Substrate and Subsurface Mapping of Naples Bay Using Geophysical Techniques: Implications for Oyster Reef Restoration

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Executive Summary

The characterization of an estuary's sedimentary substrate is an important and necessary component of any restoration effort. In Naples Bay, an estuary in Southwest Florida where restoration projects are pending, the substrate affects the distribution of a critical valued ecosystem, oyster reefs. Unfortunately, mapping of the substrate cannot be accomplished visually because the estuarine waters are generally opaque due to dissolved organics and suspended sediment. Substrate characterization, however, can occur remotely using geophysical acoustic technologies (side-scan sonar and CHIRP). The purpose of this study was to employ these two geophysical instruments to characterize the substrate and shallow sub-bottom of Naples Bay and its neighboring waterways (Dollar Bay, Gordon River, Rock Creek, Haldeman Creek, and Gordon Pass) to aid in future oyster reef restoration planning. Substrate maps were generated for the entire study area using side-scan sonar, and subsurface acoustic profiles were produced using CHIRP for selected tracks within these estuaries. Sediment grab samples were taken throughout the study area; grain size distributions were obtained using a Malvern laser particle size analyzer; these results were used to calibrate the side-scan images against substrate type.

Six types of signals were recognized from the side-scan sonar surveys throughout the study region. These correspond to the following types of substrates: (1) sandy mud; (2) muddy sand; (3) sand; (4) oyster reefs; (5) low density oyster shell; and (6) anthropogenic structures (channels and bulkheads).

Northern Naples Bay is relatively mud-rich due to suspended sediments delivered through the Gordon River and from a number of boat canals alongside the eastern margin of the bay. Three subtidal oyster reefs are found here, and these are surrounded by sand-rich substrates indicating the importance of a coarser, traction-transported sediment for reef foundation. Other areas of muddy sand exist elsewhere in northern Naples Bay; these could serve as oyster reef substrate in future restoration efforts. Bulkheads or docks are common along both the eastern and western margins of northern Naples Bay, meaning that little potential for future development of fringing oyster reefs exists. A mud-rich region exists in the southern half of Naples Bay; this may indicate a

downstream spatial shift in the turbidity maximum zone due to freshwater inundation from the Golden Gate Canal.

Southern Naples Bay and Haldeman Creek have more natural substrate conditions due less prolific development along the bay's eastern margin. Side-scan sonar located fringing oyster reefs along this side of the southern bay. In addition, areas of low density oyster shell are found within and along the margins of the southern-most region of southern Naples Bay. These represent areas of former productive reef growth. Expansive regions of sand and shelly substrate exist for future reef restoration, however. Haldeman Creek delivers enough freshwater to provide the ideal brackish water salinities for oyster reef development, and fringing reefs are still found along the eastern edge of the creek's mouth. Within the central portion of Haldeman Creek's mouth, a sandy delta exists. Though this substrate is coarse, the high mobility of these sands precludes reef development.

Dollar Bay is relatively mud free; sands and muddy sands compose most of the bay's subtidal floor. Oyster reefs, both fringing and isolated, and low density oyster shell substrate are found throughout much of the bay. Oyster reefs are conspicuously absent from the bay margins just south of Gordon Pass. Tidal flows may be too swift and salinities too high to support reef development here.

Finally, the lower reaches of Gordon River and Rock Creek support fringing oyster reefs, and this despite the pervasive freshwater influence.

Twenty four seismic CHIRP profiles were taken throughout the study region. Most of these exhibited no discernable features in the sub-bottom. Buried oyster reefs were conspicuously absent from all but one track. The majority of the reefs that formerly existed throughout Naples Bay were not buried by subsequent sedimentation, but rather were physically removed through dredging. Similarly, buried oyster reefs were not detected from the sub-bottom of Dollar Bay, yet numerous isolated and fringing reefs still exist.

The fringing reefs lining the eastern margin of southern Naples Bay and both margins of Dollar Bay exhibit structure within the sub-bottom. This indicates that a history of fringing reef development existed throughout the estuaries' evolution. Both these and the side-scan results underscore the importance of shoaling substrates along the bay margins for reef development.

Throughout the sub-bottom of northern Naples Bay, Gordon River, and Haldeman Creek exists a highly irregular surface with considerable vertical relief that represents an antecedent erosional topography generated prior to marine flooding and the creation the estuaries.

