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Source: Journal of Coastal Research, 33(1) : 1-22

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/JCOASTRES-D-16A-00003.1

Journal of Coastal Research	33	1	1–22	Coconut Creek, Florida	January 2017

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

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ABSTRACT

Makowski, C.; Finkl, C.W., and Vollmer, H.M., 2017. Geoform and landform classification of continental shelves using geospatially integrated IKONOS satellite imagery. *Journal of Coastal Research,* 33(1), 1–22. Coconut Creek (Florida), ISSN 0749-0208.

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 senor 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; Mumby 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

DOI: 10.2112/JCOASTRES-D-16A-00003.1 received 29 January 2016; accepted in revision 21 February 2016; corrected proofs received 22 July 2016; published pre-print online 1 September 2016.
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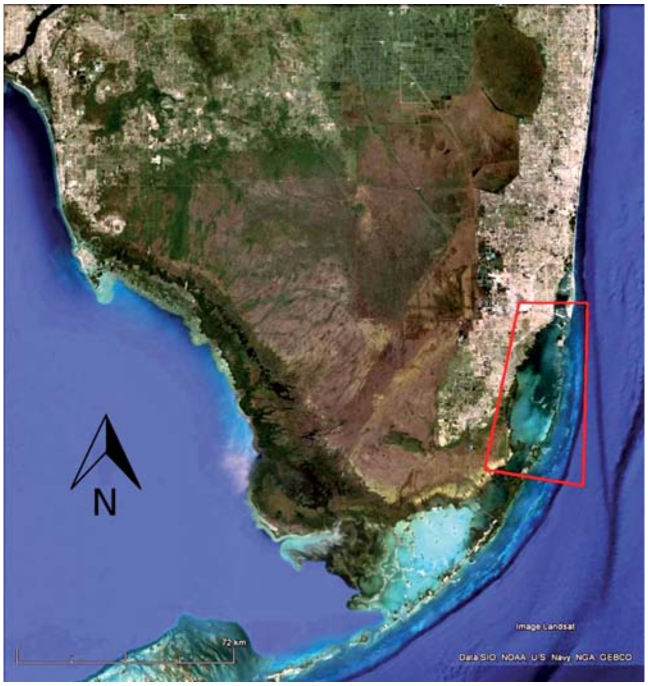

Figure 1. LANDSAT satellite imagery zoomed in over the southern region of peninsular Florida, U.S.A. The red polygon outlines the segment of continental shelf used in this study. Included in the area of investigation is a diverse mix of coastal environments, including highly urbanized Miami, Florida; the Florida Keys National Marine Sanctuary (FKNMS); Everglades National Park; Biscayne Bay Aquatic Preserve; Biscayne Bay National Park; and John Pennekamp Coral Reef State Park. Source: Google™ Earth (2015).

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; Nunn, 1994). 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

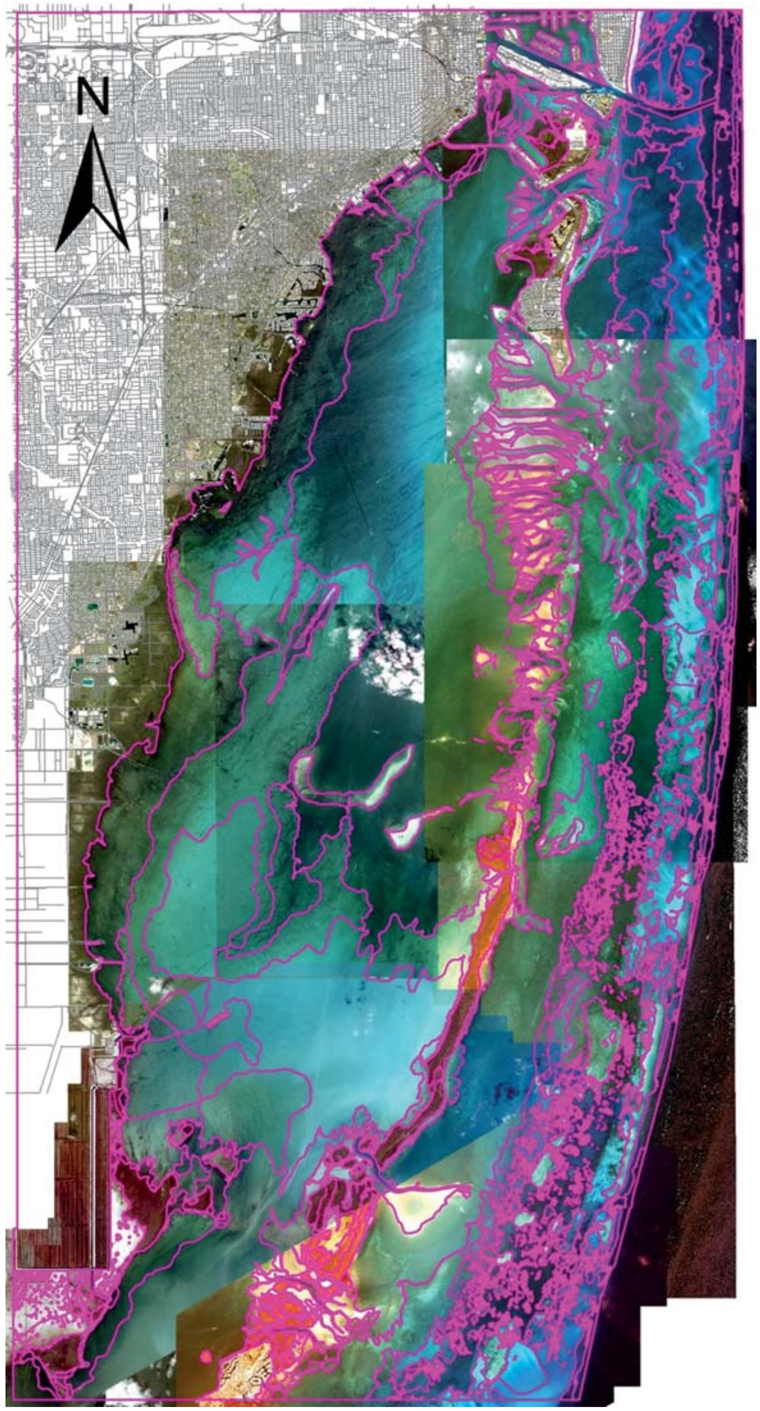

Figure 2. Exported view of cognitive delineation results from interpreting enhanced IKONOS-2 satellite imagery. Of the 3888 vector polygons digitally created in the study area (outlined in magenta), note the increase in complexity of benthic features with the westward distance offshore of the Florida 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 1. *Definitions table for geoforms and associated landforms along the SE Florida continental shelf, including locations, definitions, descriptions, and references.*

Geoform	Landform	Location	Definitions, Descriptions, and References
Coral Reef		The Florida Reef Tract (FRT), a shelf-edge barrier reef system, lies seaward of Hawk Channel and the Atlantic Ocean Littoral Zone	The only living coral barrier reef in the continental United States, the FRT mimics the planform arc 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 protozoans; 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)
	Barrier Reef	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	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)
	Patch Reef	Isolated reef patches scattered in backreef, intra-reefal, inner reef, and outer reef zones	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; Finkl, Benedet, and Andrews, 2005a; Jaap, 1984; Lidz, 2006; Lidz, Hine, and Shinn, 1991; Lidz *et al.*, 1991, 1997; Shinn, 1963)
	Aggregated Reef	Occupies the backreef zone between the seaward margins of Hawk Channel and the intra-reefal sediment flats	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; Mumby and Harborne, 1999; Shinn, 1963)
	Coral Apron	Deltoidal shaped accumulations of coral scree and finer-grained carbonate sediments along the lee side of aggregated and barrier reefs	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)
	Reef Gap	Perpendicular to shore-parallel and shelf-parallel barrier reefs separating them into tracts or segments	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)
Hardbottom		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	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.*, Chiappone and Sullivan, 1994; Finkl, 2004; Finkl *et al.*, 2008; Lidz *et al.*, 2006)

Table 1. Continued.

