Investigation of Sediment Ridges Using Bathymetry and Backscatter near Clearwater, Florida

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Investigation of Sedimentary Ridges Using Multibeam Bathymetry and Backscatter near Clearwater, Florida

by

Lewis Stewart

A thesis submitted in partial fulfillment of the requirements for the degree of Master’s of Science with a concentration in Geological Oceanography
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ABSTRACT

Changes in sediment morphology on the West Florida Shelf is investigated over a 14-year time period using multibeam bathymetry and backscatter in water depths between 10 m and 20 m, off the coast of Indian Rocks Beach, Pinellas County, Florida. Bathymetric surveys collected in 2002 (Kongsberg EM 3000 at 300 kHz) and 2016 (Reson 7125 at 400 kHz) were processed using CARIS Hips and Sips to create bathymetric maps and backscatter images. These data were then interpreted and compared in order to test hypotheses and answer questions related to sediment migration and sediment volume change.

The following questions prompted this study:

A. How mobile is the sediment on the limestone?

B. What sedimentary changes occurred following the 2002 and 2003 deployments of mines for an Office of Naval Research project?

C. How much sediment was removed during dredging and how closely does it compare to the Army Corps of Engineers’ reported estimate during the beach renourishment of Sand Key in 2012?

In order to answer these questions, hypotheses were tested:

Hypothesis A:

The sediment ridges in the study site have not migrated significantly over the limestone hard bottom during the 14-year time period (Hafen, 2001; Edwards et al. 2003).
Hypothesis B:
There is no change in sediment volume where the mine-like object were placed and removed after the ONR mine burial experiment (Wolfson 2005; Wolfson et al. 2007).

Hypothesis C:
Changes in sediment volume between 2002 and 2016 will match the amount estimated by the Army Core of Engineers who dredged the area.

Results show that the sediment ridges in the study area had some migration over the limestone hard bottom during the 14-year time period. The results also found that there was a sediment volume change where mine-like objects were placed and removed during the Office of Naval Research mine burial experiment because of a dredging operation in 2012 that dredged sediment from the experimental area. Specific areas investigated that surround the dredging area showed significant loss of sediment, with the change in hydrodynamics from dredging influencing this sediment loss. The volume of sediment removed from the aforementioned dredging cut was found to be within 16% of that estimated in the Army Corps of Engineers report prior to the dredging.

Geologic interpretations of the backscatter images interpreted strong backscatter returns as limestone, mid strength returns as coarse shell hash and weak returns as fine to medium-grained sediments. The weak returns were found primarily on the sediment ridges. The dredging cut showed stronger returns than the surrounding ridge, indicating that underlying coarse sediments were most likely compacted and composed of shell hash.

Using satellite remote sensing as a way to gather continual repeat coverage at high resolution (2 m) data to determine absolute depth in these water depths is investigated and preliminary results suggest that processed 250 m pixel MERIS data will give a similar depth range as multibeam bathymetry. The higher-resolution 0.5 m pixel raw WorldView 2 data shows NW-SE trending structure, suggesting the seafloor morphology will be more visible.
INTRODUCTION

Background

The West Florida Shelf (WFS) is one of the widest continental shelves in North America and is economically and environmentally important because of its fisheries, beaches, and coral reefs. It runs the length of the west coast of Florida from latitudes 24.5° N to 30° N from longitudes 81° W to 85° W with the Florida Keys enclosing most of its southern edge (Figure 1). The WFS extends approximately 150 km offshore from Florida’s west coast, reaching depths of 120 m, before dropping off dramatically to over 3500 m at the western edge, known as the West Florida Escarpment, in the Gulf of Mexico (Ewing et al. 1971; Hine et al. 2003; Hine 2013). The WFS consists of a thick limestone basement covered by a thin layer of siliciclastic and carbonate sand/gravels (Edwards et al. 2003; Harrison et al. 2003; Locker et al. 2003). The distribution of this thin top layer of sediment is controlled primarily by wave and current action over geologic time. These actions are most effective near-shore, forming sand ridges that are orientated in a NW-SE direction north of Tampa Bay in the Clearwater area (Hafen 2001; Harrison et al. 2003) and in the NE-SW direction south of Tampa Bay (Twichell et al. 2003).

Previous studies contributed much to the understanding and location of the sediment morphologies in this general area (Figure 2) (Hafen 2001; Harrison et al. 2003; Hine et al. 2003; Edwards et al. 2003; Finkl et al. 2007; Locker et al. 2003; Twichell et al. 2003). The three main reasons that prompted these studies, as explained in Hafen (2001), were to understand the subaqueous sand ridges on the WFS, expand the knowledge of the hydrologic conditions, and determine the geologic extent and sedimentary characteristics of the sand ridges. These bedforms are important for beach replenishment programs (Pilkey & Clayton 1989; Leonard et al. 1990;
Finkl et al. 2007) and for developing depositional models for shelf-deposited sands to aid in exploration of hydrocarbon-bearing shelf sandstones in the rock record (Rine et al. 1991).

A major beach renourishment program was carried out on the beaches of Sand Key in 2012, with one burrow area being located within the study area (red polygon in Figure 5). The United States Army Corps of Engineers calculated they would need approximately 800,000 cubic yards of sand to renourish the beach, but they estimated 1.2 million cubic yards were removed to compensate for losses in dredging and transport. The depth of the borrow cut was reported to be between 0.2 and 2.0 m. This work will calculate change of depth and sediment volume removed by subtracting the 2016 bathymetry from the 2002 bathymetry.

The near-shore geological environment between the shore and the study area was previously examined and interpreted in a number of studies (Hafen 2001; Harrison et al. 2003; Edwards et al. 2003; Locker et al. 2003; Wolfson 2005; Wolfson et al. 2007). Specifically studies by Hafen (2001) and Harrison et al. (2003) determined that sediment ridges are the dominant feature in the area. Patches of coarse-grained carbonates and exposed karsified limestone hard bottom segregate these NW-SE trending siliciclastic shoreline-oblique sand ridges. The siliciclastic sand ridges are chiefly formed from fine-grained quartz sands. These studies also found that the sediment that makes up these ridges was migrating, primarily in a north-south direction with the prevailing currents (Hafen 2001). The coarse-grained carbonates are composed mainly of reworked shell hash (Locker et al. 2002; Locker et al. 2003). It is well documented in these studies that this area of the WFS is low energy, sediment-starved, dominantly mixed siliciclastic/carbonate sedimentary environment. However, the following questions remain:

A. How mobile is the sediment on the limestone?

B. What sedimentary changes occurred following the 2003 deployments of mines for an Office of Naval Research (ONR) project?
C. How much sediment was removed during dredging and how closely does it compare to the United States Army Corps of Engineers’ reported estimate during the beach renourishment of Sand Key in 2012?