Acknowledgments

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Introduction

The restoration of Southwest Florida's estuaries is a major component of the Greater Everglades restoration effort. Locally in Collier and Lee Counties, the issue is of high priority, as reflected by the South Florida Water Management District's funding of its Watershed Initiatives (including the Naples Bay Initiative). Estuarine restoration cannot occur without a thorough characterization of the estuary's substrate. Many valued ecosystem components of Southwest Florida's estuaries are subtidal (e.g., sea grass beds, oyster reefs) and are therefore obscured from easy viewing. Because these estuarine waters are generally opaque due to dissolved organics and suspended sediments, a simple visual mapping of the substrate is not possible. Consequently, substrate characterization must occur remotely using acoustic technologies.

Restoration design and performance measure targeting also require an understanding of the pre-altered state of the estuary – knowing what the distribution of pre-alteration habitats was. This information was typically not recorded historically, but vestiges of those habitats may remain buried in the subsurface under a thin veneer of sediment. The distribution of oyster reefs is an excellent example. Oyster reefs generally form hummocky and hardened structures on the estuarine floor. After burial they can be recognized from sediment cores, but this type of investigation is costly, time consuming, and not geographically comprehensive. Alternatively, remote sensing, acoustic methods can be used to map structures in the shallow subsurface.

This study employed two remote sensing, acoustic, geophysical instruments for mapping: side-scan sonar for mapping the sedimentary substrate and shallow seismic CHIRP for profiling the subsurface immediately below the instrument. Both instruments were owned and operated by Dr. Dellapenna and his research assistants from Texas A&M University at Galveston. Side-scan sonar and CHIRP have been used successfully by Dr. Dellapenna for these same applications concerning oyster reef health and restoration problems in Texas (Bronikowski 2004). Additionally, the effectiveness of these tools was established for Naples Bay during a preliminary study conducted the previous year (Savarese et al. 2004a).

The study region of focus was Naples Bay, Collier County. Naples Bay is unduly influenced by freshwater as a point-source pollutant from storm-water management discharge from the Golden Gate Canal through the Gordon River. Although restoration design work has yet to occur, restoration science is being funded, through the Naples Bay Initiative and other, locally funded efforts, to fulfill scientific needs in preparation for restoration planning. This study provides substrate and shallow subsurface imaging of Naples Bay and its neighboring waterways (including Dollar Bay, Gordon River, Haldeman Creek, Rock Creek, and Gordon Pass).

Oyster reef habitat was prolific throughout Naples Bay prior to the onset of development in the 1950s. The total area of oyster reef has declined from a pre-alteration size of 50.7 to 12.4 acres (comparing aerial photographs from 1953 to those delineated in 2005; Schmid et al. 2006), a loss of 81.7% in area. Most of this was fringing oyster reef habitat located along the east and west shores of the middle region of northern Naples Bay and of southern Naples Bay (Schmid et al. 2006). Loss of this habitat was presumably due to a combination of both dredging and burial through non-reef sedimentation. Regardless, suitable habitat for future oyster recruitment and survival may still exist. Side-scan provides data on existing substrate sedimentology, allowing managers to forecast appropriate sites for future reef restoration. Additionally, CHIRP surveys are used to locate the existence of older reefs that have been subsequently buried by recent sediments.

Finally, in addition to the correct water quality, oyster reef development also requires appropriate sedimentologic conditions. Oyster larvae seek out coarse substrates (e.g., sands or shell gravels) and survive best on those substrates with minimal traction transport of sediment (Kennedy, 1996). Consequently, the restoration of water quality and quantity is not sufficient to ensure reef formation. The right substrate must also exist. We have facilitated oyster reef development in a number of estuaries (Henderson, Estero River, and Caloosahatchee River) by depositing a coarse shell substrate at low intertidal depths and in geographic locations having the most appropriate water quality for oyster growth and reproduction. (See web links at: http://www.floridaenvironment.com/programs/fe30602.htm; http://www.bonitanews.com/03/05/bonita/d916684a.htm; http://www.newspress.com/news/local_state/030511oysters.html.) This “gardening” approach to reef restoration is costly and time intensive. Reefs will restore naturally assuming the appropriate substrates exist. Unfortunately, the sedimentologic characteristics of the bay floors within Naples Bay have not been determined, making it difficult to assess the potential for natural reef restoration.

