohydrologic Systems, Marsh Prairie Regimes, Mangrove Forest Biomes, and Everglades Swampland Systems (Makowski, Finkl, and Vollmer, 2016). Landforms include Intertidal Mud Flat, Supratidal Mud Flat, and Anthropogenic Modified Coastal Plain (Finkl, 1994; Finkl and Makowski, 2013; Finkl and Restrepo-Coupe, 2007; Finkl et al., 2008; Hoffmeister, 1974; White, 1970; Wolanski, 2007). 

Table 2. Quantity of cognitively classified vector polygons (n) and calculated areas (km²) for nine selected landforms interpreted from the IKONOS-2 satellite imagery. Each individual percentage from the total is listed in brackets below.

<table>
<thead>
<tr>
<th>Geoform</th>
<th>Quantity of Vector Polygons, n [%]</th>
<th>Calculated Area, km² [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coral Reef</td>
<td>2824 [72.6]</td>
<td>119.7 [8.5]</td>
</tr>
<tr>
<td>Hardbottom</td>
<td>63 [1.6]</td>
<td>32.7 [2.3]</td>
</tr>
<tr>
<td>Island</td>
<td>135 [3.5]</td>
<td>44.5 [3.1]</td>
</tr>
<tr>
<td>Sediment Flat</td>
<td>474 [12.3]</td>
<td>692.2 [49.2]</td>
</tr>
<tr>
<td>Dune and Beach</td>
<td>7 [0.2]</td>
<td>1.4 [0.1]</td>
</tr>
<tr>
<td>Ridge Field</td>
<td>20 [0.5]</td>
<td>57.8 [4.1]</td>
</tr>
<tr>
<td>Channel</td>
<td>63 [1.6]</td>
<td>44.4 [3.2]</td>
</tr>
<tr>
<td>Delta</td>
<td>5 [0.1]</td>
<td>12.6 [0.9]</td>
</tr>
<tr>
<td>Peninsula and Coastal Plain</td>
<td>297 [7.6]</td>
<td>402.1 [28.6]</td>
</tr>
<tr>
<td>Total</td>
<td>3888 [100]</td>
<td>1407.4 [100]</td>
</tr>
</tbody>
</table>

and Andrews, 2008; Finkl, Benedet, and Andrews, 2005b; Finkl et al., 2008; Hoffmeister, 1974; Lidz, 2006; Lidz, Hine, and Shinn, 1991; Lidz, Robbin, and Shinn, 1985; Lidz et al., 1997, 2006). Deltas are depositional geofoms produced from the shoaling sedimentation of paleochannel tidal passes. Representative landforms include Ebb-Tidal Deltas and Flood-Tidal Deltas (Davis and Fitzgerald, 2004; Davis, Hine, and Shinn, 1992; Finkl and Andrews, 2008; Finkl, Benedet, and Andrews, 2005b; Finkl et al., 2008; Lidz, Hine, and Shinn, 1991; Schwartz, 2005). The final geoform identified was categorized as the Peninsula and Coastal Plain, which includes the low-lying marshlands of the Everglades within the Southeast Distal Florida Physiographic Realm and such morphodynamic zones as Tree Island Biohydrologic Systems, Marsh Prairie Regimes, Mangrove Forest Biomes, and Everglades Swampland Systems (Makowski, Finkl, and Vollmer, 2016). Landforms include Intertidal Mud Flat, Supratidal Mud Flat, and Anthropogenic Modified Coastal Plain (Finkl, 1994; Finkl and Makowski, 2013; Finkl and Restrepo-Coupe, 2007; Finkl et al., 2008; Gorsline, 1963; Hoffmeister, 1974; White, 1970). Locations, definitions, and descriptions of all interpreted geofoms and associated landforms along the continental shelf study area are provided in Table 1.