Geoform	Landform	Location	Definitions, Descriptions, and References
	Subtidal Pavement	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	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)
	Rubble Fields and Dredged Spoil Piles	Deposits in the Atlantic Ocean Littoral Zone, offshore of Fisher Island, and in northern Biscayne Bay	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 Fong, 1997)
Island		Coral and mud-based Florida Key archipelago that separates Biscayne Bay from Hawk Channel	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)
	Bay Key	Small, compacted mud islands between karst islands or as solitary subaerial landforms (exposed banks) in Biscayne Bay	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)
	Karst Island	Limestone-cored keys that separate Biscayne Bay and Card Sound from Hawk Channel	Islands in the Florida Keys composed of oolitic grainstone (*i.e.* Miami Limestone), fossil coral reef rock (*i.e.* Key Largo 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)
	Salina	Low-lying depressions in karst islands or bay keys	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)
Sediment Flat		Unconsolidated seafloor extensively found throughout Biscayne Bay, Card Sound, Hawk Channel, the Atlantic Ocean Littoral Zone, and in intra-reefal pockets of the FRT	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, Robbin, and Shinn, 1985; Lidz, Hine, and Shinn, 1991)
	Intertidal Sand Flat	Periodically exposed sediment flats found in Biscayne Bay	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)

Table 1. Continued.

Geoform	Landform	Location	Definitions, Descriptions, and References
	Planar Bed Forms and Ripples	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	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)
Dune and Beach		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	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)
	Bay Beach	Low energy beach systems along the bay side of Fisher Island, Virginia Key, and Key Biscayne	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)
	Ocean Beach	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	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)
Ridge Field		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	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)
	Discrete Ridges	Isolated, single sand ridges orientated in the same direction within the field in Biscayne Bay, Hawk Channel, and the FRT	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, 2004; Finkl and Andrews, 2008; Finkl, Andrews, and Benedet, 2006; Finkl *et al.*, 2007; Stapor, 1982)
	Complex Ridges	Field of crisscrossing sand ridges in Hawk Channel and the Atlantic Ocean Littoral Zone	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)

Table 1. Continued.

Geoform	Landform	Location	Definitions, Descriptions, and References
Channel		Intra-key conduits connecting Biscayne Bay and Card Sound with Hawk Channel, or as solitary grooves cut within the offshore bank of Biscayne Bay	Low relief, elongated tidal conduits that are cut into seafloor bank sediments or karst bedrock that facilitate the exchange of water between Biscayne Bay, Card Sound, and Hawk Channel; neochannels are modern-day tidal channels that are cut into sedimentary band deposits, whereas paleochannels are older features, probably inlets, that were associated with lower sea levels and cut into bedrock (*e.g.*, Banks *et al.*, 2007; Davis and Fitzgerald, 2004; Finkl, 2004; Finkl 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)
	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	Distributary or straight channels cut through unconsolidated carbonate bank deposits; these subtidal channels facilitate tidal flows between Biscayne Bay, Card Sound, and Hawk Channel (*e.g.*, Davis and Fitzgerald, 2004; Finkl, 2004; Finkl and Andrews, 2008; Lidz, 2006; Lidz *et al.*, 1997, 2006)
	Paleochannel	Bedrock channels separating the Florida Keys	Channels cut through the karstified bedrock of the Florida Keys archipelago; these paleochannels, former inlets or Pleistocene rivers, are stable conduits between Biscayne Bay, Card Sound, and Hawk Channel; paleochannels typically display flood- and ebb-tidal deltas and may have associated sediment flats (*e.g.*, Banks *et al.*, 2007; Davis and Fitzgerald, 2004; Finkl, 2004; Finkl and Andrews, 2008; Finkl, Benedet, and Andrews, 2005b; Lidz, 2006; Lidz *et al.*, 1997, 2006)
	Seafloor Channel	Tidal channels cut within the banks of Biscayne Bay	Low relief tidal channels cut into carbonate sand flats of Biscayne Bay; these seafloor channels may be straight or bifurcate into complex distal segments before merging imperceptibly with sandy-muddy bottoms; they may be uncolonized or contain seagrass meadows (*e.g.*, Banks *et al.*, 2007; Biber, 2007; Davis and Fitzgerald, 2004; Finkl, 2004; Finkl and Andrews, 2008; Lidz, 2006)
Delta		A triangular tract of sediment deposited at the termini of tidal paleochannels that are transitional between Biscayne Bay, Card Sound, and Hawk Channel	A depositional geoform produced from the shoaling sedimentation at the termini of transitional paleochannel tidal passes between Biscayne Bay, Card Sound, and Hawk Channel; paleochannels typically contain ebb- and flood-tidal deltas, depending on the shoaling location (*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; Lidz, Hine, and Shinn, 1991; Schwartz, 2005)
	Ebb-Tidal Delta	Deltaic formations in transitional paleochannels on seaward termini in Hawk Channel	A triangular-shaped accumulation of sediment at the seaward terminus tidal paleochannels in Hawk Channel; these small ebb-tidal deltas are modified by ocean waves and currents that cross over the FRT to produce asymmetrical delta forms (*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; Lidz, Hine, and Shinn, 1991)
	Flood-Tidal Delta	Deltaic formations in transitional paleochannels on shoreward termini in Biscayne Bay and Card Sound	A triangular-shaped accumulation of sediment at the shoreward terminus tidal paleochannels in Biscayne Bay and Card Sound; these small flood-tidal deltas are modified by fetch-limited bay waves and currents to produce asymmetrical delta forms (*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; Lidz, Hine, and Shinn, 1991)

Table 1. Continued.

Geoform	Landform	Location	Definitions, Descriptions, and References
Peninsula and Coastal Plain		Low-lying, marshlands (Everglades) of Southeast Distal Florida and the Southeast Florida Coastal Zone adjacent to Biscayne Bay and Card Sound	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 urban and agricultural areas, except for areas in the south, where they are composed of intertidal and supratidal mud flats with organic-rich sediments (Finkl and Makowski, 2013; Finkl and Restrepo-Coupe, 2007; Finkl *et al.*, 2008; Gorsline, 1963; Hoffmeister, 1974; White, 1970)
	Intertidal Mud Flat	Shallow, muddy, carbonate shores along the fringes of the Everglades fronting lower Biscayne Bay and into Card Sound	Shallow-sloped, low energy muddy shorelines adjacent to lower Biscayne Bay and into Card Sound; intertidal mud flats contain poorly sorted, silty, carbonate sediments with high organic contents; mangroves and other wetland vegetation are often present (*e.g.*, Finkl, 1994, 2004; Finkl and Andrews, 2008; Finkl and Restrepo-Coupe, 2007; Finkl *et al.*, 2008; Hoffmeister, 1974; White, 1970; Wolanski, 2007)
	Supratidal Mud Flat	Backshore mud flats landward of intertidal muddy areas that merge with Southeast Distal Florida ecotonal successions	Low gradient, muddy backshores lying landward of intertidal mud flats; these mud flats, which contain organic-rich mud soils and are seldom inundated, support a variety of wetland vegetation, including marsh prairie regimes and tree island biohydrologic systems of Southeast Distal Florida (*e.g.*, Finkl, 1994, 2004; Finkl and Andrews, 2008; Finkl and Restrepo-Coupe, 2007; Finkl *et al.*, 2008; Hoffmeister, 1974; White, 1970; Wolanski, 2007)
	Anthropogenic Modified Coastal Plain	Urban development and agricultural lands on the Atlantic Coastal Plain and drained Everglades in the Southeast Florida Coastal Zone	Urban development (*i.e.* cities and suburbs to form a conurbation) mixed with commercial agricultural lands, small farm plots, and open space in the Everglades and along the Atlantic Coastal Plain within the Southeast Florida Coastal Zone (*e.g.*, Finkl, 1994; Finkl and Makowski, 2013)

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

Geoform	Quantity of Vector Polygons, n [%]	Calculated Area, km^2 [%]
Coral Reef	2824 [72.6]	119.7 [8.5]
Hardbottom	63 [1.6]	32.7 [2.3]
Island	135 [3.5]	44.5 [3.1]
Sediment Flat	474 [12.3]	692.2 [49.2]
Dune and Beach	7 [0.2]	1.4 [0.1]
Ridge Field	20 [0.5]	57.8 [4.1]
Channel	63 [1.6]	44.4 [3.2]
Delta	5 [0.1]	12.6 [0.9]
Peninsula and Coastal Plain	297 [7.6]	402.1 [28.6]
Total	3888 [100]	1407.4 [100]

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 geoforms 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 geoforms and associated landforms along the continental shelf study area are provided in Table 1.