With these problems and applications in mind, this study's purpose was multi-fold. First, the side-scan sonar was used to characterize substrate types within Naples Bay. Field work was conducted in May, 2005, and the resulting data were processed and interpreted throughout the summer and fall of 2005. Side-scan sonar correctly identified a number of substrate types in Naples Bay. Second, we used the shallow seismic CHIRP to document the presence or absence of shallowly buried oyster reefs under Naples Bay. Those profiles that traversed the interior portions of the bay showed little indication of shallowly buried reefs. The periphery of the bay and substrate surrounding interior bay islands did, however, exhibit reef development in the subsurface. Third, the substrate mapping results are intended to aid in the selection of sites most appropriate for oyster reef gardening or natural recruitment once satisfactory water quality conditions are achieved through hydrologic restoration. Our preliminary results show that appropriate natural substrates are abundant in Naples Bay. Fourth, CHIRP was used to reveal older topographies and sedimentologic features under Naples Bay. These results indicate that a complex, pre-marine flooding topography existed formally, and this has influenced the development of the existing estuarine-scape that Naples Bay presently occupies.

Project Scope and Objectives

Two research objectives were defined for this project:

1. Survey of subtidal bay floor for oyster reefs and substrate sedimentology.

The principal goal of this project was the characterization of the bay floor for Naples Bay and its associated waterways. Although subtidal oyster reefs are less common than intertidal reefs, they may exist in appreciable numbers. Unfortunately, the water clarity in Naples Bay is poor, making it impossible to see the substrate through the water column. Similar problems exist when attempting to characterize the substrate's grain size. Future reef development requires coarser sedimentary substrates (sands or gravels). Mapping appropriate substrates is not practical using grab sample techniques. Remotely sensing the substrate geophysically is the most practical and cost-effective method for both these purposes.

Side-scan sonar (see description below) was used to characterize the seafloor of Naples and Dollar Bays and their tributaries. Because side-scan sonar generates diagnostic reflectance images for different sedimentary textures, sediment grabs were used to correlate texture against image type.

2.   Survey of bay's subsurface.

Oyster reefs that have died over recent history due to anthropogenic influences on freshwater delivery may be partly or completely buried under thin veneers of sediment. Savarese has located shallowly buried reefs along the Southwest Florida coast inadvertently through sediment coring (Savarese et al. 2003, 2004b). Coring or probing the subsurface, however, is not practical when trying to systematically map large areas. A CHIRP subbottom profiler, a small and easily transportable acoustic device (see description below), has been successfully used to map shallowly buried oyster reefs in San Antonio, Galveston, and Lavaca Bays in Texas by Dr. Dellapenna (Bronikowski 2004). The technique has also been used locally in Charlotte Harbor to locate buried karst topography (Duncan et al. 2003); in that study the investigators detected subsurfaces shaped like oyster reefs, but they never ground-truthed their observations to confirm their identity. Finally, CHIRP was used to map buried oyster reefs within the Ten Thousand Islands (in Blackwater and Faka Union Bays; Savarese et al. 2004a).

CHIRP profiles were run throughout Naples Bay study area to elucidate the subsurface structures and topographies and to locate shallowly buried oyster reefs.

Materials and Methods

Equipment: Side-scan sonar.— The side-scan sonar makes acoustic images analogous to aerial photographs, with the bottom-return intensity reflecting sediment texture, topography, bottom roughness, and cultural debris. The side-scan sends out a pulse of sound that is narrow along track and wide across track. The pulse scatters off the seafloor to the side of the boat's track and some returns to the sonar and is converted into image pixels depending on the intensity of the sound return. With each "ping" the side-scan sonar makes a thin strip of image, showing the bottom from some distance on either side of the sonar. The side distance (swath width) of these images is dependent on the depth of the water. In very shallow water, as will be encountered in most of the area to be surveyed, the swath width will be only 60-100 meters. In deeper water, larger swath widths are possible. By repetitive pinging as it moves along, an image is built up digitally. The "backscatter" of sound off the bottom, which forms the side-scan sonar image, depends on surface roughness and scattering within the thin layer of sediment near the surface. Coarse and hard sediments typically cause strong returns whereas fine sediments give weak returns. In addition, objects with hard surfaces that face the sonar, such as mounds, trenches, and shipwrecks, also cause strong returns. Such objects also typically cause acoustic shadows (with weak returns) on the sides that face away from the sonar. Thus, the side-scan sonar makes an acoustic "aerial photo" of the sea bottom, typically with a resolution of centimeters or less. In terms of assessing and mapping reefs, side scan sonar data can be used to generate a mosaic of geo-rectified images of the seabed. The mosaic provides a visual image of the seabed, and can be used to accurately determine the location of reef-building materials, geo-hazards and other potential habitat components of the seabed.