These questions were addressed by studying sediment changes after 14 years using multibeam bathymetry and backscatter data. The study site (Figure 6) is approximately 25 km west of Clearwater in 10-20 m water depth, covering an area 6 km by 6 km. The study site was selected where the ONR Mine burial and scour study took place in 2002 and 2003 (Wolfson 2005; Wolfson et al. 2007).

By using high-resolution multibeam bathymetry and backscatter data from 2002 and 2016 the following hypotheses are tested to answer questions A, B, and C.

Hypothesis A:

The sediment ridges in the study site have not migrated significantly over the limestone hard bottom during the 14-year time period (Hafen 2001; Edwards et al. 2003).

Hypothesis B:

There is no change in sediment volume where the mine-like objects were placed and removed after the ONR mine burial experiment (Wolfson et al., 2007).

Hypothesis C:

Changes in sediment volume between 2002 and 2016 will match the amount estimated by the United States Army Corps of Engineers who dredged the area.

Literature Review of the West Florida Shelf

Hafen (2001) noted that the majority of previous studies did not integrate a range of spatial or temporal scales to study the hydrological and sedimentary processes over the WFS. Understanding these hydrologic processes and resulting sedimentary morphologies in the coastal
ocean helped provide modern analogs for interpretation of structure in the geological record (Hequette & Hill 1995). Large scale morphology is assumed to be simply the integral of small scale behavior, but this commonly held assumption is not well tested (Holman 1995). During the GIS analyses of the side-scan data, Hafen (2001), detected sediment movement in multiple directions, similar to that seen by Davis et al. (1996), using the sharp contrast between high and low backscatter as the boundary of where sediment was located. Over time the total measured amounts of movement in each direction were nearly equal. With this Hafen (2001) noticed mixed signals with regards to the movement of sediment, there was no constant or measureable movement of sand ridge borders, within his high level of uncertainty of the side-scan data position. These studies answered many questions, however more work is needed to understand the mobility of the bedforms (Hafen 2001). Some of the questions and comments from Hafen (2001) were that a more comprehensive set of current velocity data are needed to determine if the mean current strength is great enough and sustained long enough to cause large scale movement or if sediment movement is only caused by occasional strong localized forcing events.

Due to the lack of accurate bathymetric data from offshore Sand Key at the time of survey, Harrison (1996) was unable to assess long-term trends in sand ridge movement in the area. However, his side-scan studies over a six-month period suggested at least 5 meters of lateral sediment motion occurred along the flanks of these ridges (within an uncertainty of 25 m of side-scan data location). The movement was mainly focused on the northern flanks of the ridges while the southern flanks appear to be stable. These shifts were deemed to be local and did not imply movement of the entire ridge. It was proposed that the currents that are strong enough to impact the bottom sediments were generated by the passage of winter storm fronts.

The storm fronts mentioned above also determined the forcing factor that is responsible for fine and coarse-grained sediment transport in a study farther south near the mouth of Tampa Bay shown in Figure 2 (Donahue 2002). It is assumed sediment transport will occur more easily during the winter months because the passage of frequent extratropical storms.
A nearby study relating to the stratigraphic framework of the sediment ridges on the WFS inner shelf (Edwards et al. 2003) took a series of seismic reflection profiles and side-scan sonar (Figure 3 and 4) over an area between the ONR study site and Clearwater Beach. They found that the sand ridge field rests on top of flat, relatively featureless limestone bedrock, apart from some depressions. The ridges are composed of a mainly mixed siliciclastic/carbonate sand facies with some integrated, coarser shelly facies. This suggests that these bedforms are migrating. They noted a lack of evidence for sediment exchange between the shoreface and inner shelf, as the ridge topography does not extend to the shoreface. Sediment transport was noted but there did not appear to be a net direction of transport. The underlying stratigraphy within the sand ridges resting upon and containing low-energy facies and the apparent absence of these facies in the bedrock troughs suggested that little to no lateral migration was occurring (Edwards et al. 2003).

**Literature Review of Other Shelf Environments**

The following summary includes other studies near-shore but not on a carbonate platform. Nonetheless, the sedimentary bedforms show many similarities with this study area. Rine et al. (1991) looked at the generation of late Holocene sand ridges on the New Jersey shelf. The primary motivation for the study was to determine the origins of the ridges and as analogues for ancient shelf oil deposits. Their study area consisted of 2 areas: the near-shore in 20 m water depth roughly 4.8 km offshore and a mid-shelf region in 25-36 m water depth, 40 km offshore. The near-shore sediment ridges in the study area had a 30° orientation to shore, which they interpreted to be a response to extratropical (winter) storms. The mid-shelf sediment ridges were orientated sub-parallel to shore, in the direction of the prevailing currents.

Studies were carried out on the central Dutch coast (van de Meene et al. 1996) where the inner shelf is characterized by large linear sand ridges orientated obliquely to the dominant tidal current directions. The sand ridges were found to have a height of 1-6 m; they were 1-4 km wide
and 10-35 km in length in a water depth of 14-20 m. The shape of the ridges is variable, either symmetrical or asymmetrical (in both directions). The sediment seabed pattern reflects the varying interaction between waves approaching from the SW, W, or NW and the generally NE-SW running shore-parallel tidal currents. A sporadic distribution of megaripples was noticed and they tended to be found most commonly in the inter-ridge troughs in 16 m water depth.

A study in the Norton Basin of Alaska (Nelson et al. 1980) mapped large bedforms and scour features with side-scan sonar in 20-35 m water depths. Many series of sand ridges, swales, and ripple fields exist in the area off of St. Lawrence Island. The swale areas appeared to undergo periodic erosion. The sand waves in the area had 1-2 m amplitude with a wavelength spacing of either 10-20 m or 150-200 m. The ripple height was 4-10 cm with lengths of 20-100 cm.

Cacchione et al. (1995) measured changes in bed elevation that resulted from sediment transport and deposition. Cacchione et al. (1995) proposed that the measured current velocities and ocean wave data were responsible for the observed suspended sediment concentrations moving along the bottom boundary layer. Green et al. (1988) found similar results where quantitative large-scale modeling using a time averaged sedimentary transport rate from empirical data, testing the links between velocity distribution and sediment transport.

