Investigation and Review of the Surface and Sub-Surface Sediment Distribution of Reach E for the Delaware River and Bay Main Channel Deepening Project

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EXECUTIVE SUMMARY

The Delaware Coastal Program within the Office of the Secretary of the State of Delaware Department of Natural Resources and Environmental Control (DNREC) and the University of Delaware Geosciences Department have conducted a bottom and sub-bottom mapping study to identify and constrain the surface and sub-surface sediment grain size distribution for the navigation channel in Reach E of the proposed Delaware River and Bay Main channel Deepening project. Reach E is located in the lower Delaware Bay between River Miles 6 (approximate channel station 512+000, near Brown Shoal) and 42 (approximate channel station 351+200, off Woodland Beach, Delaware; Figure 1). The purpose of this study was to assess the grain size distribution of sediments in Reach E that are proposed to be removed as part of the Main Channel Deepening project of the Delaware River and Bay. It is the assertion of the Philadelphia District of the Army Corps of Engineers (PD-ACOE) that the sediments that are removed from Reach E can be used as a beneficial resource for the State of Delaware. This study in the form of a data review and acoustic survey was implemented to validate the results presented by the PD-ACOE for the State of Delaware Wetlands and Subaqueous Lands Permit as to the suitability of the sediments for coastal construction and beach restoration.

In reviewing the data provided by the PD-ACOE, numerous discrepancies and sampling errors were found. The existing data collected by the PD-ACOE is therefore considered inadequate to be used as a sole source of information in reaching a sound decision as to the potential coastal construction impacts and sustainability of the sediments to be dredged. Specific concerns about the PD-ACOE sediment data include:

- Sediment grain size samples collected from vibracores by the PD-ACOE and its contractors were composites of larger volumes of material. Any deposits with thicknesses less than 15.2 cm (6 in) were not uniquely sampled, but rather lumped within larger composite samples. Thin layers of extremely coarse sediments dominate the surface of sub-reaches E2 and E5 and are present in

sub-reach E4 . When they are not proportionally sampled, as when using a composite methodology, the resultling samples suggest that these reaches are characterized by overall erroneously coarse grain sizes.

An artificial skewing of the grain size results occurred due to the inappropriate sampling scheme. The erroneous nature of the reported grain sizes is reflected in that they do not match the descriptions of the sediments in the core logs. The thin coarse-grained surficial sediments should have been separately sampled. They are not representative of the larger volume finer-grained sub-surface sediments and should not have been included in the top composite samples, but rather separated into their own samples for sieve analysis.

The PD-ACOE cores which contain discrepancies between the composite sample grain size results and the core log descriptions are**:**

- Sub-reach E5: DRV-78, DRV-67, DRV-66R1, DRV-21 and DRV-68
- Sub-reach E4: DRV-17
- Sub-reach E2: DRV-70, DRV-68, DRV-64, DRV-63, DRV-62 R1, DRV-61 R1, DRV-88 R2, DRV-60, DRV-87, DRV-59, DRV-86 and DRV-58

- Several cores contained missing sections and thus un-sampled sediments at the surface. These cores were used by the PD-ACOE to characterize entire vertical sections. These characterizations would not include the un-sampled sections and would not be representative of the actual sediments that are present.

The cores that contain missing sections are:

- Sub-reach E5: DRV-65 R1 (0.0 to 0.4 ft un-sampled) and DRV-20 (0.0 to 1.1 ft un-sampled).
- Sub-reach E4: DRV-75 (0.0 to 2.0 ft un-sampled)

- Sub-reach E2: DRV-69 (0.0 to 2.5 ft un-sampled)

- Grain size class ranges used by the PD-ACOE and its contractors do not match the standardized Wentworth scale commonly used by geologists to describe grain sizes of sediment samples. The PD-ACOE's use of the Unified Soil Classification System (USCS) standard (commonly used by soil scientists and engineers) resulted in data that cannot easily be compared to existing outside source data. When comparing PD-ACOE data to the other source data the terminology of grain sizes is not identical, this can result in misunderstandings of the representative grain sizes. This is especially disconcerting when reviewing the d-50 (mean grain size calculations) that are reported by the PD-ACOE.

- Large scale gaps exist between core locations that make it very difficult to accurately determine the trend in sub-surface grain size distributions and the estimation of the total mean grain size per sub-reach. There is simply too much heterogeneity in the sediment grain sizes to accurately estimate mean grain sizes from the existing data. Additional cores are needed to fill in the data gaps that exist in the sub-reaches. Data gaps between existing cores include:

  - Sub-reach E6 contains a 3.6 mile gap between cores DRV-26 and DRV-82.

  - Sub-reach E5 contains a 1.3 mile gap between cores DRV-78 and DRV-77 and a 1.0 mile gap between DRV-76 and DRV-67. The disparities between the reported grain sizes of the cores is significant.

  - Sub-reach E2 contains a 1.9 mile gap between DRV-70 and DRV-69 and a 3.2 mile gap between DRV-68 and DRV-64.

The sediment sampling errors, discrepancies in grain size descriptions, and gaps in core locations reduce the validity of the PD-ACOE's efforts to accurately characterize the sub-surface sediments for Reach E. It is the strong recommendation of this review

that additional cores be collected in sub-reaches E2 and E5. This is the only way to get grain size data that can be used to accurately assess the potential viability and resiliency of a confined disposal facility (CDF) to be created on Kelly Island. Cores need to be collected adjacent to the existing locations and over areas that have not been sampled. These cores should be analyzed using a methodology that separates the coarser surface deposits into discrete samples, with grain size results reported for surficial and subsurface sediments. Additional cores also need to be collected in sub-reach E6 to confirm the PD-ACOE results and determine if that entire sub-reach needs to be re-sampled.

The key element of a new sampling project must be be constrain the distribution (areal and thickness) of the surficial coarse deposits. In analyzing the existing and future grain size information, the results need to be spatially weighted within the sub-reaches to better represent spatial variations and trends. The need for weighting is documented by confirming that several cores occurred where sediment grain size distributions were localized and thus could not be considered representative of larger areas of a given sub-reach.

In terms of the beneficial use of dredged sediment at Broadkill Beach for horseshoe crab spawning habitat, the average grain size data from sub-reaches E6 and E7 indicated a mean grain size fraction of 1.4% gravel. The current foreshore sediments of Broadkill Beach contain 20.0% gravel. This discrepancy between grain sizes means that the requirements set by the ASMFC Fishery Management Plan for Horseshoe Crab that placed sediment matches existing conditions would not be met. According to the PD-ACOE, the mean grain size of the beneficial use deposits would be ~0.30 to 0.35 mm, with a very small gravel fraction (Appendix D).

According to Smith et al. (2002) and Botton et al. (1994) these beneficial use sediments would be inadequate for horseshoe crab habitat. Because of their finer nature with a very small gravel fraction, the proposed beach to be constructed would likely have a detrimental effect on horseshoe crab spawning habitat. The potential Broadkill Beach nourishment by the PD-ACOE does not meet the beneficial use requirements for this project for horseshoe crab habitat in the Delaware Bay.

The existing PD-ACOE sediment data does not meet the minimal lithologic and volumetric data requirements that are necessary for the development of an engineering design for the Kelly Island CDF. At this time no detailed plans have been presented for the CDF project, so there is little that can be evaluated to validate the feasibility of such a project. Due to the lack of confidence in the validity of the existing grain size data, it is doubtful that a CDF design could pass a rigorously engineering and geological review.

At this time not enough data has been collected, or provided, by the PD-ACOE to allow the State of Delaware to adequately assess the outcome of the proposed beneficial use of the Reach E sediments. In addition to the lack of sediment data, not enough information has been provided to accurately predict how the Broadkill Beach nourishment and Kelly Island CDF projects will respond to wave conditions at these locations. Without good constraints on the grain sizes of the sediments within Reach E, it is possible that the dredged sediments may be outside of the projects design and expectation. This could result in an outcome that would deviate significantly from the project's initial design and result in significant negative ecological impacts. Even after sediment analyses of new cores that need to be collected, it is essential that information be provided to the State of Delaware indicating that the beneficial use projects will be able to achieve their proposed purpose and not become a financial burden and/or ecological catastrophe.

Table of Contents

I. Introduction 1

II. Methods of Investigation 10

i. Chirp Sub-bottom Profiling System 10

ii. Roxann Seabed Classification System 12

iii. Sediment sampling 15

III. Results and Interpretation 17

i. Bottom Sediment Distribution 17

ii. Sub-bottom Sediments and Bottom Morphology Based on Chirp Profiles 21

iii. Sub-Reach Surface and Sub-surface Analysis 27

a. Sub-Reaches E6 and E7 27

b. Sub-Reaches E1 thru E5 45

IV. Discussion 100

References Cited 124

Appendix A: Chirp Sub-bottom Profile Images 127

Appendix B: ACOE Core logs and Composite Samples Sieve Data 151

Sub-Reach E7 152

Sub-Reach E6 155

Sub-Reach E5 175

Sub-Reach E4 201

Sub-Reach E3 207

Sub-Reach E2 220

Sub-Reach E1 251

Appendix C: Delaware Coastal Program Reach E Surface Sediment Grab Sample Sieve Results 254

Appendix D: Delaware River Deepening - Dredged Material Characterization for Reach E. 259

Appendix E: Delaware Coastal Program Broadkill Beach Sediment Grab Sample Sieve Results 262

LIST OF FIGURES AND TABLES

Figure 1. Regional location map for the Delaware navigation channel bottom and sub-bottom mapping survey. The survey area is shown by thick red line. Black dots denote 0.5 mile intervals of River Miles as defined by the Delaware River Basin Commission. River Mile 0 is located at the southernmost end of the navigation channel. 3

Figure 2.Proposed generalized design of the Kelly Island CDF (EA, 2009). 4

Figure 3. Kelly Island Geotextile Tube/Berm Cross Section. 5

Figure 4. Generalized cross-section of the proposed Broadkill Beach nourishment project (EA, 2009). 7

Figure 5. Chirp tow-fish on fantail of *R/V First State*. Tow-fish deployed aft using A-frame. 11

Figure 6. Schematic diagram of chirp sonar system imaging the sub-bottom.....11

Figure 7. Example image of chirp sub-bottom profile. Profile was collected along the western side of the navigation channel near River Mile 23 along a trackline that was oriented from northwest (left side of the profile) to southeast (right side of the profile). Horizontal lines mark depths at 5 m intervals below the chirp tow-fish. Vertical lines occur at one minute time intervals and, given an average ship's speed of 5 knots, are spaced approximately 150 m (492 ft) apart. 11

Figure 8. Schematic diagram of Roxann acoustic system. Shown are the (upper image) first (E1) and (lower image) second (E2) echoes that are associated with the system.....14

Figure 9. Real-time Roxmap display showing the depth (lower right window), the box plot being currently used to classify the incoming data and area of data clustering (upper right window), and the tracklines collected with their corresponding sediment classification values. 14

Figure 11. Petite ponar grab sampler with open bottom and spring loaded pin hanging off of the pivot point. 16

Table 1. US standard sieve number and sieve size used by the Army Corp of Engineers and Penn State Agriculture Analytical Services, compared to the standard Wentworth sediment size classes.....15

Figure 12. The Wentworth grain size scale for sediments (Folk, 1974).....16

Figure 14. Variogram constructed for the Roxann bottom sediment point data, also showing the model used in the interpolation.....19

Table 2. Sediment classification ranking and associated sediment descriptions for the Roxann data that was used to make the interpolated sediment maps.....20

Figure 15. Chirp profile images along Liston Range near River Mile 40.5 and 38. Chirp files are bm_052510_f6 (top) and bm_052510_f9 (bottom). Top profile is located along the western side of the navigation channel near River Mile 40.5; bottom profile along the eastern side near River Mile 38. 23

Figure 16. Chirp profile images approaching the Ship John, Ben Davis Point, and Cross Ledge Shoals. Chirp files are bm_052010_f4 (top – Ship John Shoal), bm_052010_f0 (middle – Ben Davis Point Shoal) and bm_052510_f17 (bottom – Cross Ledge Shoal). Top profile is located along the eastern side of the navigation channel near River Mile 37; middle profile along the eastern side near River Mile 33; bottom profile along the western side near River Mile 28. 24

Figure 17. Chirp profile images along Miah Maull Range to Brandywine Range near River Mile 17.5 to 17. Chirp files are bm_052710_f0 (top) and bm_052510_f24 (bottom). Top profile is located along the western side of the navigation channel; bottom profile along the eastern side.....25

Figure 18. Chirp profile image along Brandywine Range near River Mile 12. Chirp file is bm_052710_f5. Profile is located along the eastern side of the navigation channel. 26

Figure 19. Map of tracklines, grab samples, and core locations within sub-reach E6 and E7. 28

Figure 20. Roxann seabed classification map of sub-reach E6 and E7. 30

Figure 21. Roxann seabed classification map, core locations, and grab sample locations of the lower sub-reach E6 and E7. 31

Figure 22. a) Vertical curtains of chirp sub-bottom profiles starting at the southern extent of E6 and E7. b) Vertical curtain chirp-profile with overlay of Roxann seabed classification. These extents contain core locations of DRV-84, DRV-27, and DRV-83 (red cylinders from right to left). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).....32

Figure 23. Vertical curtains of chirp sub-bottom profiles starting at the southern extent of E6, just north of DRV-83 to the north of DRV-26 (red cylinder to left; grab sample MC52710-1 shown to south of core DRV-26 (green diamond). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 34

Figure 24. a) Vertical curtains of chirp sub-bottom profiles at the southern extent of E6, around core DRV-26 (red cylinder at center). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification (core DRV-26 (red cylinder) and grab sample MC52710-1 shown to south of core DRV-26 (green diamond)). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).....35

Figure 25. Roxann seabed classification map, core locations, and grab sample locations for the central region of sub-reach E6 (between cores DRV-26 , to the south, and DRV-25, to the north).....36

Figure 26. a) Vertical curtains of chirp sub-bottom profiles for the central region of sub-reach E6 (between cores DRV-26, to the south, and DRV-25, to the north). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the central region of sub-reach E6 (between cores DRV-26, to the south, and DRV-25, to the north). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 37

Figure 27. Roxann seabed classification map, core locations, and grab sample locations for the northern and central region of sub-reach E6 (between cores DRV-82, to the south, and northern extent of sub-reach E6 to the north. 38

Figure 28. a) Vertical curtains of chirp sub-bottom profiles for the central region of sub-reach E6 (between cores DRV-82, to the south, and DRV-81, to the north). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the central region of sub-reach E6 (between cores DRV-82, to the south, and region to north of DRV-81). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 40

Figure 29. a) Vertical curtains of chirp sub-bottom profiles for the northern central region of sub-reach E6 (between cores DRV-81 (red cylinder) and MC52710-2 (green cylinder) to the south (to the right) and region to the north of DRV-81. b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the northern central region of sub-reach E6. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).....41

Figure 30. a) Vertical curtains of chirp sub-bottom profiles for the northern central region of sub-reach E6 around core DRV-24 (red cylinder). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the northern central region of sub-reach E6 (between area to south of DRV-24 and area to north of DRV-24). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 42

Figure 31. a) Vertical curtains of chirp sub-bottom profiles for the northern region of sub-reach E6, between region to south of DRV-80 (red cylinder in center) to northern extent of E6. b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the northern central region of sub-reach E6. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).....43

Figure 32. Graph of the top composite samples grain size composition verses the distance of the cores locations along sub-reach E6. 42

Figure 34. Roxann seabed classification map for sub-reaches E1 thru E5. 49

Figure 35. Map of tracklines, grab samples, and core locations within sub-reach E5.....50

Figure 36. Roxann seabed classification map of sub-reach E5. 51

Figure 37. Roxann seabed classification map, core locations, and grab sample locations for the southern region of sub-reach E5. 52

Figure 38. a) Vertical curtains of chirp sub-bottom profiles for the southern extent of sub-reach E5, cores DRV-23 (left) and DRV79 (right) shown at center (red cylinders). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the southern extent of sub-reach E5. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 53

Figure 39. a) Vertical curtains of chirp sub-bottom profiles for the southern extent of sub-reach E5 (north of core DRV-23), core DRV-78 shown at left center (red cylinders). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the southern extent of sub-reach E5. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 55

Figure 40. Vertical curtains of chirp sub-bottom profiles for the southern extent of sub-reach E5 between core DRV-79 (shown at right; red cylinders) and core DRV-78 (shown at left; re cylinder). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 56

Figure 41. a) Vertical curtains of chirp sub-bottom profiles for the southern central extent of sub-reach E5, between core DRV-78 (red cylinders at right) and DRV-22 (red cylinder at far left). Also, shown are core DRV-77 R1 (right of DRV-22), and grab samples MC052710-4 (right of DRV-77R1) and MC052710-5 (adjacent to DRV-22) b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the southern central extent of sub-reach E5. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 57

Figure 42. Vertical curtains of chirp sub-bottom profiles for the southern central extent of sub-reach E5, in region south of core DRV-77 R1 (red cylinders at left) and DRV-22 (red cylinder at far left). Also, shown are grab samples MC052710-4 (right of DRV-77R1) and MC052710-5 (adjacent to DRV-22). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 58

Figure 43. a) Vertical curtains of chirp sub-bottom profiles for the central extent of sub-reach E5 (north of core DRV-23), core DRV-78 shown at left center (red cylinders). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the southern extent of sub-reach E5. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 60

Figure 44. a) Vertical curtains of chirp sub-bottom profiles for the north central extent of sub-reach E5, core DRV-76 shown at right (red cylinders) and core DRV-67 shown at left(red cylinder). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the north central extent of sub-reach E5. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).....62

Figure 45. a) Vertical curtains of chirp sub-bottom profiles for the northern extent of sub-reach E5 (cores contained in view are (from right to left; red cylinders)): DRV-67, DRV-21, DRV-66, and DRV-65). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the northern extent of sub-reach E5. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).....63

Figure 46. a) Vertical curtains of chirp sub-bottom profiles for the northern boundary of sub-reach E5 (cores contained in view at center are (from right to left; red cylinders): DRV-65, DRV-75, and DRV-20). Also shown is grab sample MC052710-6 (green diamond), adjacent to DRV-75. b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the northern boundary of sub-reach E5. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).....64

Figure 47. Graph of the top composite samples grain size composition verses the distance of cores locations along sub-reach E5.....67

Figure 48. Map of tracklines, grab samples, and core locations within sub-reach E4.....72

Figure 49. Roxann seabed classification map of sub-reach E4.....73

Figure 50. Map of tracklines, grab samples, and core locations within sub-reach E3.....74

Figure 51. Roxann seabed classification map of sub-reach E3.....75

Figure 52. Graph of the top composite samples grain size composition verses the distance of cores locations along sub-reach E4.....75

Figure 53. a) Vertical curtains of chirp sub-bottom profiles for the southern boundary of sub-reach E4 (cores contained in view at right are (red cylinders): DRV-20 (in E5) and DRV-75). b) Vertical curtains of chirp sub-bottom profiles for the northern boundary of sub-reach E4 (core and grab sample contained in view at far left are: DRV-74 (red cylinder) and MC052710-8 (green diamond)). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).....77

Figure 54. Graph of the top composite samples grain size composition verses the distance of cores locations along sub-reach E3.....78

Figure 55. a) Vertical curtains of chirp sub-bottom profiles for the southern boundary of sub-reach E3 (cores contained in view at center are (red cylinders): DRV-19 (right core) and DRV-73(left core)). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the southern boundary of sub-reach E3. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).....79

Figure 56. Graph of the top composite samples grain size composition verses the cores locations distance along sub-reach E2. 81

Figure 57. a) Vertical curtains of chirp sub-bottom profiles for the northern boundary of sub-reach E3 (cores contained in view at left center are (red cylinders): DRV-17 (lower left core) and DRV-70 (upper core in sub-reach E2)). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the northern boundary of sub-reach E3. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 82

Figure 58. Map of tracklines, grab samples, and core locations within sub-reach E2. 85

Figure 60. Roxann seabed classification map within the southern extent of sub-reach E2. 87

Figure 61. Vertical curtains of chirp sub-bottom profiles for the southern boundary of sub-reach E2 and northern boundary of sub-reach E3 (cores contained in view at right center are (red cylinders): DRV-17 (lower right core in sub-reach E3) and DRV-70 (upper core in sub-reach E2)). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 88

Figure 62. a) Vertical curtains of chirp sub-bottom profiles for the southern region of sub-reach E2 (north of DRV-70 and south of DRV-69). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the southern region of sub-reach E3. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 90

Figure 63. Vertical curtains of chirp sub-bottom profiles for the southern region of sub-reach E2 (north of DRV-70 and south of DRV-69), grab sample MC052710-13 (green diamond). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 91

Figure 64. Vertical curtains of chirp sub-bottom profiles for the southern region of sub-reach E2 (core DRV-69 (red cylinder) shown at far left and grab sample MC052710-13 (green diamond at right) and MC052710-14 (green diamond at far left, adjacent to DRV-69)). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 91

Figure 65. Vertical curtains of chirp sub-bottom profiles for the south central region of sub-reach E2 (shown are cores DRV-69 (red cylinder, at far right) and DRV-68 R2 (red cylinder, at far left) and MC052710-14 (green diamond at far right, adjacent to DRV-69)). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 92

Figure 66. Vertical curtains of chirp sub-bottom profiles for the central region of sub-reach E2 (shown are core DRV-68 R2 (red cylinder, at center)). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 92

Figure 67. Vertical curtains of chirp sub-bottom profiles for the central region of sub-reach E2 (area is to the north of Figure 66). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 93

Figure 68. Vertical curtains of chirp sub-bottom profiles for the north central region of sub-reach E2 (area is to the north of Figure 67). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 93

Figure 69. Vertical curtains of chirp sub-bottom profiles for the northern region of sub-reach E2 (area is to the north of Figure 68, and just south of core DRV-64). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 94

Figure 70. Vertical curtains of chirp sub-bottom profiles for the northern region of sub-reach E2 (cores shown at left are (from right to left): DRV-64, DRV-63 (lower core at left), and DRV-62 (upper core at left)). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 94

Figure 71. Vertical curtains of chirp sub-bottom profiles for the northern region of sub-reach E2 (cores shown at left are (from right to left): DRV-64 (far right) , DRV-63 (lower core at right), DRV-62 (upper core at right center), DRV-61 (lower core at center), DRV-88 (upper core at center), DRV-60 (to the lower left of DRV-88, but obscured by lower vertical curtain), DRV-87 (upper core at left center), DRV-15 (lower core at far left), and DRV-59 (upper core at far left). Also shown is grab sample MC052710-15 (green diamond at center), adjacent to DRV-88. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 96

Figure 72. Vertical curtains of chirp sub-bottom profiles for the northern region of sub-reach E2 (cores shown at left are (from right to left): DRV-88 (upper core at right), DRV-60 (to the lower left of DRV-88), DRV-87 (upper core at right center), DRV-15 (lower core at center), DRV-59 (upper core at left center), DRV-86 (lower core at left), DRV-58 (to the left of DRV-86, but obscured by lower vertical curtain), and DRV-85 (top core to left, in sub-reach E1). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 96

Figure 73. Vertical curtains of chirp sub-bottom profiles for the northern region of sub-reach E2 (cores shown at left are (from right to left): DRV-87 (upper core at right), DRV-15 (lower core at right), DRV-59 (upper core at right center), DRV-86 (lower core at right center), DRV-58 (to the left of DRV-86, but obscured by lower vertical curtain), and DRV-85 (top core to center, in sub-reach E1). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft). 97

Figure 74. Roxann seabed classification map within the northern extent of sub-reach E2, and southern extent of E1. 98

Figure 75. Generalized cross-section of the proposed Broadkill Beach nourishment project (EA, 2009). 101

Figure 76. Sample sites on the beach at Broadkill Beach. 103

Figure 77. Diagram of the beach profile gradient resulting from several sediment grain size and exposure to different wave height to wavelength (H/L) ratios (Wright and Short, 1982). 106

Figure 78. Cross-section of the proposed Kelly Island confined disposal facility (EA, 2009). 109

Figure 79. The Wentworth grain size scale for sediments (Folk, 1974). 118

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I. Introduction

The Delaware Coastal Program within the Office of the Secretary of the State of Delaware Department of Natural Resources and Environmental Control (DNREC) and the University of Delaware Geosciences Department have conducted a bottom and sub-bottom mapping study to identify and constrain the surface and sub-surface sediment grain size distribution for the navigation channel in Reach E of the proposed Delaware River and Bay Main Channel Deepening Project (lower Delaware Bay between River Miles 6 (approximate channel station 512+000, near Brown Shoal) and 42 (approximate channel station 351+200, off Woodland Beach, Delaware; Figure 1). The purpose of this study was to assess the grain size distribution of sediments in Reach E that are proposed to be removed through the Main Channel Deepening Project of the Delaware River and Bay.

It is the assertion of the Philadelphia District of the Army Corps of Engineers (PD-ACOE) that the sediments that are removed from Reach E can be used as a beneficial resource for the State of Delaware. This study in the form of a data review and acoustic survey was implemented to validate the results presented by the PD-ACOE, for the State of Delaware Wetlands and Subaqueous Lands Permit, as to the suitability of the sediments for coastal construction and beach restoration.

The acoustic survey consisted of running two parallel tracklines along Reach E of the navigation channel, one along the eastern side and the other along the western side of the channel. The approximate distance between the tracklines was 270 meters (m) (~900 feet (ft)). The methodology used in the survey, collecting acoustic Roxann seabed classification and chirp sub-bottom profiling data and “ground-truth” sediment grab samples, was developed during the Delaware Bay Benthic Mapping Project carried out by the Coastal Program over the past seven years. Over the course of four days, 103.1 miles of trackline and 14 sediment surface grab samples were collected though Reach E.

In this report, the Roxann seabed classification and chirp sub-bottom profiling data collected during the survey, were integrated with the coring and grain size data that

was provided by the PD-ACOE to assess the quality of the grain size data and the grain size distribution of the Reach E surface and sub-surface sediments. The report includes a brief outline of the Roxann seabed classification and chirp sub-bottom profiling systems, methods used to classify and develop the surficial sediment maps, images of the chirp profiles that were collected, a general discussion of the sub-bottom sediment layers and bottom morphology delineated by the profiles, and an integrated assessment of all data collected in each sub-reach of Reach E.

The material that is proposed to be removed from Reach E of the Delaware River and Bay Main Channel Deepening Project were identified by the PD-ACOE as sediments that may be used for beneficial reuse along the State of Delaware's Bay coast. Approximately 4,081,700 cubic yards (cy) of material are to be removed, 2.5 million cubic yards (mcy) are to be placed at Kelly Island to create an impoundment or confined disposal facility (CDF) and 1.6 mcy are to be placed at Broadkill Beach for beach restoration (EA, 2009). Both projects were outlined as being beneficial to increasing or restoring horseshoe crab spawning habitat. The total footprint of the Kelly Island CDF will be 120 to 140 acres, with 60 acres of interior impounded habitat and 60 to 80 acres of areas associated with the protective beach and dune (EA, 2009; Figure 2).