Equipment: CHIRP sub-bottom profiler.—The CHIRP profiler functions similarly to sonar, but operates at seismic frequencies that are more suitable for substrate penetration. The sub-bottom profiler creates a linear cross section of the bay bottom along the track of the tow vessel by sending out a "chirp" of energy from 2-16 kHz, with return signals differing based on the bottom type encountered. Some sound bounces off the bottom itself, whereas some penetrates and reflects off interfaces within the sediment. Repeating the send/receive action, a strip chart makes a profile showing the penetration and the characteristics of the reflections. Different bottom types have different reflection characteristics. Mud and sand bottoms have clearly different surface reflection signatures, making it possible to produce highly accurate maps of surface sediment type based on reflection characteristics. The sequence of subsurface sediments can be resolved on the decimeter scale and the sub-bottom profiler can typically penetrate up to 10-40 m into the seabed, depending on sediment type and water depth. The limitation of sub-bottom profiling is that it acquires data only along the boat track; there are no data collected between tracks.

Navigation.—Position was determined using a Trimble AG132 Differential GPS with Everest, which was fed digitally into a Gateway Laptop and logged using Hypack Coastal Oceanographic software. Hypack was also used to create survey lines and was used as a chart plotter for navigation of these lines. The layback of the tow fish (fore and aft) to the DGPS antennae was estimated by measuring the distance from the antennae to the transom and then measuring the amount and angle of the tow cable from the transom to the tow fish. The offset (a beam) was determined by measuring the offset of the DGPS antennae to the tow point of the cable on the transom. Errors for position of the fish in relation to the bottom should be limited to the error inherent in DGPS (less than 1 meter).

Data collection & processing.—Side-scan sonar data were collected using an Edgetech 272 tow fish at 100 kHz, and data acquisition and processing was performed using a CODA topside computer. Each trackline was conducted with swath widths for the port and starboard channels at 100 m each. The lines were spaced 100 m apart, giving 150% coverage of most portions of the grid. The net result is that when the side-scan sonar mosaic is generated, targets are overlapped on reciprocating lines. For the processing of side-scan sonar data and the generation of the mosaic, each side scan line was read into CODA, quality control of the bottom picking was performed, and Time Variable Gain (TVG) was uniformly applied to all data. The final offset and laybacks were refined and the mosaic was output as a Georectified TIF image and imported into ArcGis as a GeoTiff image for the locations of targets and other seabed feature. Final mosaics in this paper are presented using the GeoTiff images to preserve the highest image quality. CHIRP data were collected and processed using the software package

Delph Seismic Plus. Once the channels were identified, maps were made using DOQQ aerial photographs in ArcGis.

Field locations & track positions.—Naples Bay, and its associated waterways, is located north of Gordon Pass west of the spit upon which a portion of the City of Naples sits (Figure 1). A number of subregions were chosen for side-scan sonar surveys and CHIRP profiles: (1) the portion of Naples Bay north of the confluence of Haldeman Creek (Northern Naples Bay; Figure 2); (2) the portion of Naples Bay from Haldeman Creek south to Gordon Pass (Southern Naples Bay; Figure 3); (3) Dollar Bay (Figure 4); (4) Haldeman Creek (Figure 6); (5) Gordon Pass (Figure 4); (6) Rock Creek (Figure 9); and (7) Gordon River (Figure 9). Oral historical accounts claim that the northern subregion contained a great deal of oyster reef substrate prior to development of the coastal fringe of the bay. The coastal margin of the southern subregion is still relatively undeveloped and contains numerous intertidal oyster reefs today.

A total of 87 sidescan lines were completed throughout the study area. The breakdown by subregion is as follows: 2 in Gordon River; 1 in Rock Creek; 35 in North and South Naples Bay; 1 in Haldeman Creek; and 48 in Dollar Bay. Selected portions or each subregion were selected for CHIRP survey. In total, 24 shallow seismic profiles were generated: 3 in Gordon River; 10 in North and South Naples Bay; 3 in Haldeman Creek; 2 in Gordon Pass; 2 offshore of Gordon Pass; 3 in Dollar Bay; and 1 in Rock Creek. The location of these surveys is illustrated in Figures 10-15.

Calibration of side-scan signal through sedimentary analysis.— In order to calibrate the side-scan acoustic signal with substrate type, a series of sediment grab samples was taken from the study area. A total of 61 sediment samples were taken with a ponar grab. Their locations are shown in Figures 16-20; GPS coordinates for these sites are listed in Table 1. The spatial distribution of localities is as follows: 17 in Dollar Bay; 7 in Gordon Pass, 31 in North and South Naples Bay; 3 in Haldeman Creek; 1 in Rock Creek; and 2 in Gordon River.

Grain size analysis, reporting mean grain size and sorting, for all samples was accomplished using a Malvern Mastersizer 2000e laser particle size analyzer. Results are plotted as histograms and as cumulative percent volume curves. Mean grain size and sorting values were obtained using the Folk graphic method (Boggs 2006). Grain sizes are reported using the phi scale.