Geomorphic response models were created for barrier coastlines based on historical shoreline changes (McBride et al. 1995). They established eight classifications for large-scale changes over spatial scales of 10-100 km, noting shoreline response was heavily influenced by sediment supply.

Multiple studies have been carried out in the area of Fire Island, New York (Schwab et al. 2014; Goff et al. 2015 and references therein). They conducted studies in 8-25 m water depths at 2 distinct areas offshore of Fire Island. Schwab et al. (2014) used bathymetry, backscatter and CHIRP seismic data to determine sediment ridge morphology in the area. They found that the sediment ridges were 1-6 m thick and orientated themselves between 20°-50° to the shoreline. This orientation was similar to predominant storm waves and alongshore-current directions.
Goff et al. (2015) studied the impact that Super Storm Sandy had on the Schwab et al. (2014) study sites. They found that a steady migration of sediment bedforms was occurring over a long-time period, but much more rapid migrations occurred due to Sandy. They located swales and depressions that were not present prior to Sandy and the existing bedforms had migrated to the southwest. They also saw that bedforms rotated towards more acute angles with respect to the shoreline while they were active and attached to the shoreface. Modern theoretical models of sand ridge formation do not predict this behavior. However, it was accurately predicted in the kinematic model of Swift & Field (1981), which describes how sand ridges form at a non-orthogonal angle to the shoreline.

A study modeling the impacts of dredging in the US Gulf of Mexico and Atlantic continental shelves (Hayes & Nairn 2004) stated that concerns with repeated dredging of sediment shoals may eventually result in the ‘deflation’ of these features by permanently altering natural processes that maintain their forms. They also had concerns that during the development of monitoring protocols there was a limited ability to determine if there might be a limit beyond which the removal of sand from a ridge would lead to deflation of the bathymetric features by affecting wave pattern and velocities. These affects could lead to changes in long-shore and cross-shore sand transport patterns and changes in erosion and accretion rates.
METHODS

Multibeam sonar as a tool for bathymetric mapping and backscatter imaging is common place in marine research (Finkl et al. 2007; Wolfson et al. 2007; Goff et al. 2015; and references therein). Multibeam data were collected during two basic time intervals spaced 14-years apart. In April 2002, during an ONR mine burial and scour experiment, Kongsberg Simrad EM 3000 multibeam sonar data were collected aboard the R/V Suncoaster (Wolfson et al. 2007). The EM 3000 is a 300 kHz multibeam swath sonar that consists of 127 overlapping beams. The beams are 1.5° x 1.5°, which produces a swath of 130° perpendicular to the ships heading. Kongsberg Simrad states the vertical uncertainty of the EM 3000 sonar is 5-10 cm (root-mean-squared error). Wolfson et al. (2007) estimate a seafloor depth position uncertainty of ±10 cm during their survey using an RTK base station in Clearwater Beach. In June 2016 a Reson 7125 200/400 kHz multibeam sonar was used aboard the R/V Weatherbird. The 400 kHz mode was used in this study. The sonar has 512 beams in the 400 kHz mode and a swath width of 140° to 165°. The vertical and positional positioning is estimated to be comparable (0.9 m) to the estimates above using Applanix POS/MV 320 position and motion system and a subscription RTK service.

The data were processed using CARIS Hips and Sips 10.1. Prior to processing, tidal information from the survey areas was calculated using the MLLW chart datum. Wolfson et al. (2007) determined that there was a tidal offset from the tide station at NOAA Clearwater Station 8726724 to the study site by making use of deployed pressure sensors at the study site. In order to compensate for this offset, an amplitude factor of 0.94 and a phase lag of 4 minutes were applied to the NOAA tide record. This modified tide record was then used to reprocess of the original and new multibeam bathymetry data.
Once the tide corrections were applied to the data, bathymetry maps were created for April 2002 (Figures 7 and 8) at a horizontal grid cell spacing of 0.1 m and the data from June 2016 (Figure 9) at a horizontal grid cell spacing of 0.1 m. Backscatter images were then created for all of the surveys. The original data has a horizontal grid cell spacing of 5.0 m (Figure 10) for the entire survey area and a grid cell spacing of 0.2 m (Figure 11) for the comparison area. The new data has a horizontal grid cell spacing of 0.2 m (Figure 12) for comparison to the original data. Backscatter data in this area were shown to be useful to identify sediment and limestone (Hafen 2001; Harrison et al. 2003).

After processing the multibeam data in CARIS, these data were then imported into QPS Fledermaus software for analysis. The bathymetric maps and backscatter images from 2002 were compared with those from 2016 to determine if the sediments have moved significantly over time. The 2002 bathymetry data were subtracted from the 2016 data to determine if any sediment migration occurred after mine-like objects were removed after 14 years (Figure 13). Total volume removed after the dredging operation can also be determined from Figure 13.

Three areas of interest from the 2002 and 2016 bathymetry and backscatter data (Red, Green, and Blue boxes in Figures 11 and 12) were compared. Changes in area of weak backscatter (presumably siliciclastic sediments) were calculated by subtracting the 2002 areas from the 2016 areas. This was done to investigate net horizontal changes of sedimentary boundaries. Changes in volume calculations were made to investigate overall sediment volume change in the Red Box (Figure 14, 15, and 16), Green Box (Figure 17, 18, and 19), and Blue Box (Figure 20, 21, and 22). Volume change was calculated by subtracting the 2002 bathymetric data in the areas of interest from the 2016 bathymetric data in the same area. Calculating volume per meter squared to allow each area to be normalized so that rates of sediment volume change could be determined from these three areas.

Geological interpretations for 2002 and 2016 (Figures 23 and 24) were created after analyzing the bathymetry and backscatter. Slope figures (Figures 25 and 26) were created to help define the morphology of the study site. The slope figure for 2016 (Figure 26) clearly defines the
area of the dredging operations. The final bathymetric maps, backscatter images, and slope figures were imported into ArcMap 10.2 and provide co-registered geologic interpretations for each time period. This co-registration allows for direct comparisons to be made. For example, the comparison of the 2016 interpretation with the 2002 backscatter shows the changes in the sediment pattern (Figure 27).
RESULTS

Overall description of surveys

The 2002 0.2 X 0.2 m EM 3000 (300 kHz) multibeam bathymetry data

The deepest part (20.3 m) of the survey area is farthest from shore and the shallowest section (9.3 m) is closest to shore, along the top of a broad ridge (Figure 7). There are two major ridges that are visible in the survey area. These ridges, with an average depth of ~14 m have an average relief of 1.5 m. These ridges are visible in the bathymetric map (Figure 7) but are also defined by low backscatter data (Figure 10). The deeper areas appear to correlate to strong backscatter areas. The peak-to-peak spacing of the two sediment ridges is ~3500 m and the parallel crests strike in a NW-SE direction, with the deepest troughs being farthest from shore.