Features of the project include:

- 60 acres of impounded area where the substrate will consist of an estimated 55,000 cy of silt and 645,000 cy of sand.
- An offshore containment dike made of 1.7 mcy of sand that will provide up to 5,000 linear ft of sandy beach. The crest of the dike will be at +10 ft MLW providing substantial spawning habitat for horseshoe crabs (Figure 3).
- A geotextile tube within the core of the offshore dike that provides overwash protection and contingency protection against breaching (Figure 3).
- Timber groins to limit sand transport along the beach.
- Options for water level control or free tidal exchange with the bay.

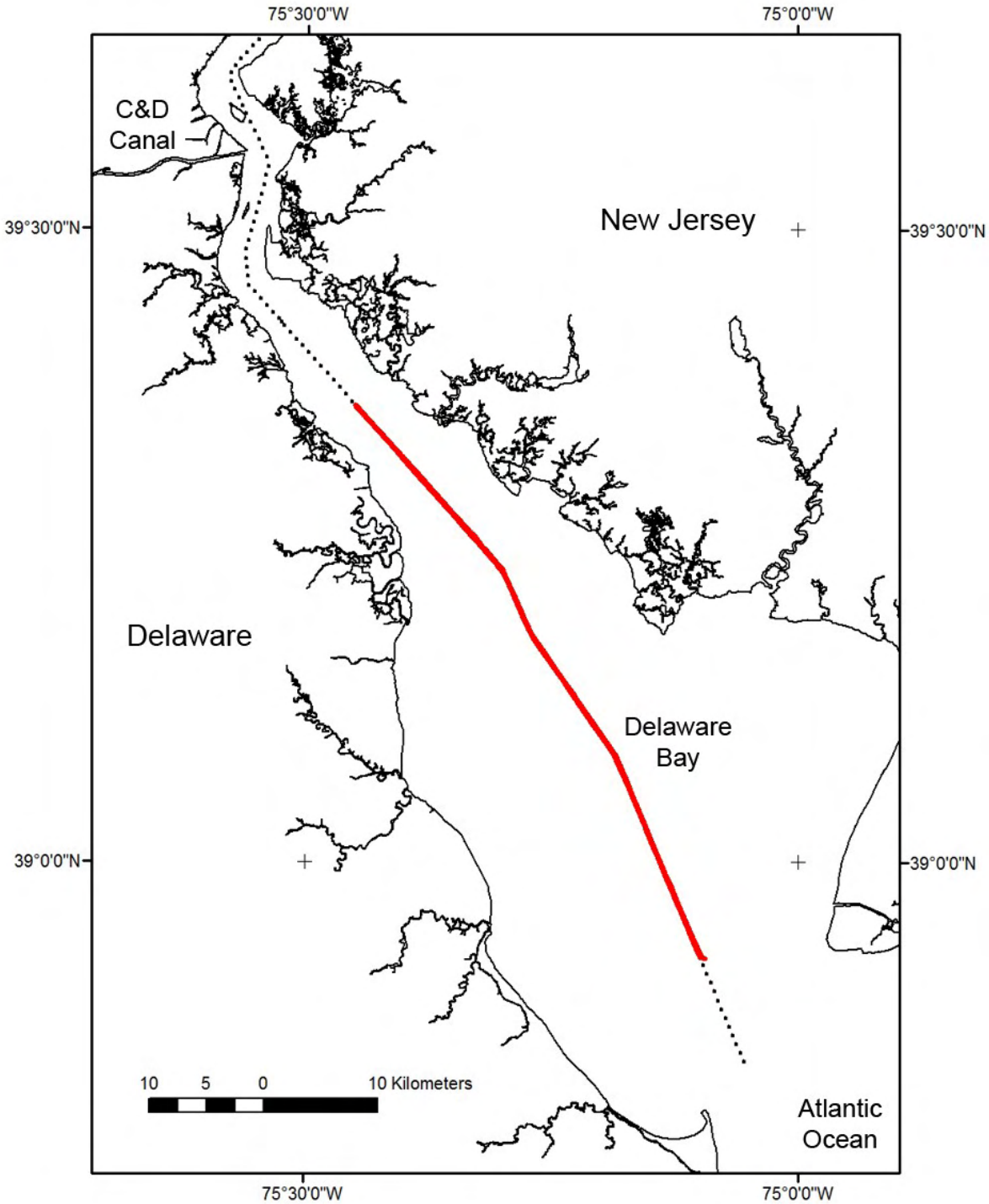


Figure 1. Regional location map for the Delaware navigation channel bottom and sub-bottom mapping survey. The survey area is shown by thick red line. Black dots denote 0.5 mile intervals of River Miles as defined by the Delaware River Basin Commission. River Mile 0 is located at the southernmost end of the navigation channel.

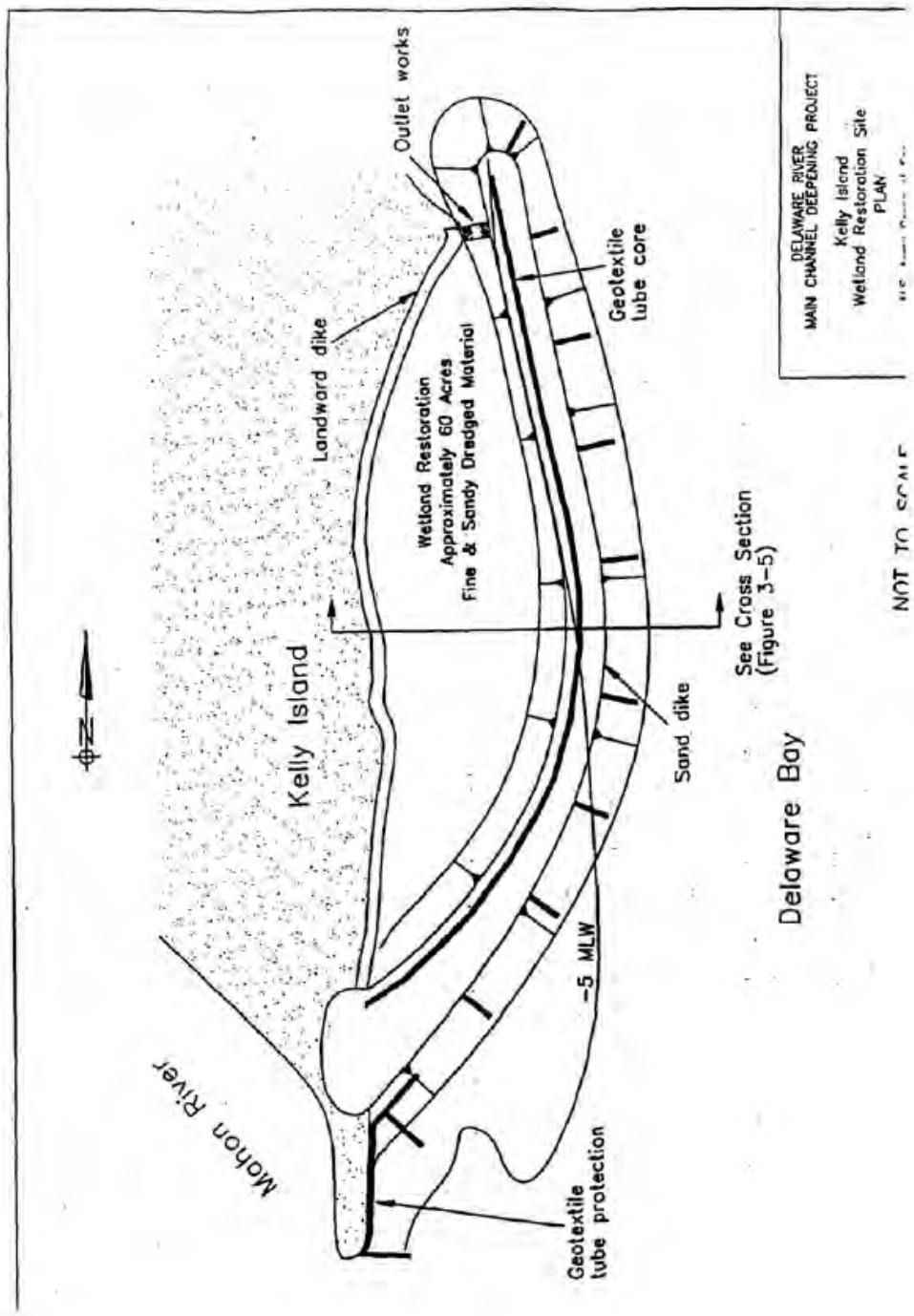


Figure 2.Proposed generalized design of the Kelly Island CDF (EA, 2009).

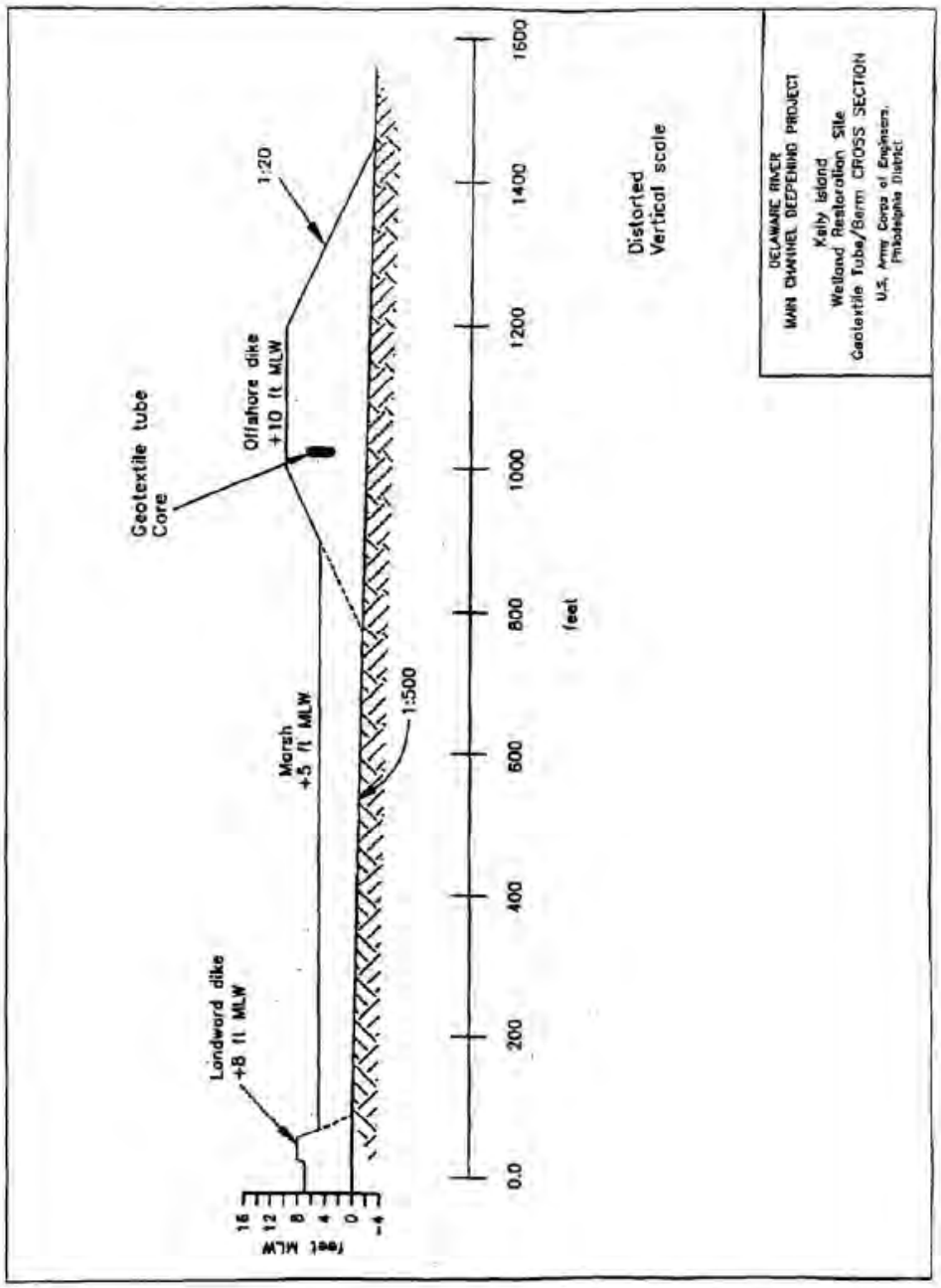


Figure 3. Kelly Island Geotextile Tube/Berm Cross Section.

Construction of the sand dikes will begin at the south end gaining access to the site from the Mahon River channel. Once the dikes are constructed, the interior will be filled. Filling will take approximately 4 months. The total time to construct Kelly Island is 6 months. The crest width of the shoreward dike will be 200 ft at its narrowest and 350 ft at its widest. The volume of sand in the cross section of the dike will be constant, i.e. 845 cy per linear yard. Therefore, the crest width of the dike in shallow water will be greater than in deeper water. The total volume of sand required for the offshore dike is 1.7 mcy (which includes a quantity sufficient to offset an estimated 1 ft of settlement). The offshore slope of the dike is estimated to be initially 1:20, and after the first year of "weathering" it should equilibrate to a milder 1:40 slope (EA, 2009).

The Broadkill Beach beach restoration was authorized as a project to protect the community from coastal and storm damage. The Broadkill Beach plan consists of a 100 ft wide berm at an elevation of +8 ft NGVD (Figure 4). The nourishment plan contains the following components:

- A berm extending seaward 100 ft from the design line. The beachfill extends from Alaska Avenue southward for 13,100 linear ft. Tapers of 1,000 ft extending from the northern project limit and 500 ft extending from the southern project limit brings the total project length to 14,600 linear ft.
- On top of the berm lies a dune with a top elevation of +16 ft NGVD and a top width of 25 ft.
- A total initial volume of 1,567,281 cy of sand fill would be placed along the area, with 31,289 cy of silt to clayey sand placed on the beach before the sand placement. This fill volume includes initial design fill requirements and advanced nourishment. Note that the initial volume design quantity will change over time due to natural accretion and erosion.
- Periodic nourishment of 358,400 cy of sand fill would be placed every 5 years.
- Planting of 174,800 square yards of dune grass and 21,800 linear ft of sand fence are included for dune stability.

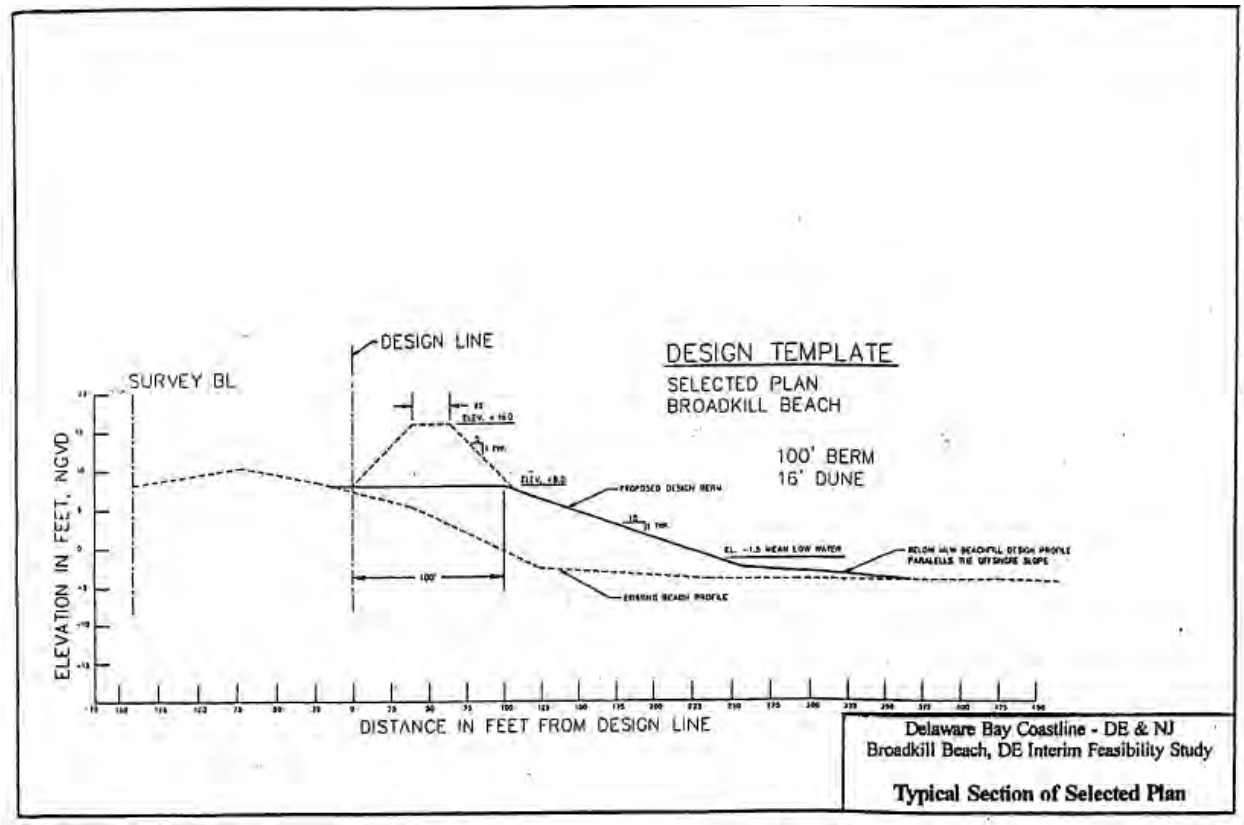


Figure 4. Generalized cross-section of the proposed Broadkill Beach nourishment project (EA, 2009).

Broadkill Beach has been receiving nourishment since 1957. Approximately 1,150,600 cy of material has been placed to date. The approximate length of beach periodically nourished for Broadkill varies from 5,500 ft (for truck-fill placement) to 15,190 ft (for offshore large scale nourishment). Kelly Island has never received nourishment. The sandy beach deposits of the Kelly Island region consist of approximately 400 to 1,300 ft long pocket beaches (only 30 to 130 ft in width) which are bisected by projections of marsh. These pocket beaches consist of thin layers (2 inches (in) to 2 ft) of sand which overlay intertidal Holocene (peats and peaty muds) and Delaware Bay Group (silty clays to clayey silts) deposits.

The general rule of thumb for both DNREC and the PD-ACOE is to match grain size of fill material to the native receiving beach grain sizes. The current grain size distribution for Broadkill Beach was determined for this assessment through surface sediment samples. The results of the sediment samples will be reviewed in the Discussion Section of this report. The native receiving beach grain size distribution greatly affects a beach's resistance to storm erosion and utilization of the beach face by horseshoe crabs. Coarser grain sizes are more resistant to storm erosion, which is especially important in areas like Kelly Island where a dominate northwestern fetch results in this region having the highest rate of shoreline erosion in Delaware (Kraft et al., 1992). Broadkill Beach and Kelly Island both are known areas of active horse crab spawning, and because grain size plays an important role in egg development the beach sediments should be consistent with the ASMFC Fishery Management Plan for Horseshoe Crab (1998).

The ASMFC Fishery Management Plan for Horseshoe Crab (1998) recommends that the grain size of the sand placed on a beach undergoing re-nourishment should be consistent with the grain sizes that already exist within the spawning habitat at that beach. Thus, the material at a "beneficial use" site should be similar in grain size to that at the beach in question. Smith et al. (2002) in a review of horseshoe crab habitats concluded that the source of sediment for beach nourishment should be chosen to reflect a coarse-grained estuarine beach. They suggested that the material should have a gravel sub-fraction and have a mean sediment size of 0.35 to 0.50 millimeters (mm) in the sand fraction (Smith et al., 2002).

Botton et al. (1994) noted that the grain size of beaches that had the greatest horseshoe crab spawning concentrations in Delaware Bay were from 0.6 to 0.8 mm, with a median grain size of 0.7 mm (Brady and Schrading, 1996). Penn and Brockmann (1994) found that fine-grained, poorly drained sediments impeded horseshoe crab egg development and that eggs placed in coarse well-drained sediments were prone to desiccation.

Slope has been determined to be an important orientation cue for nesting horseshoe crabs. Crabs that are not able to orient themselves to the water become stranded and desiccate on the beach. Botton and Loveland (1987) found that a slope of 6° seaward (approximately 1V:10H) allowed both sighted and blinded crabs to orient to the shoreline. Any slope shallower than this caused crabs to have trouble finding their way back to the water line. It has also been found that adult horseshoe crabs are sensitive to hydrogen sulfide because it affects the development of eggs. In order for crabs to successfully nest on a beach underlain by marsh, there should be a minimum of 8 in (20.3 centimeters (cm)) of sand cover, but 16 in (40.6 cm) is optimal (personal communication Stew Michels, 2010).

II. Methods of Investigation

i. Chirp Sub-bottom Profiling System

An Edgetech X-STAR chirp sonar system with a SB-216S tow-fish was used to collect the sub-bottom data in the survey. The fish was towed aft of DNREC's Division of Fish & Wildlife research vessel *First State* at a depth of ~3 meters (m) (~10 ft) below the water surface (Figure 5). The system transmitted a linearly swept (2 to 12 kHz) wide-band frequency modulated sound pulse at an interval of 5 cycles per second. During operation, chirp pulses travel through the water column and seabed and are reflected when they encounter changes in acoustic impedance, the product of the sonic velocity and density of the sub-surface materials through which the pulses are passing. The reflected sound energy travels back to the system as a function of travel time and its amplitude is digitally recorded (Figure 6). Because acoustic reflecting boundaries almost always occur at interfaces between different geologic materials, spatial changes in the amplitude, continuity, and geometry of the chirp reflections associated with these boundaries can be used to interpret sub-bottom structure and stratigraphy (i.e., the layering of sub-bottom sediments).

Given the 2-12 kHz frequencies used by the chirp system, the vertical resolution of the boundaries between differing sub-surface sediment layers is estimated to be on the order of 20-30 cm (8-12 in). With a sampling interval of 5 cycles per second and an average vessel speed of 5 knots, the distance between individual traces (i.e., the horizontal resolution) of the chirp sonar is on the order of 0.5 m (1.6 ft). Sonar reflections were observed to maximum depths of ~20 m (60 ft) below the bay bottom. More commonly, penetration depths were on the order of 2-10 m (6-30 ft) below the bay bottom. The chirp data were recorded with co-registered GPS positional data to a computer hard drive.

The chirp data was primarily used to image sub-bottom sedimentary layers to provide constraints on sediment type and their thickness and continuity. It was also integrated with the RoxAnn sediment classification information to examine bottom sediment distribution and, in a limited sense, to describe the bottom morphology (e.g.,

Figure 5. Chirp tow-fish on fantail of *R/V First State*. Tow-fish deployed aft using A-frame.

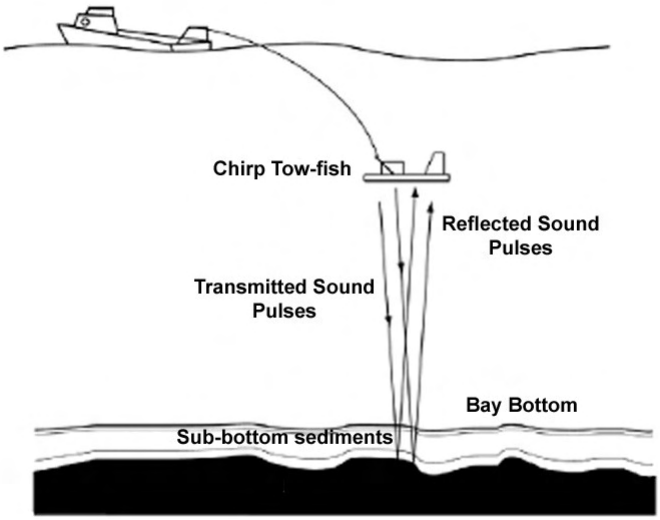


Figure 6. Schematic diagram of chirp sonar system imaging the sub-bottom.

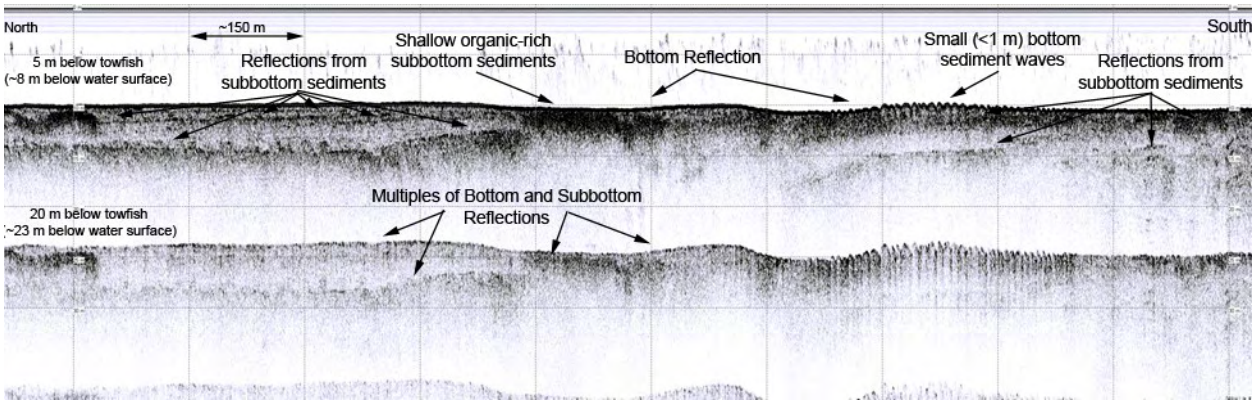


Figure 7. Example image of chirp sub-bottom profile. Profile was collected along the western side of the navigation channel near River Mile 23 along a trackline that was oriented from northwest (left side of the profile) to southeast (right side of the profile). Horizontal lines mark depths at 5 m intervals below the chirp tow-fish. Vertical lines occur at one minute time intervals and, given an average ship's speed of 5 knots, are spaced approximately 150 m (492 ft) apart.

sediment waves) of the navigation channel. An example chirp sub-bottom profile collected in the Reach E survey area is shown in Figure 7.