Results and Discussion

Types of side-scan sonar signals & their interpretations.

Six types of signals were recognized from the side-scan sonar surveys. Each represents a characteristic acoustic reflection pattern produced by the sonar. Sediment ground-truthing and grain-size analysis were used to confirm a substrate's environmental interpretation. The geographic distribution of sediment samples and the results from the grain size analyses are reported in Table 1. Complete grain size distribution histograms and cumulative percent frequency curves are found in Appendix I.

(1) *Sandy mud bottoms.* Sandy mud substrates contain a mix of sand- and mud-sized particles where the mud fraction (composed of silt + clay) predominates. These substrates typically have a minimal reflection and consequently have acoustic signals that appear dark and homogeneous. These substrates are also typically planar over large distances, adding to the dark composition. For most of the sediment samples taken throughout the study area, the mud fraction is dominated by silt-sized particles. Clays make up less than 6% by volume of all samples taken from sandy mud substrates, while silts may compose up to 87% of these samples (Table 1).

(2) *Sand bottoms.* Sandy substrates are composed of greater than 90% sand with the remaining 10% or less within the mud-sized fraction. Samples within Gordon Pass, southern-most Naples Bay, and northern-most Dollar Bay have sand concentrations up to 99% by volume (Table 1). Because sandy substrates are influenced by traction-transport currents that can generate sedimentary structures on the bottom (e.g., ripples, dunes, channel-forms), they tend to exhibit stronger (i.e., brighter) reflectors with a systematic distribution pattern determined by the spacing of the structures. Sandy substrates can be distinguished from muddy sand substrates (see type 3 below) by the degree of brightness of the reflectors.

(3) *Muddy sand bottoms.* Muddy sand substrates contain a mixture of sand and mud, but the sand fraction predominates. Reflectors are intermediate in brightness between sandy and sandy mud substrates and the presence of discrete sedimentary structures is less likely.

(4) *Oyster reefs.* Because oysters typically form hard clumps or pavements on the seafloor and because this is accompanied with high relief relative to the surrounding soft substrates, subtidal and intertidal oyster reefs typically have bright reflections on the sonar-ward side of the structure and a dark shadow on the leeward side. If the reef is dominated by clumps interspersed with muds, rather than pavements, the reflectors can have a light/dark mottled appearance. Reefs may be isolated structures, surrounded on all sides by subtidal substrate, or they may be structures that fringe the bay margins. Isolated reefs are usually elliptical or elongate in shape and fringing reefs follow the contours of the shoreline; the shape of the reflector mimics these geometries.

(5) *Low density oyster shell.* In many regions along the bay margins, particularly in Southern Naples and Dollar Bays, substrates are composed of low densities of oyster shell. These may contain living oysters within small clumps or dead, disarticulated oyster valves. The side-scan acoustic reflectors are bright with a homogeneous distribution along the substrate. Patches of interbedded mud and sand are absent, causing there to be no mottled appearance to the reflectors as is typically seen on well-developed oyster reefs.

(6) *Anthropogenic structures: channels and bulkheads.* Dredged channels, because of their sloped gradient, reflect strongly on one side and have dark shadows on the other. Bulkheads produce strong, solidly bright reflectors.

Distribution of substrate types.

Northern Naples Bay.—The side-scan sonar results from northern Naples Bay (Figure 21) show a variety of natural and anthropogenically effected substrates. The majority of the substrate's surface area is composed of either sandy mud or muddy sand. Because tidal and fluvial currents are subdued here, relative to Southern Naples Bay, and because of the proximity to the suspended load issuing from Gordon River (flocculation due to marine and freshwater mixing), this northern region of Naples Bay receives a larger amount of mud deposition. In addition, the area immediately adjacent to two large boating canals along the northeastern shoreline appears to be experiencing greater suspending-sediment deposition (Figure 22). This may be indicating a source of fine-grained sediment, silts and clays, from within the boating canals' watersheds.

Side-scan sonar identified three subtidal oyster reefs in the northern survey area (Figure 22). Water over these reefs is relatively deep. Consequently, these structures are subtidal and would go undetected at low tide (extreme low tides might expose them). Their identity as reefs was successfully confirmed; surface dives by a snorkeler retrieved oyster clumps. These oyster reefs have developed within fields of muddy sand, a substrate type that is conducive to reef development. Relatively extensive areas of muddy sand exist in northern Naples Bay, indicating that appropriate substrates do exist for future reef restoration.