For the purposes of onscreen cognitive interpretation of geoforms 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 SmartBoard®

Table 3. *Quantity of cognitively classified vector polygons (n) and calculated areas (km^2) for seven selected landforms interpreted from the IKONOS-2 satellite imagery. Each individual percentage from the total is listed in brackets below.*

Landform	Quantity of Vector Polygons, n [%]	Calculated Area, km^2 [%]
Patch Reef	2705 [69.5]	119.7 [8.5]
Subtidal Pavement	44 [1.1]	31.0 [2.2]
Bay Key	77 [2.0]	5.3 [0.4]
Karst Island	54 [1.4]	37.4 [2.6]
Planar Bed Forms and Ripples	429 [11.0]	681.5 [48.4]
Discrete Ridges	7 [0.2]	21.0 [1.5]
Complex Ridges	13 [0.3]	36.8 [2.6]

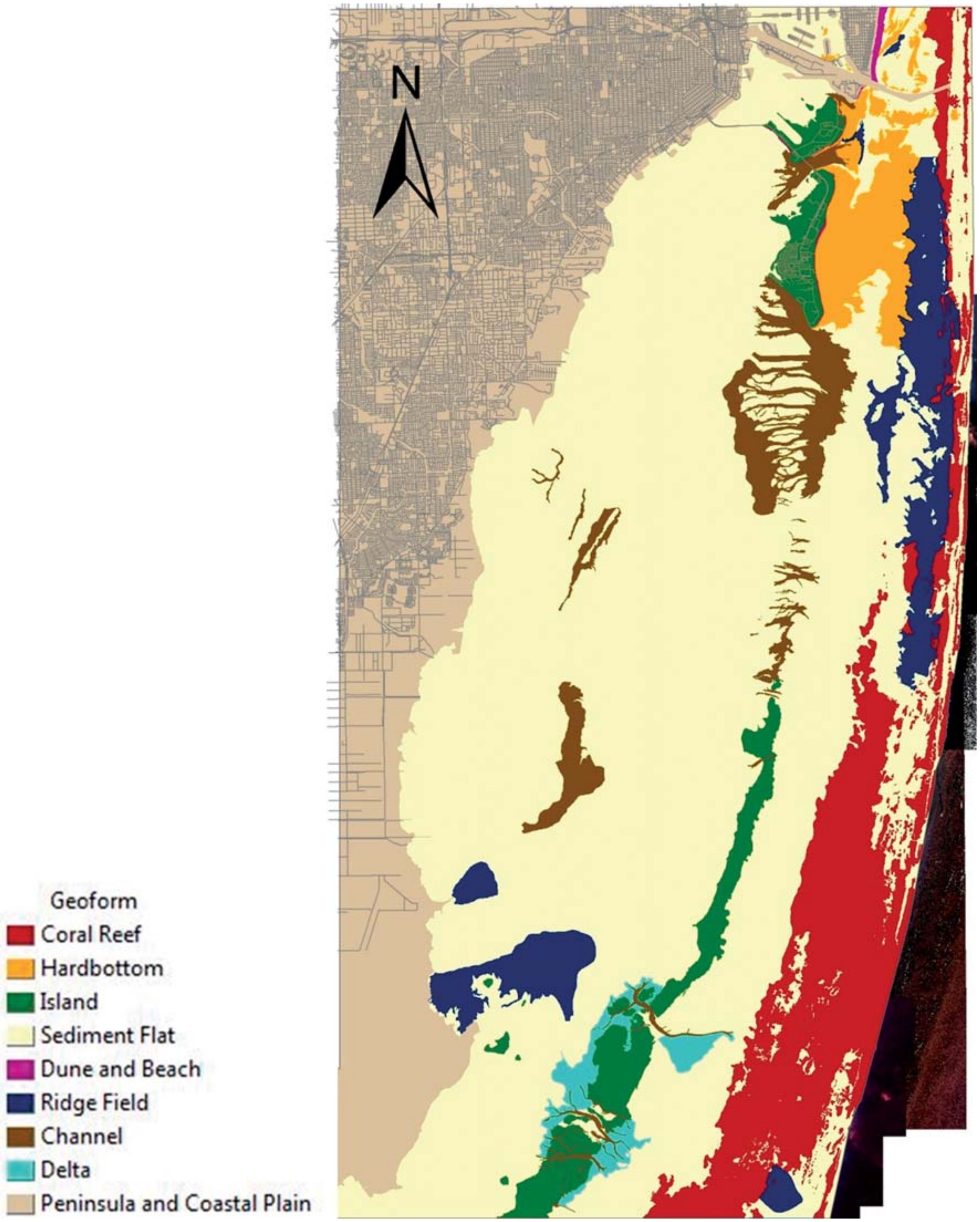

Figure 3. Geographic representation of geoforms from the interpreted IKONOS-2 satellite imagery (*viz*. Figure 2). The legend identifies nine (9) geoforms classified from the imagery and are color coded to show the spatial relationships among them. The broader-scale geoforms allow for a more detailed delineation with associated landforms (*viz*. Figure 4). A nominal scale of 1:230,000 was set for this image export out of ArcMap.