For the purposes of onscreen cognitive interpretation of geofoms and landforms, enhanced IKONOS-2 satellite images were imported into ESRI’s ArcGIS 10.3 ArcMap program and displayed on a 1.2 m interactive SmartBoard³.
overlay system. This allowed for the real-time, onscreen digitization of geoform and landform features based on varying color tones, saturations, textures, and relative spectral reflectance signatures. Closed vector polygons were drawn around areas of similar visual composition, thereby cognitively delineating the boundaries of specific geoforms and landforms as defined in Table 1. A nominal scale of 1:6000 was selected when cognitively digitizing boundaries.

Figure 3. Geographic representation of geoforms from the interpreted IKONOS-2 satellite imagery (viz. Figure 2). The legend identifies nine (9) geoforms classified from the imagery and are color coded to show the spatial relationships among them. The broader-scale geoforms allow for a more detailed delineation with associated landforms (viz. Figure 4). A nominal scale of 1:230,000 was set for this image export out of ArcMap.
as no minimum mapping unit (MMU) was designated for this study. Individual geoform and landform thematic-layered maps, along with associated legends, were created, with vector polygons being assigned a specific classifying color that corresponded to the appropriate cognitive interpretation mapping unit.

Attribute tables of all interpreted geoforms and landforms were compiled for the purpose of analysis and directly

Figure 4. Geographic distribution of landforms as interpreted from IKONOS-2 satellite imagery, subdividing the larger-scale geoforms (viz. Figure 3). The legend provides a color distinction for each classified landform interpreted from the imagery (viz. Figure 2) and allows for visual understanding of spatial parameters, as related to the 24 landforms identified. This image export was set at a 1:230,000 nominal scale within the layout view feature of ArcMap.
corresponded to the cognitively digitized polygons. By doing so, a multitude of spatially queried information, including the areal extents of each classified geoform and landform, could be stored for further investigation and analysis.

**RESULTS**

Application of the previously described methods resulted in a classification of possible geoforms and landforms occurring along the SE Florida continental shelf. In addition to providing full-extent area maps showing the distribution of cognitively interpreted geoforms and landforms, those classifying units that recorded the highest and lowest number of vector polygons, as well as the greatest and smallest calculated areas, are reported. Furthermore, smaller-scale call-out figures are shown to provide side-by-side results of IKONOS-2 image interpretation by comparing annotated images with those containing superimposed color coded classifying units.

An amalgamation of 14 GeoEye IKONOS-2 satellite scenes resulted in a platform of high-resolution, multispectral images for the purposes of classifying 1407.4 km² of the study area. A total of 3888 cognitive vector delineations were interpreted from the IKONOS-2 imagery (Figure 2). The boundaries of nine (9) geoforms and 24 associated landforms, with corresponding legends, are shown with color-assigned visual representations exported from ArcMap (Figures 3 and 4).

Among all the classifying units, the Coral Reef Geoform and associated Patch Reef Landform recorded the highest number of cognitively delineated vector polygons, with 2823 and 2705, respectively. The lowest number of vector polygons were tallied by Delta Geoforms (n = 5) and the Ebb-Tidal Delta Landform (n = 2). Additionally, the Sediment Flat Geoform and associated Planar Bed Forms and Ripples Landform recorded the greatest total areas, with 692.3 km² and 681.5 km², respectively, while the Dune and Beach Geoform (1.4 km²) and associated Bay...
Figure 6. Example of the Hardbottom Geoform in relation to the Port of Miami. The IKONOS-2 satellite image in the left panel shows the benthic signature differences between the Subtidal Pavement Landform versus the Rubble Fields and Dredged Spoil Piles Landform, while the right panel overlays color-coded classification units to visually demonstrate the interpreted features. In addition to the colors and units provided in the legend, yellow areas in the right panel represent the Planar Bed Forms and Ripples Landform, which is a subclassification unit of the Sediment Flat Geoform, and tan areas represent the Anthropogenic Modified Coastal Plain Landform associated with the Port of Miami. Both panels were exported out of ArcMap at a nominal scale of 1:8000 within the layout view feature.