The human effects on the substrate of the northern region are obvious among the side-scan sonar results (Figures 21 & 22). Bulkheads rimming the eastern shoreline generate strong acoustic shadows, as do the boating channels running along the western and eastern margins of the bay. In addition, numerous propeller scars cross-cutting the substrate (not shown in a figure) are indicated.

An extensive region of sandy mud dominates the southern half of northern Naples Bay (Figure 21). The predominance of mud here seems enigmatic; no freshwater sources are nearby. This may represent a geographic shift of the turbidity maximum zone as a response to the freshwater inundation Naples Bay receives from the Gordon River. Because the brackish water mixing zone has shifted southward due to the freshwater influx from the Golden Gate Canal, this region may represent the new locus of suspended sediment deposition.

Southern Naples Bay and Haldeman Creek.—The side-scan sonar images from the southern region of Naples Bay and the confluence of Haldeman Creek (Figures 23-26) exhibit more natural substrate conditions. A large portion of the southern Bay's and lower Haldeman Creek's eastern shorelines are still fringed by mangroves and oyster reefs. The western shores are extensively developed.

Fringing oyster reefs are located along the eastern margin of lower Haldeman Creek (Figure 24) and along the eastern edge of southern Naples Bay due south of the mouth of Haldeman Creek (Figure 23). Lower density oyster shelly substrate exists south of the point located between the northern bay and Haldeman Creek and along the eastern margin just northeast of the entrance of Gordon Pass. These shell substrates represent areas of former reef development. The majority of the subtidal portion of the bay's interior is composed of muddy sand, and coarser sand is found within Gordon Pass and in the southern extreme of the southern bay (Figure 26). The swifter tidal flows within the southern bay and within Gordon Pass are more conducive for sand transport and deposition. The eastern flank of the southern bay contains expansive coarse sand substrates for future oyster reef development.

Lastly, Haldeman Creek provides enough freshwater to create the brackish water conditions presently to support reef development. An area of sandy substrate appears just south of the mouth of Haldeman Creek (Figure 24). These sediments were deposited as part of a delta complex formed at the creek's mouth. While oyster reefs fringe the area east of the mouth, the sands within the delta are probably too mobile to support oyster settlement. The intertidal habitat just west of the Winstar property, though not surveyed in the study because of the shallow water depths, undoubtedly contains very appropriate reef development substrate as well (Figure 25).

Dollar Bay.—Dollar Bay is relatively mud free (Figures 27-29) with sands and muddy sands making up most of the substrate within the bay's interior. When muds are present, they are composed almost of exclusively of silts; clays are essentially absent. Oyster reefs and low density oyster shell substrates are found at numerous locations around the bay's margin (Figures 28 & 29). Four isolated oyster reefs were located in the northern half of the bay; 3 were identified in the southern half. Oyster reefs are conspicuously absent from the bay margins just south of Gordon Pass (Figure 28). These coarser sandy substrates are perhaps too mobile due to tidal currents and waters too saline to support larval settlement and extensive oyster productivity. South of here Dollar Bay has extensive suitable substrate for oyster reef development.

Gordon River and Rock Creek.—The aerial extent of subtidal substrate in these two tributary streams of northern Naples Bay is limited. The substrate is dominated by muddy sands, but these are found within natural or artificial fluvial channels where sediments are highly mobile and are frequently reworked. Fringing oyster reefs, however, are found in the lower reaches of both Gordon River and Rock Creek (Figure 30).

CHIRP sub-bottom profiles.

Most of the 24 CHIRP profiles taken throughout the study area exhibited no discernable features in the subsurface. (A complete package of CHIRP profiles for the entire 24 lines is available in Appendix II.)

Conspicuously absent from all but one of the profiles (Line 8_1, taken across the mouth of Haldeman Creek; Figure 33) are buried oyster reefs. Reefs in the shallow sub-bottom are apparently absent, indicating that the pre-existing reefs that occurred within the interior of Naples Bay, prior to the dredging and degradation associated with development, were relatively young structures without a protracted late Holocene history. One of the CHIRP profiles (Line 5; Figure 32) passed over an existing subtidal oyster reef in northern Naples Bay. This reef exhibits structure at some depth below the substrate and appears to have some Holocene history. The one buried oyster reef located at the mouth of Haldeman Creek (Line 8_1; Figure 33) is anomalous. This profile, however, is located over the creek's delta. It's possible that the onset of sedimentation associated with the appearance of Haldeman Creek drowned out oyster reef development.

Similarly, buried oyster reefs are conspicuously absent from the sub-bottom of Dollar Bay, and this bay has not experienced the degree of reef habitat loss as has Naples Bay. One present-day subtidal reef was traversed by a CHIRP profile (Line 17; Figure 33), and the associated seismic trace indicates that this reef, like the subtidal reef in northern Naples Bay, has a late Holocene history.