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,

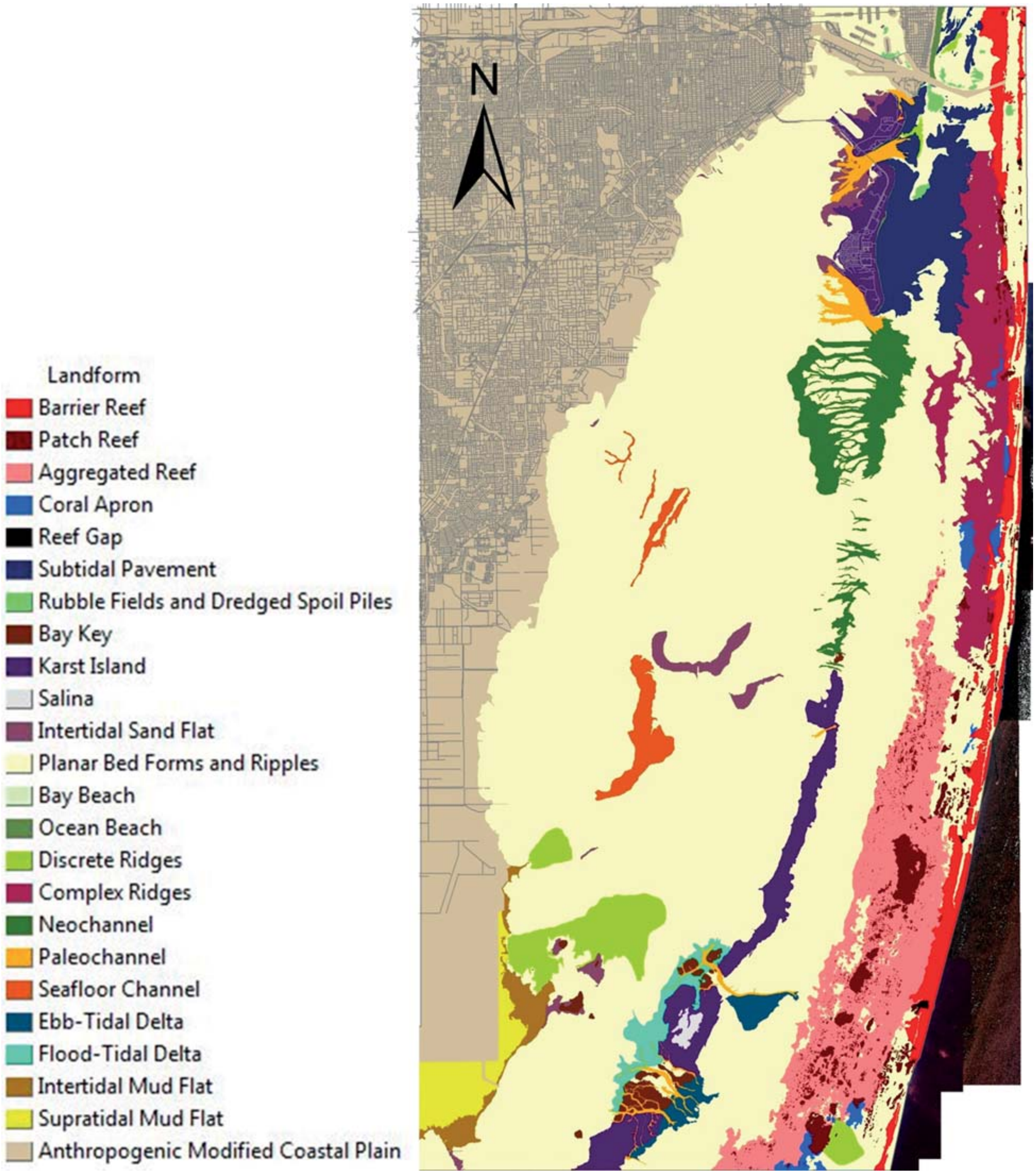

Figure 4. Geographic distribution of landforms as interpreted from IKONOS-2 satellite imagery, subdividing the larger-scale geoforms (*viz*. Figure 3). The legend provides a color distinction for each classified landform interpreted from the imagery (*viz*. Figure 2) and allows for visual understanding 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.

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 complied for the purpose of analysis and directly

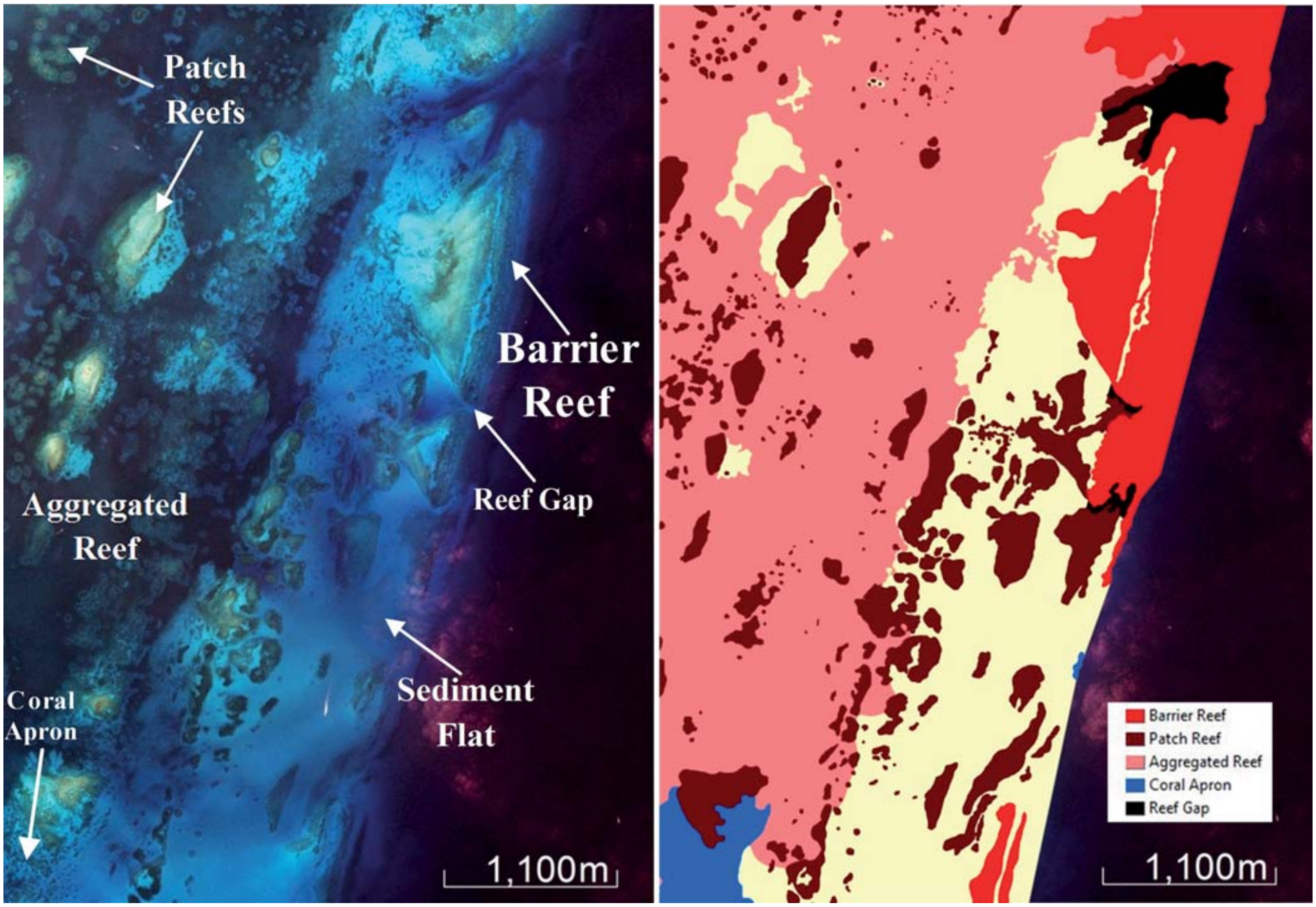

Figure 5. In order to interpret and classify the separate components of the Coral Reef Geoform, the left panel shows associated landform examples of Barrier Reef, Patch Reef, Aggregated Reef, Coral Apron, and Reef Gap within the IKONOS-2 satellite image. The right panel overlays color coordinated classification units, as show in the legend, on top of the IKONOS-2 to visually demonstrate the spatial distribution of landforms. 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. The blacked out portion on the right-hand side of both panels represents where the water depth exceeded the threshold by which the IKONOS-2 sensor could visually register any benthic spectral signatures. The satellite image and interpretive overlay panel were exported out of ArcMap program at a nominal scale of 1:24,000 within the layout view feature.