The example profile illustrates the utility of using the chirp system to image sub-bottom and bottom sediments. Along the left side of the profile, a prominent sub-bottom reflection is observed ~5 m (16 ft) beneath the bottom. This reflection can be traced for a distance of 600 m (1,968 ft) along the profile, shallowing to less than 3 m (10 ft) beneath the bay bottom towards the south. Above this reflection, a series of horizontally continuous reflections are observed at depths of 1 m (3 ft) to 2 m (7 ft) beneath the bottom. Near the middle of the profile at relatively shallow depths (<1 m (3 ft)) beneath the bottom, high-amplitude (dark color in profile) reflections are observed. These high-amplitude reflections are most likely associated with the presence of organic-rich sediments. Gases produced by the decay of organic material can accumulate in the pores of sediments. In terms of acoustics, gas is associated with a very high (approaching a value of 1) acoustic impedance. This means that the down-going acoustic energy is nearly, if not all, reflected when gases are encountered in the subsurface. Further to the south, the chirp profile indicates the presence of small (<1 m (3 ft) amplitude) sediment waves along the bottom of the navigation channel. These sediment waves are most likely generated by tidal currents causing movement of sediments along the bottom of the channel.

ii. Roxann Seabed Classification System

The Roxann system is a remote acoustic sounder that can be used to develop sediment classifications and bathymetry of the sea floor. The 200 kHz single beam transducer pings at a rate of 1 cycle per second and can be used in depths of ~1 to 50 m (3 to 150 ft). The transducer for the Roxann generates sound waves that come into contact with the sea floor, and the way these sound waves, or echoes, are reflected are utilized to classify various bottom types (e.g., sandy vs. muddy). The properties (e.g., amplitude & shape) of a sound wave reflected from the sea floor is determined mainly by the roughness and hardness of the bottom, the change in acoustic impedance between water and sea floor materials, and how sound reverberates within materials at

the water/sea floor interface. The bottom roughness affects the degree to which sound is scattered when it strikes and is reflected off the sea floor. For example, a rougher bottom will cause a greater degree of scattering. The change in acoustic impedance (the product of the sonic velocity and density of a material) can be related to the hardness of the bottom. A harder bottom (e.g., sandy) will have a higher acoustic impedance contrast with water, and thus larger amplitudes of sound will be reflected at the boundary (e.g., Madsen 2004).

Roxann bottom classifications are based on two primary echo pulses (Figure 8). The first echo is reflected directly from the sea floor and the second is reflected off the sea floor, off the sea surface, and then reflected again off the sea floor (commonly called the first multiple). These two echoes are used to develop Roxann's E1 and E2 parameters.It has been shown that the properties of the first echo (E1) primarily arise from the roughness of the bottom (and its effect on the scattering of sound) and the properties of the second echo (E2) are a function of the hardness of the sea floor (related to the degree of change in acoustic impedance between water and sea floor materials). In real-time, E1 (roughness) and E2 (hardness) values as measured by the Roxann system are plotted on a computer screen and digitally recorded with co-registered GPS positional data (Figure 9). In order to relate the roughness and hardness values to actual bottom types, grab samples are collected at locations that correspond to areas where boxes of similar E1and E2 values are clustered.

The scheme used to classify the Roxann data for the Reach E navigation channel survey was based upon the Delaware Bay and River Benthic Mapping Project's Roxann box plot that has been verified with 550 grab samples collected during the Projects's 2004, 2005, 2006, 2007, and 2008 field seasons (Figure 10).

Sediment grab samples were collected in the Reach E survey area after the acoustic surveying was completed to verify the correlation of the acoustic data with bottom sediment type using the Benthic Mapping Project box plot and to determine if there was the potential for non-unique sediment classifications.

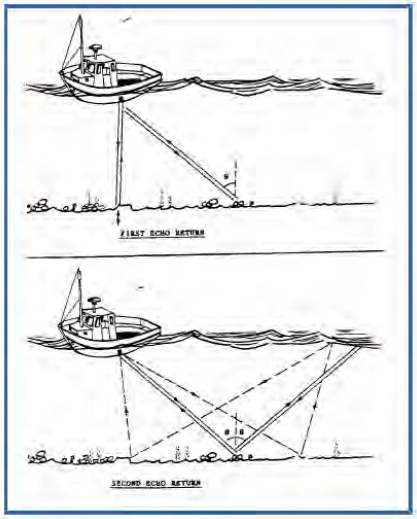


Figure 8. Schematic diagram of Roxann acoustic system. Shown are the (upper image) first (E1) and (lower image) second (E2) echoes that are associated with the system.

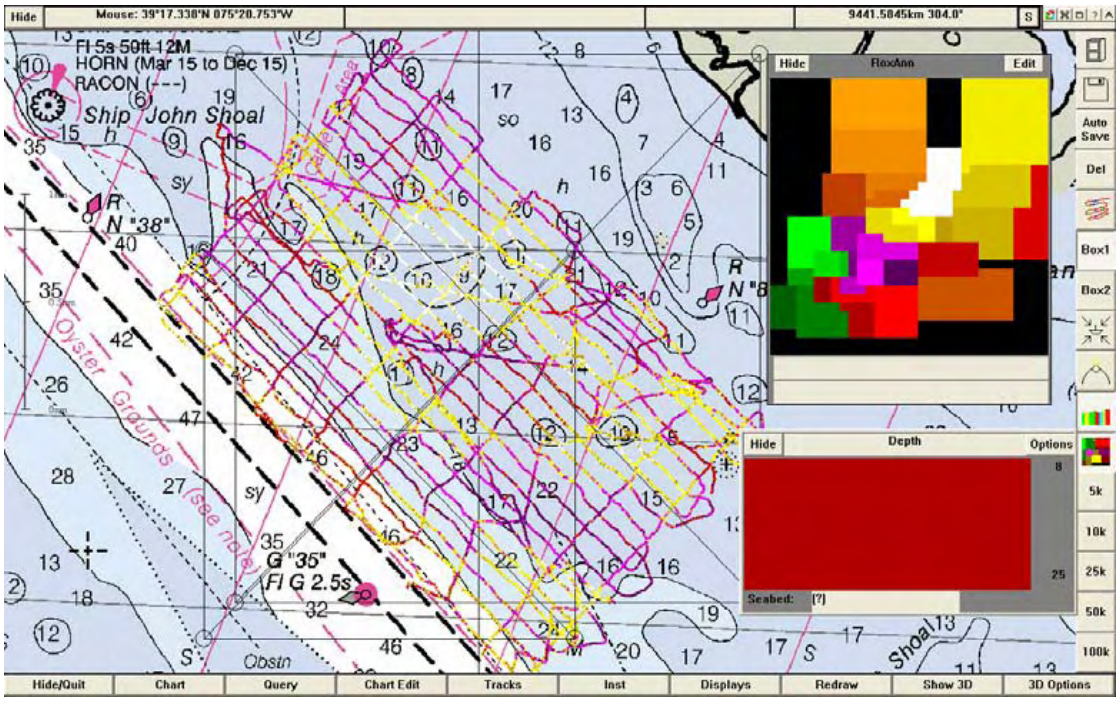


Figure 9. Real-time Roxmap display showing the depth (lower right window), the box plot being currently used to classify the incoming data and area of data clustering (upper right window), and the tracklines collected with their corresponding sediment classification values.

From the Benthic Mapping Project, we have observed non-unique sediment classifications associated with some clusters of (E1, E2) points. These non-unique classifications can occur with the presence of shell material, tube worms (e.g., *Sabellaria vulgaris*, *Dioptra cuprea*, and *Spiochaetopterus costarum*), peat, or pre-Holocene, highly compacted and silts and sands on the bay bottom. For example, gravel and dense shell material both have similar (E1, E2) values and will cluster in the same range (i.e., co-classify) , exposures of peat on the bottom co-classify with silty medium-grained sands, and pre-Holocene silty fine-grained sands to fine-grained sandy silts co-classify as sandy granule-sized pebbles and gravel.

iii. Sediment sampling

The 14 sediment grabs in the Reach E survey area were collected using a Petite Ponar sampler (Figure 11), which has an opening of 15.2 x 15.2 cm (6 x 6 in), generating a total potential sampling area of 232.4 cm^2 (36 in^2). The Petite Ponar is a spring loaded sampler which pivots on an axis and when it encounters the bottom the retrieval rope is pulled and the ponar swings shut. It will typically retrieve 5 to 15 cm (2 to 6 in), in depth, of sediments (depending on sediment type, harder and coarse sediments will limit the ponar's penetration into the bottom). The retrieved sediment samples are placed in whirl-pak sample bags and stored in coolers. The sediment samples were sent to the Pennsylvania State University Analytical Lab for grain size analysis.

The sediment size classes for the sieve data from the PD-ACOE vibra-core composite samples and the DNREC surface sediment samples vary considerably in which sieve (and subsequent grain diameter) were used to segregate the sediment samples into their sediment size classes (Table 1). The sediment size classes and grain diameters that are considered to be the standard by geologists for determining the grain size of samples are the Wentworth size classes published in Folk (1974). The PD-ACOE used sizes for classes based upon the Unified Soil Classification System (ASTM D2487-10 Standard Practice for Classification of Soils for Engineering Purposes), which

are distinctly different than the standard Wentworth sizes (Table 1). The Unified Soil Classification System (USCS) is a soil classification system used by soil sciences and engineering disciplines to describe the texture and grain size of unconsolidated soils (ASTM, 1985).

Considering the surface and sub-surface sediments of the Delaware Bay to be soils and not benthic sediments, is a departure from the classic notion that a soil consists of layers (soil horizons of variable thickness) of mineral constituents with air, water, dead organic matter and various types of living organisms (Birkeland, 1999). Benthic sediments do not form by pedogenesis, where soil is formed through the combined effects of physical, chemical, biological (including anthropogenic) processes upon bedrock or other soil parent materials (Buol et al., 1997).

Figure 11. Petite ponar grab sampler with open bottom and spring loaded pin hanging off of the pivot point.

Army Corp US Standards Sieve Used (Number; USCS)	Sieve Size (mm)	Penn State Agriculture Analytical Services US Standards Sieve Used (Number)	Sieve Size (mm)	Wentworth Standard Class Breaks	Sieve Size (mm)	Wentworth Sediment Size Classes
4	4.75	5	4	5	4	Pebble to Boulders
10	2	10	2	10	2	Granule
20	0.85	18	1	18	1	Very Coarse Sand
40	0.43	35	0.5	35	0.5	Coarse Sand
60	0.25	60	0.25	60	0.25	Medium Sand
100	0.15	140	0.105	120	0.125	Fine Sand
200	0.072	270	0.053	230	0.0625	Very Fine Sand
< 200	< 0.072	< 270	< 0.053	< 230	< 0.0625	Coarse Silt to clay

Table 1. US standard sieve number and sieve size used by the Army Corp of Engineers and Penn State Agriculture Analytical Services, compared to the standard Wentworth sediment size classes.

US Standard Sieve Mesh #		Millimeters	Microns	Phi (ϕ)	Wentworth Size Class
		4096		-12	
		1024		-10	Boulder (-8 to -12 ϕ)
		256		-8	
		128		-7	Cobble (-6 to -8 ϕ)
		64		-6	
		16		-4	Pebble (-2 to -6 ϕ)
5.00		4.00		-2	
6.00		3.36		-1.75	
7.00		2.83		-1.5	Granule
8.00		2.38		-1.25	
10.00		2.00		-1.0	
12.00		1.68		-0.75	
14.00		1.41		-0.5	Very Coarse Sand
16.00		1.19		-0.25	
18.00		1.00		0.0	
20.00		0.84		0.25	
25.00		0.71		0.5	Coarse Sand
30.00		0.59		0.75	
35.00	1/2	0.50	500	1.0	
40.00		0.42	420	1.25	
45.00		0.35	350	1.5	Medium Sand
50.00		0.30	300	1.75	
60.00	1/4	0.25	250	2.0	
70.00		0.210	210	2.25	
80.00		0.177	177	2.5	Fine Sand
100.00		0.149	149	2.75	
120.00	1/8	0.125	125	3.0	
140.00		0.105	105	3.25	
170.00		0.088	88	3.5	Very Fine Sand
200.00		0.074	74	3.75	
230.00	1/16	0.0625	62.5	4.0	
270.00		0.053	53	4.25	
325.00		0.044	44	4.5	Coarse Silt
		0.037	37	4.75	
	1/32	0.031	31	5.0	
	1/64	0.0156	15.6	6.0	Medium Silt
	1/128	0.0078	7.8	7.0	Fine to Very Fine Silt
	1/256	0.0039	3.9	8.0	
		0.0020	2.0	9.0	
		0.00098	0.98	10.0	
		0.00049	0.49	11.0	Clay
		0.00024	0.24	12.0	
		0.00012	0.12	13.0	
		0.00006	0.06	14.0	

Figure 12. The Wentworth grain size scale for sediments (Folk, 1974).

The divisions between granules and very coarse sands (US standard sieve #10) and between medium sands and fine sands (US standard sieve #60) are the only divisions that are consistent between the Wentworth and the USCS schemes. The PD-ACOE (using the USCS scheme) divides pebbles and granules using sieve #4, while the Wentworth scale uses sieve #5, a difference of 0.75 mm in terms of defining the diameters of these sediments. The lower limit of very coarse to coarse sands is marked by the PD-ACOE at the #20 sieve, while the Wentworth scale sets it at the #18 sieve (a difference of 0.15 mm). The division between coarse sands to medium sands is set by the PD-ACOE at sieve #40; the Wentworth scale sets it at the #35 sieve (a difference in of 0.07 mm). The fine sand to very fine sand division for the PD-ACOE is at sieve #100, while the Wentworth scale uses sieve #120 (a difference 0.025 mm). The division between very fine sand to coarse silt is set by the PD-ACOE as being at sieve #200, while the Wentworth scale uses sieve #230 (a difference of 0.0095 mm) (Figure 12, Table 1).

The surface sediment samples, which were collected through this project to verify the Roxann seabed classification results, were sieved by the Penn State Agriculture Analytical Services. These samples were only used to verify the Roxann results, with the sieve size class results comparable to the Wentworth scale. The only differences in sieve size used, as compared to the Wentworth scale, were the divisions between fine sands to very fine sands (set by Penn State as the #140 sieve (a difference of 0.020 mm) compared to the Wentworth size #120 sieve) and very fine sands to coarse silts (set as sieve #270 (a difference of 0.0095 mm) compared to the Wentworth size of the #230 sieve) (Figure 12, Table 1).

III. Results and Interpretation

i. Bottom Sediment Distribution

In order to generate bottom sediment distribution maps, the sediments that were surveyed using the RoxAnn system and classified using the Delaware Bay Benthic Mapping box plot were placed into a ranking scale numbered from 0 to 28 with 0 representing the finest grained sediments (i.e., fluidized clay) and 28 representing

dense shell material (Table 1). The ranking scale used both the Wentworth and Shepard sediment classification schemes (Figures 12, 13 and 14) to describe grain size and sediment type (Wentworth, 1922; Shepard, 1954; Schlee, 1973).

The ranking scale is not linear, in that the discrepancy between finer grained (clay and silt-sized) sediments is less distinct for each change in ranking unit when compared
to the coarser grained (sand to gravel-sized) sediments (Table 1). This non-linearity is reflective of differences in the degree of variation in depositional environments and logarithmic increases in phi-size (diameter) of sediments. There is less change in the depositional environments of finer grains (clay and silt) as a result of similar current regimes, sorting, and reworking patterns as compared to coarse sediments that are much more variable with respect to current velocities, sorting, and winnowing e.g., Poppe et al., 2003).

The sediment ranking scale values (0 to 28) were gridded using Surfer®8 surface and terrain modeling software. Block kriging and a nugget effect were used in the gridding. Block kriging utilized the existing point data values weighting them as a function of proximity to the grid point being determined (e.g., Isaaks and Srivastava, 1989). The use of a nugget effect was based on the assumption that there was very little, if any, lateral correlation or trends within the bottom sediments. Nugget effect models assume a lack of spatial correlation in which data values at any particular location bear no similarity to adjacent data values (e.g., Isaaks and Srivastava, 1989). Without the nugget effect, the gridding routine would assume that there would be a linear progression of sediment types between different data points (i.e. fine to coarse sand and coarse sand with organic material would be inserted between sandy silt and coarse sand even though that is not what is occurring along the bottom (Table 2).

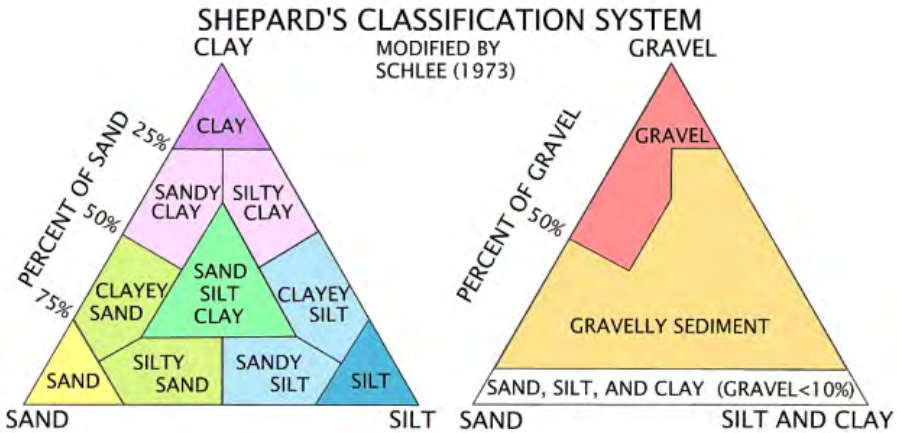


Figure 13. Shepard's sediment classification scheme based upon the proportion of sand, silt and clay. The major classification breaks along each axis are 25%, 50%, and 75%. The central sand/silt/clay region is further split into 3 regions, where the triangle outline represents a 20% proportion (Poppe et al., 2003; Schlee, 1973).

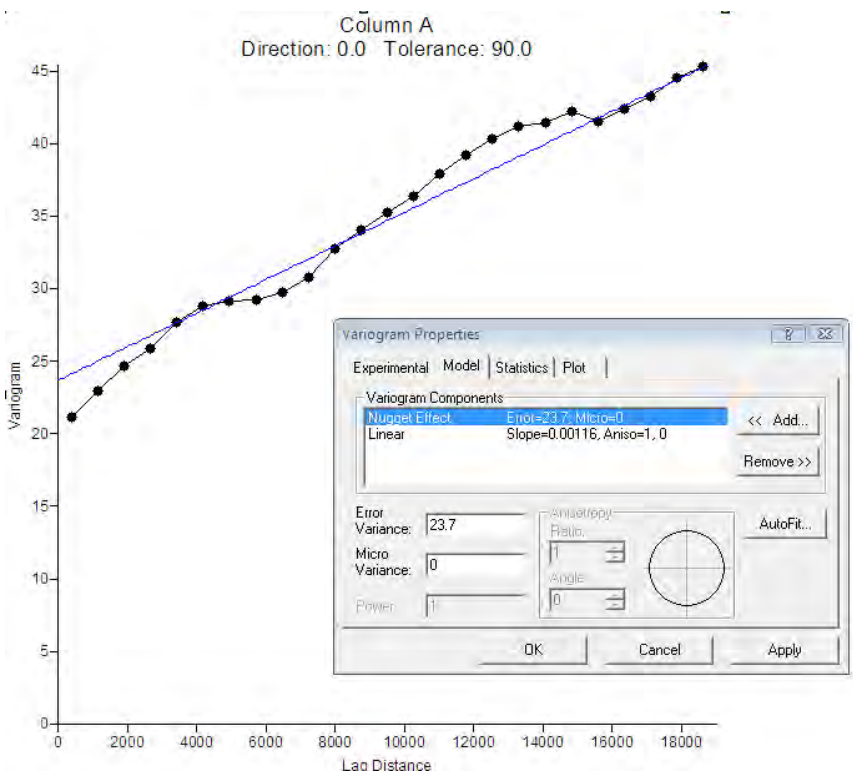


Figure 14. Variogram constructed for the Roxann bottom sediment point data, also showing the model used in the interpolation.

Sediment Classification Ranking	Sediment Description
0-1	
1-2	Clay
2-3	
3-4	
4-5	
5-6	
6-7	Silt
7-8	
8-9	Sandy Silts
9-10	
10-11	Fine Sand
11-12	
12-13	Silty Fine to Medium Sands
13-14	Silty Medium Sand
14-15	
15-16	Fine to Medium Sand
16-17	
17-18	Fine to Medium Sand, with abundant shell material and/or pebbles
18-19	
19-20	Coarse Sand, with varying amounts of pebbles
20-21	
21-22	
22-23	Moderate Shell Material / Sandy Pebbles
23-24	
24-25	
25-26	Abundant Shell Material / Gravel
26-27	
27-28	Dense Oyster Shell

Table 2. Sediment classification ranking and associated sediment descriptions for the Roxann data that was used to make the interpolated sediment maps.

ii. Sub-bottom Sediments and Bottom Morphology Based on Chirp Profiles

Along the navigation channel between River Miles 42 and 6, the chirp sub-bottom profiling data is of relatively high quality. It can be used to constrain the nature of the bottom and sub-bottom sediments and the bottom morphology of the channel. In this discussion, the major features observed in the chirp profiles are described from the northwestern portion (in the vicinity of River Mile 42, approximate channel station 351+200) to the southeastern end (in the vicinity of River Mile 6, approximate channel station 512+000) of the navigation channel in Reach E.

Between River Miles 42 and 37, a high amplitude bottom reflection is observed in the chirp profiles. The RoxAnn system, and confirmed by sediment grab samples, indicates that these sediments are silts to silty sands. This bottom layer, as constrained by the chirp data, is on the order of 1-2 m (3-7 ft) thick. It is thicker between River Miles 42 and 38.5 and noticeably thins between River Miles 38 and 37 (Figure 15). The surficial sediments are underlain by organic-rich sediments, as evidenced by the high amplitude of the chirp reflections at the boundary between the overlying surficial silts and silty sands and these sediments (Figure 15). The high amplitude chirp reflections in these sub-bottom sediments are indicative of the presence of naturally-occuring gases (e.g., hydrogen sulfide and/or methane) within the pore spaces of these sediments. The gases would be generated by the decay of the organic material. In some locations, there is evidence of “degassing” of the organic-rich sediments through the surficial sediments. This is especially well pronounced near River Mile 38 (Figure 15).

The bottom character of the navigation channel appears to be profoundly influenced by the presences of shoals (e.g., Ship John Shoal, Ben Davis Pt., Cross Ledge). In the vicinity of the shoals, the bottom is dominated by sediment waves with amplitudes that vary from less than 1 m (3 ft) to more than 2 m (7 ft) and there is evidence of erosion into sub-bottom sediments (Figure 16). The sediment waves and erosion are likely to be caused by the effect of the channeling (or focusing) of bottom and near bottom currents due to the presence of the nearby shoals.

Along the Miah Maull Range and the northern start of the Brandywine Range between River Miles 23 to 15, sub-bottom reflections indicate the presence of

paleochannels in the sub-surface. Examples of chirp images of smaller paleochannels are shown in Figure 17. These paleochannels are generally 150-250 m (500-800 ft) wide with the bases of the channels occurring at depths of 5-8 m (16-26 ft) beneath the bottom. They were most likely formed as drainage systems (e.g., tidal creeks) during past times of lower sea-level. The areas surrounding the paleochannels would have been exposed as land/marsh surfaces. As sea-level rose, these paleochannels, and the surrounding surfaces would have been in-filled by coarse- to fine-grained sediments of the estuary.

Further evidence of the influence of bordering shoals is shown near River Mile 14.5 to 14, in the vicinity of Fourteen Foot Bank and continuing southeastward to the end of the survey near Brown Shoal at River Mile 6, where the chirp profiles are characterized by the presence of bottom sediment waves with amplitudes from < 1 m to greater than 2 m. The most prominent sediment waves are observed along the eastern side of the navigation channel between River Miles 13 and 10.5 as the Brandywine Shoal is approached (Figure 18).

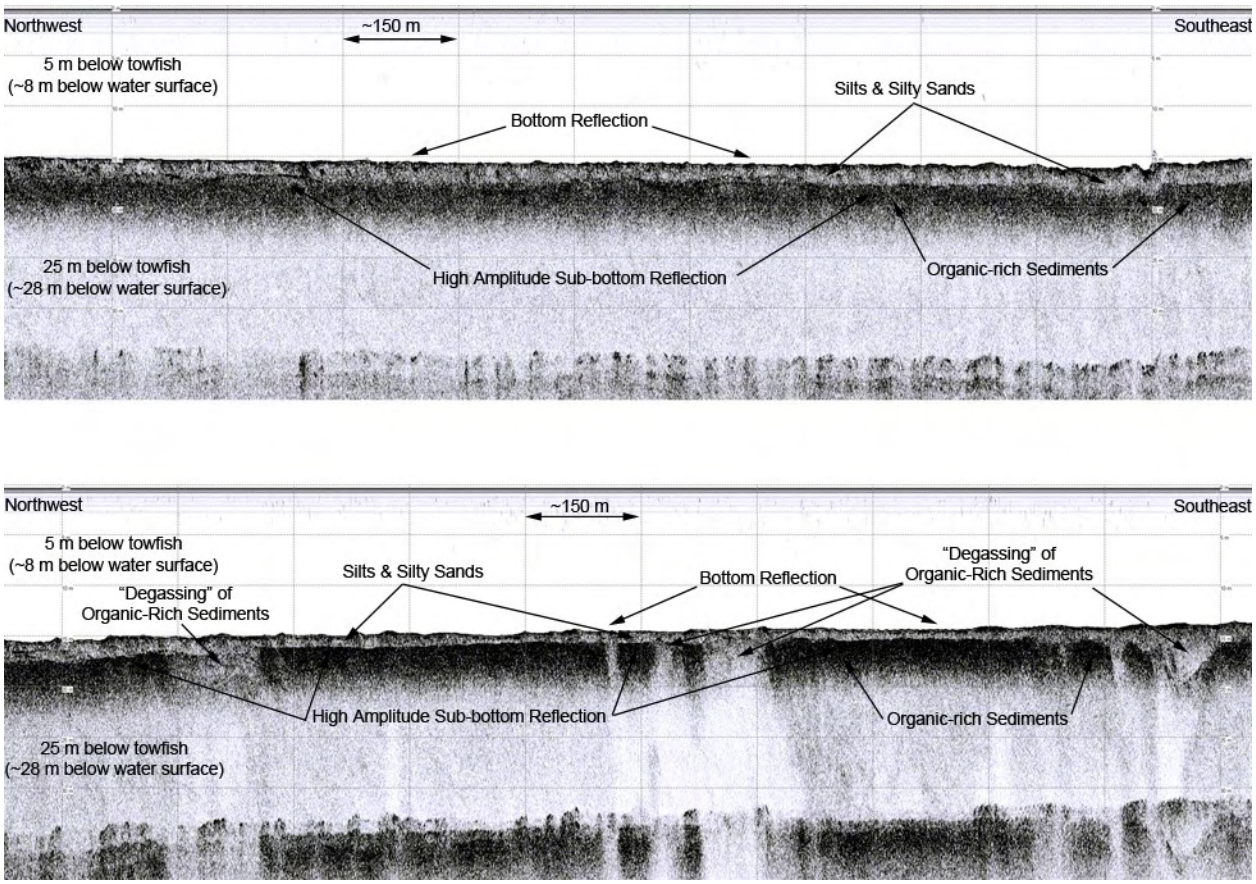


Figure 15. Chirp profile images along Liston Range near River Mile 40.5 and 38. Chirp files are bm_052510_f6 (top) and bm_052510_f9 (bottom). Top profile is located along the western side of the navigation channel near River Mile 40.5; bottom profile along the eastern side near River Mile 38.