Traces of older oyster reefs are found along the bays' margins below the present fringing reefs. This suggests that the bay margins remained stable for some length of time and supported reef growth. This pattern is consistent with what is seen in other areas of Southwest Florida, particularly the Ten Thousand Islands. Oyster reefs in many of the Ten Thousand Island estuaries are concentrated along the bay interior margins. Cores taken from these reefs indicate reef histories may extend back ~2500 ybp (Savarese et al. 2002, 2004b). The interiors of the bays presently lack oyster reefs, and CHIRP profiles taken from these regions also show buried reefs are absent.

These results emphasize the importance of maintaining bay margins for natural habitat. Although isolated oyster reefs still exist throughout Naples and Dollar Bays and the work by Schmid and others has documented the distribution of additional isolated reefs prior to the 1950s (Schmid et al. 2006), fringing reefs were perhaps of greater historical significance and supported greater oyster productivity. Isolated reefs, however, with the appropriate substrate type and water quality are still supportable in the absence of natural fringing habitat.

At deeper depths within the sub-bottom (1-3 m), a highly irregular surface reflector with considerable vertical relief appears under the tracks from the northern region of Naples Bay, Gordon River, and Haldeman Creek (for example, see Lines 1, 2, 3, 8_1; Figures 31-34). This appears to be a ravinement surface, erosion created during a sea level low-stand, and may represent a former freshwater drainage system now covered by more recent estuarine sediments. There is also some evidence to suggest that the present-day boating channel, which probably followed the path of a natural channel within the bay, follows an antecedent low in the topography on that ravinement surface (Line 3, 5; Figure 32). The existing channel sits above a low in the ravinement structure, and recent sediments fill the channel down to that surface. The existing channel within Dollar Bay (Line 17; Figure 33) also appears to reside on an ancient antecedent topographic low. The position of this channel, however, has shifted position through time.

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Report to the City of Naples, funded by the South Florida Water Management District. 58 p.

Table 1. Localities from which sediment samples were taken for side-scan image calibration. For each locality: GPS coordinates (latitude / longitude in degrees); the percent clay, silt, and sand fractions; graphic mean grain size in phi units and the corresponding Wentworth size class; graphic standard deviation in phi units and the corresponding sorting values.

Sample	Latitude	Longitude	Clay	Silt	Sand	Graphic Mean (phi)	Mean Size	Graphic StdDev (phi)	Sorting
DB-52	26.09699	-81.78745667	0.00	0.00	99.89	2.50	fine sand	0.68	moderately well
DB-53	26.09701833	-81.78571167	0.71	8.95	90.34	3.13	very fine sand	1.03	poorly
DB-54	26.09494	-81.78467	1.49	19.31	79.20	2.77	fine sand	1.88	poorly
DB-55	26.09435	-81.78763	2.63	35.23	62.13	4.23	coarse silt	1.89	poorly
DB-56	26.0927566	-81.7867733	1.23	10.42	88.35	2.27	fine sand	1.20	poorly
DB-56A	26.09230833	-81.78751333	1.81	21.26	76.93	3.7	very fine sand	1.71	poorly
DB-57	26.09262	-81.78386667	2.58	30.49	66.62	3.97	very fine sand	2.08	very poorly
DB-58	26.09079	-81.7846333	2.19	27.77	69.44	3.23	very fine sand	2.08	very poorly
DB-59	26.09070833	-81.78781	1.87	19.67	77.97	3.4	very fine sand	1.98	poorly
DB-60	26.08895167	-81.78762667	3.51	39.13	57.36	4.40	coarse silt	2.02	very poorly
DB-61	26.08922333	-81.78551833	0.63	4.65	94.72	2.70	fine sand	0.85	moderately
DB-62	26.08519333	-81.78842333	2.81	47.45	49.74	4.07	coarse silt	1.94	poorly
DB-64	26.08374667	-81.78775167	3.29	38.31	58.35	4.4	coarse silt	1.96	poorly
DB-65	26.084135	-81.7862083	0.56	3.55	95.88	2.03	fine sand	0.58	moderately well
DB-66	26.0825566	-81.7859166	0.92	6.14	92.94	2.23	fine sand	0.91	moderately
GP-68	26.09913167	-81.78919833	0.73	5.94	91.50	2.17	fine sand	1.51	poorly
GP-69	26.097515	-81.79448	0.57	4.67	94.76	2.07	fine sand	0.72	moderately
GP-70	26.09512333	-81.799015	0.74	5.06	94.20	2.83	fine sand	0.85	moderately
GP-71	26.09280667	-81.79836	0.66	4.10	95.25	2.2	fine sand	0.74	moderately
GR-67	26.143145	-81.78673	2.10	35.38	62.52	3.87	very fine sand	2.03	very poorly
GR-68	26.1511066	-81.785995	0.78	7.04	92.18	2.00	medium sand	0.97	moderately
HC-36	26.11813	-81.784825	4.73	86.95	8.33	5.63	medium silt	1.33	poorly
HC-37	26.12062333	-81.78491333	1.92	24.28	73.80	3.13	very fine sand	1.88	poorly
HC-38	26.11554167	-81.78580333	2.11	21.13	76.77	3.6	very fine sand	1.88	poorly
NB-01	26.136145	-81.79064667	3.33	40.51	56.15	4.33	coarse silt	2.04	very poorly
NB-02	26.13609167	-81.788345	3.38	45.50	50.85	4.43	coarse silt	2.11	very poorly