The 2002 5 X 5 m EM 3000 (300 kHz) multibeam backscatter data

The strong backscatter areas cover approximately 60% of the survey area (Figure 10). The strong backscatter is interpreted to be hard bottom or large clastic debris, i.e., limestone or large shell hash (Locker et al. 2002; Harrison et al. 2003; Hine et al. 2003; Finkl et al. 2007). The low backscatter is interpreted to be soft bottom, i.e., medium to fine grained sediments. The low backscatter locations correspond to the sediment ridges visible in the bathymetric map of the area (Figure 7). There are also small, enclosed areas of low backscatter, surrounded by large areas of high backscatter. These enclosed areas are interpreted to be pockets of trapped sediment in the rough karst surface.
This survey (Figures 9) covers a smaller area than the 2002 survey and is shown as the black polygon in Figure 7. The minimum depth of the survey is 10.5 m, which is in the SE corner, closest to shore. The maximum depth is 16.6 m; the deepest section of the survey was in the northern part, farthest from shore. The bathymetry of the area is uniformly shallower through the middle of the survey. This shallower area relates to the broad NW-SE oriented ridge observed in the 2002 survey (Figure 7). A very distinct unnatural, dredging feature is observed in the southern area of this survey (Figure 9 and outlined as a red polygon in Figures 7 and 10). The average depth of dredging below the original seafloor is between 0.8 and 2.4 m (Figure 13). The cut has clearly defined edges where visible within the survey area when viewing the slope figure and depth difference figure (Figures 13 and 26). The dredging cut covers an area of 0.95 km² (Figures 7, 13, and 26).

The low backscatter covers approximately 80% of the survey area (Figure 12), which overlies the sediment ridge in the southern part of the 2002 survey (Figure 7, 10, and 23). The mid-strength backscatter data are interpreted to be coarse shell hash. The strong backscatter is interpreted to be limestone. These very strong backscatter areas appear in the most northern and southern points of this survey and correspond to the troughs between the sediment ridges in Figures 7 and 10 and the mid-strength backscatter appears within narrow crevices visible within the low backscatter areas. The dredging cut, visible in Figures 9, 13, and 26, is also visible as slightly stronger backscatter (Figure 12).
Geologic Interpretations

Geologic interpretations of the multibeam bathymetry and backscatter data from 2002 and 2016 are shown in Figures 23 and 24. Interpretations from previous studies in this area were used as a reference (Edwards et al. 2003; Harrison et al. 2003; Locker et al. 2003). Strong backscatter returns were interpreted as limestone, mid strength backscatter returns as coarse shell hash and weak backscatter returns as fine to medium-grained sediments. The dredging cut is visible in the center of the weak backscatter area where stronger returns now are visible compared to the 2002 data.

Results for Question A: How mobile is the sediment on the limestone?
Hypothesis: The sediment ridges in the study site have not migrated significantly over the limestone hard bottom during the 14-year time period (Hafen 2001; Edwards et al. 2003).

Comparison of 2002 and 2016 surveys
Bathymetry Comparison

A surface change was created (Figure 13) by subtracting the 2002 bathymetry from the 2016 bathymetry to determine the changes in depth over the time period. The dredging increased the depth between 0.8 and 2.4 m. This range is within the depth increases estimated by the environmental assessment of the beach renourishment project (1-2 m) (USACE 2011)

Slope was calculated for both 2002 and 2016 (Figures 25 and 26). These figures show that the area is relatively flat, with a maximum calculated slope of 5° observed on the edges of the sediment ridges, along the dredge cut, and in limestone areas a slope of 0°-2° is observed along the central flat part of the sediment ridges (green areas in both figures). The slopes from the 2016 survey (Figure 26) are similar to the 2002 survey (Figure 25). Both surveys are relatively flat, except for edges related to dredging. For both surveys, rugosity values were found
to be between 1.0 and 1.01, which show the seafloor in this area is generally smooth. This finding is consistent with the slope and backscatter patterns (Figures 25, 26, 10, 11, and 12).

**Back Scatter Comparison**

Comparing the backscatter data from 2002 and 2016 (Figure 10, 11, and 12) cannot be done in a quantitative sense, because they were collected using different multibeam frequencies causing backscatter values not to correlate. However, a rough qualitative comparison can be made (in terms of strong verses weak backscatter response).

The same basic backscatter features are visible in both surveys (Figures 11 and 12). The dredging cut is subtly visible in the 2016 survey (Figure 12), with a small increase in backscatter intensity in the dredging cut area. This slightly stronger response indicates that a stronger backscatter layer has been exposed after the removal of the overlying sediment. This underlying layer is interpreted to be compacted sediment (Figures 10, 11, and 12). The shape and overall position of small dark chasm’s in both the 2002 and 2016 surveys correlate well (see green box in Figures 11 and 12). However, these narrow areas of high backscatter extend further into the low backscatter area in the 2016 survey (Figure 12). These narrow areas are interpreted to be shell hash and possible limestone farthest from the dredging cut (Figures 11 and 24).

**Red Box area of interest**

The Red Box is located towards the northern edge of the 2016 and the 2002 comparison backscatter image (Figure 14). It covers an area of 28,856 m², with a very visible area of low backscatter in the center, surrounded by an area of high backscatter. The shape of both the high and low backscatter in this area has changed over the 14 year time period. The yellow and red lines on the backscatter images outline this, red denotes the 2016 outline and yellow the 2002 outline. The areas within these lines for both the 2002 and 2016 surveys were calculated, giving an area for 2016 of 19,082 m² and an area of 15,417 m² for 2002 (Table 3). An area change
calculation between these areas in the 2016 and 2002 surveys gave a net loss of low backscatter, sediment area of \(-3,665 \, \text{m}^2\) over the 14 years between surveys. The difference in volume between the bathymetry maps of 2002 and 2016 (Figure 15) of the area was taken to calculate the volume sediment loss for the area (Figure 16). This gave a total volume loss of \(7589 \, \text{m}^3\) between the surveys (Table 3). This result was then used to calculate volume per square meter, in order to compare with the losses in the Green and Blue boxes. The volume per square meter result for the Red Box is \(0.26 \, \text{m}^3 / \text{m}^2\) (Table 3).