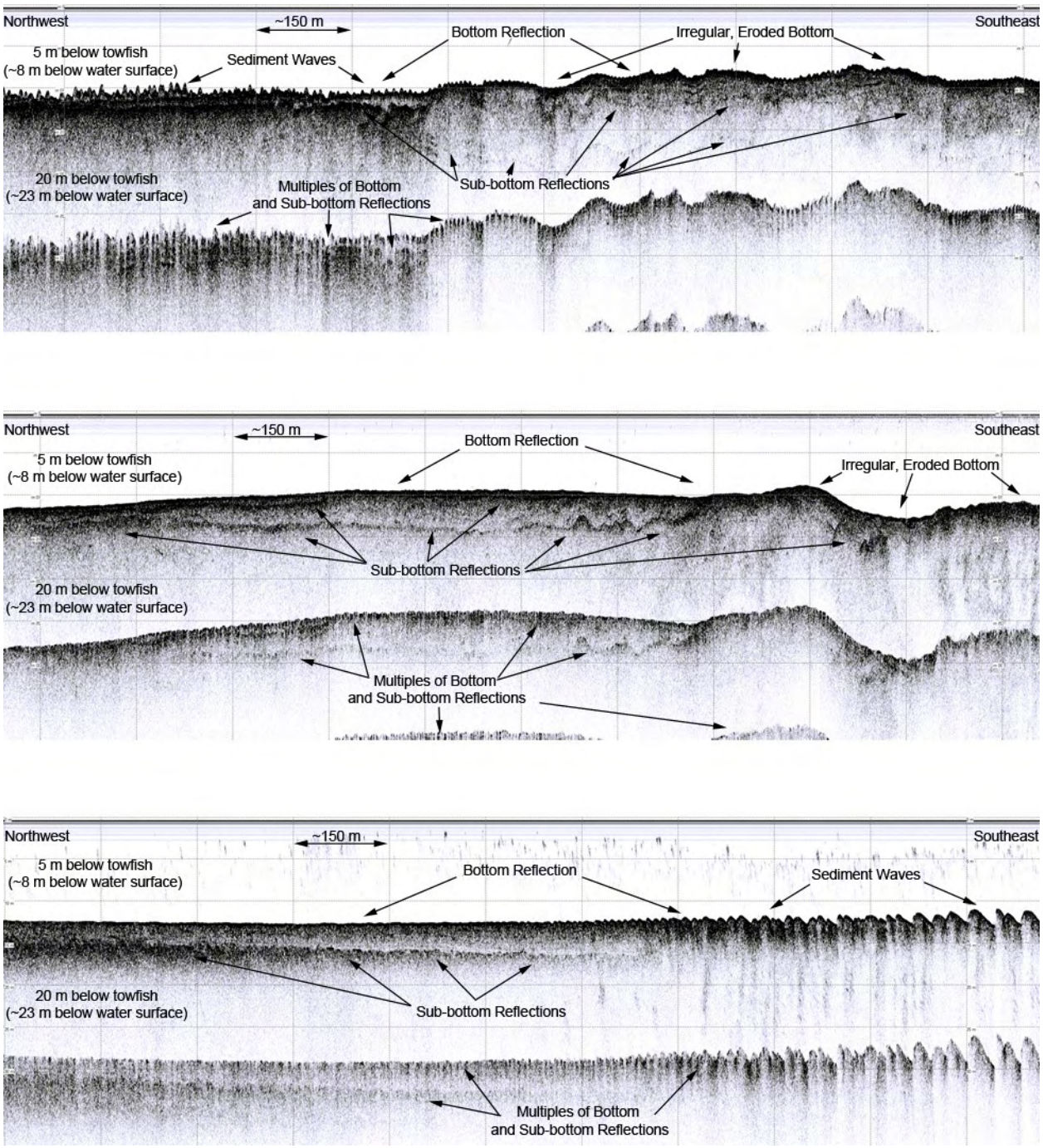


Figure 16. Chirp profile images approaching the Ship John, Ben Davis Point, and Cross Ledge Shoals. Chirp files are bm_052010_f4 (top – Ship John Shoal), bm_052010_f0 (middle – Ben Davis Point Shoal) and bm_052510_f17 (bottom – Cross Ledge Shoal). Top profile is located along the eastern side of the navigation channel near River Mile 37; middle profile along the eastern side near River Mile 33; bottom profile along the western side near River Mile 28.

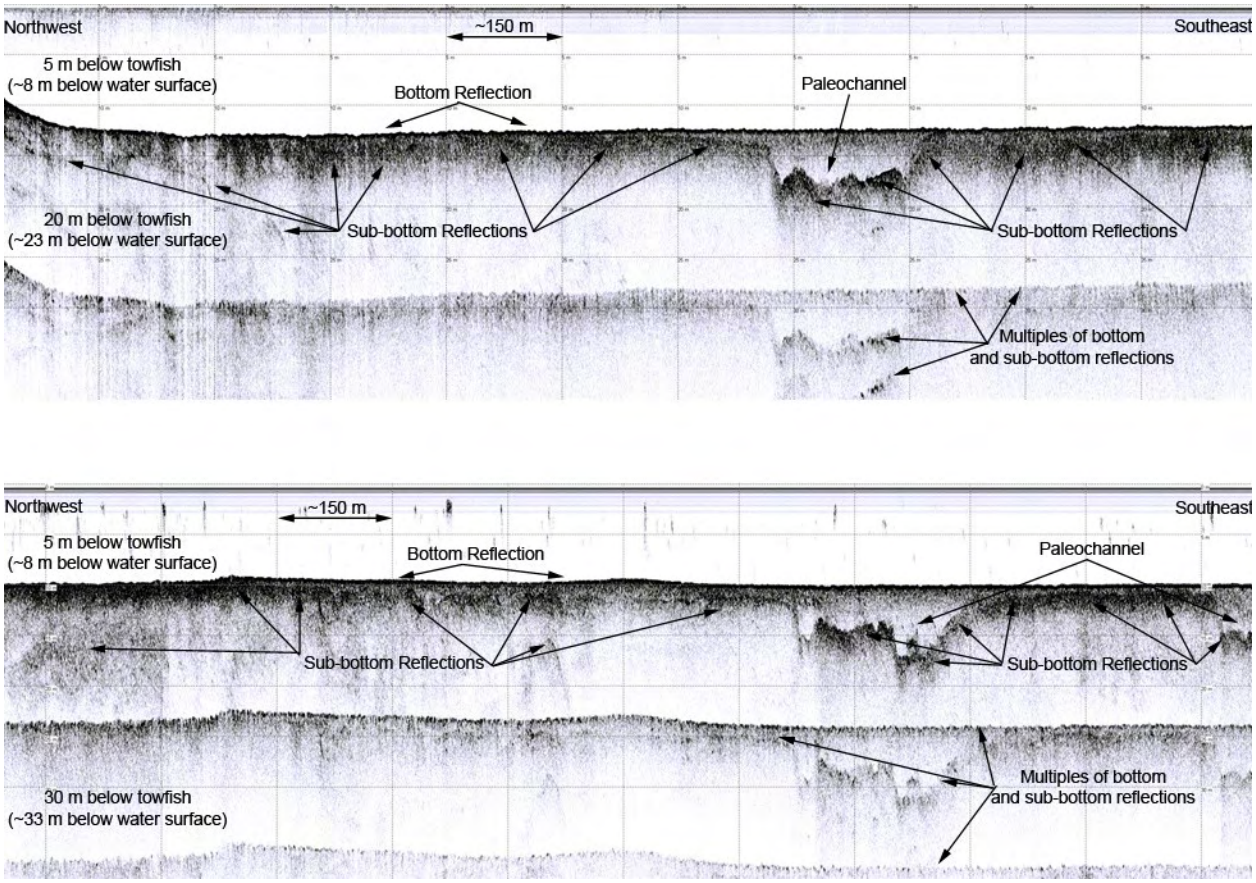


Figure 17. Chirp profile images along Miah Maull Range to Brandywine Range near River Mile 17.5 to 17. Chirp files are bm_052710_f0 (top) and bm_052510_f24 (bottom). Top profile is located along the western side of the navigation channel; bottom profile along the eastern side.

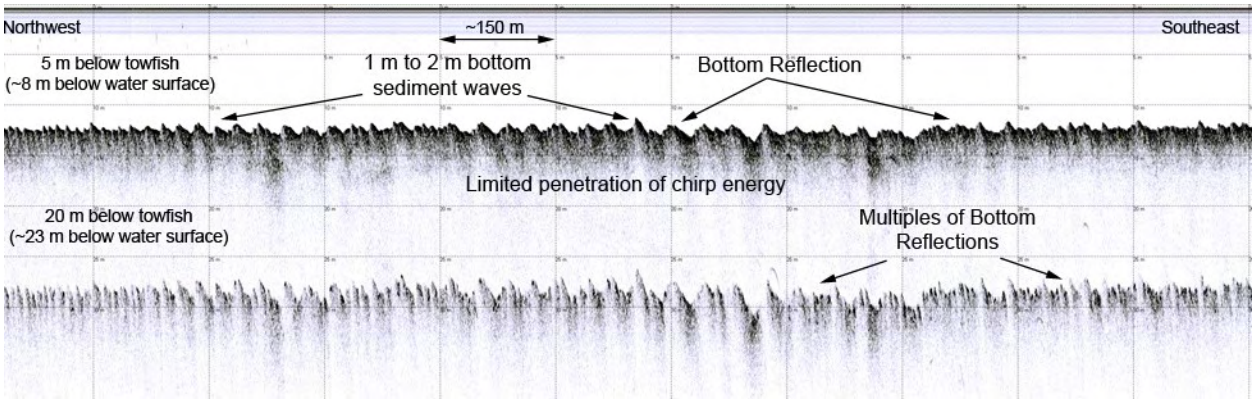


Figure 18. Chirp profile image along Brandywine Range near River Mile 12. Chirp file is bm_052710_f5. Profile is located along the eastern side of the navigation channel.

iii. Sub-Reach Surface and Sub-surface Analysis

a. Sub-Reaches E6 and E7

Sub-reaches E6 and E7 of the PD-ACOE Lower Main Channel Deepening Project occur from the southern extent of the proposed maintenance area (approximate channel station 512+000) through channel station 461+000 to the north (Figure 19). The sediment dredged from these sub-reaches (~ 1.6 mcy) is proposed to be used as fill for Broadkill Beach nourishment. Nine vibra-cores were previously collected (in 1991 and 2001) through these sub-reaches and used to define the sub-surface sediment character and distribution (Figure 19). In this investigation, 31.5 kilometers (km) (17 nautical miles (nm)) of chirp sub-bottom and Roxann seabed classification data and two sediment grab samples were collected through these sub-reaches to enhance the previously collected data (Figure 19). A bottom sediment distribution map based on the Roxann data was generated for these sub-reaches (Figure 20).

The bottom sediments of sub-reaches E6 and E7 are dominated by finer grained sediments (sandy silt to fine sands) with sporadic areas of coarser sediment (silty fine to medium sands to medium to coarse sands; Figure 20, Appendix C). Of the cores that have previously been collected within these sub-reaches, the tops of six of the nine cores are below the required minimal dredging depth (46 ft MLLW). These cores however can be viewed in conjunction with the chirp data to develop a broader sub-bottom sediment distribution for these sub-reaches.

The dredging prism for sub-reach's E6 and E7 is a 1000 ft wide channel to a depth of 46 ft MLW (45 ft with a 1 ft allowable overdepth), with a channel side slope ratio of 3:1, for a total channel length of 50,700 ft (EA, 2009). This dredging prism would include the top 0.8 ft of core DRV-81, 1.3 ft of core DRV-25 and 3.2 ft of core DRV-82 (GBA, 2010).

Beginning at the southern extent of the survey area, top sediment samples DRV-84 s-1 (0.0 to 5.0 ft), DRV-27 0–0.8 (0.0 to 0.8 ft) and DRV-83 S-1 (0.0 to 0.8 ft) show a dominant grain size distribution of fine to medium sands (DRV-84 s-1: 77.2% fine sand and very fine sand, 2.9% medium sand with 16.9% silts and clays and 3.0% coarse and very coarse sand; DRV-27 0-0.8: 47% medium sand, 27% fine and very fine sand with

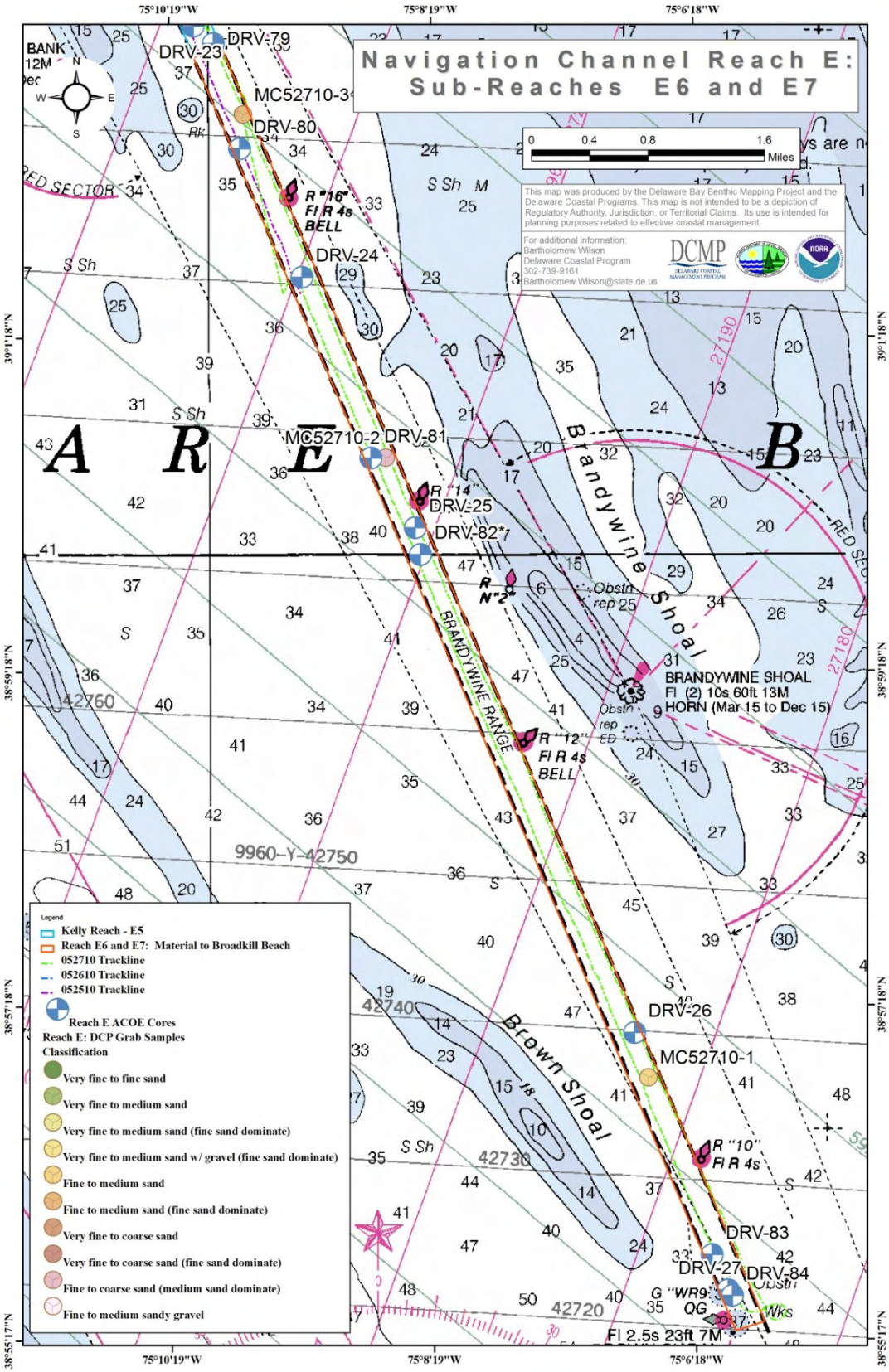


Figure 19. Map of tracklines, grab samples, and core locations within sub-reach E6 and E7.

3% silts and clays, 22% coarse and very coarse sand and 1% granules and gravel; DRV-83 S-1: 47.8% fine sand and very fine sand, 26.9% medium sand with 2.9% silts and clays, 20.8% coarse and very coarse sand and 1.6% granules and gravel (Appendix B).

There is some variation in grain sizes of these top sediment samples, with DRV-27 0-0.8 having the largest percentage (22%) of coarse and very coarse sand and DRV-84 the least (3.0%). DRV-84 has the highest percentage of silts and clays (16.9%). It is likely that this variation reflects the patchy nature of the coarser surface sediments that are observed within the area (Figures 21 and 22a). There is a slight overall gradation in grain size from finer to coarser within this portion of the sub-reaches and thus based on their location this is reflected in samples from the cores (Figure 21 and 22b). For example, DRV-83 is located close to two areas where coarser-grained sediments are observed in the Roxann-generated bottom sediment map (Figure 22b).

In the chirp sub-bottom data, there are no significant shallow reflectors suggesting major variations in sediment grain sizes (Figure 22a). Many of the observed reflectors are localized cut and fill sequences or are deeper reflections (~ 7 meters below the sediment water interface; Figure 22a).

Moving to the north through sub-reach E6, the bottom sediments continue to be dominated by finer grained sandy silts and fine sands (Figure 21). The chirp sub-bottom suggests little variation in sub-bottom grain sizes with only smaller cut and fill sequences, which likely mark small paleo-channels or scour zones infilled with sediments with grain sizes that differ from the surrounding sediments (Figures 23 and 24a). Core DRV-26 in the sample interval 0.0–0.5 ft, located in the center of the navigation channel 3.0 km (1.6 nm) north of DRV-83, contains 49% fine sand and very fine sand, 25% medium sand with 5% silts and clays, 20% coarse and very coarse sand and 1% granules and gravel (Appendix B).

The next core within sub-reach E6, DRV-82, is ~6.7 km (3.6 nm) to the north of DRV-26 (Figure 25). The interval between these cores is characterized, in proximity to Buoy R”12”, by a higher occurrence of coarser sands (Figure 25 and 26b). The absence of prominent near surface reflections in the chirp sub-bottom data

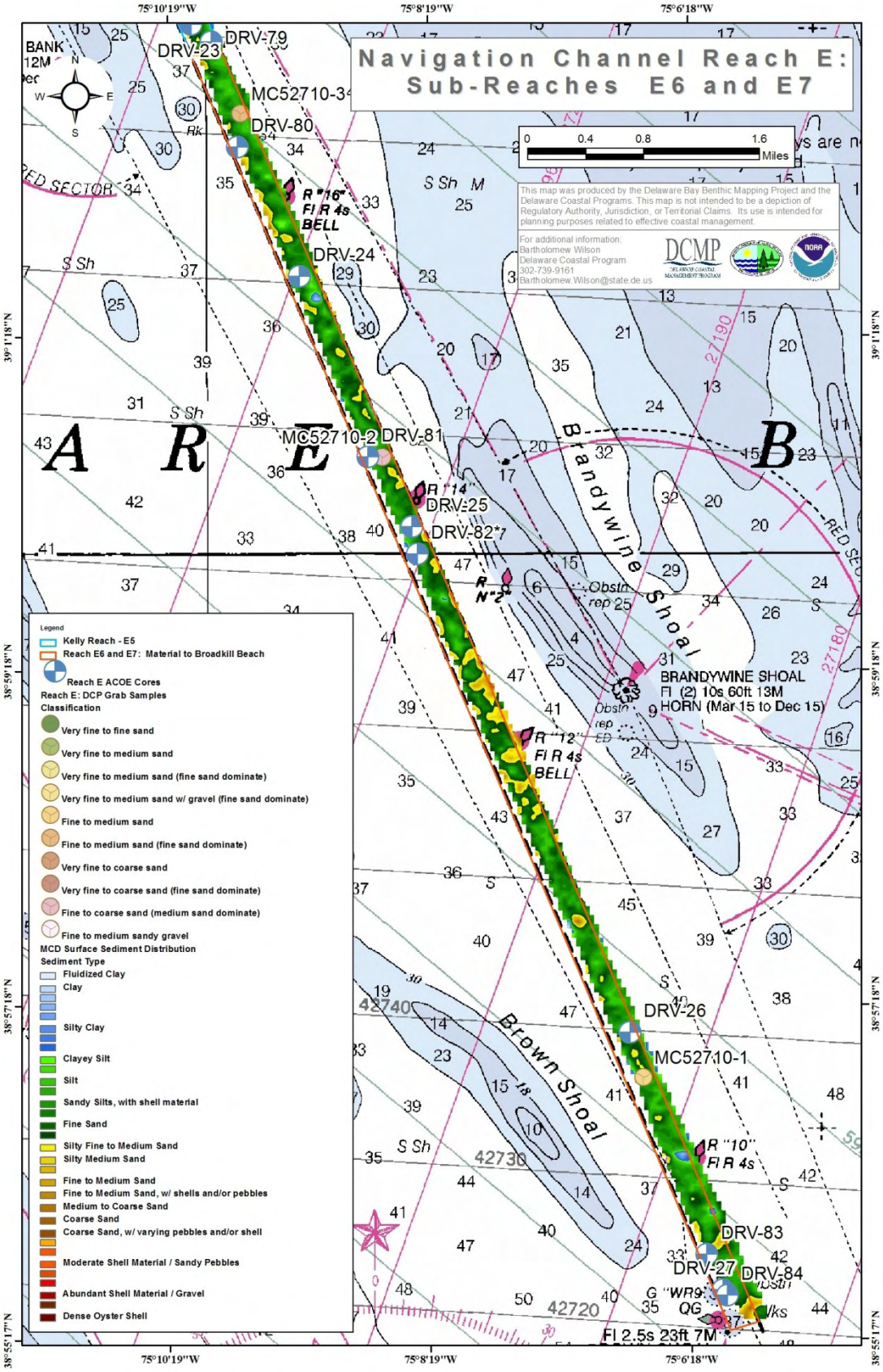


Figure 20. Roxann seabed classification map of sub-reach E6 and E7.

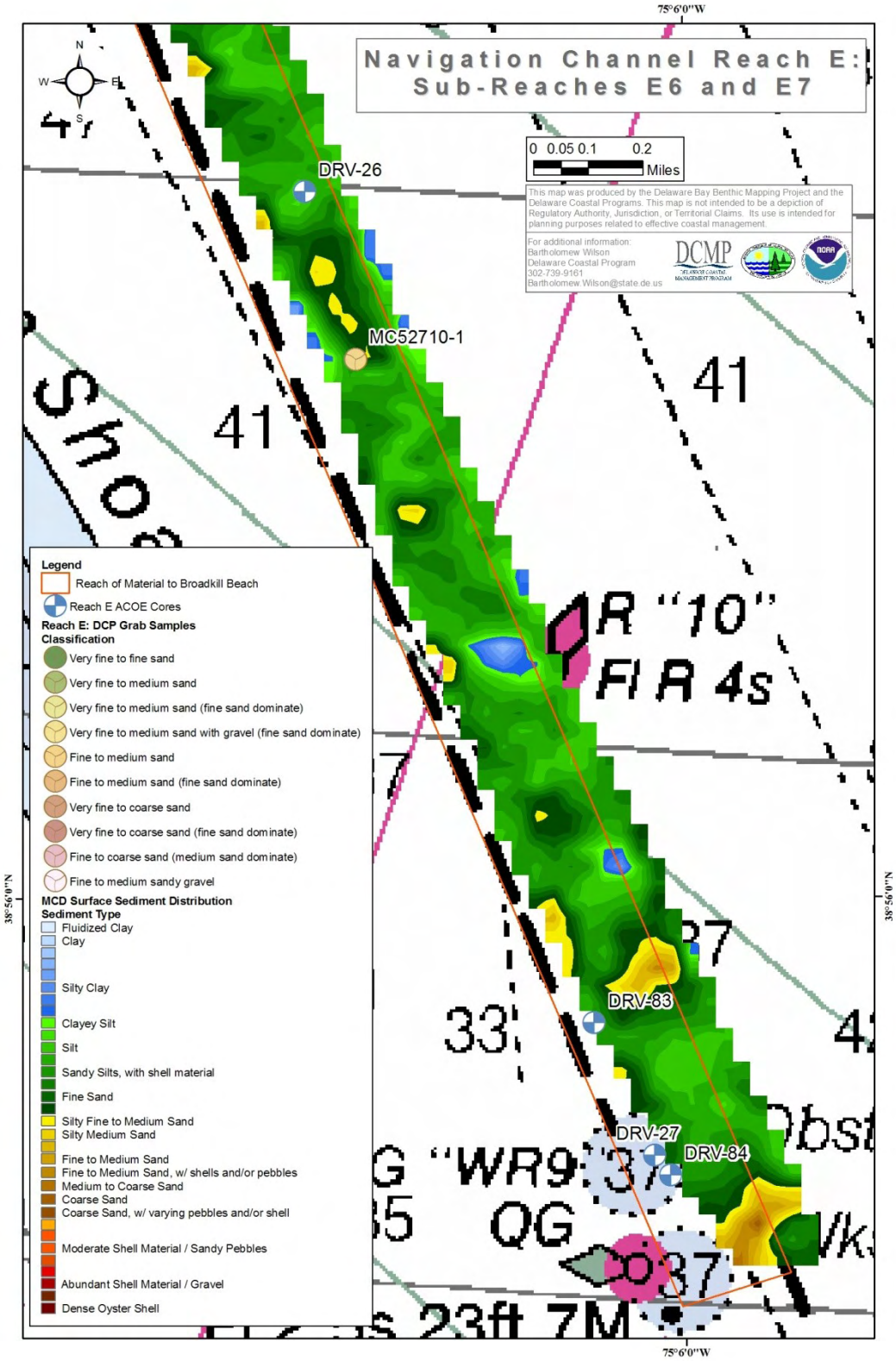
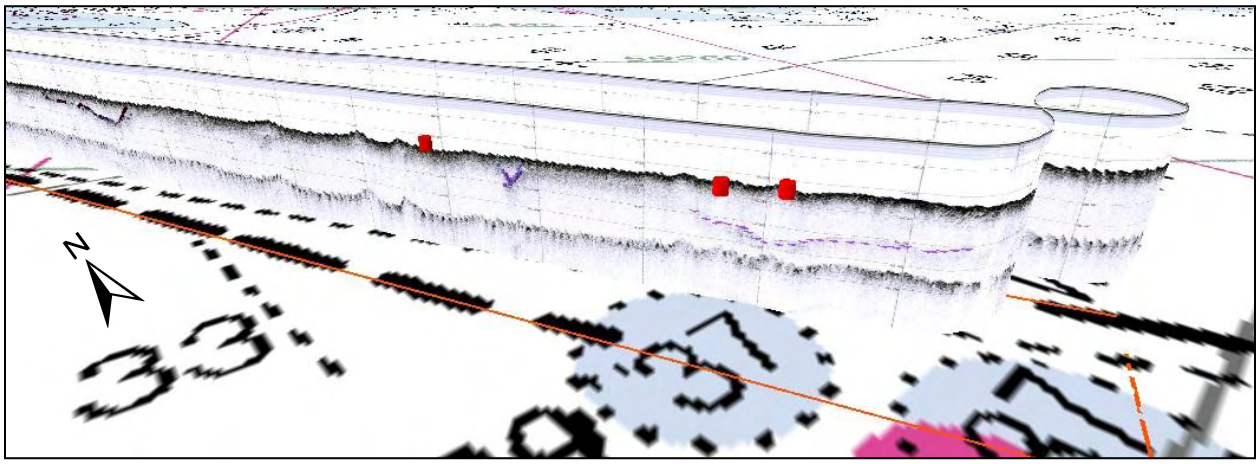
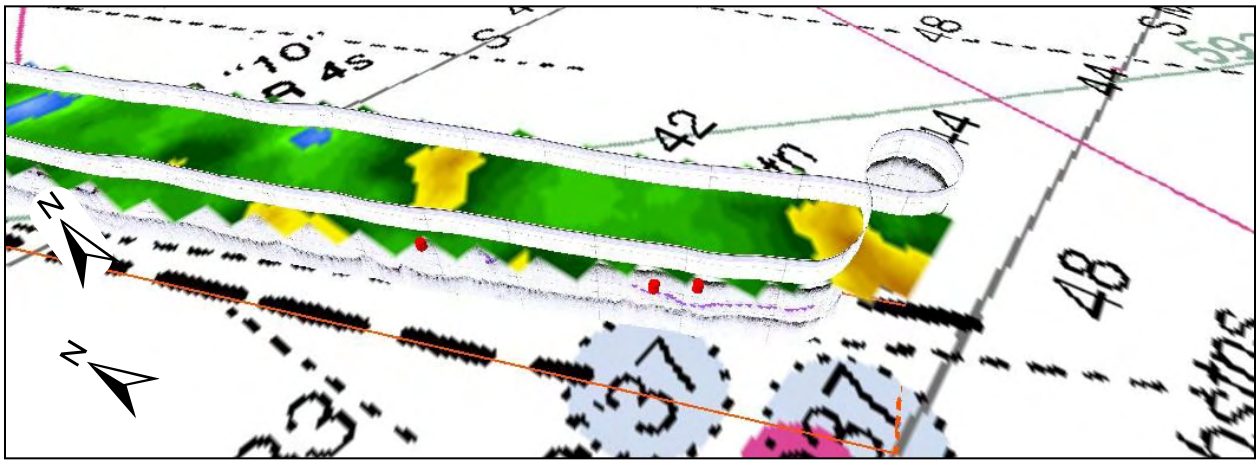


Figure 21. Roxann seabed classification map, core locations, and grab sample locations of the lower sub-reach E6 and E7.



a.



b.