NB-03	26.13484167	-81.79162167	1.73	17.40	80.86	3.03	very fine sand	1.78	poorly
NB-05	26.13483333	-81.78843667	2.96	59.39	37.65	4.47	coarse silt	1.82	poorly
NB-06	26.13292167	-81.791805	3.91	32.01	64.08	4.07	coarse silt	2.18	very poorly
NB-08	26.13295167	-81.78889833	2.63	21.75	75.62	3.67	very fine sand	1.99	poorly
NB-10	26.131266	-81.7908116	0.89	7.66	91.45	2.13	fine sand	1.09	poorly
NB-11	26.131285	-81.78870167	5.34	76.00	18.67	5.77	medium silt	1.71	poorly
NB-12	26.12989667	-81.79402333	3.53	34.99	61.48	4.2	coarse silt	2.02	very poorly
NB-14	26.12999833	-81.79095333	5.95	76.66	17.39	5.37	medium silt	1.61	poorly
NB-15	26.12995333	-81.78944333	2.95	24.84	72.21	3.83	very fine sand	2.00	very poorly
NB-16	26.12988667	-81.78762833	1.80	19.93	78.27	3.10	very fine sand	1.80	poorly
NB-18	26.128425	-81.789405	3.29	29.38	67.33	4.03	coarse silt	2.06	very poorly
NB-19	26.12845167	-81.78781	3.09	28.32	68.59	3.77	very fine sand	2.13	very poorly
NB-23	26.12413667	-81.79246667	5.31	76.41	18.28	5.23	medium silt	1.61	poorly
NB-24	26.1239766	-81.78935	3.88	84.51	11.61	5.37	medium silt	1.38	poorly
NB-25	26.12214833	-81.79269	4.83	64.27	30.71	5.30	medium silt	1.96	poorly
NB-27	26.122375	-81.790115	4.60	77.70	17.70	5.23	medium silt	1.52	poorly
NB-30	26.11885167	-81.79168167	3.69	81.79	14.52	5.77	medium silt	1.40	poorly
NB-31	26.118965	-81.79021833	5.28	72.80	21.88	5.17	medium silt	1.68	poorly
NB-34	26.116695	-81.78929167	3.46	57.49	39.05	4.63	coarse silt	1.78	poorly
NB-35	26.11521	-81.78808333	0.87	9.23	88.70	2.33	fine sand	1.54	poorly
NB-39	26.11376167	-81.78699333	1.16	13.78	84.60	2.20	fine sand	1.57	poorly
NB-40	26.1136166	-81.7859666	1.07	14.11	84.82	2.70	fine sand	1.25	poorly
NB-41	26.1117	-81.78723333	2.43	26.89	70.68	4.00	very fine sand	1.84	poorly
NB-43	26.1100666	-81.78727	3.62	33.84	62.54	3.97	very fine sand	1.89	poorly
NB-44	26.11017167	-81.78608333	3.19	37.73	58.92	3.97	very fine sand	1.87	poorly
NB-45	26.10791333	-81.787545	2.66	32.95	64.38	3.9	very fine sand	1.73	poorly
NB-46	26.10762333	-81.78611833	1.49	17.24	80.58	3.3	very fine sand	1.73	poorly
NB-49	26.10263333	-81.78614333	1.19	14.79	84.02	3.3	very fine sand	1.23	poorly
NB-50	26.10086667	-81.787185	0.48	3.37	96.06	2.8	fine sand	0.62	moderately well
RC-66	26.14135333	-81.78610667	1.07	10.95	87.98	2.1	fine sand	1.18	poorly