**Green Box area of interest**

The Green Box is located towards the eastern edge of the 2016 and the 2002 comparison backscatter image (Figure 17). It covers an area of \(226,406 \, \text{m}^2\), with a very visible area of low backscatter in the center, surrounded by an area of high backscatter. The shape of both the high and low backscatter in this area has changed over the 14 year time period. The yellow and red lines on the backscatter images outline this, red denotes the 2016 outline and yellow the 2002 outline. The areas within these lines for both the 2002 and 2016 surveys were calculated, giving an area for 2016 of \(91,113 \, \text{m}^2\) and an area of \(94,694 \, \text{m}^2\) for 2002 (Table 3). An area change calculation between these areas in the 2016 and 2002 surveys gave a net loss of low backscatter, sediment area of \(-3,581 \, \text{m}^2\) over the 14 years between surveys. The difference in volume between the bathymetry maps of 2002 and 2016 (Figure 18) of the area was taken to calculate the volume sediment loss for the area (Figure 19). This gave a total volume loss of \(20,039 \, \text{m}^3\) between the surveys (Table 3). This result was then used to calculate volume per square meter, in order to compare with the losses in the Red and Blue boxes. The volume per square meter result for the Green Box is \(0.08 \, \text{m}^3 / \text{m}^2\) (Table 3).
**Blue Box area of interest**

The Blue Box is located towards the southern edge of the 2016 and the 2002 comparison backscatter image (Figure 20). It covers an area of 189,843 m\(^2\), with a very visible area of high backscatter in the center, surrounded by an area of low backscatter. The shape of both the high and low backscatter in this area has changed over the 14 year time period. The yellow and red lines on the backscatter images outline this, red denotes the 2016 outline and yellow the 2002 outline. This area within the Blue Box is different from that in the other areas of interest as the low backscatter, sediment is located outside of the outlines rather than inside. The dredging area is visible at the northwestern edge of the area and as this sediment was artificially removed is not used in the further calculations. The areas within these lines for both the 2002 and 2016 surveys were calculated, giving an area for 2016 of 178,646 m\(^2\) and an area of 181,916 m\(^2\) for 2002 (Table 3). An area change calculation between these areas in the 2016 and 2002 surveys gave a net loss of low backscatter, presumed to be sediment, of -3,270 m\(^2\) over the 14 years between surveys. The difference in volume between the bathymetry maps of 2002 and 2016 (Figure 21) of the area was taken to calculate the volume sediment loss for the area (Figure 22). This gave a total volume loss of 48,678 m\(^3\) between the surveys (Table 3). This result was then used to calculate volume per square meter, in order to compare with the losses in the Green and Blue boxes. The volume per square meter result for the Blue Box is 0.256 m\(^3\) / m\(^2\) (Table 3).
Results for Question B: What sedimentary changes occurred following 2002 and 2003 deployments of mines for an Office of Naval Research project?

Hypothesis: There is no change in sediment volume where the mine-like object were placed and removed after the ONR mine burial experiment.

The dredging operation prevents addressing the original question. However, the areas unaffected by dredging appear to have remained mostly unchanged. Examining the area during the ONR mine experiment (Table 2 and Figure 8), one can see scour and sinking of the elongated A3 mine (Wolfson 2005; Wolfson et al. 2007), visible in the final survey of the project prior to the removal of the mine and other objects. One of the inert mine-like objects in one of the surveys was not recovered at the end of the experiment. While analyzing the 2016 survey (Figure 9), within the dredging cut, an unidentified object is visible 267 m west of the southern mine experiment site (Figure 28) at a depth of 15 m at position 27° 57.8392’ N 83° 02.9167’ W. The object has a length of 2 m and a width of 1 m with a larger scour pit surrounding the object (Figure 28). This unusual object is discussed further in the discussion section.

Results for Question C: How much sediment was removed during a 2012 dredging operation and how closely does it compare to the Army Corps of Engineers’ reported estimate?

Hypothesis: Changes in sediment volume between 2002 and 2016 will match the amount estimated by the Army Corps of Engineers who dredged the area.

The subtraction of the 2002 survey from the 2016 survey shows the depth change created by the dredging operation (Figure 13). The depth difference is between 0.8 and 2.4 m. This depth change is within the limits specified in the environmental assessment undertaken for the Sand
Key beach renourishment project (USACE 2011) that was between 1 m and 2 m of sediment would be removed from the site. The area of the dredging cut was measured to be 0.95 km² in the area of the survey (Figures 13 and 26). The environmental assessment estimated that 1.25 million cubic yards of sediment were removed from the site. Subtracting the 2002 survey from the 2016 survey gives a volume of 800,613 m³ (1,047,162 cubic yards) (Table 1). This result gives a difference of 155,204 m³ (203,000 cubic yards) or a 16% less volume of sediments than reported by the Army Corps of Engineers (USACE 2011).
DISCUSSION

Geological Interpretations

The geological interpretations for both 2002 and 2016 (Figures 23, 24, and 27) show that the sediment ridges are primarily composed of fine-to-medium grained sediments and that the troughs between the ridges were primarily limestone or coarse shell hash. The slopes (Figures 25 and 26) and rugosity of 1.0 – 1.01 show that the area is relatively flat and smooth. This correlates with findings of other studies in the area (Locker et al. 2002; Harrison et al. 2003; Finkl et al. 2007), which describe the substrates in the area as a primarily flat area of fine-to-medium grained sediment and limestone. The wide and flat sediment ridges and toughs are consistent with low slope values. The most obvious feature difference between the surveys is the 2012 dredging cut visible in the 2016 bathymetry and slope figures (Figures 9 and 26). The dredging removed between 0.8 m and 1.4 m of sediment (Figure 13). A slight change in backscatter return was noticed in the dredging cut area between 2002 and 2016. The increase of depth and increase in backscatter intensity indicates that the sediment was removed and the underlying sediment was most likely roughed up from the dredging process and possibly composed of some shell hash.

Sediment mobility

In general, the features visible in the 2002 survey are visible in the 2016 and match up relatively well in position, relief, and depth. These show that the major features of the study site such as the sediment ridges have not migrated significantly over the 14-year time period. The bathymetric
change (Figure 13) shows that there has been very little depth and relief change over the survey area, excluding the dredging cut. However when looking at finer details, some changes are visible in both the bathymetric maps and the backscatter images between the 2002 and 2016 surveys.