Figure 22. a) Vertical curtains of chirp sub-bottom profiles starting at the southern extent of E6 and E7. b) Vertical curtain chirp-profile with overlay of Roxann seabed classification. These extents contain core locations of DRV-84, DRV-27, and DRV-83 (red cylinders from right to left). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

suggests that there are no substantial changes in the sub-surface (Figure 26a). It should be noted that while the Roxann-generated bottom sediment distribution map shows the presence of coarser-grained sediments, there are no available cores with which to correlate. This has implications for the PD-ACOE's estimation of the average sediment grain size within the E6 sub-reach.

The northern extent of sub-reach E6, from core DRV-82 to station 461+300, has four additional cores over an interval of 5.2 km (2.8 nm) (Figure 27). Cores, DRV-82, DRV-25and DRV-81 occur over a stretch of 1.5 km (0.8 nm) (Figure 27). The top composite samples from these cores are characterized by poorly graded sands (Appendix B). DRV-82 S-1 (0.0–2.5 ft) is 35.7% coarse and very coarse sand, 37.5% medium sand, 20.8% fine sand and very fine sand with 5.6% silts and clays and 0.4% granules and gravel; DRV-25 0-5.0 (0.0–5.0 ft) is 64% coarse and very coarse sand, 24% medium sand, 5% fine sand and very fine sand with 2% silts and clays and 5% granules and gravel; and DRV-81 S-1 (0.0-1.75 ft) is 22.0% coarse and very coarse sand, 48.1% medium sand, 22.8% fine sand and very fine sand with 6.7% silts and clays and 0.4% granules and gravel (Appendix B). DRV-25 is characterized by the largest grain sizes with 64% coarse and very coarse sand and 5% granules and gravel. There is a difference in the time when these cores were collected (DRV-25 in 1991 and DRV-81 and -82 in 2001), that should be taken into account when comparing the differences in the bottom sediment grain sizes. The chirp sub-bottom data in this area do not have significant reflectors suggesting that there is not a notable variation in the sub-surface deposits (Figure 28b).

The interval between DRV-81 and DRV-24 is ~2.5 km (1.4 nm). The last core, DRV-80, in the E6 sub-reach is located 1.9 km (1 nm) to the north of DRV-24, and is 1.3 km (0.70 nm) from the northern boundary of sub-reach E6 (Figure 27). The bottom sediments in this portion of the sub-reach are similar to that observed to the south (i.e., dominated by sands with some silts and distinct patches of coarser sands (Figure 27 and 30b). The top composite sample from core DRV-24 (0.0–3.0 ft) has 29% coarse

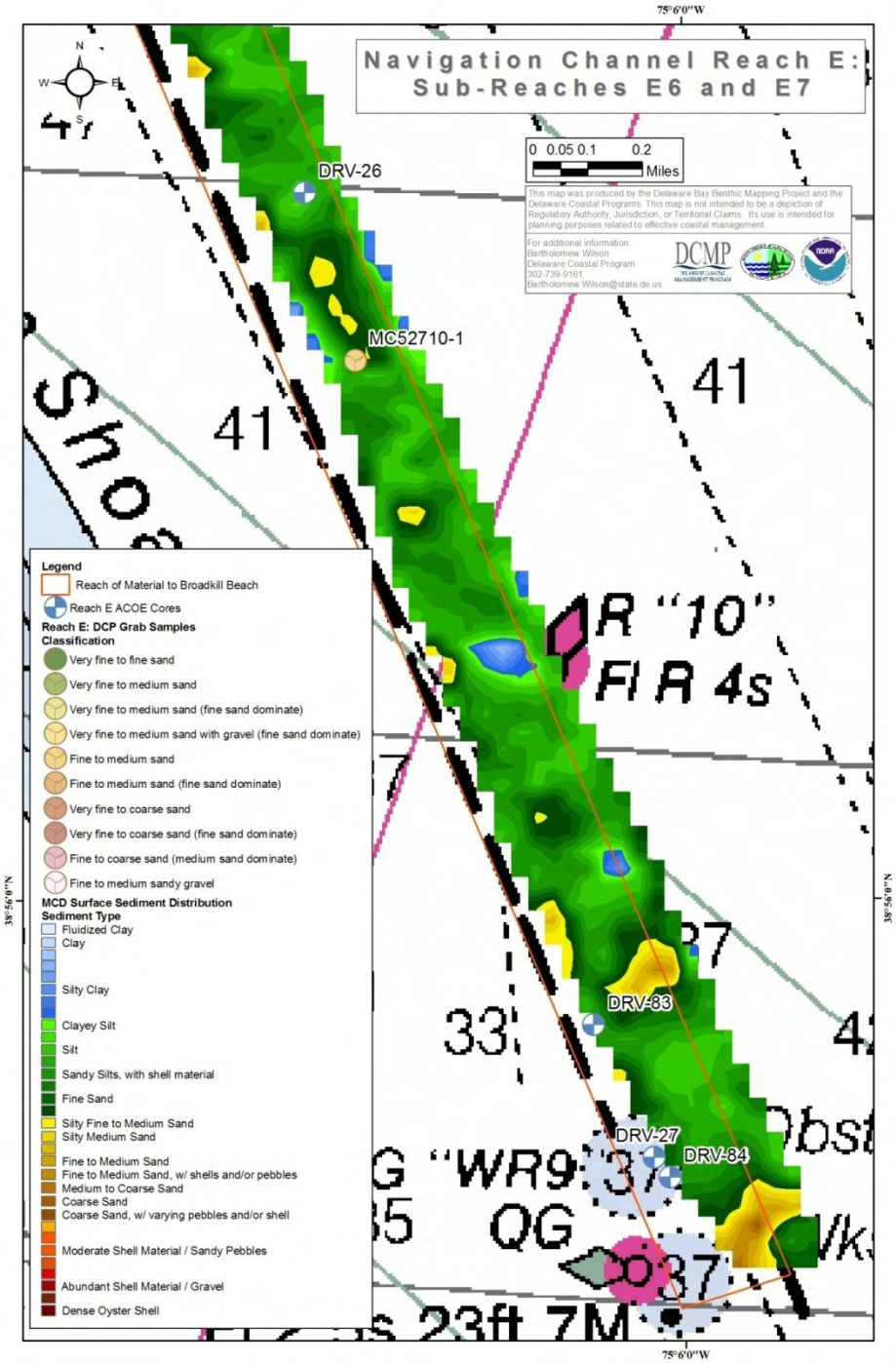
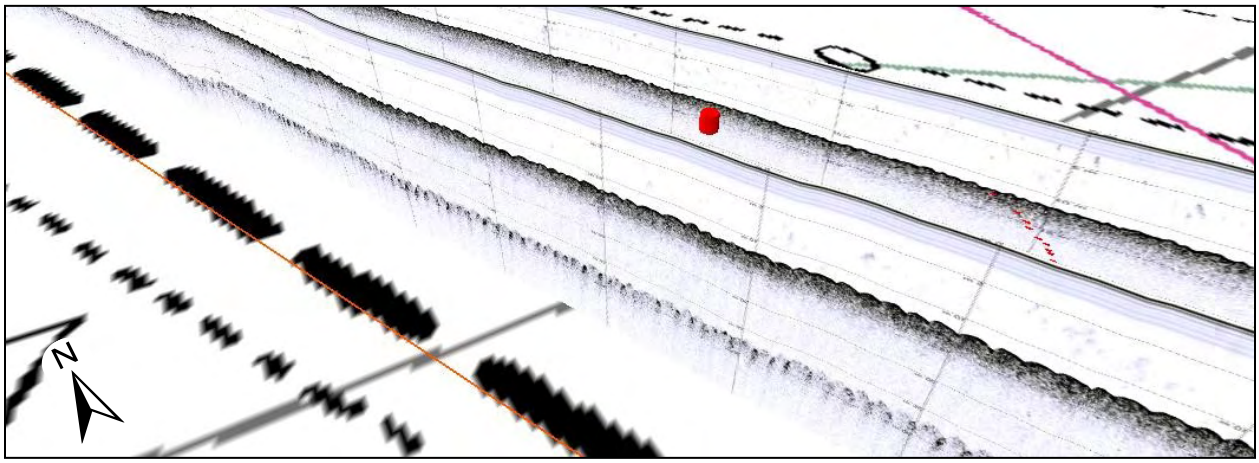
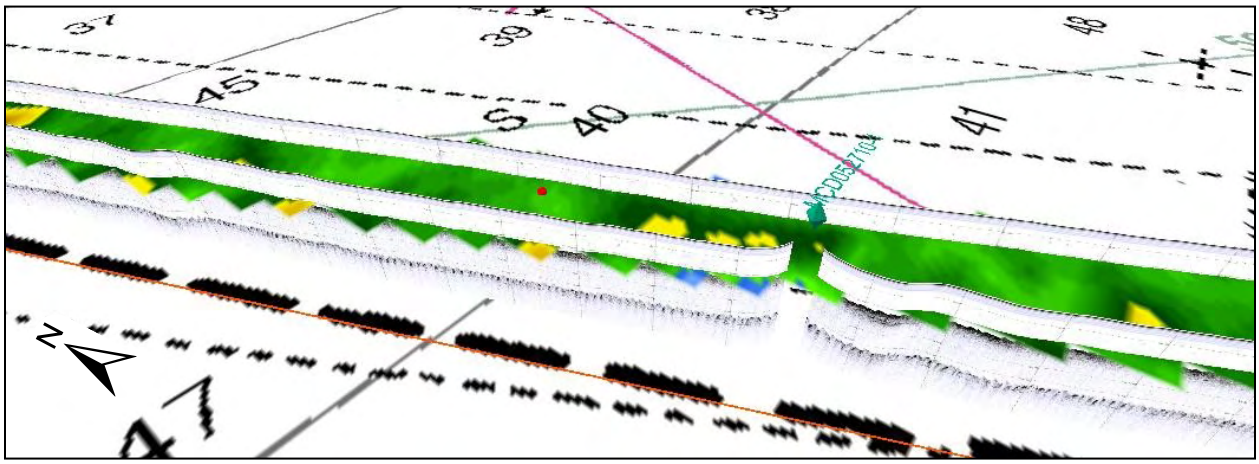


Figure 23. Vertical curtains of chirp sub-bottom profiles starting at the southern extent of E6, just north of DRV-83 to the north of DRV-26 (red cylinder to left; grab sample MC52710-1 shown to south of core DRV-26 (green diamond). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).



a.



b.

Figure 24. a) Vertical curtains of chirp sub-bottom profiles at the southern extent of E6, around core DRV-26 (red cylinder at center). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification (core DRV-26 (red cylinder) and grab sample MC52710-1 shown to south of core DRV-26 (green diamond)). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

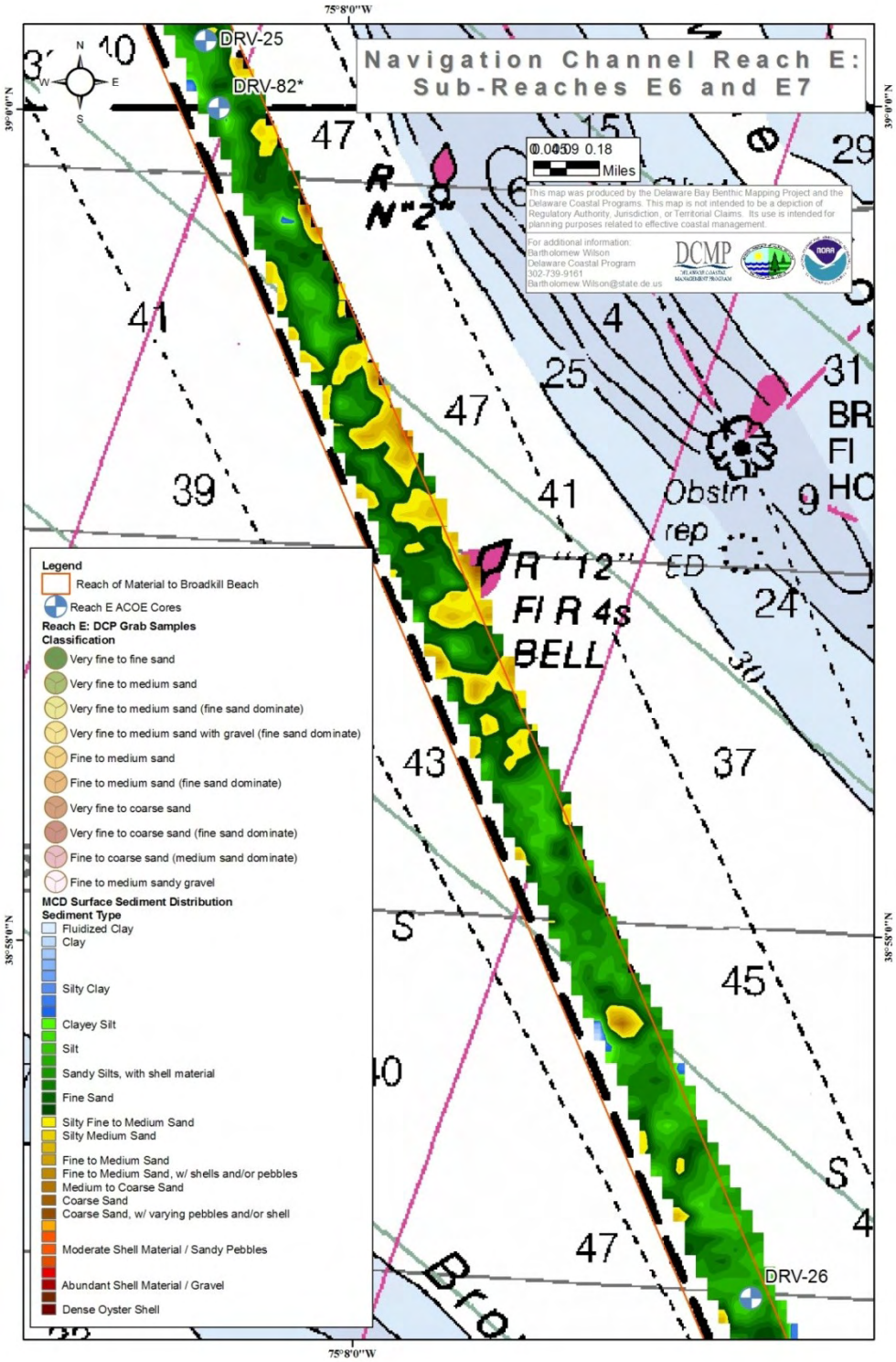
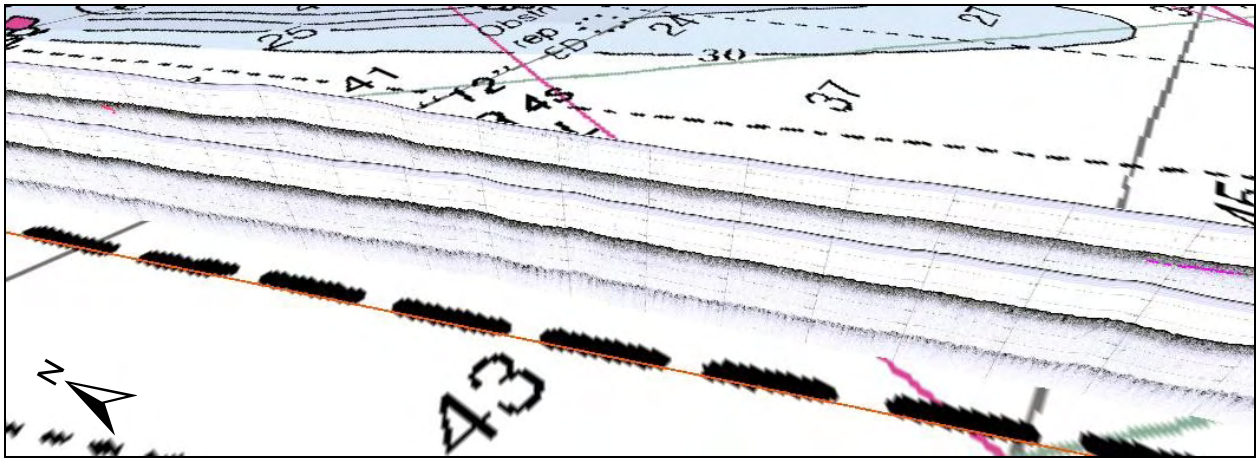
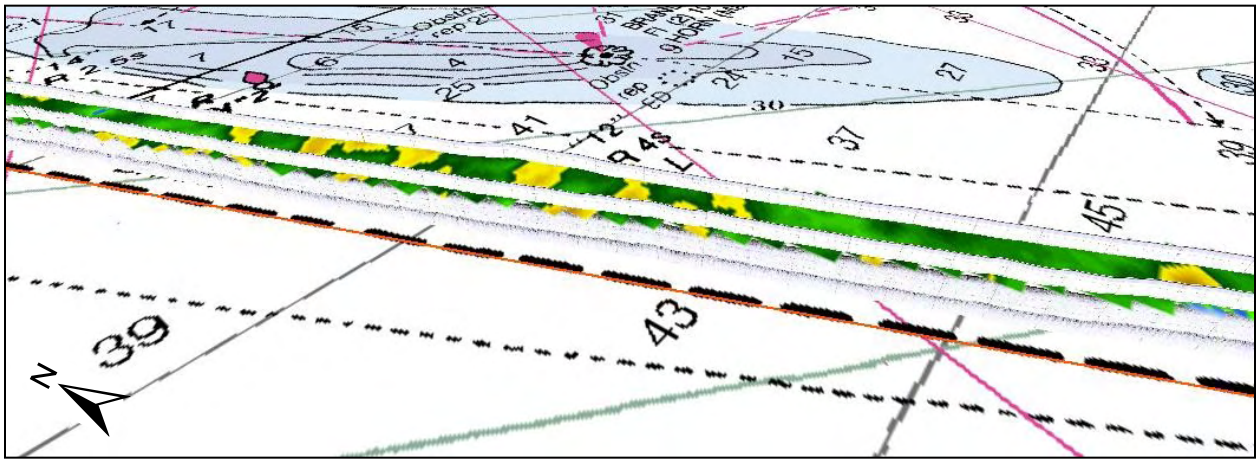


Figure 25. Roxann seabed classification map, core locations, and grab sample locations for the central region of sub-reach E6 (between cores DRV-26 , to the south, and DRV-25, to the north).



a.



b.

Figure 26. a) Vertical curtains of chirp sub-bottom profiles for the central region of sub-reach E6 (between cores DRV-26, to the south, and DRV-25, to the north). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the central region of sub-reach E6 (between cores DRV-26, to the south, and DRV-25, to the north). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

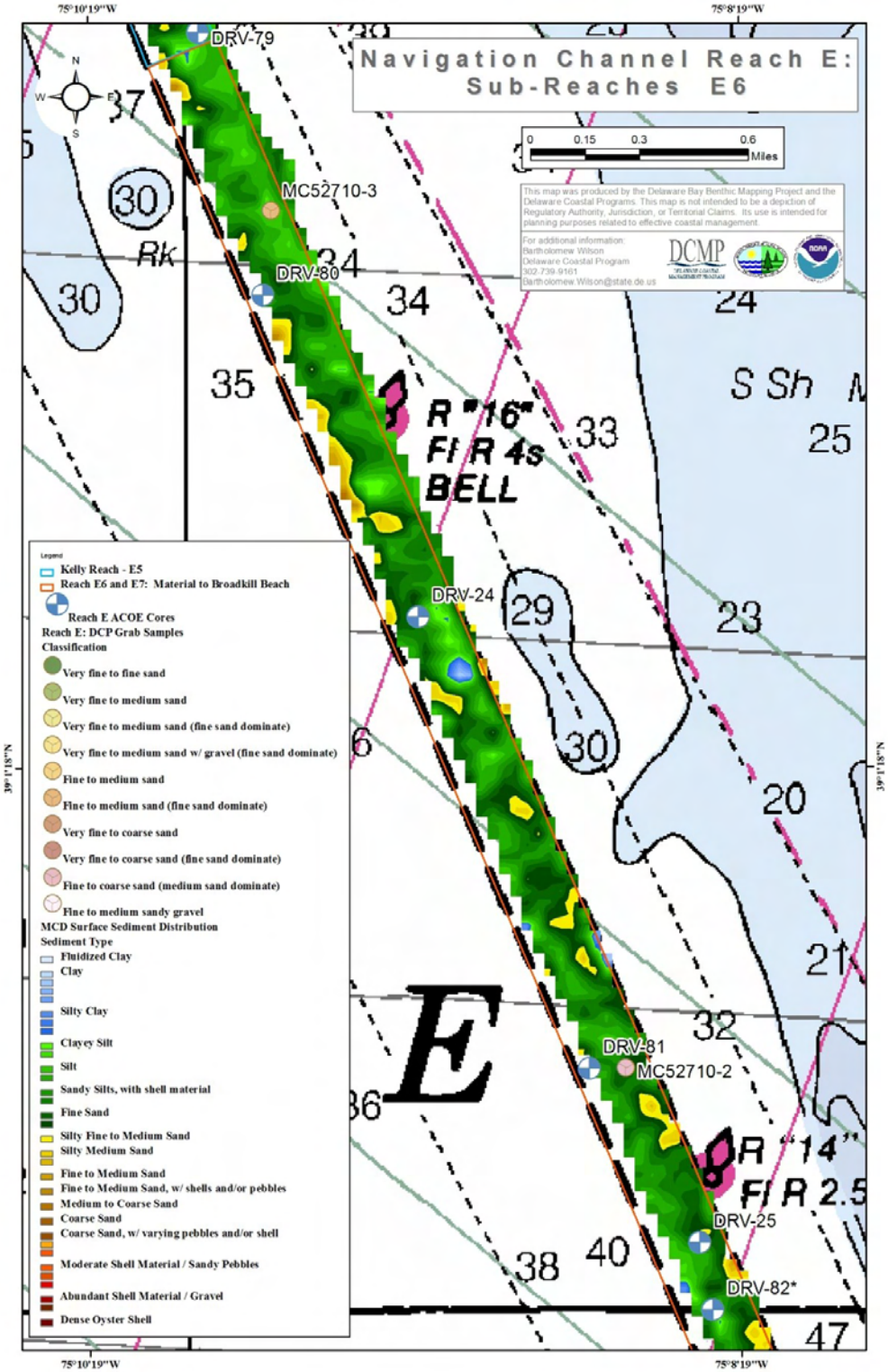
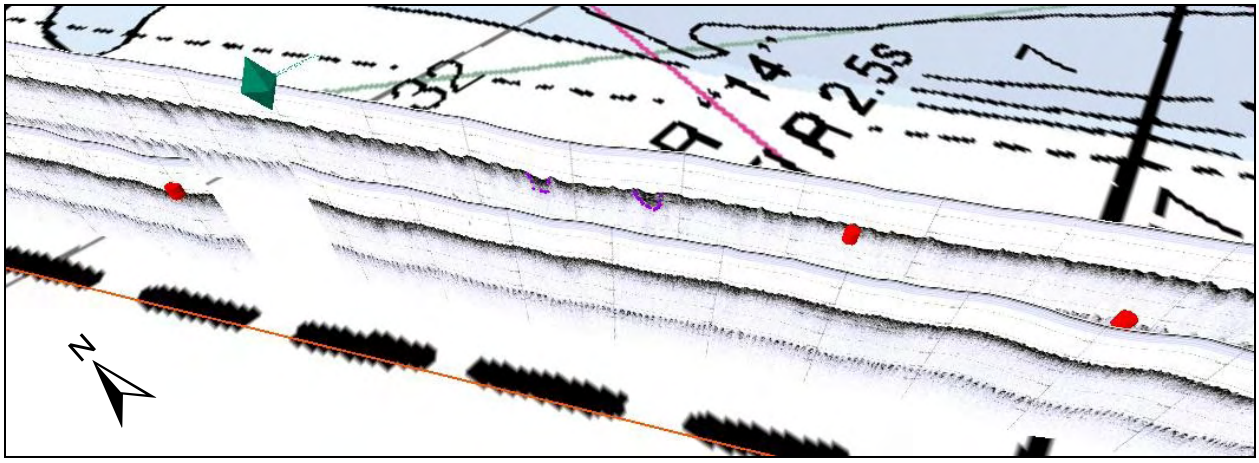


Figure 27. Roxann seabed classification map, core locations, and grab sample locations for the northern and central region of sub-reach E6 (between cores DRV-82, to the south, and northern extent of sub-reach E6 to the north.