Figure 7. Detailed example showing visual spectral characteristics of the IKONOS-2 imagery (left panel) when identifying the Island Geoform and the associated landform examples of Bay Key, Karst Island, and Salina in relation to Biscayne Bay. The right panel overlays landform classification units assigned by color to visually demonstrate spatial distribution of interpreted features. In addition to the colors and units provided in the legend, yellow areas in the right panel represent the Planar Bed Forms and Ripples Landform, which is a subclassification unit of the Sediment Flat Geoform; orange areas represent Paleochannel Landforms; and teal areas represent Flood-Tidal Delta Landforms. The sharp contrast in the top left-hand corner of the left panel is indicative of merging two separate IKONOS-2 satellite images from the same sampling area. Both panels were exported out of ArcMap in the layout view feature at a nominal scale of 1:8000.
Figure 8. Zoomed in example of an IKONOS-2 satellite image (left panel) and the superimposed classifying units (right panel) that represent the breakdown of the Sediment Flat Geoform into two (2) associated landforms: Intertidal Sand Flat and Planar Bed Forms and Ripples. The Intertidal Sand Flat Landform occasionally breaches the water's surface in relation to the tides, whereas the Planar Bed Forms and Ripples Landform constitutes the majority of the surrounding benthos. A nominal scale of 1:9000 was used for both panels exported out of ArcMap.

Figure 9. Detailed example of two (2) landforms associated within the Dune and Beach Geoform in relation to Biscayne Bay and Hawk Channel. Spectral reflectance patterns in the left panel (IKONOS-2 image) show the terrestrial and supratidal signatures of both the Bay Beach Landform and Ocean Beach Landform. The right panel contains color coded mapping units from the landform legend (viz. Figure 4) that are an interpretation of the left panel, where classifications are placed on top of the satellite imagery for visual comparison and analysis. In addition to the colors and units provided in the legend above, yellow areas in the right panel represent the Planar Bed Forms and Ripples Landform, which is a subclassification unit of the Sediment Flat Geoform; orange areas represent Paleochannel Landforms; dark purple areas represent Karst Island Landforms; light purple areas represent Intertidal Sand Flat Landforms; dark blue areas represent Subtidal Pavement Landforms; light green areas represent Rubble Fields and Dredged Spoil Pile Landforms; and tan areas represent the Anthropogenic Modified Coastal Plain Landform. Both panels were exported out of ArcMap at a nominal scale of 1:20,000 within the layout view feature.
Beach Landform (0.1 km²) recorded the smallest total areas. Figures 5 through 14 illustrate specific small-scale results when applying geoform and landform classifying units to the raw, uninterpreted IKONOS-2 satellite imagery.

**ANALYSIS**

Analysis of interpreted geoforms along the SE Florida continental shelf showed that the Coral Reef Geoform was among the most optimal for cognitive recognition in the IKONOS-2 imagery. When compared with other geoforms identified, Coral Reef recorded the greatest quantity of vector polygons, with over 72% of the overall total, but only constituted less than 10% of the total study area (Table 2). This was possible because of specific recognition of color, tone, texture, pattern, and spectral reflectance from the Coral Reef Geoform benthic signatures allowing for a more precise delineation without grossly overestimating the size of such features along the seafloor.

Further examination of the landforms associated with the Coral Reef Geoform shows that geomorphological recognition of Patch Reef was the most optimal. With nearly 70% of all the vector polygons drawn in the study area and less than 2% of the total area classified (Table 3), Patch Reef Landform interpretation can be considered precise due to specific tone, hue, and spectral reflectance differences when the sunlight hits the sand or seagrass halos that usually surround these isolated reef patches. The IKONOS-2 imagery provides the visual means to discern these differences when interpreting the various landforms associated with geoforms such as Coral Reefs (Figure 15).