There are local features that have changed their morphology over the time period. These features are best seen in the backscatter images (Figures 11 and 12) where intrusions of strong backscatter, now interpreted as limestone or coarse shell hash (Harrison et al. 2003; Hine et al. 2003; Locker et al. 2003) are visible in both surveys (Red, Green, and Blue boxes in Figures 11 and 12). However, these intrusions are much more pronounced in the 2016 survey (Figure 12) suggesting some sediment loss or migration has occurred in these areas. Looking at each of them in more detail it is clear that sediment loss has occurred and a loss rate per year was calculated. The Red Box (Figures 14, 15, and 16) had a sediment area loss of -3,665 m$^2$ and sediment loss of 0.263 m$^3$ per square meter, during the 14 year time period. The Green box (Figures 17, 18, and 19) showed very similar total area change as the Red box with a sediment loss area of -3,581 m$^2$, but only had a negligible sediment loss of 0.080 m$^3$ per square meter, during the 14-year time period. The Blue box (Figures 20, 21, and 22) again showed similar changes as the Red box with a sediment area loss of -3,270 m$^2$ and a 0.256 m$^3$ per square meter during the 14 year time period.

Previous studies (Hafen 2001; Harrison et al. 2003) noted that the migration and change in sediment occurred on the northern edges of the sediment ridges. The Red box area, situated along the northern edge of a wide sediment ridge, had the greatest change in sediment volume per square meter. Yet, the Green box, which is also on the northern edge of the ridge, but closer to the dredging area, does not show the expected large changes predicted by the previous studies. The Blue box on the southern edge of the ridge and closest to the dredging area, has a sediment volume loss much more similar to the Red box, also inconsistent with the observations of
previous work. Although the dredging may not have had a direct impact on these areas of interest, it is documented that the impact of dredging sediment ridges has an impact on the hydrodynamics of the water and currents close to the sea floor (Hayes & Nairn 2004). This change in hydrodynamics could lead to changes in long-shore and cross-shore sand transport patterns. These hydrodynamic changes could account for the difference between the Red and Green areas, as well as inconsistencies with previous studies (Hafen 2001; Harrison et al. 2003). Although sediment loss and movement has been noted to occur over these 3 specific areas, it is not known where this sediment has migrated. Previous studies show that the currents in this area flow in a north-south direction (Hafen 2001; Harrison 1996) and that this shelf area is sediment starved with little input of new sediment (Harrison et al. 2003; Locker et al. 2003). From this information, it is assumed that the lost sediment from the three areas of interest migrated either north or south from their original positions over the 14-year time period.

This analysis supports the hypothesis that the sediment ridges in the study site have not migrated significantly over the limestone hard bottom during the 14-year time period, although within the 3 areas of interest tested, there was visible sediment migration, however the exact direction and ultimate fate of this sediment is unknown. Limited back and forth migration, in a north-south direction is expected to be primarily tidal current dominated because the study site is in 9 m to 20 m water depth, where most surface waves will not often interact with the substrate (Hafen 2001; Harrison et al. 2003). However, between 2004 and 2005 many hurricanes passed by this area with large surface waves. However, winter extratropical storms are most likely the cause of this sediment movement (Edwards et al. 2003; Hafen 2001; Harrison et al. 2003; Locker et al. 2003). With the length of the time period and the number of hurricanes that pass through the area, more sediment ridge migration would be expected as was seen in similar water depths of 8 m to 25 m near Fire Island, NY that was directly impacted by Hurricane Sandy causing upwards of 70 m sediment migration (Goff et al. 2015), although this was on a continental shelf not a carbonate platform. The main difference of these two sights is that the broad shallow West
Florida Shelf prevents large amplitude swells from reaching shore. Thus, the overall shelf geometry and slope appears to play an important role on sediment transport versus depth alone.

The hypothesis related to the ONR mine burial and scour study was not possible to test fully due to the 2012 dredging event, except in some very small limited areas, which showed no substantial change. However, an unidentified object may have been uncovered by the dredging operation (Figure 17). It lies 267 m west of the southern most experiment site at a depth of 15 m and at the edges of the dredging. This object was determined not to be a mine-like object, as its profile differs from what would be expected by a mine-like object (Figure 17). Because of this, it remains unknown as to what this object is. But looking at the profile it has, it could be a sunken boat. Visual inspection by SCUBA or video would reveal the identity of the object.

In the environmental assessment prior to this project commencing, it was stated that 1.25 million cubic yards of sediment would need to be dredged to obtain 800,000 cubic yards of sediment to renourish the beaches of Sand Key. These 1.25 million cubic yards would take into account sediment lost due to re-suspension and drainage of water from the dredge. The bathymetric difference (Figure 11) show that the depth of the dredging cut had an average depth difference between 0.8 and 2.4 m compared to the base surface. The dredging cut covers 0.95 km². The statistical comparison gave a volume difference 16% less than the estimated volume from the environmental assessment (USACE 2011). The overall dredging cut area may extend farther southwest of the southwestern edge of the 2016 survey. This possible larger dredging area may account for the 16% difference in the results.

Nonetheless, as the original estimate and the volume comparison between the 2002 and 2016 surveys are within 16% of each other supports the hypothesis that the sediment volume change between 2002 and 2016 approximately matches the amount estimated by the United States Army Corps of Engineers with the uncertainty of the existing data constraints. To fully test the hypothesis, a multibeam survey extending further southwest to cover the complete dredging area would be needed.
Preliminary Effort in Using Remote Sensing Data to Investigate Sedimentary Bedforms

A preliminary effort of using of satellite optical data to study these sedimentary ridges was undertaken to determine its effectiveness. Satellite optical data have been primarily used to supplement traditional field techniques used in geologic mapping rather than being the primary method, because of the higher resolution of multibeam sonars (Lyzenga 1978; McIntyre et al. 2006) and because of the complications due to combined atmospheric, water, and bottom signals that affect satellite optical data (Jerlov 1976). With the introduction of more modern high-resolution multispectral sensors, light that is reflected from the seafloor can be spectrally deconvolved and used to gather information on the benthos (Bierwirth et al. 1993; Werdell & Roesler 2003). Models and programs used to extract and interpret remote sensing data are improving and becoming more effective in separating the optical signals. Estimation of bottom depths are becoming more accurately (Lee et al. 1999; Hu 2008).

A possible question that can be addressed comparing satellite remote sensing and multibeam data is, how well does remote sensing measure sediment transport or geomorphological changes?