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 km^2 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 km^2 and 681.5 km^2, respectively, while the Dune and Beach Geoform (1.4 km^2) and associated Bay

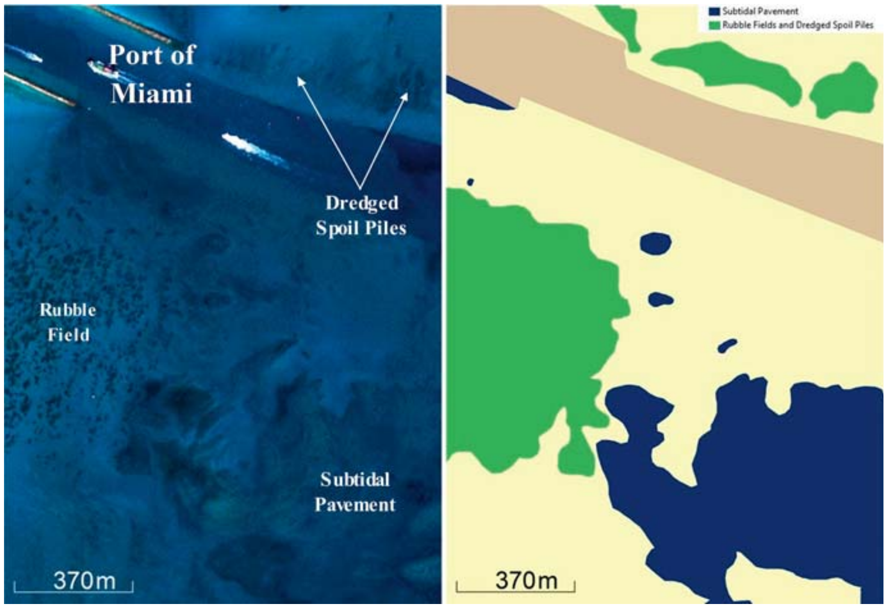

Figure 6. Example of the Hardbottom Geoform in relation the Port of Miami. The IKONOS-2 satellite image in the left panel shows the benthic signature differences between the Subtidal Pavement Landform versus the Rubble Fields and Dredged Spoil Piles Landform, while the right panel overlays color coded 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.

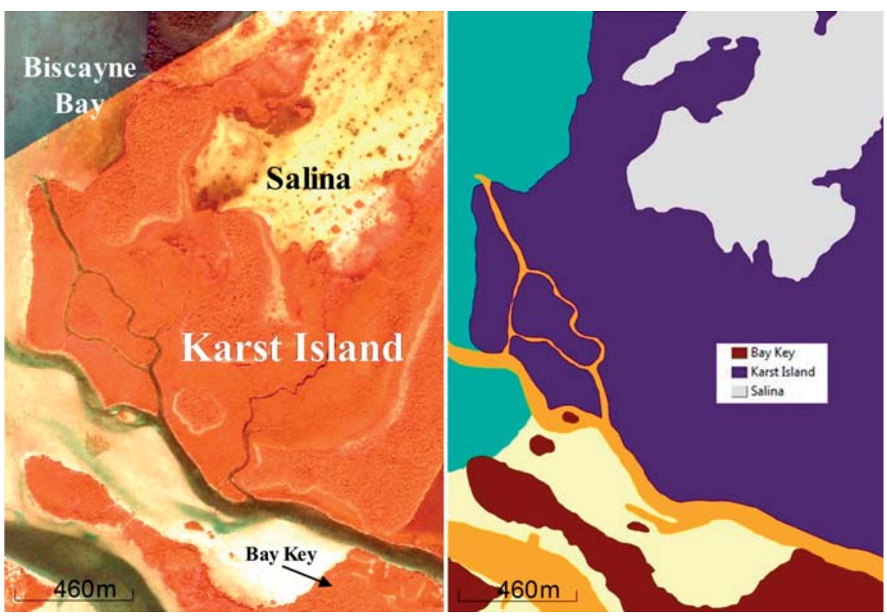

Figure 7. Detailed example showing visual spectral characteristics of the IKONOS-2 imagery (left panel) when identifying the Island Geoform and the associated landform examples of Bay Key, Karst Island, and Salina in relation to Biscayne Bay. The right panel overlays landform classification units assigned 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.

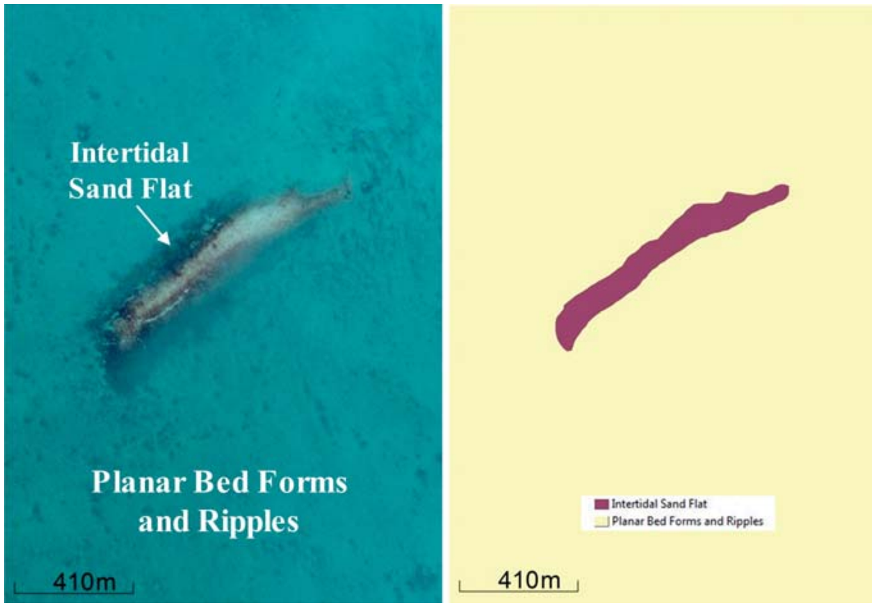

Figure 8. Zoomed in example of an IKONOS-2 satellite image (left panel) and the superimposed classifying units (right panel) that represent the breakdown of the Sediment Flat Geoform into two (2) associated landforms: Intertidal Sand Flat and Planar Bed Forms and Ripples. The Intertidal Sand Flat Landform 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.