When analyzing the Hardbottom Geoform, a greater recognition of structural textures and color saturations was shown for Subtidal Pavement Landforms. This is because distinct
Figure 11. Detailed example of Channel Geoform interpretations using IKONOS-2 satellite imagery. The left panel shows the identification of associated landforms, which include Neochannel and Paleochannel, while the right panel overlays mapping units of specific color (viz. Figure 4) on top of the satellite imagery to visually demonstrate spatial dynamics. In addition to the colors and units provided in the legend above, yellow areas in the right panel represent the Planar Bed Forms and Ripples Landform, which is a subclassification unit of the Sediment Flat Geoform; dark purple areas represent Karst Island Landforms; and dark blue areas represent Subtidal Pavement Landforms. A nominal scale of 1:16,000 was used for both panels when exported out of ArcMap.

Figure 12. Detailed example of a Channel Geoform (as interpreted by the Seafloor Channel Landform) in relation to the Sediment Flat Geoform (as interpreted by the Planar Bed Forms and Ripples Landform) in Biscayne Bay. The left panel shows the high-resolution IKONOS-2 satellite image by which the color coded classification units were overlaid (right panel). The sharp contrast along the top portion of the left panel is indicative of merging two separate IKONOS-2 satellite images from the same sampling area. Both panels were exported out of ArcMap at a nominal scale of 1:20,000 within the layout view feature.
tones and spectral reflectance of the rigid exposed Pleistocene limestone outcrops allowed for a higher level of textural contrast and color saturation characteristics to be identified in the IKONOS-2 imagery and demarcated along the seafloor. Similarly, Bay Key and Karst Island Landforms, both associated with the Island Geoform, showed individual recognition from one another during cognitive interpretation. Specific visual cues in the IKONOS-2 imagery allowed for identification of small, compact mud islands (i.e. Bay Key) versus those main islands formed from oolitic grainstone, fossil coral reef rock, and coquina shell bedrock (i.e. Karst Island). However, analysis of landforms associated with the Sediment Flat Geoform showed that Planar Bed Forms and Ripples were grossly recognizable within the IKONOS-2 imagery mainly because of the general tone and spectral reflectance of the unconsolidated materials. This then provided a basis for large-scale differentiation of seafloor sedimentary deposits versus rigid, hard structures, such as reef or hardbottom. Further analysis of unconsolidated materials in the IKONOS-2 imagery allowed for the detection of shelf sand waves, also known as Ridge Field Geoforms, and the discernment between those landforms oriented in the same direction (i.e. Discrete Ridges) and those forming a crisscrossing pattern of ridge and swale topography along the seafloor (i.e. Complex Ridges). This is because the spectral reflectance of light and the contrasting pattern of shadows along the benthic plane allow for interpretation of Discrete Ridges, which are aligned along one axis, versus Complex Ridges, which form along more than one axis to create a compound field of ridges (Figure 16).

DISCUSSION

Using GeoEye IKONOS-2 satellite imagery and the Geospatially Integrated Seafloor Classification Scheme (G-ISCS) method, cognitive interpretation of continental shelf geoforms and associated landforms was conducted over a coastal segment off SE Florida. Classification of benthic components
along continental shelves is predicated upon the interpretation of these standard geomorphological structural frameworks known as geoforms and landforms. The identification of such spatially distributed biophysical features potentially allows coastal researchers and resource managers to bridge the classification of larger-scale physiographic realms and morphodynamic process zones (Makowski, Finkl, and Vollmer, 2016) with more temporally influenced characteristics, such as unconsolidated sediment accumulations (e.g., sand, mud), sessile biological assemblages (e.g., scleractinian coral growth), and flora proliferations (e.g., seagrass and macroalgal cover). Hierarchical approaches to continental shelf classification prove to be most effective in locations where optimal water clarity is present, for example, along the coast of SE Florida. In addition to exhibiting favorable visual properties of the water column, the continental shelf off SE Florida contains a diverse mix of coastal environments (e.g., highly urbanized Miami, Florida; Florida Keys National Marine Sanctuary (FKNMS); Everglades National Park; Biscayne Bay Aquatic Preserve; Biscayne Bay National Park; John Pennekamp Coral Reef State Park) in which numerous geoforms and landforms could be identified and delineated along the seafloor.