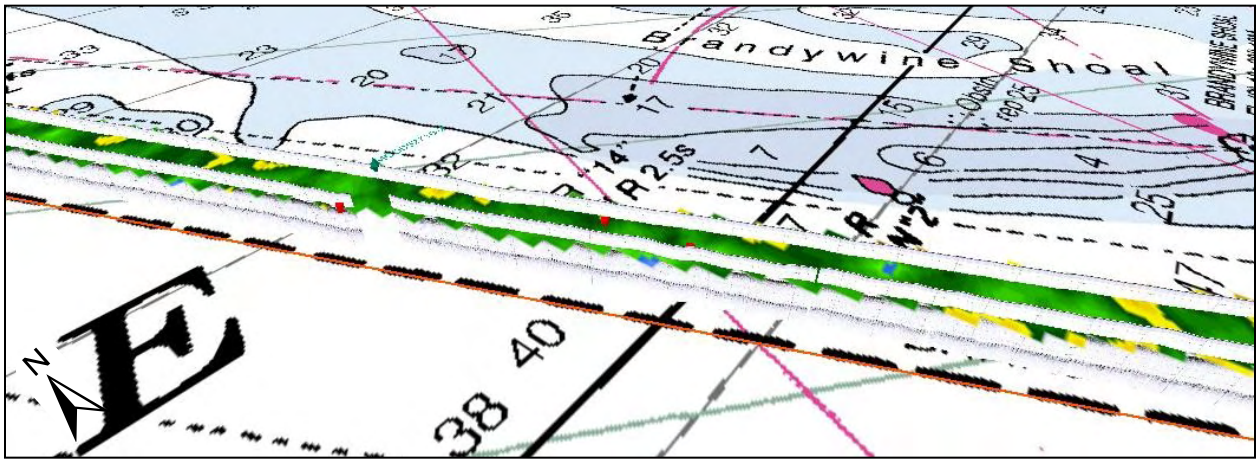
and very coarse sand, 51% medium sand, 16% fine sand and very fine sand with 2% silts and clays and 2% granules and gravel (Appendix B). Core DRV-80 as sampled between 0.0 and 0.5 ft contains 19.9% coarse and very coarse sand, 36.0% medium sand, 39.8% fine sand and very fine sand with 3.7% silts and clays and 0.6% granules and gravel (Appendix B).

Beginning near core DRV-24 there are shallow sub-surface reflections in the chirp data indicating variations in the sub-bottom sediments (Figures 29a and 30a). The sub-bottom profiles show several shallow continuous reflectors within the top 2 m (7 ft) (Figure 30a). These reflections continue to the north and high amplitude reflections are also observed. The high amplitudes suggest that there are deposits that contain higher organic content. The strong reflections are caused by the presence of gas (i.e., hydrogen sulfide and/or methane) within the sediment pores (Figure 31a).

As defined by the top composite samples from the vibra-core data, sub-reach E6 can be characterized as very sandy with variable coarse-, medium- and fine-sand fractions. The average grain size (d-50) is 0.3 mm. As shown in Figure 32, the highest percentages of coarse-grained sands occurred in cores DRV-25 and DRV-82 with 64% and 35.7%, respectively with the other cores having values ranging from 19.9% to 29%. The average relative abundance of coarse-grained sands for the sub-reach is 29.2% with a standard deviation (SD) of 15.1. The highest percentages of medium sands were found in top samples from cores DRV-24 (51%), DRV-81 (48.1%) and DRV-27 (47%) with lower percentages ranging from 24% to 37.5% in the other cores. The average relative abundance of medium sands for the sub-reach is 36.9% with SD 10.9. The highest relative abundances of fine and very fine sands occurred in two cores near the southern extent of the sub-reach, DRV-83 (47.8%) and DRV-26 (49%), and in core DRV-80 (39.8%) located at the northern end of the sub-reach. The average relative abundance of fine to very fine sands is 28.5% with SD 15.7.

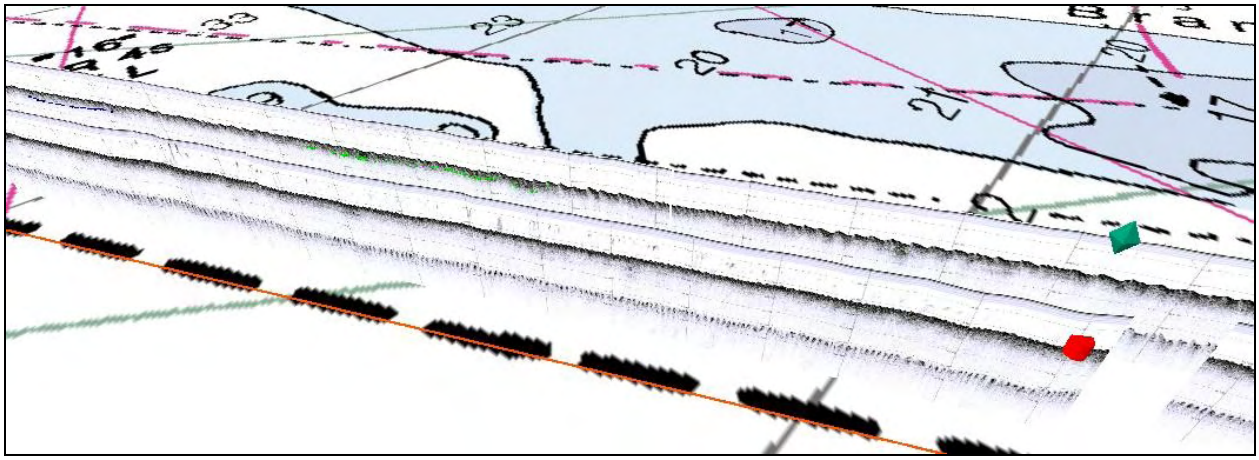


a.

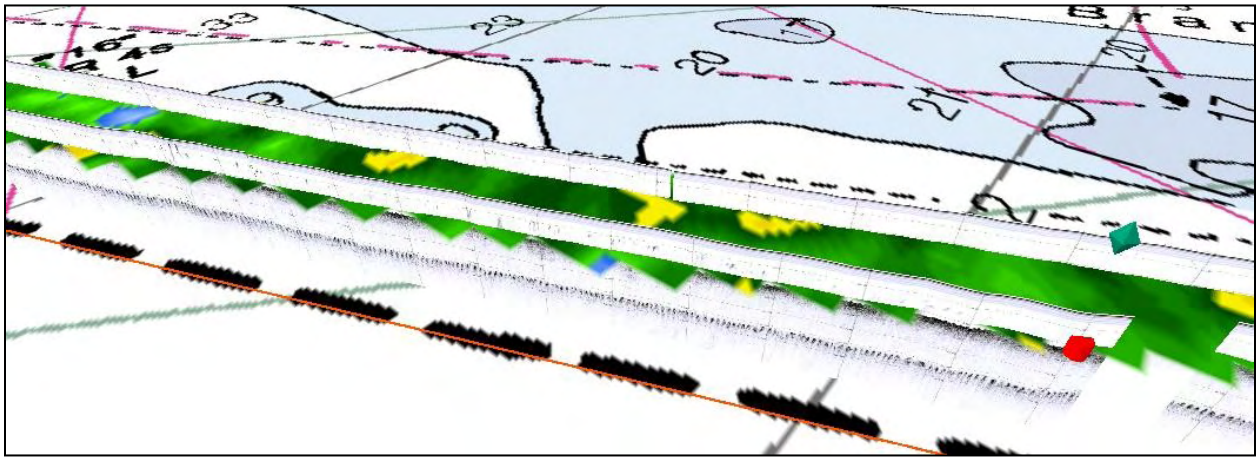


b.

Figure 28. a) Vertical curtains of chirp sub-bottom profiles for the central region of sub-reach E6 (between cores DRV-82, to the south, and DRV-81, to the north). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the central region of sub-reach E6 (between cores DRV-82, to the south, and region to north of DRV-81). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

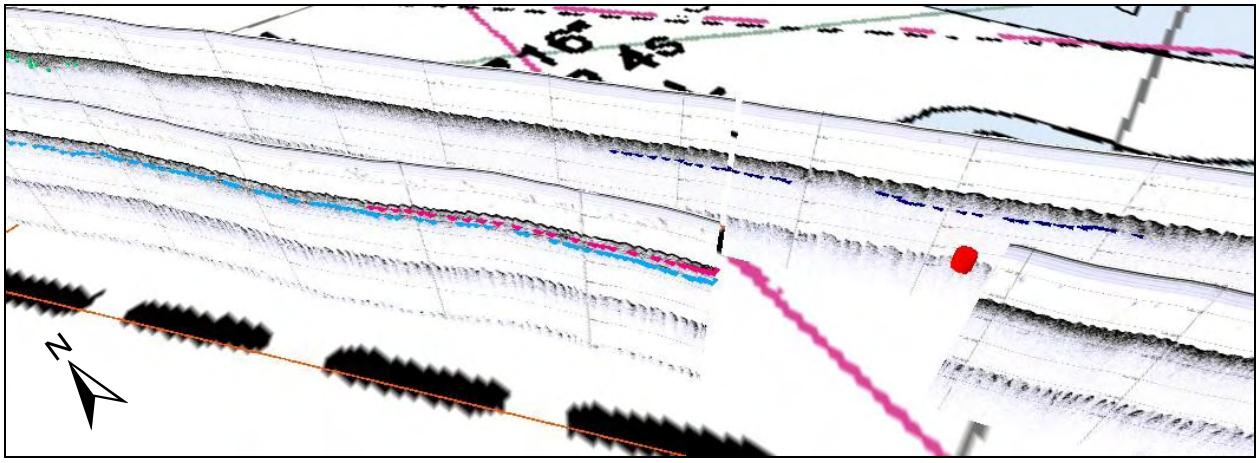


a.

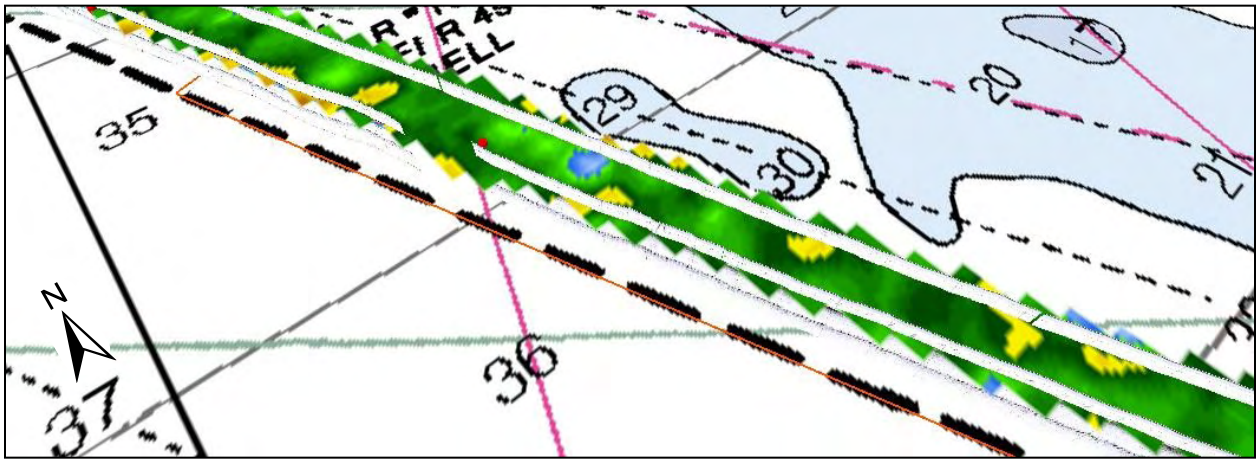


b.

Figure 29. a) Vertical curtains of chirp sub-bottom profiles for the northern central region of sub-reach E6 (between cores DRV-81 (red cylinder) and MC52710-2 (green cylinder) to the south (to the right) and region to the north of DRV-81. b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the northern central region of sub-reach E6. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

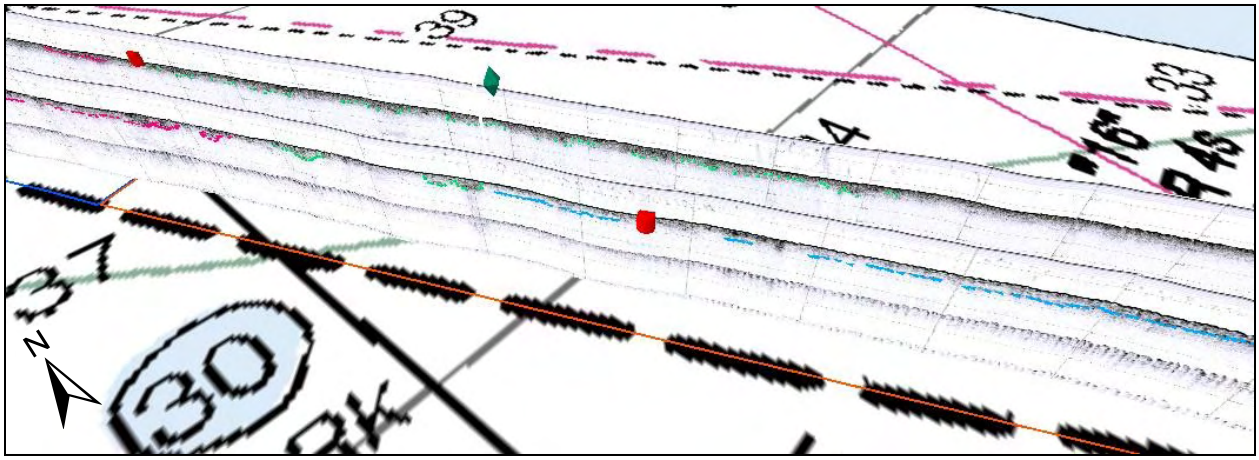


a.

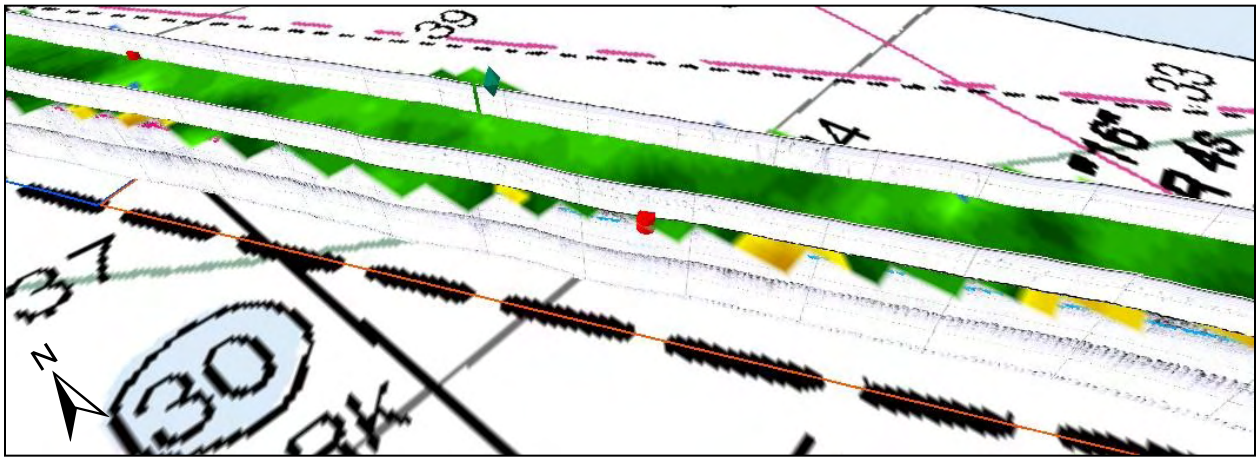


b.

Figure 30. a) Vertical curtains of chirp sub-bottom profiles for the northern central region of sub-reach E6 around core DRV-24 (red cylinder). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the northern central region of sub-reach E6 (between area to south of DRV-24 and area to north of DRV-24). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).



a.



b.

Figure 31. a) Vertical curtains of chirp sub-bottom profiles for the northern region of sub-reach E6, between region to south of DRV-80 (red cylinder in center) to northern extent of E6. b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the northern central region of sub-reach E6. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

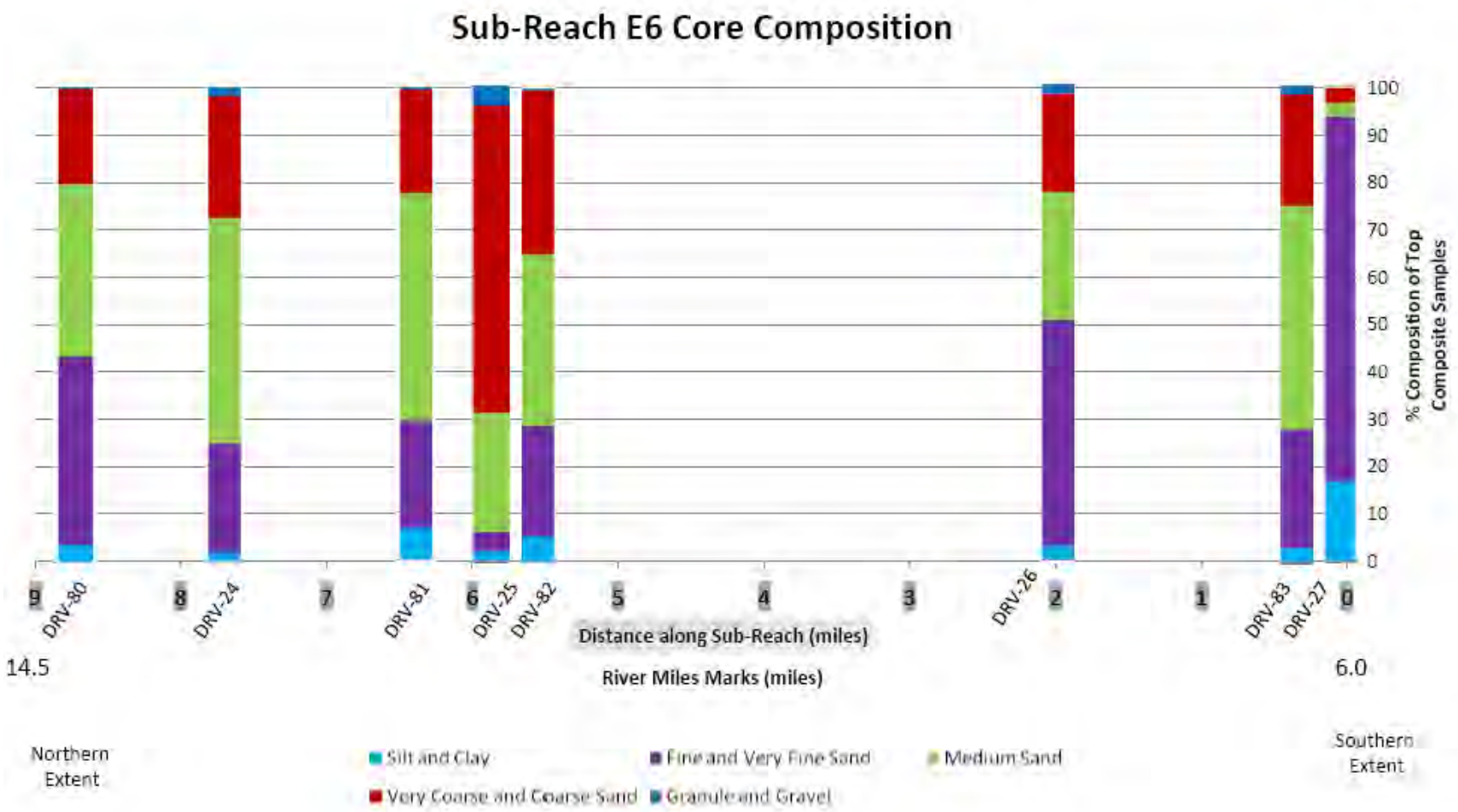


Figure 32. Graph of the top composite samples grain size composition verses the distance of the cores locations along sub-reach E6.

Given the dominance of the sand-sized sediments the relative percentages of both the largest particles, granules and gravels, and smallest, silts and clays, were low for all cores, with the exception of core DRV-25 which had 5% granules and gravels. The average relative abundance of granules and gravels is 1.5% with SD 1.5, and of silts and clays is 3.8% with SD 1.7.

The northern portion of sub-reach E7, as defined by the top composite sample from core DRV-84, is considerably finer-grained than E6. The top sample from DRV-84 is dominated by fine to very fine sands (77.2%) with silts and clays (16.9%) and low abundances of medium sands (2.9%) and coarse and very coarse sands (3.0%). The sample contained no granules or gravels. The sub-reach average grain size (d-50) is 0.1 mm. By comparison, the sub-reach E6 average grain size is 0.3 mm. Of the eight cores collected in sub-reach E6, the highest percentage of fine to very fine sands was found in the cores DRV-26 (49%) and DRV-83 (47.8%), and the highest percentages of silts and clays was 6.7%.

In the E6 sub-reach, the very fine and fine sand fractions around DRV-83 (47.8%) and DRV-26 (49%) likely highlight a finer grained sand deposit that exists at the southern end of the sub-reach extending from sub-reach E7 up the channel to the north (Figure 21). The composite top sample from DRV-27 only contains 27% fine to very fine sand, showing that either the finer fraction varies laterally and grades into coarser deposits or DRV-27 may not be a representative sample for this portion of the sub-reach. Because there is a 6.7 km (3.6 nm) gap between cores DRV-26 and DRV-82, it is not known, based from core samples, how far the finer sand fraction extends to the north through the proposed section for dredging (Figure 20). Based on the Roxann sediment classification map, there appears to be coarser-grained sediments in the vicinity of the R “12” buoy. Further to the north approaching the cores DRV-82, DRV-25 and DRV-81, the Roxann map suggests that the bottom sediments become finer grained similar to grain sizes sampled in the southern portion of sub-reach E6. Too few core samples have been collected in the central portion of sub-reach E6 to be able to constrain the lateral variability in sediment grain size variations in this area.

With the exception of core DRV-25, the predominant top sample sediment grain size is medium to fine and very fine sand (Figure 32, Appendix B). The average grain

size (d-50) reported by the PD-ACOE for this sub-reach is 0.3 mm; a simple summing and averaging of the d-50 in the eight cores in the sub-reach results in an average grain size of 0.33 mm with SD 0.11 (Appendix B). If the DRV-25 d-50 value (0.59 mm) is removed from the calculation, the average d-50 value from the remaining seven cores is 0.29 mm with SD 0.03. The rather minimal decrease (0.29 mm vs. 0.33 mm) in the reported average grain size when not including the outlier d-50 from DRV-25, points out potential issues that arise when using the top composite samples as equally weighted values. The equal weighting, and lack of sufficient sampling, is not able to take into account trends between cores, and results in potentially using values that represent only a small extent of the sample area (i.e. DRV-25).

A simple d-50 averaging of the top sample core data, given the lack of a sufficient number of cores, does not include the 6.7 km (3.6 nm) stretch of non-sampled grain size distribution that exists between DRV-26 and DRV-82, and skews the data toward a coarser grain fraction for the sub-reach with the non-representative DRV-25 value (0.59 mm). The DRV-25 d-50 value represents an outlier in the data, due to its significant difference with nearby cores (Figure 32). In order to better constrain the average grain size composition of the sub-reach, the Roxann-generated bottom sediment map, with the sub-bottom profiling data and additional cores, is needed to be used in a process that applies weighting to the core samples based on the representative volume of material that the core represents (i.e., the additional data providing information of the lateral and vertical extent of the sediments sampled in the cores).

The portion of sub-reach E6 between DRV-26 and DRV-82 needs to be further investigated with additional cores to better constrain the distribution of sediments along its 6.7 km (3.6 nm) length. Rather dramatic changes occur between these cores in grain sizes for all of the sand-sized fractions including 49% to 20.8% in very fine and fine sands, 25% to 37.5% in medium sands and 20% to 35.7% in very coarse sands for DRV-25 and DRV-82, respectively (Figure 32, Appendix B). The Roxann bottom sediment suggests that there is a coarser grained section between these two cores that has not been sampled (Figure 20).

Additional cores should also be collected, to the north and south of DRV-25, to allow for the spatial trends in the vicinity of this core to be better constrained. If the values in DRV-25 are not replicated, then the values from DRV-25 should be excluded in the calculation of an average grain size because it will be confirmed as a localized outlier and be un-representative of the sub-reach.

b. Sub-Reaches E1 thru E5

Sub-reaches E1 through E5 extend along the central and northern portions of reach E from approximately channel stations 461+300 to 351+200 (Figure 33). The sediment dredged from these sub-reaches (2.5 mcy) is proposed to be used in the construction of a confined disposal facility (CDF) adjacent to Kelly Island (central Kent County; Figure 2). Thirty-four vibra-cores were collected by the PD-ACOE within these sub-reaches (in 1991, 1999, 2001 and 2004; Appendix B). In the survey work conducted in this investigation, 159 km (86 nm) of chirp sub-bottom and Roxann classification data, and twelve sediment grab samples were collected in these sub-reaches (Figure 33). The Roxann classification bottom sediment map that was constructed for the sub-reaches is shown in Figure 34.

The PD-ACOE has designated the sediments in the sub-reaches for different uses in the construction of the CDF (Figures 2 and 3, Appendix D). The sub-reach E5 (stations 532+200 thru 461+300) sediments will be used as the initial, or lower, portion of the outer containment berm of the CDF. This involves ~1.2 mcy or 47% of the total volume of the sediments to be used from the sub-reaches. The E4 sediments (stations 421+700 thru 432+200) will be pumped into the CDF forming the lower section of the CDF interior . This amounts to ~252,064 cy or 10% of the total volume. Sediments from sub-reach E2 (stations 353+300 thru 390+200) totaling ~468,000 cy (19% of the total volume) will be used to construct the outer seaward portion of the containment berm and dune. Sub-reach E1 sediments (stations 351+200 thru 353+300) will be pumped over the E4 sediments in the DCF (~13,800 cubic yarcyds, 1% of the total

volume). The E3 sub-reach sediments (stations 390+200 thru 421+700) will be used as the final capping within the CDF (~580,000 cy, 23% of the total volume).

The sediments of sub-reaches E5 and E2 will be discussed in detail in this section due to their usage as the material to construct the containment berm and dune for the Kelly Island CDF, in accordance with the potential geotechnical design and with the characteristics of the material that will be used in the construction. Sediments from sub-reaches E1, E3, and E4 will not be discussed in detail, because they will be within the CDF and their average grain size will not affect its structural integrity.