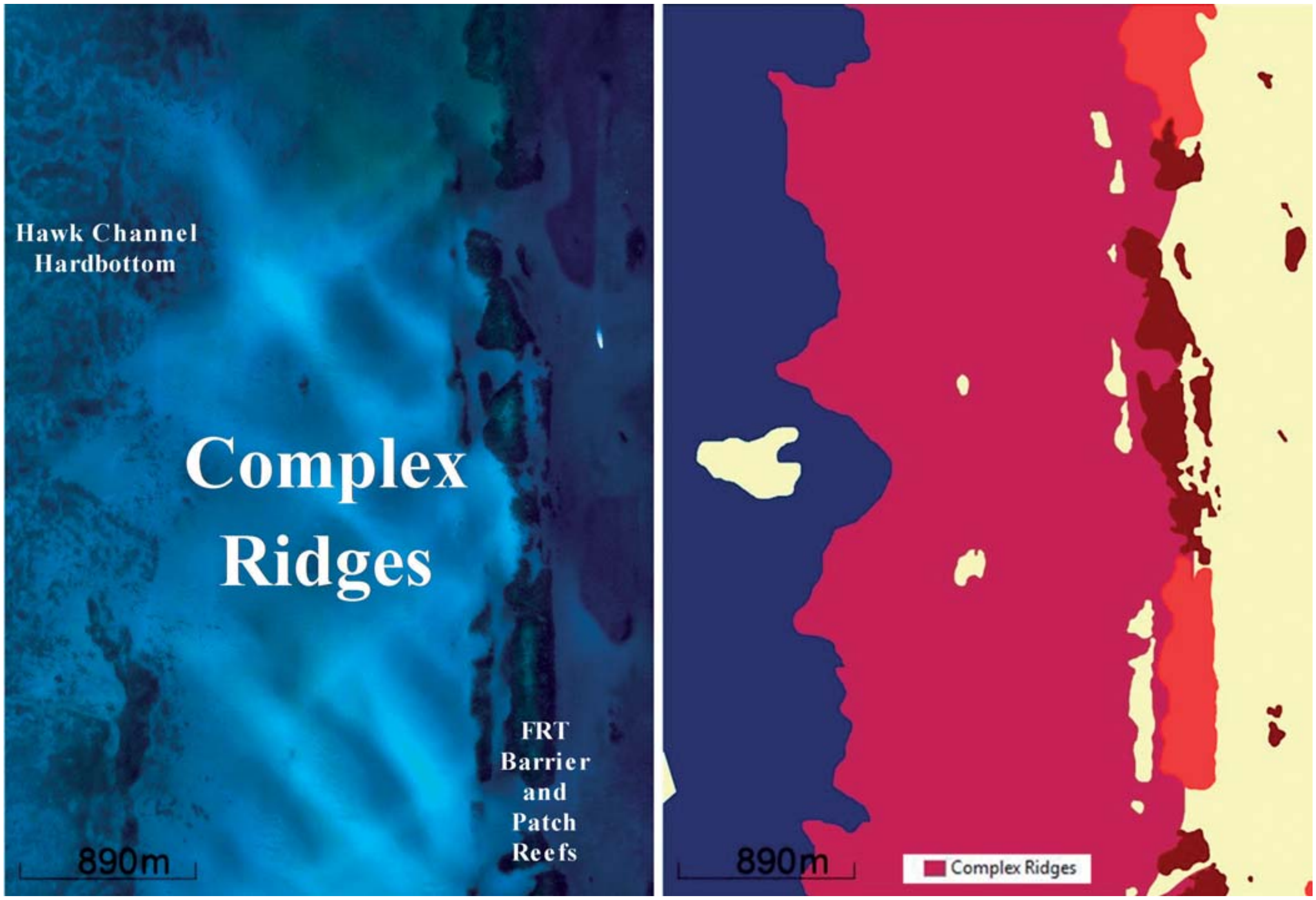

Figure 10. Detailed example showing distinctive spectral reflectance patterns for landforms associated with Coral Reef, Sediment Flat, Hardbottom, and Ridge Field Geoforms. The largest benthic feature identified in the left panel is the Complex Ridge Landform, which is located between the Hardbottom Geoforms of Hawk Channel and the Barrier and Patch Reef Landforms of the Florida Reef Tract (FRT). Notice how the high-resolution of the IKONOS-2 imagery is able to capture the characteristic crisscrossing pattern along the seafloor. The right panel overlays color-assigned classification units on top of the satellite imagery to visually demonstrate the distribution of landforms along the benthos. In addition to Complex Ridges, 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 blue areas represent Subtidal Pavement Landforms; dark red areas represent Patch Reef Landforms; and bright red areas represent Barrier Reef Landforms. Both panels were exported out of ArcMap at a nominal scale of 1:19,000 within the layout view feature.

Beach Landform (0.1 km^2) 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

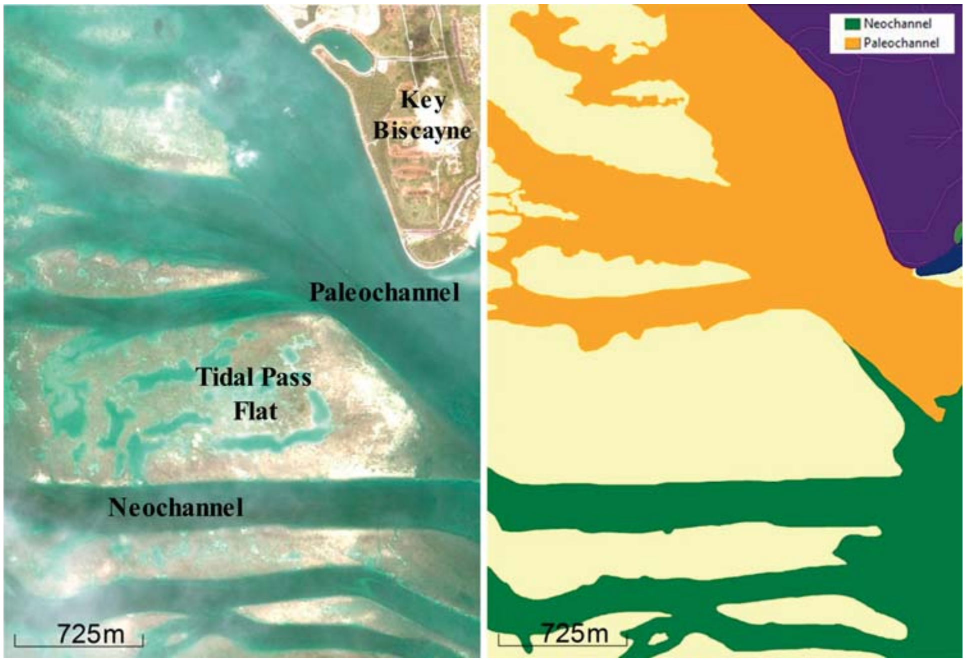

Figure 11. Detailed example of Channel Geoform interpretations using IKONOS-2 satellite imagery. The left panel shows the identification of associated landforms, which include Neochannel and Paleochannel, while the right panel overlays mapping units of specific color (*viz*. Figure 4) on top of the satellite 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.

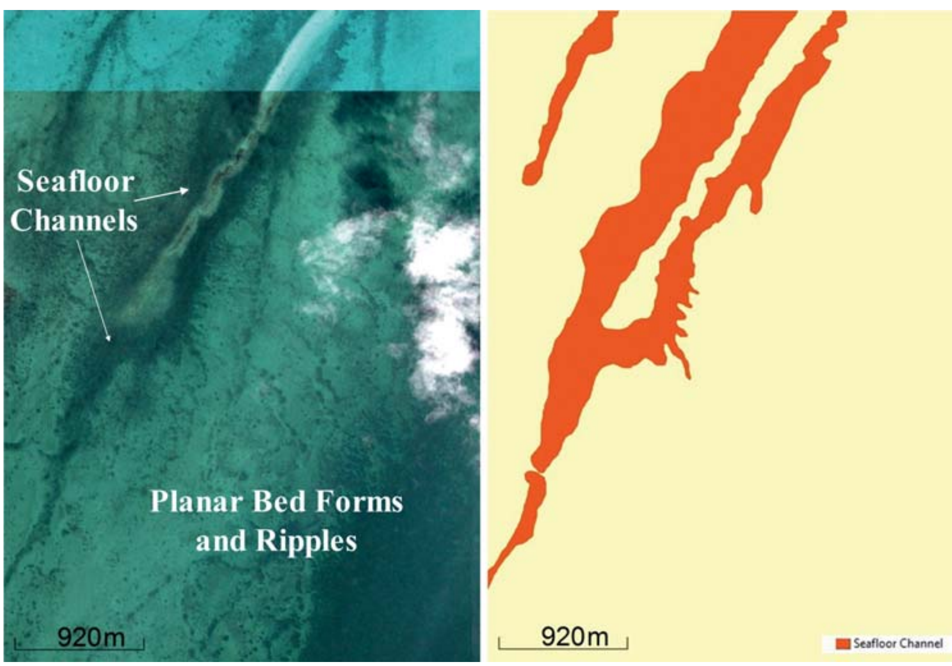

Figure 12. Detailed example of a Channel Geoform (as interpreted by the Seafloor Channel Landform) in relation to the Sediment Flat Geoform (as interpreted by the Planar Bed Forms and Ripples Landform) in Biscayne Bay. The left panel shows the high-resolution IKONOS-2 satellite image by which the color 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.