Previous studies have attempted to interpret and classify benthic geoform and landform attributes in marine environments using various remotely sensed platforms (e.g., Ansari et al., 2014; Costello, 2009; Finkl and Andrews, 2008; Finkl, Benedet, and Andrews, 2005a,b; Finkl and DaPrato, 1993; Finkl and Vollmer, 2011; Finkl and Warner, 2005; Greene et al., 1999; Heap and Harris, 2008; Kouchi and Yamazaki, 2007; Lidz et al., 2006; Madden et al., 2008; Steimle and Finkl, 2011; Valentine, Cochrane, and Scanlon, 2003; Wedding and Friedlander, 2008). For example, Finkl and Andrews (2008) and Finkl, Benedet, and Andrews (2005a,b) interpreted discrete geomorphological features within a 600 km² area of continental shelf off SE Florida using laser airborne depth sounder (LADS) imagery. They were able to successfully show geospatial relationships that included barrier coral reefs, nearshore bedrock, and
morphosedimentary features by visually mapping the airborne laser bathymetry images as continuous sequences of geoform and landform signatures. By doing so, the geomorphological features of a continental shelf region were interpreted and classified in a way never before attempted with LADS imagery. Other investigations involving the assessment of coastal marine environments have exclusively used IKONOS satellite imagery as the visual basis for their results (e.g., Andréouët et al., 2003; Dial et al., 2003; Finkl, Makowski, and Vollmer, 2014; Finkl and Vollmer, 2011; Hochberg,
Andréfouët, and Tyler, 2003; Klemas, 2011; Maeder et al., 2002; Makowski, 2014; Makowski, Finkl, and Vollmer, 2015, 2016; Mumby and Edwards, 2002; Palandro et al., 2003; Steimle and Finkl, 2011). Andréfouët et al. (2003) and Mumby and Edwards (2002) were among the first to examine the benefits of applying IKONOS satellite imagery for mapping shallow-water nearshore environments and concluded that such imagery could be used to accurately map at geomorphological spatial scales where coral, algal, and seagrass habitats exist. These findings helped to justify the use of IKONOS satellite imagery as a means to properly interpret and classify geomorphological features in marine environments. Finkl and Vollmer (2011) were able to apply that principle by incorporating multiple IKONOS satellite imagery scenes of the southern Key West National Wildlife Refuge in Florida, U.S.A., to identify over 90 mapping units that were defined in terms of geomorphologic base, geoform and landform zones (e.g., reef flats, forereef, patch reef, lagoon), biological communities (e.g., seagrass beds, macroalgae coverage, coral overgrowth), and the percentage of biological cover. Similarly, Maeder et al. (2002) used the blue, green, and red spectral bands from IKONOS images in one fixed location off of Roatan Island, Honduras, Central America, to map the biophysical features of a nearshore coral reef. Both of these studies proved that the texture, pattern, and structure of typical marine environments found in clear waters could be interpreted and mapped using high-resolution IKONOS imagery. Furthermore, IKONOS-2 satellite imagery has been considered among the most effective visual mediums when delineating the benthic seascape into major geoforms and smaller, individual landform units.
forms can be accomplished along the SE Florida continental shelf using GeoEye IKONOS-2 satellite imagery. Through geomorphological attribute analysis, the spatial distribution, quantity of occurrence, and approximate area of each interpreted geoform and landform feature was determined. Using the Geospatially Integrated Seafloor Classification Scheme (GISCS) method in tandem with IKONOS-2 imagery and ESRI ArcGIS ArcMap software, classification maps helped conclude where the distribution of specific geoform and landform biogeomorphological signatures occurred along the seafloor throughout the continental shelf region.

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LITERATURE CITED


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