I. Sub-Reach E5

Sub-reach E5 is the southernmost sub-reach that will have sediments used in the construction of the Kelly Island CDF. The E5 sub-reach has eleven vibra-cores and covers ~37 km (20 nm) of chirp and Roxann trackline data (Figure 35). The dredging prism for sub-reach E5 consists of a 1000 ft wide channel to a depth of 46 ft MLW (45 ft with a 1 ft allowable overdepth), with a channel side slope ratio of 3:1, for a total channel length of 29,100 ft (EA, 2009). This dredging prism would incorporate the top of 8 of the 11 cores, with depths of inclusion of: 4.7 ft of core DRV-78, 3.6 ft of core DRV-77- R1, 0.3 ft of core DRV-22, 3.8 ft of core DRV-76, 1.0 ft of core DRV-67, 0.4 ft of core DRV-21, 0.4 ft of core DRV-66 and 1.5 ft of core DRV-65 (GBA, 2010).

The bottom sediments of the southern half of sub-reach E5 (below the bend north of Fourteen Foot Bank Light) are dominated by sandy silts to fine sands, while the northern half consists of a variable or patchy sediment distribution that is characterized by fine to medium sands and medium and coarse sands, with sandy pebble and sandy silt to silty sand patches (Figure 36).

Beginning at the southern extent of sub-reach E5, the top composite sediment sample from core DRV-79 (S1 0-1.25 ft) is dominated by fine to very fine sand (62.3%) with a medium sand content of 26.81%, very coarse and coarse sand content of 8.05%, silt and clay of 2.6%, and granules and gravels of 0.24% (Figure 37, Appendix B). The top composite sediment sample from core DRV-80 (from sub-reach E6, 1.9 km (1 nm)

to the south of DRV-79) is also characterized by a fine to very fine sand (39.8%) with medium sand (36%) distribution, however it is somewhat coarser than the DRV-79 sample with a higher percentage of medium sands (36% vs. 26.81%), coarse and very coarse sands (19.91% vs. 8.05%) and granules and gravels (0.39% vs. 0.24) (Figure 35, Appendix B). The composite sample from core DRV-23 (sample 0-3.7 ft; 0.2 miles to the north of DRV-79), while in closer proximity to DRV-79, has a much more similar distribution to DRV-80 with 26% coarse and very coarse sands, 39% medium sands and 2% granules and gravels, 27% fine sands and very fine sands and 6% silts and clay (Figure 37, Appendix B).

Core DRV-78's top composite sediment sample (S1 0-1.0ft) is very different than the cores to the south being much coarser with 53.01% granules and gravels, 17.75% coarse and very coarse sands, 10.81% medium sands, 7.03 fine and very fine sands and 11.40% silts and clays (Figure 35, Appendix B). There is also a marked change observed in the sub-surface sediments as characterized by the chirp sub-bottom profiling data. Near DRV-78, an undulatory reflector is observed at a depth of 1.5 to 2.0 m (5 to 6.5 ft) below the surface along the profile collected on the eastern side of the navigation channel (Figure 39a). High amplitude reflections, indicative of higher concentrations of organic material, are observed in the sub-bottom profile along the channel's western side (Figure 39a). The bottom sediments in the area, as constrained by the Roxann data, are dominated by sandy silts and fine sands, but several large patches of coarser medium to coarse and very coarse sands do occur as well as the very coarse top sediment sample from core DRV-78 (Figure 39b).

The changes in sub-bottom sediments are a result of the presence of two paleochannels that occur in the area (Figure 39a). The channel labeled PC1 is approximately 500 m (1640 ft) to the south of DRV-78, and is on the order of 200 to 250 m (650 to 820 ft) wide and 2.5 to 6 m (8 to 20 ft) deep. PC2 is located 750 m (2460 ft) to the north of DRV-78 and is of similar width and slightly deeper (3 to 7 m; 10 to 23 ft) than PC1 (Figures 39a, 40, and 41). Both paleochannels trend perpendicular to the

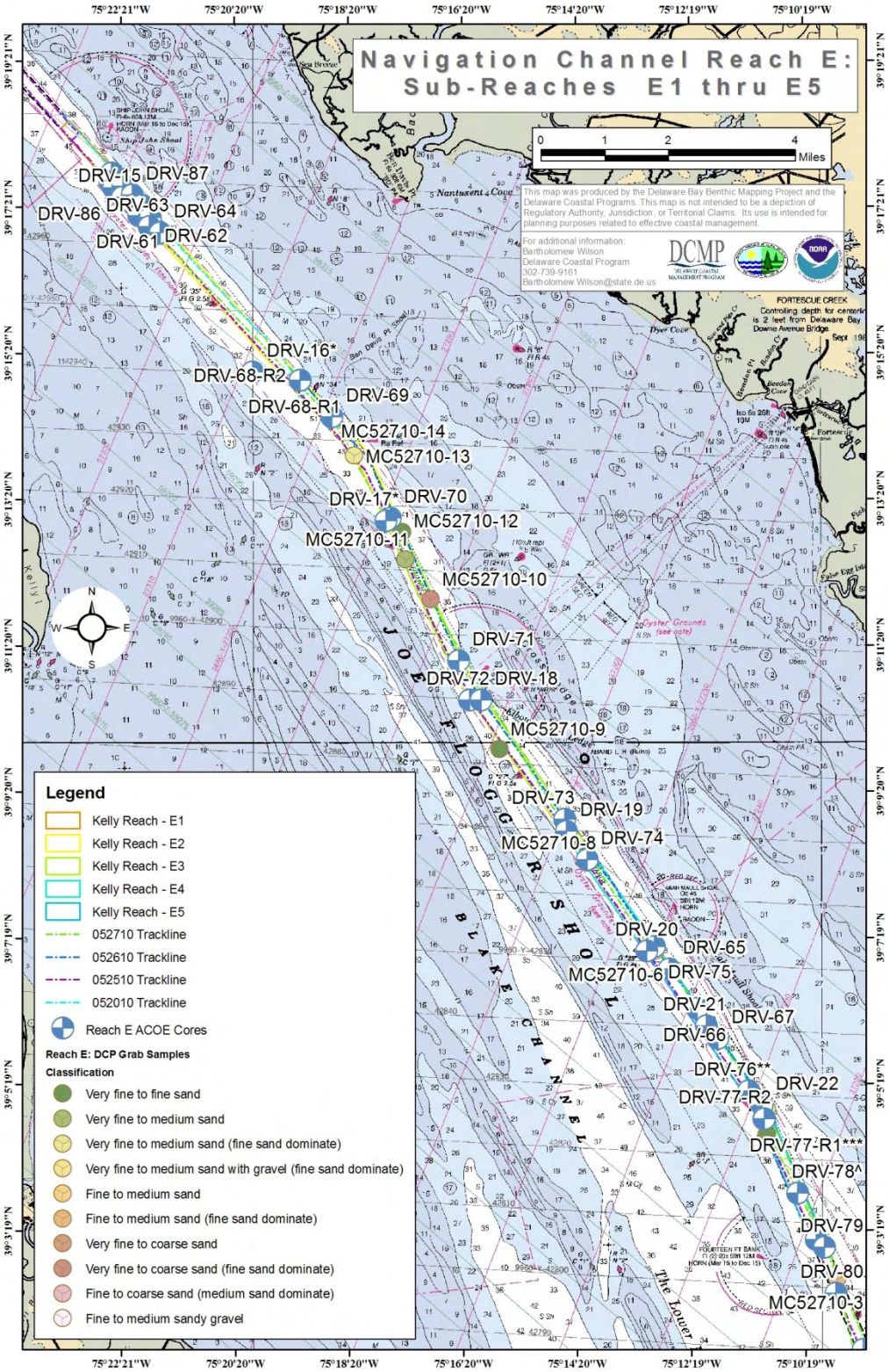


Figure 33. Map of tracklines, grab samples, and core locations within sub-reach E1 thru E5.

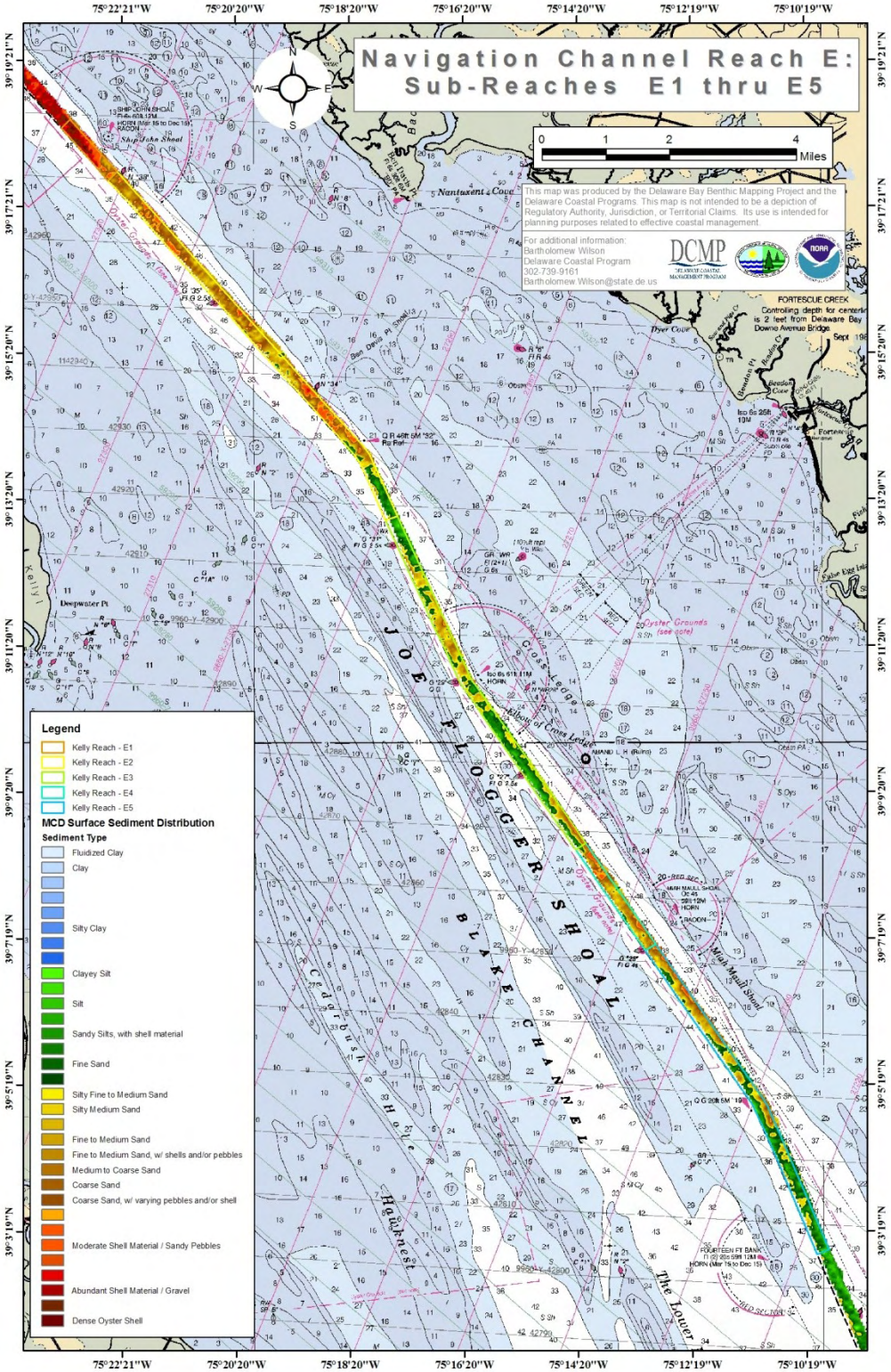


Figure 34. Roxann seabed classification map for sub-reaches E1 thru E5.

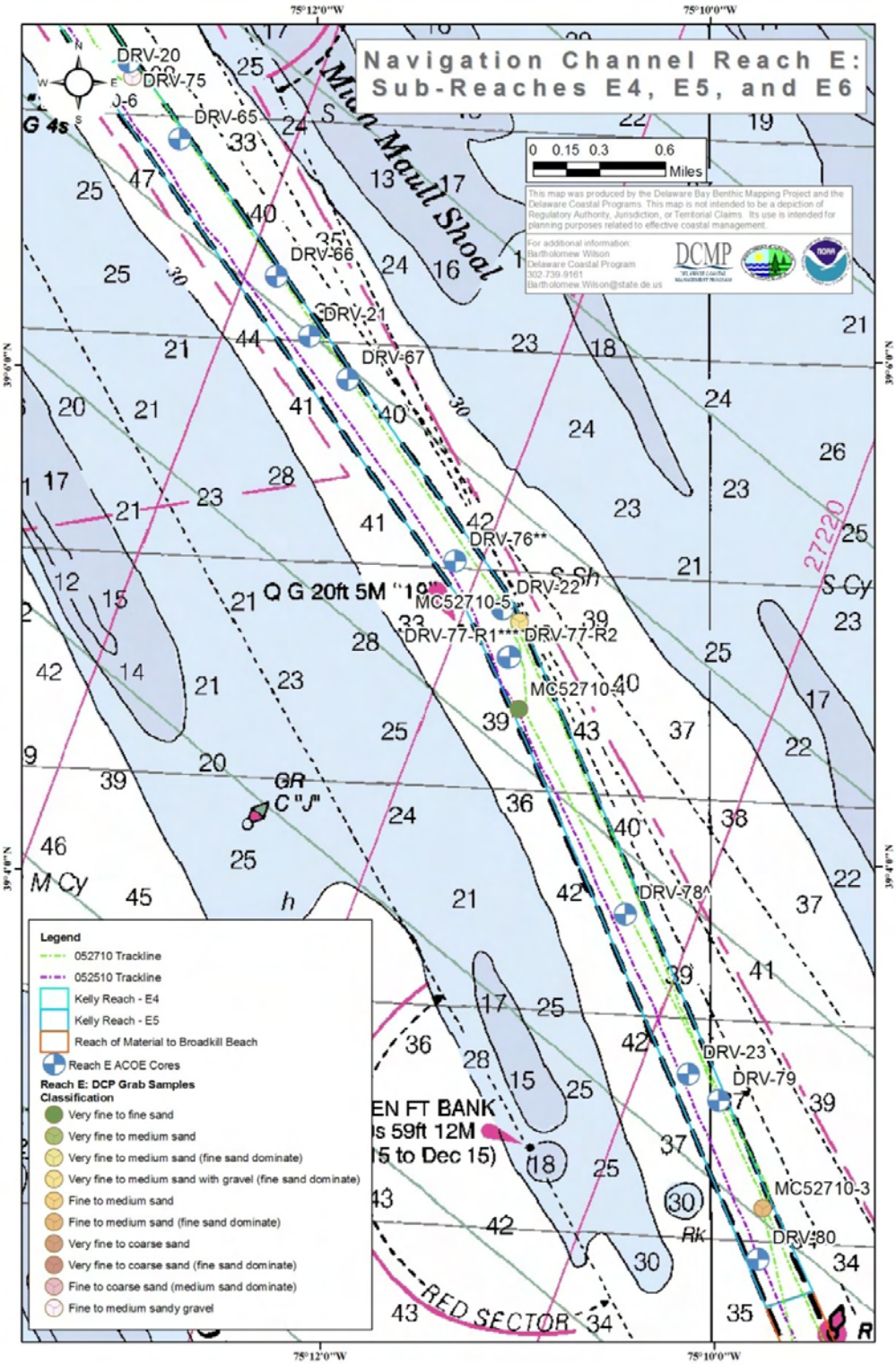


Figure 35. Map of tracklines, grab samples, and core locations within sub-reach E5.

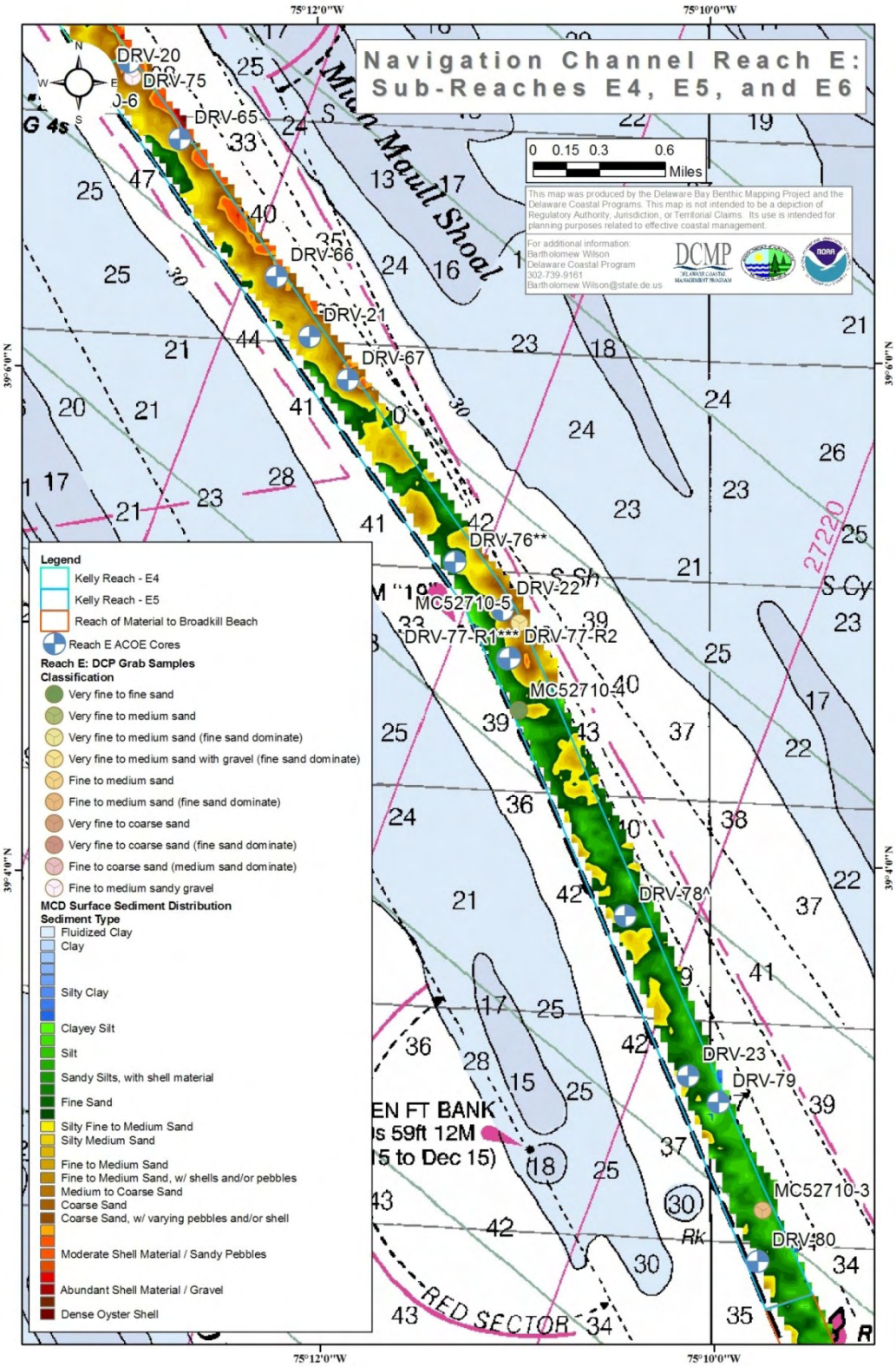


Figure 36. Roxann seabed classification map of sub-reach E5.

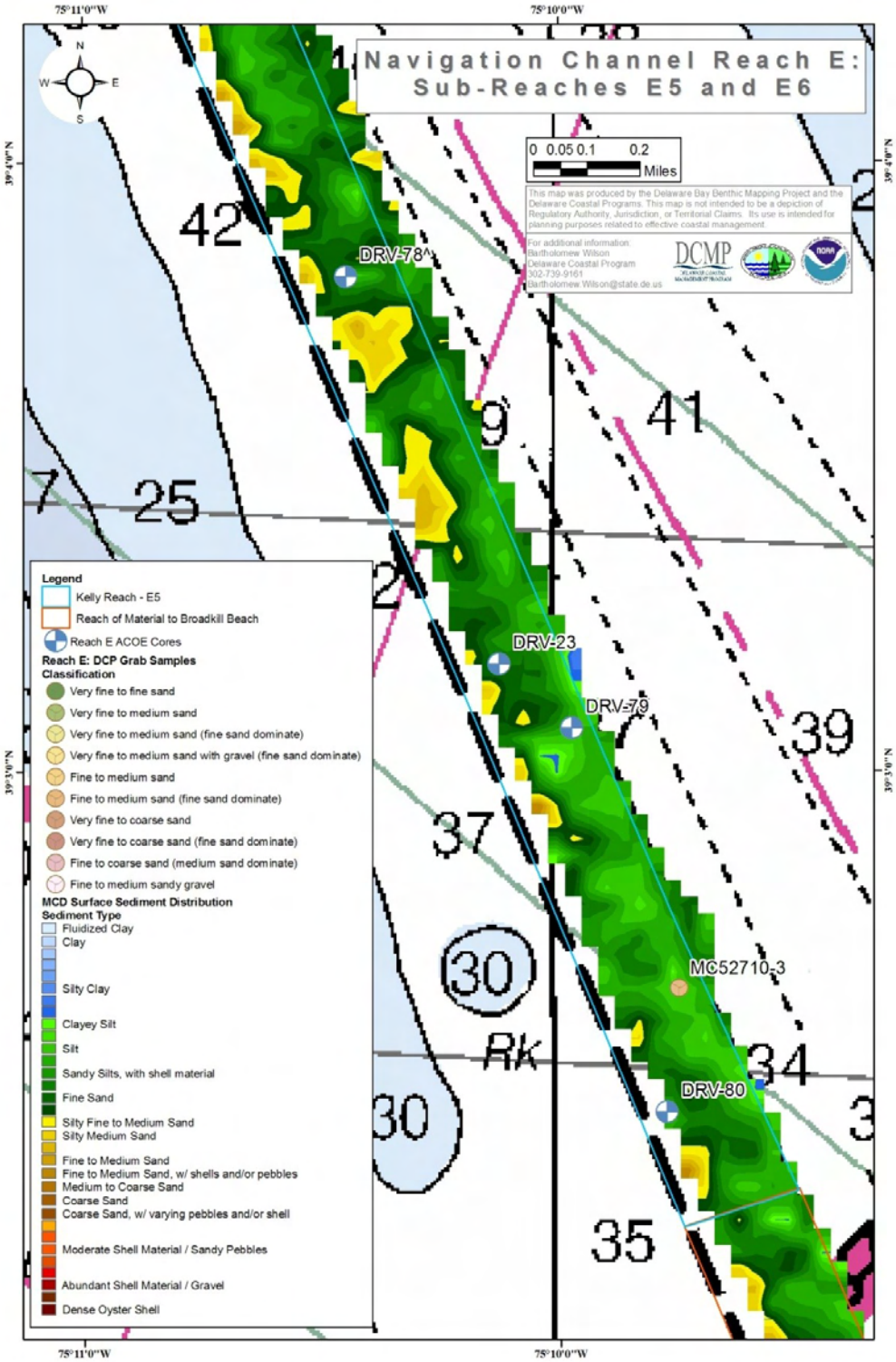
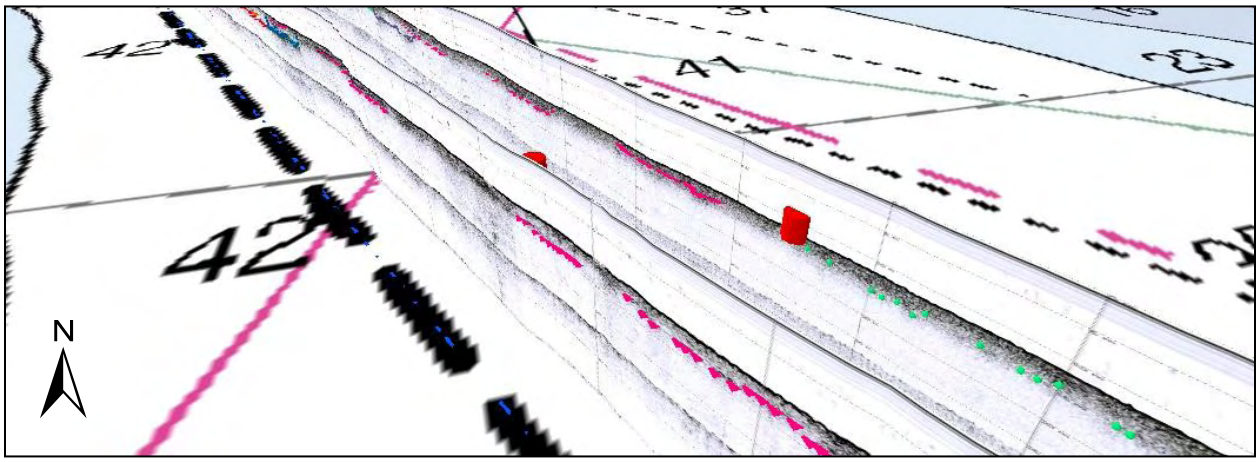
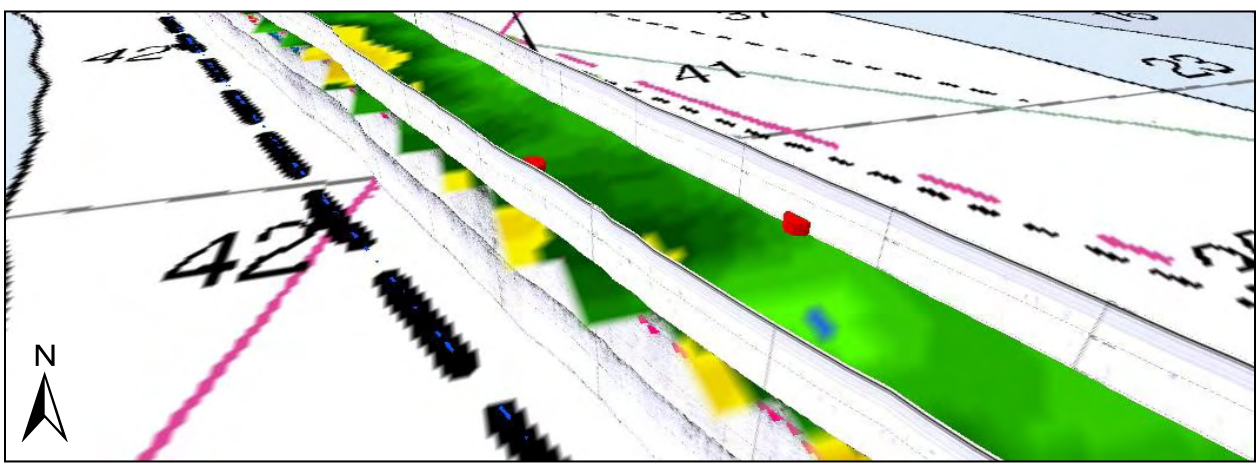


Figure 37. Roxann seabed classification map, core locations, and grab sample locations for the southern region of sub-reach E5.



a)



b)

Figure 38. a) Vertical curtains of chirp sub-bottom profiles for the southern extent of sub-reach E5, cores DRV-23 (left) and DRV79 (right) shown at center (red cylinders). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the southern extent of sub-reach E5. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

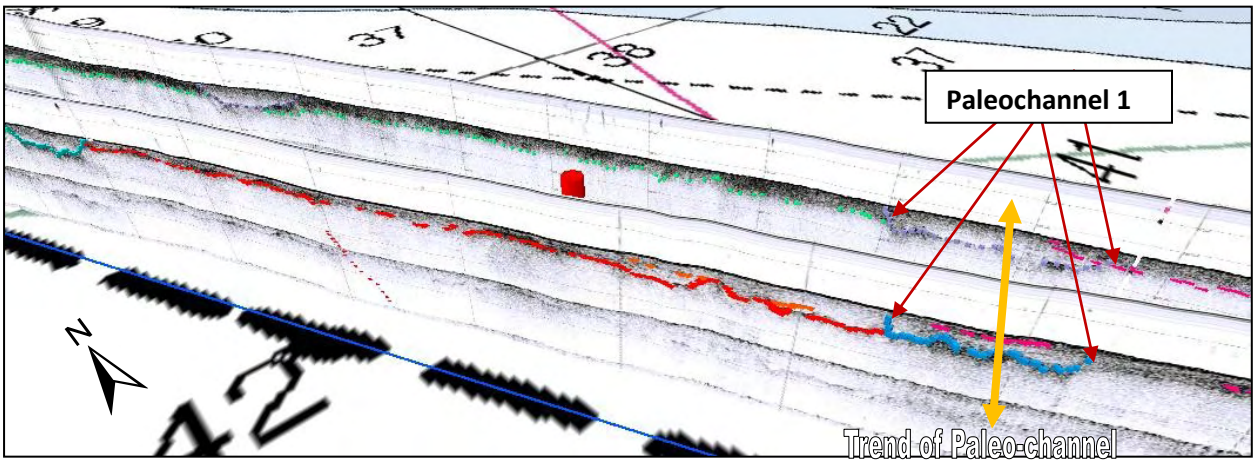
navigational channel in a generally east to west direction, and contain noticeably different sediments within their infill, as compared to sediments outside them. The infill sediments have a lower amplitude (lighter) signature, which is most likely the result of lower organic content (Figure 39a, 40, and 41).