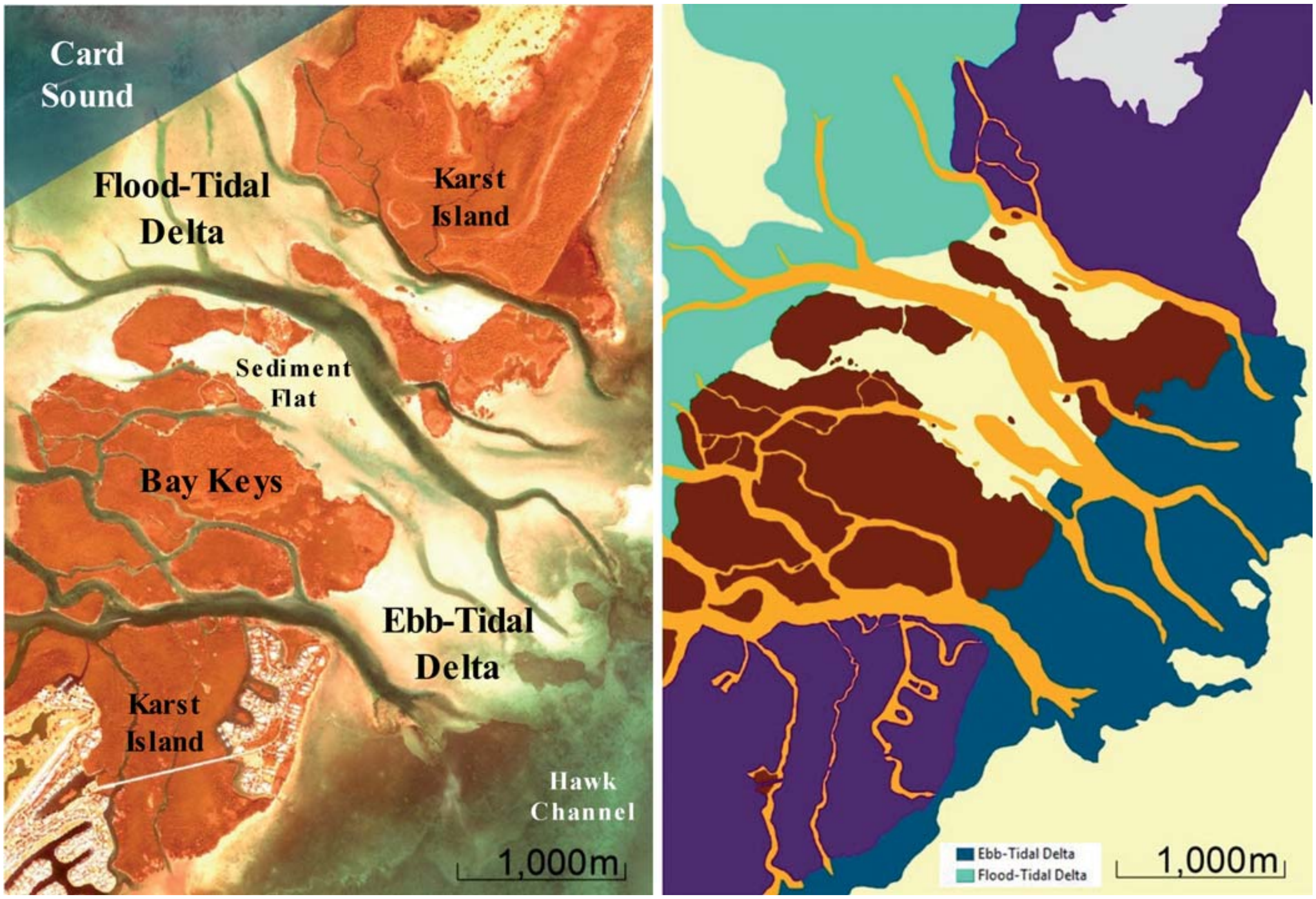

Figure 13. Detailed example of IKONOS-2 satellite imagery (left panel) showing the two (2) landforms associated with the Delta Geoform, along with surrounding features. The left panel shows Ebb-Tidal Delta Landforms and Flood-Tidal Delta Landforms, while the right panel represents interpreted distribution of features by overlaying color coded mapping units from the landform legend (*viz.* Figure 4) on top of the satellite imagery. 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; brown areas represent Bay Key Landforms; and grey areas represent the Salina Landform. 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. A nominal scale of 1:23,000 was used for both panels exported out of ArcMap.

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 seabottom. 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

Figure 14. Detailed example of three (3) landforms associated within the Peninsula and Coastal Plain Geoform in relation to Card Sound. Spectral reflectance patterns in the left panel (IKONOS-2 image) show the gradational transition coalescence of the Supratidal Mud Flat Landform into the Intertidal Mud Flat Landform. Also shown is an example of the urbanized Anthropogenic Modified Coastal Plain Landform. The right panel contains color coded mapping units that are an interpretation of the left panel, where classifications are placed on top of the satellite imagery for visual comparison. 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. Both panels were exported out of ArcMap at a nominal scale of 1:18,000 within the layout view feature.

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 macroalgae 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 km^2 area of continental shelf along 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