Using processed MERIS data (250 m x 250 m pixel resolution) and raw, unprocessed Worldview-2 data (0.5 m x 0.5 m pixel resolution) a brief study of results over the study site was undertaken. Analyzing the MERIS derived bathymetry image (Figure 29), depths ranging from 10 m to 25 m with increasing depth with distance from shore. This depth range is similar to the 10-20 m depth range in the 2002 multibeam survey (Figure 5). The fact that the noisy MERIS and multibeam bathymetry both show similar depths supports the hypothesis that these data may be used to monitor sediment transport with additional processing or smoothing but only on very large spatial scales. The sediment ridges and troughs visible in the multibeam data are not significantly visible in the noisy MERIS data (Figures 7 and 29). For these features to be visible,
more processing or, more importantly, higher resolution data are needed. New satellite remote sensing data, such as that from WorldView-2 (Figure 30), with a resolution of 0.5 m x 0.5 m should show these broad ridge features.

Although the 250 m x 250 m pixel MERIS data provide a 10-25 m depth range close to the multibeam bathymetry depth range of 10-20 m, it is still too noisy and too low in resolution to be useful to measure sediment volume or depth changes. However, the higher resolution (0.5 m x 0.5 m) WorldView-2 data should yield more promising results based on analysis of the raw unprocessed data. After processing, it might provide sufficient resolution to measure sediment volume change. This analysis did not precede further due to lack of time and available data without apparent water turbulence issues. However, future work in this area appears warranted.

**Future Work**

The main focus of possible future work will be to collect more acoustic and satellite optical data over this study site, and to the north and south of the 2016 survey site, to further investigate the direction of sediment migration. These new data should be collected at more frequent time intervals, on a yearly basis if possible, so that migration of the sediment can be observed more accurately. The other focus of future work will be to survey the dredging area again and extend the survey further to the west to determine the western edge of the survey so that a more accurate estimate of sediment volume removed during the dredging operation can be determined. This extended survey could address the missing 16% between the USACE estimate and the calculated dredging volume in this study.
CONCLUSIONS

The multibeam bathymetry and backscatter comparisons between the 2002 and 2016 survey revealed that overall, there was not significant sediment migration over the limestone during the 14-year time period. The sediment ridges and limestone are visible in both surveys and the depths of the surveys are within 0.1 m of each other showing that little change has occurred. A geologic interpretation of the area covered in 2002 and 2016 is provided, outlining three major areas, showing strong backscatter returns as limestone bedrock, intermediate returns are coarse shell hash and weak returns as fine to medium-grained sediments. These results are similar to those found by other studies in the area. The dredging cut from 2012, obvious in the 2016 survey, also removed a significant portion of the sediment ridge associated with The Office of Naval Research (ONR) mine burial and scour experiment. Three specific areas of interest surrounding the dredge area were found to have changed shape between the 2002 and 2016 surveys. The Red box showed a sediment area change of -3.665 m$^2$ and a volume change of 0.263 m$^3$/m$^2$. The Green box showed a sediment area change of -3.581 m$^2$ and a volume change of 0.080 m$^3$/m$^2$. The Blue box showed a sediment area change of -3.270 m$^2$ and a volume change of 0.256 m$^3$/m$^2$. These areas displayed sediment loss over the time period, however, the direction and position of this lost sediment is unknown. The change in hydrodynamics of the sediment ridge as a result of the dredging operation will have influenced the migration of sediment within these areas. An unidentified object with large scour pit was uncovered by the dredging operation, 267 m west of the southern most original ONR mine burial and scour study site.
The statistical volume comparison between the 2002 and 2016 bathymetric surveys gave a sediment volume difference of 800,613 m$^3$. This difference is within 16% less than the original estimate. This shortage may be, in part, due to the 2016 survey may not fully encompass the dredging cut towards the southwest. Additional annual acoustic and satellite optical data surround this perturbed area of dredging, may lead to a more accurate assessment of sediment transport.
REFERENCES


Table 1: Statistical results from the comparison between the 2016 and 2002 multibeam surveys showing volume and depth change in the dredging cut. Yellow highlighted column shows the sediment volume that was removed during the dredging operation.

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<th>Area (m²)</th>
<th>Slope (%)</th>
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<th>Overdredge allowance (m)</th>
<th>Minimum change (m)</th>
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<td>0.000</td>
<td>45954.279</td>
<td>1413878.736</td>
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<tr>
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<td>45954.279</td>
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<td>1413878.736</td>
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Table 2: Deployment position coordinates of equipment used in the 2003 Office of Naval Research mine burial and scour experiment.

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Table 3: A. Areas and area change for the Red, Green, and Blue Boxed areas of interest for the 2002 and 2016 surveys with an uncertainty of 0.1 m² for the 2002 data and 0.09 for the 2016 data. The larger, 2002 uncertainty was used for calculations. B. Total areas, Total Volume change and the volume change per square meter for the Red Green and Blue Boxes areas of interest for the 2002 and 2016 surveys.