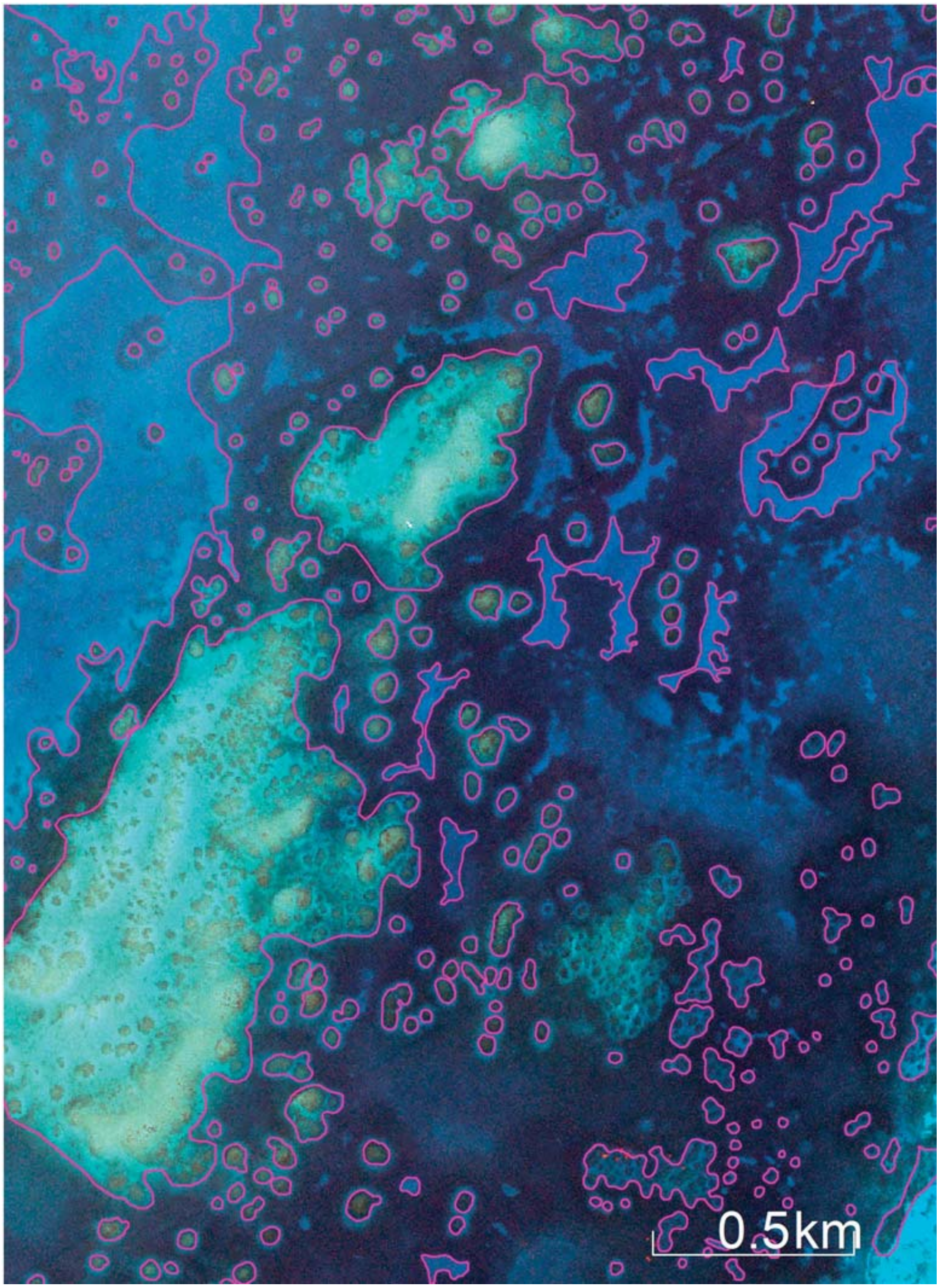

Figure 15. Detailed example showing the advanced level of recognition in Patch Reef Landforms, constituting a subdivision of the Coral Reef Geoform, as seen in the high-resolution IKONOS-2 satellite imagery. The cognitively interpreted magenta lines highlight the optimal level of color, tone, texture, pattern, and bottom spectral reflectance shown in IKONOS-2 imagery for Patch Reef Landform identification. This image was exported out of ArcMap within the layout view feature at a nominal scale of 1:14,000.

morphosedimentary features by visually mapping the airborne laser bathymetry images as continuous sequences of geoform and landform signatures. By doing so, the geomorpholoical 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.*, Andréfouët *et al.*, 2003; Dial *et al.*, 2003; Finkl, Makowski, and Vollmer, 2014; Finkl and Vollmer, 2011; Hochberg,

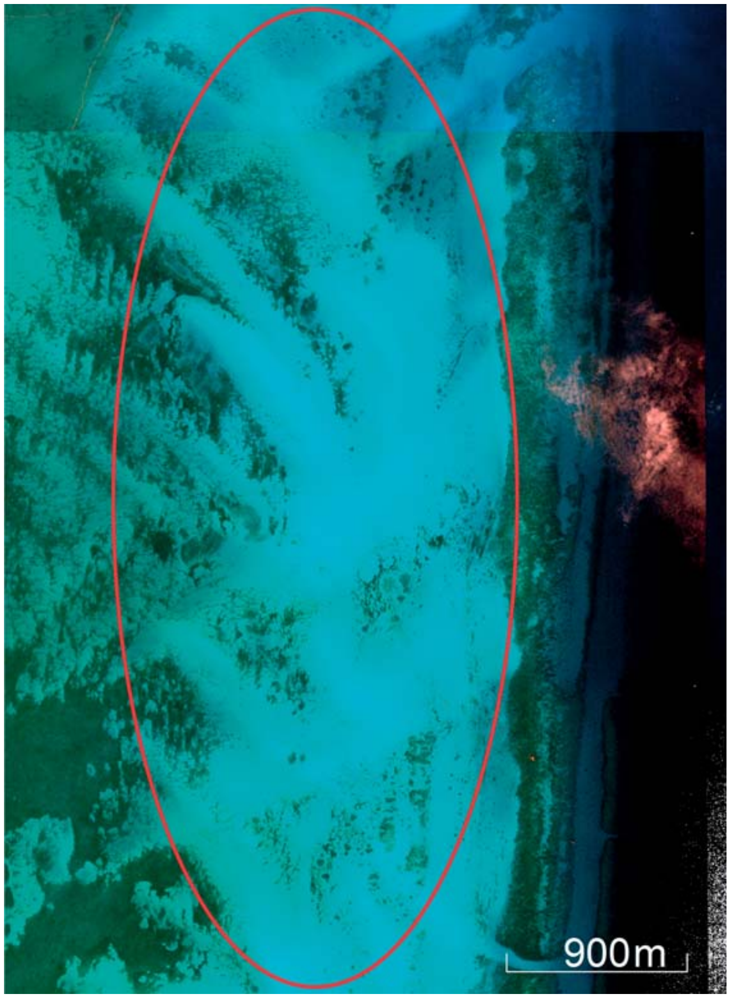

Figure 16. IKONOS-2 satellite image showing the color, tone, and bottom spectral reflectance patterns to identify Ridge Field Geoform areas. The red circle is drawn around a Complex Ridge Landform feature. This interpretation was made because of the benthic sand waves forming a crisscrossing pattern of ridge and swale topography along the seafloor, thereby appearing along more than one axis to create a compound field of ridges. The sharp contrast along the top portion of the figure is indicative of merging two separate IKONOS-2 satellite images from the same sampling area. The blacked out portion on the right-hand side of the image represents where the water depth exceeded the threshold by which the IKONOS-2 sensor could visually register any benthic spectral signatures. This image was exported out of ArcMap at a nominal scale of 1:21,000 within the layout view feature.

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 images 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

(Makowski, Finkl, and Vollmer, 2015, 2016; Mumby and Edwards, 2002).

For this study, classification maps were created in ArcMap to visually represent the spatial distribution of geoform and landform features along the continental shelf by superimposing color coded units over interpreted IKONOS-2 satellite images. As shown in this paper's analysis, IKONOS-2 image scenes provided optimal recognition qualities (*i.e.* color, tone, texture, pattern, saturation, and relative spectral reflectance) that permitted suitable cognitive interpretation of the marine benthos, especially when attempting to interpret those environments offshore in deeper water. Typically, other lower-resolution satellite imagery (*e.g.*, LANDSAT Thematic Mapper) become less effective in depths exceeding 15–18 m because light penetration (*i.e.* attenuation of the reflected spectral signal) and underwater clarity (due to increased turbidity) becomes restricted throughout the water column (Makowski, 2014; Makowski, Finkl, and Vollmer, 2016; Mumby and Edwards, 2002). Conversely, the IKONOS-2 images visually penetrate in deeper waters offshore to interpret major geomorphologcial signatures of submerged environments without serious degradation of tone, texture, and pattern signatures. A prime example of such optimal visual properties was seen from the results of this study when the Coral Reef Geoform was identified and further delineated into the individual Barrier Reef, Patch Reef, Aggregated Reef, Coral Apron, and Reef Gap landforms (Figure 5). Overall, this study showed that IKONOS-2 images were suitable for the cognitive interpretation for geoforms and landforms along the continental shelf, as shown by the net result of 3888 vector polygons being drawn to demarcate the geomorphological framework of the region (Figure 2). Even though at deeper depths (*i.e.* greater than 50 m) the bottom reflectance signal is completely absorbed by the water column, IKONOS-2 images still provided enough detail for coastal (terrestrial) and benthic marine environment recognition along the continental shelf to complete the perceived geoform and landform classification over the study area.

As a census of geoform and landform attributes is interpreted, mapped, and ultimately compiled into a central database, it is postulated that a true hierarchical classification of a specific region begins to form when these attributes link larger-scale units (*i.e.* physiographic realms and morphodynamic zones) with smaller, more temporally influenced benthic features (*e.g.*, dominant sediment, dominant biological cover). For this particular study area, Makowski, Finkl, and Vollmer (2016) have already reported an interpretation of physiographic realms and morphodynamic zones. Therefore, when the geoform and landform data from this study are added to those previous datasets, a true representation of the geomorphological framework along the continental shelf begins to take form. Future studies may contribute sediment and biological classification units, along with ranges in coverage, which would then provide an inclusive geo-referenced spatial database for the continental shelf region.

CONCLUSIONS

This study verified that cognitive interpretation, classification, and mapping of benthic geoforms and associated landforms 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 (G-ISCS) 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.

ACKNOWLEDGMENTS

Special appreciation goes to the Coastal Education and Research Foundation, Inc. (CERF) and to the GeoEye Foundation®, both of which provided logistical and financial support for this research. Individual acknowledgments are given to those external peer reviewers for their suggestions of improvement.

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