<table>
<thead>
<tr>
<th></th>
<th>Red Box</th>
<th>Green Box</th>
<th>Blue Box</th>
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<tbody>
<tr>
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</table>
Figure 1: Map of Florida showing the West Florida Shelf. The location of Florida within the United States, inset. Box shows the overall location of the study site.
Figure 2: Areas of previous studies relating to sediment and shelf morphology near Tampa Bay (modified from Harrison et al. 2003) with the 2002 survey shown in green.
Figure 3: Side-scan mosaic and location of chirp sonar lines near the 2002 ONR survey site, which is due west of this site. Line A-A’ follows. Modified from Edwards et al. (2003).
Figure 4: Seismic line A-A’ located within the sand-ridge field. Illustrating the poor acoustic contrast between the overlying sediments and the underlying rock using lower-frequency data and chirp sonar. Below is an interpretation of the sand ridge facies over the tertiary limestone, visible in the troughs. Modified from Edwards et al. (2003).
Figure 5: Bathymetry from the 2002 survey with the 2012 dredging area outline (red) and the 2016 survey site outline (black). This map has a grid cell spacing of 0.2 m. The deepest depth is 17.2 m and the shallowest depth is 9.8 m.
Figure 6: Zoomed in area from Figure 1 showing the West Florida Shelf off the coast of Clearwater, Pinellas County, FL. The outline of both the 2002 and 2016 survey sites are shown in the figure. The larger 2002 survey (blue) encompasses the 2016 survey (black line).
Figure 7: Bathymetric map from the entire 2002 Kongsberg EM 3000 (300 kHz) multibeam survey, at 5.0 m grid cell spacing. The 2002 comparison area (yellow), the 2016 survey area (black), and the dredging cut (red) are outlined in the figure. The deepest depth in the survey is 20.3 and the shallowest depth is 9.3 m atop the sediment ridge.
Figure 8: Multibeam bathymetry of the 2003 mine burial study area (Wolfson, 2005; Wolfson et al., 2007). The black dashed lines represent the ship track during the survey. White outlines are scaled to the actual dimensions of the deployed equipment.
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Figure 10: Multibeam backscatter intensity image from the 2002 survey area collected using a Kongsberg EM 3000 (300 kHz) multibeam. This image has a grid cell spacing of 5.0 m. Light grey denotes low intensity, soft bottom and dark grey denotes high intensity, hard bottom. The comparison area (yellow), 2016 survey (black), and the dredging cut (red) are shown.
Figure 11: Multibeam backscatter intensity image from the 2002 survey within the comparison area collected using a Kongsberg EM 3000 (300 kHz) multibeam system. This backscatter has a grid cell spacing of 0.1 m. Light grey denotes low intensity, soft bottom and dark grey denotes high intensity, hard bottom. The green and red boxes show areas of interest in sediment mobility.
Figure 12: Multibeam backscatter intensity image from the 2016 survey collected using a Reson 7125 (400 kHz) multibeam system. This backscatter has a grid cell spacing of 0.1 m. Light grey denotes low intensity, soft bottom and dark grey denotes high intensity, hard bottom. The dredging cut is visible in the center of the survey below the green box. The green and red boxes show areas of interest in sediment mobility.
Figure 13: Bathymetric change resulting from subtracting the 2016 survey (Figure 9) and the 2002 survey (Figure 5) to determine the sediment volume change from the dredging operation in 2012. The depth change ranged 1.3 m change to -2.4 m change, with the dredging cut depths being 0.8 m to 1.4 m.
Figure 14: 0.2 m Backscatter image of the Red Box area of interest, with the 2016 survey on the left and the 2002 survey on the right. The red and yellow lines define the outline of the strong to weak backscatter for the 2016 and 2002 surveys, respectively.
Figure 15: 0.1 m Bathymetric map of the Red Box area of interest, with the 2016 survey on the left and the 2002 survey on the right. The red and yellow lines define the outline of the strong to weak backscatter for the 2016 and 2002 surveys, respectively.
Figure 16: Bathymetric change resulting from subtracting the area within the Red Box of the 2016 survey (Figure A7) and the 2002 survey (Figure A3) to determine the sediment volume change within this area. The depth change ranged 1 m change to -1 m change.
Figure 17: 0.2 m Backscatter image of the Green Box area of interest, with the 2016 survey on the left and the 2002 survey on the right. The red and yellow lines define the outline of the strong to weak backscatter for the 2016 and 2002 surveys, respectively.
Figure 18: 0.1 m Bathymetric map of the Green Box area of interest, with the 2016 survey on the left and the 2002 survey on the right. The red and yellow lines define the outline of the strong to weak backscatter for the 2016 and 2002 surveys, respectively.
Figure 19: Bathymetric change resulting from subtracting the area within the Green Box of the 2016 survey (Figure A7) and the 2002 survey (Figure A3) to determine the sediment volume change within this area. The depth change ranged 1.2 m change to -1.79 m change.
Figure 20: 0.2 m Backscatter image of the Blue Box area of interest, with the 2016 survey on the left and the 2002 survey on the right. The red and yellow lines define the outline of the strong to weak backscatter for the 2016 and 2002 surveys, respectively. Visible in the northwestern corner of the 2016, left survey is the southern edge of the dredging cut. This area was not included in calculations.
Figure 21: 0.1 m Bathymetric map of the Blue Box area of interest, with the 2016 survey on the left and the 2002 survey on the right. The red and yellow lines define the outline of the strong to weak backscatter for the 2016 and 2002 surveys, respectively. Visible in the northwestern corner of the 2016, left survey is the southern edge of the dredging cut. This area was not included in calculations.
Figure 22: Bathymetric change resulting from subtracting the area within the Blue Box of the 2016 survey (Figure 9) and the 2002 survey (Figure 5) to determine the sediment volume change within this area. The depth change ranged 0.78 m change to -1.82 m change. Visible in the northwestern corner of the 2016, left survey is the southern edge of the dredging cut. This area was not included in calculations.
Figure 23: Geologic interpretation of the 2002 backscatter image. The key shows the geologic interpretation.
Figure 24: Geologic interpretation of the 2016 backscatter image. The key shows the geologic interpretation.
Figure 25: Slope of the 2002 survey area. The maximum slope in the survey is 5° and the lowest is 0°. The highest slope is found on the sides of the sediment ridges and the lowest on the top of the sediment ridges. Slopes may be greater but are smoothed due to 5 x 5 m grid. ROV video from the 2003 ONR project has shown relief near vertical scarps in the limestone and low relief bedforms on the sediment ridges. The 2002 comparison area (yellow), 2016 survey (black), and the dredging cut (red) are shown.
Figure 26: Slope of the 2016 survey area. The maximum slope in the survey is 5° and the lowest is 0°. The highest slope is found on the edges of the dredging cut and the lowest found inside the dredging cut and on top of the sediment ridges.
Figure 27: Geologic interpretation of the 2016 survey compared to the backscatter data from 2002. The key shows the geologic interpretation. The interpretation from 2016 overlies the 2002 backscatter image to show the change over time. Grey represents strong backscatter, hard bottom and white represents weak reflectance, sediments.
Figure 28: A 2 m long unidentified object visible in the 2016 survey that was uncovered by the 2012 dredging operation. The depth profile of the object and the surrounding scour pit are visible. Artifacts are present inside the black polygon. Insert: Cross section of the unidentified object along the black line.
Figure 29: MERIS absolute depth encompassing the 2002 survey area. Image has a grid cell spacing of 250 m. The deepest depth is 24.1 m and the shallowest depth is 7.6 m. The depths range within the 2002 multibeam bathymetry is from 20.3 m to 9.3 m (inside yellow polygon). The MERIS depth range within the yellow polygon is from 10 m to 20 m. Although similar in depth range, the NW-SE ridge structures are not visible in this MERIS data image.
Figure 30: Raw, unprocessed WorldView-2 data from August 12th, 2016 showing digital numbers that can be used to calculate radiance and reflectance. Depth estimates will be possible after data processing.