A third paleochannel, PC3, is present 1550 m (5080 ft) north of DRV-78, and 450 to 650 m (1480 to 2130 ft) south of DRV-77. PC3 is wider than PC1 and PC2 (360 to 470 m; 1180 to 1540 ft) but of similar depth (3 to 7 m; 10 to 23 ft) to that of PC2 (Figure 42). PC3 also trends across the channel, but more to the southwest and northeast (Figure 42). As with the other paleochannels to the south, PC3 is also filled with contrasting sediments.

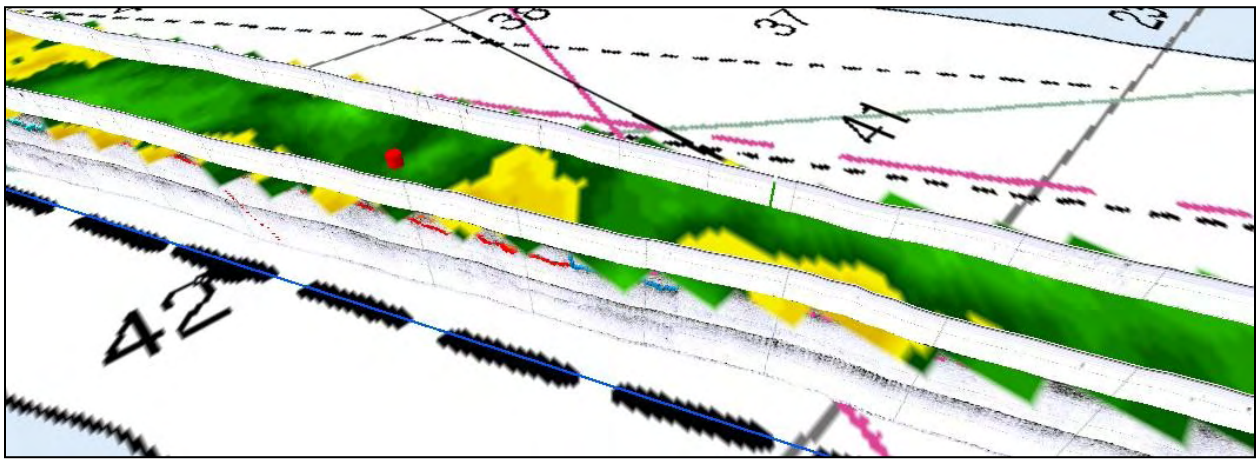
To the north of DRV-78, the Roxann bottom sediment map and top composite sediment samples show a transition from the finer-grained sandy silts and very fine to fine sands, with patchy coarse sediments, to fine to medium sands (ranging from silty fine to medium sand to coarse sand) with smaller fine grained regions (especially toward the western portion of the channel) (Figures 36, 41b and 43b). The chirp data also reveal more organic rich sediments (1.5 to 2.5 m (5 to 8 ft) thick) in the shallow sub-surface (Figure 43a and b).

The sub-bottom sediments as shown in the log for core DRV77 (2.4 km (1.3 nm) north of DRV-78) show a transition back to grain size distributions that more closely reflect those seen in cores DRV-23 and DRV-79 (Appendix B).The top composite sample from Core DRV-77 (sample S-1 0–1.0 ft) contains 10.18% granules and gravel, 25.2% coarse and very coarse sand, 33.82% medium sand, 27.09% fine sand and very fine sand, and 3.73% silts and clays (Appendix B). The higher gravel content of DRV-77, relative to DRV-23 and DRV-79, likely reflects the patchy coarser surface sediment distribution that was mapped in this region by the Roxann survey.

A variable bottom sediment is observed in the top composite samples in nearby cores DRV-22 and DRV-76. Core DRV-22 (sample 0-1 ft) which is 400 m (1300 ft) north of DRV-77 contains 64% granules and gravel, 29% coarse and very coarse sand, 3% medium sand, 3% fine sand and very fine sand and 1% silts and clays (Appendix B). Core DRV-76 (sample 0.25-2.5 ft) which is 900 m (2900 ft) north of DRV-77 contains



a)



b)

Figure 39. a) Vertical curtains of chirp sub-bottom profiles for the southern extent of sub-reach E5 (north of core DRV-23), core DRV-78 shown at left center (red cylinders). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the southern extent of sub-reach E5. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

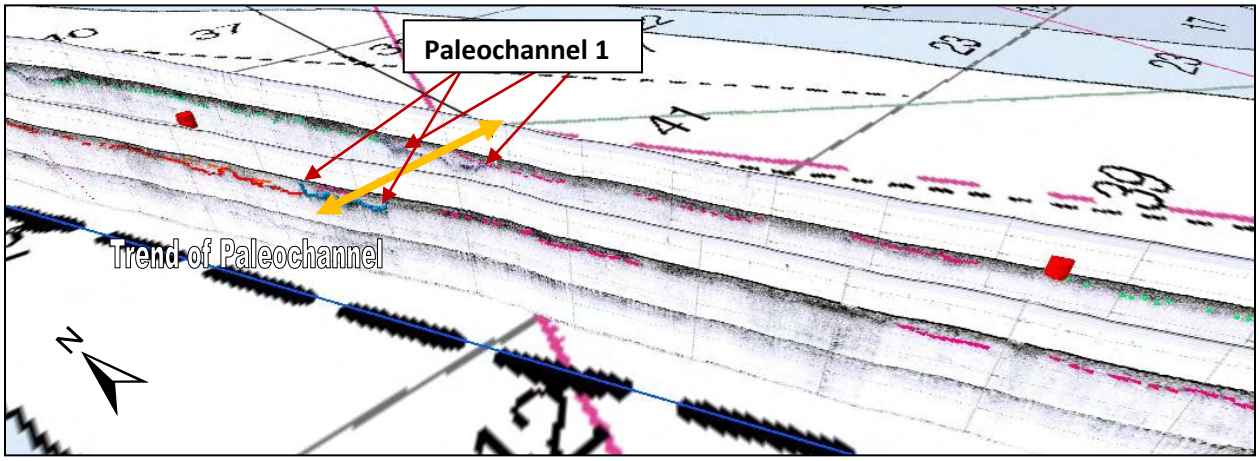
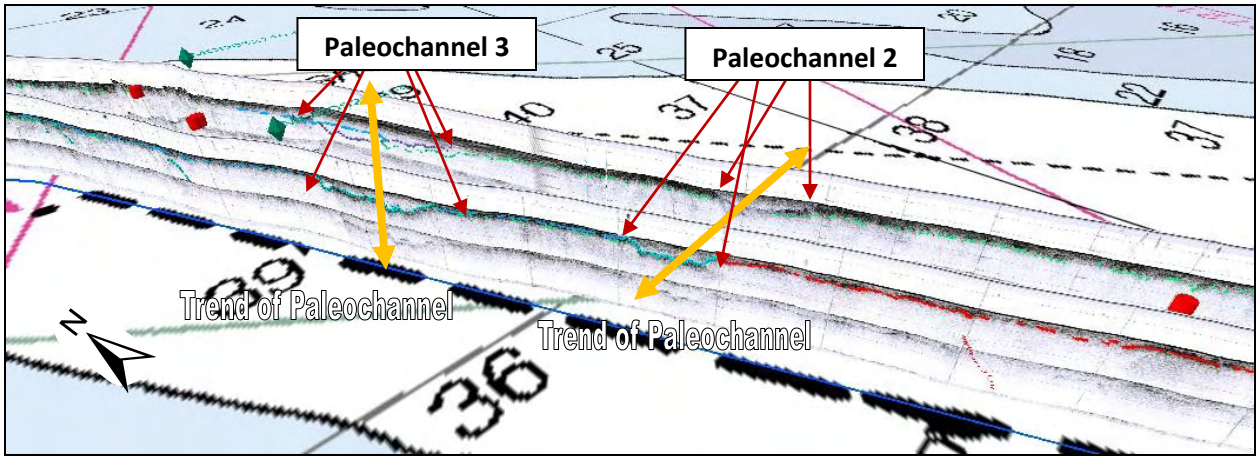
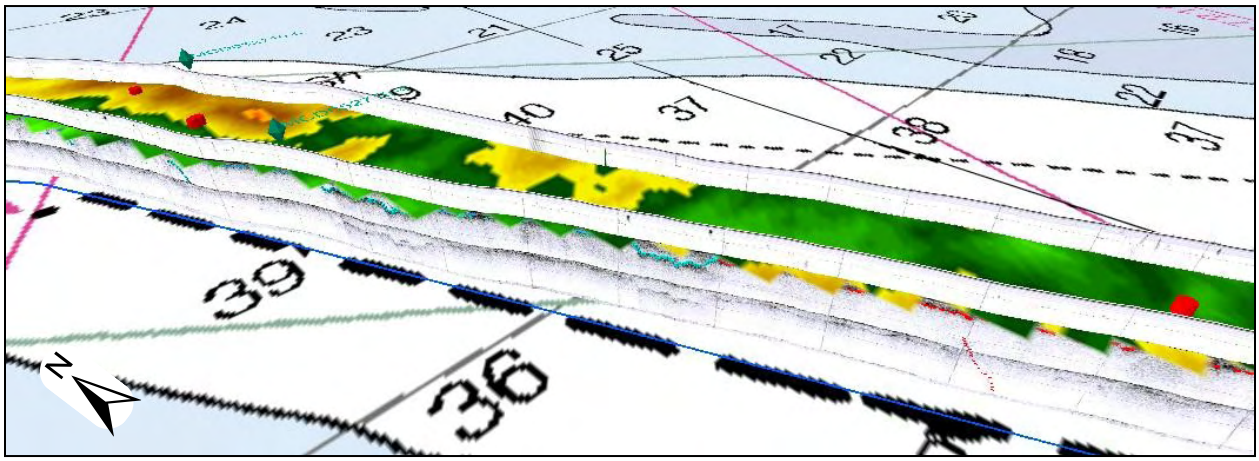


Figure 40. Vertical curtains of chirp sub-bottom profiles for the southern extent of sub-reach E5 between core DRV-79 (shown at right; red cylinders) and core DRV-78 (shown at left; re cylinder). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).



a)



b)

Figure 41. a) Vertical curtains of chirp sub-bottom profiles for the southern central extent of sub-reach E5, between core DRV-78 (red cylinders at right) and DRV-22 (red cylinder at far left). Also, shown are core DRV-77 R1 (right of DRV-22), and grab samples MC052710-4 (right of DRV-77R1) and MC052710-5 (adjacent to DRV-22) b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the southern central extent of sub-reach E5. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

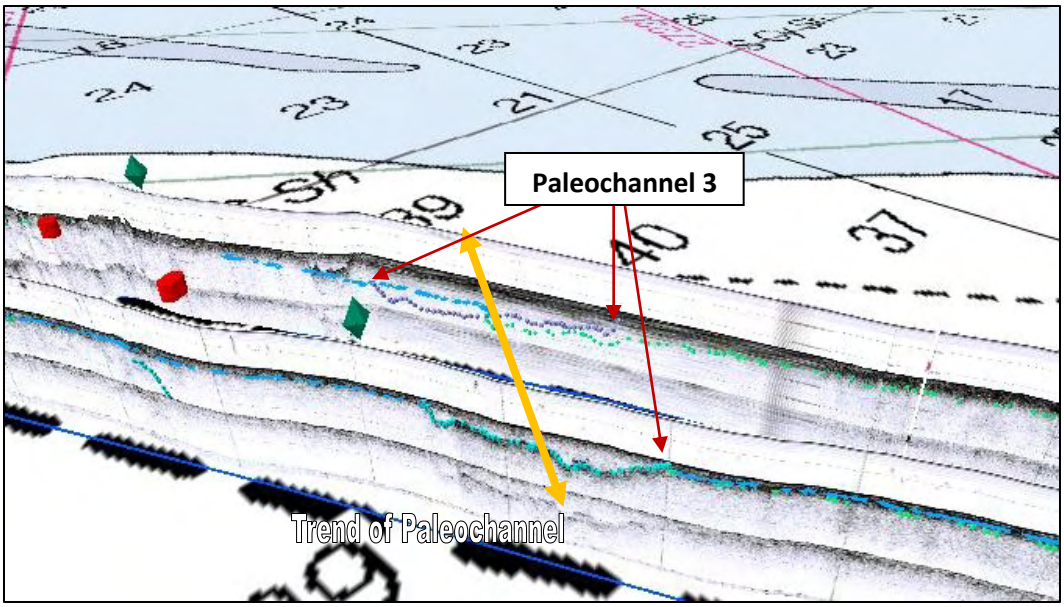
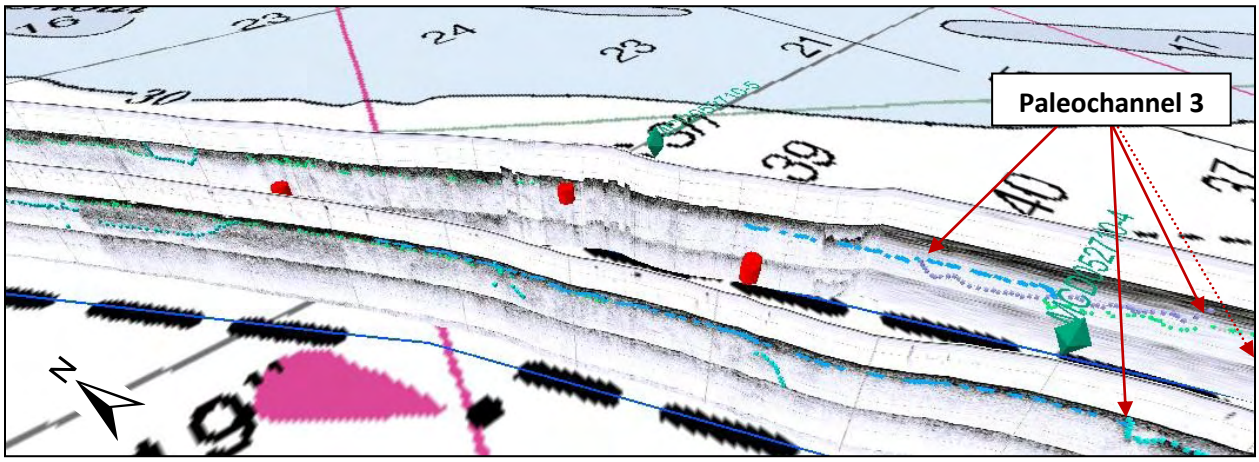


Figure 42. Vertical curtains of chirp sub-bottom profiles for the southern central extent of sub-reach E5, in region south of core DRV-77 R1 (red cylinders at left) and DRV-22 (red cylinder at far left). Also, shown are grab samples MC052710-4 (right of DRV-77R1) and MC052710-5 (adjacent to DRV-22). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

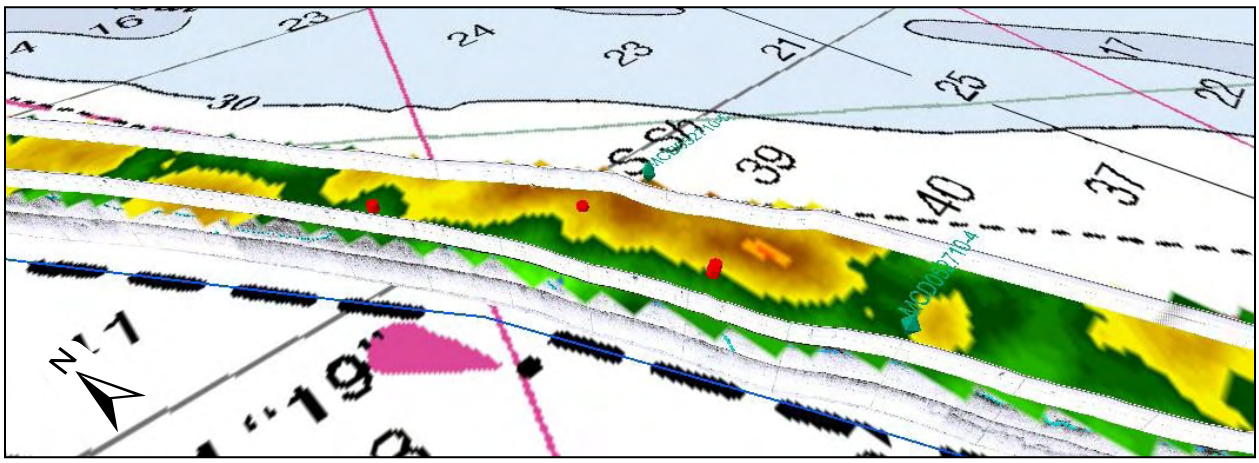
6.59% granules and gravel, 7.79% coarse and very coarse sand, 4.62% medium sand, 46.26% fine sand and very fine sand and 34.74% silts and clays (Appendix B). The distinctly different grain size distributions for the composite samples for these three cores (DRV-77, DRV-22, and DRV-76) are not correlated with reflection events in the chirp sub-bottom profiles along this stretch of the sub-reach (Figure 35 and 43a).

The noticeable changes in the sub-bottom as imaged by the chirp data occur to the south of DRV-77 and to the north of DRV-76; Figure 43a). Thus the bottom sediment variability appears to be a relatively surficial feature and does not occur in the sub-surface, at least as could be constrained by the chirp system. The composite sediment samples collected below the top samples for all three cores contain considerably finer sediments. DRV-77 R1 (S-2; 1.0–3.5 ft) is approximately 75% medium sand or finer material and DRV-76 (S2; 2.5–5 ft) is 98.34% medium sand or finer material (Appendix B). This suggests that the sub-bottom sediments below the top composite samples are fairly uniform being dominated by medium grained sands or smaller sediments, while the bottom deposits contain coarser grain sizes. Furthermore, DRV-76 S1 was a composite from 0.25 ft to 2.5 ft, and did not sample sediments at the bottom. DRV-76 S1 more closely matches DRV-77 R1 S2 and DRV-22 (1.6-5.3 ft) samples in grain size distribution than that of the top composite samples DRV-77 S1 and DRV-22 (0-1.6 ft). Thus the results suggest that it is the bottom sediments within the upper 0.3 to 0.5 m (1 to 1.6 ft) or less that contribute the majority of the coarser sands and gravels to the composite samples in the near bottom sediments identified in DRV-77 and DRV-22.

The location of the cores supports this assessment with the Roxann map indicating the coarsest surface deposits occurring along the eastern margin of the navigation channel (near the bend) while the western margin is characterized by finer grained surface sediments (Figure 36, Figure 43b). Core DRV-77 was collected near the edge of the coarser eastern margin, and DRV-76 to the farthest west and most distal to the coarser eastern side of the navigation channel (Figure 36). To better constrain the variability in grain size of the sediments both in an areal and a vertical sense would necessitate a more detailed investigation of the thickness and lateral extent of the coarser surface sediments. The thickness of the very coarse sediments



a)



b)

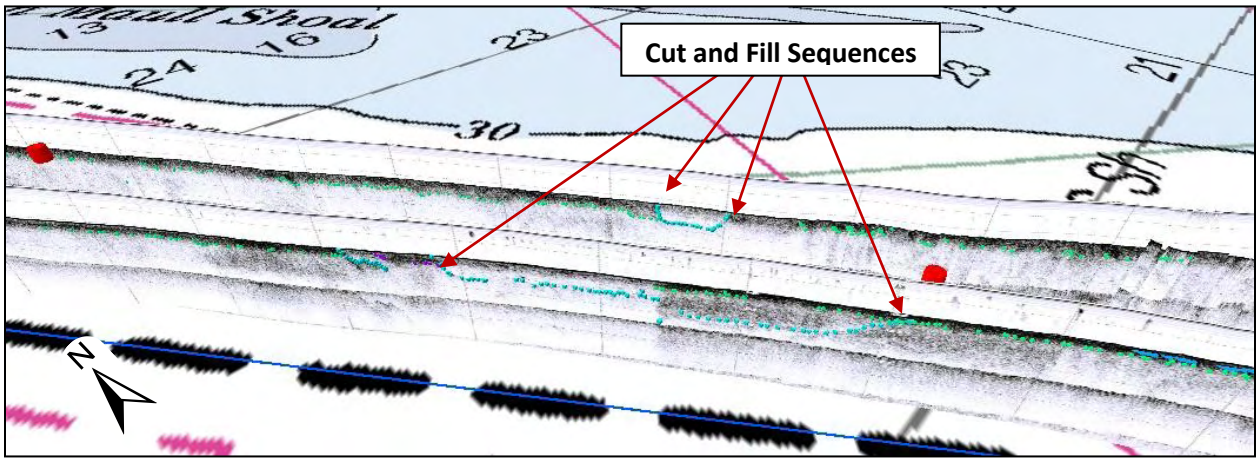
Figure 43. a) Vertical curtains of chirp sub-bottom profiles for the central extent of sub-reach E5 (north of core DRV-23), core DRV-78 shown at left center (red cylinders). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the southern extent of sub-reach E5. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

The sub-reach between core DRV-76 and DRV-67 (1.8 km (0.96 nm) to the north) as shown by the Roxann map is characterized by the familiar pattern of patches of mixed coarser sands (silty fine to medium sand to coarse sands) surrounded by finer sediment deposits (silts to fine sands; Figure 36). The top composite sample from core DRV-67 (S1 0-1.6 ft) contains a rather coarse sediment grain size distribution with 16.9% granules and gravels and 14.3% coarse and very coarse sands with 50.9% medium sands, 8.8% fine and very fine sands and 4.2% silts and clays (Figure 35, Appendix B).

The chirp sub-bottom data along this portion of the sub-reach shows two nested cut and fill sequences on the western side of the channel starting approximately 30 m (100 ft) north of DRV-76, with maximum depths approaching 5 and 7 m (16 and 23 ft) below the surface, and a smaller cut and fill sequence on the east side of the channel approximately 200 m (650 ft) north of DRV-76, with a maximum depth of 5 m (16 ft) (Figure 44a). The sediments in the smaller eastern cut and fill and the shallower western cut and fill have a lower amplitude signature, denoting that they contain less organic material than the surrounding deposits (Figure 44a). The chirp data to either side of these cut and fill sequences, has a strong, high amplitude signature at, and near, the surface (to depths of 1 to 2 m (3 to 7 ft), which represents either gaseous, highly compacted or coarse sediments.

Starting south of DRV-67 and continuing to the northernmost extent of sub-reach E5, the chirp data is characterized by a high-amplitude bottom reflection (Figures 45a and 46a). The surface sediment distribution from the Roxann map and the available cores suggest that this strong reflection is associated with very coarse bottom sediments (Figure 36). The eastern margin of the navigation channel in this portion of the sub-reach contains the coarsest gravel and sandy pebble areas; especially between DRV-66 and DRV-65, and also all along the western margin of the navigation channel adjacent to DRV-65 and DRV-20 (Figure 45b and 46b).

The cores in this area are located into two groups, three north central cores (DRV-67, DRV-21, and DRV-66) and the two cores nearest the northern extent of sub-reach E5 (DRV-65 and DRV-20; Figure 36). The top composite samples of the three north central cores DRV-67 (S1, 0-1.6 ft), DRV-21 (0-5 ft) and DRV-66 R1 (0–0.5 ft)



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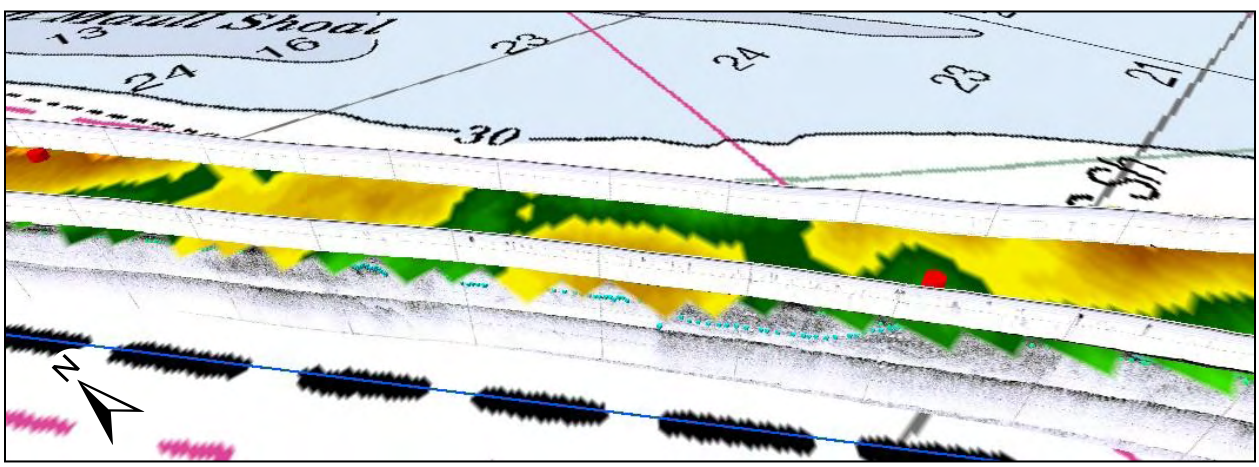
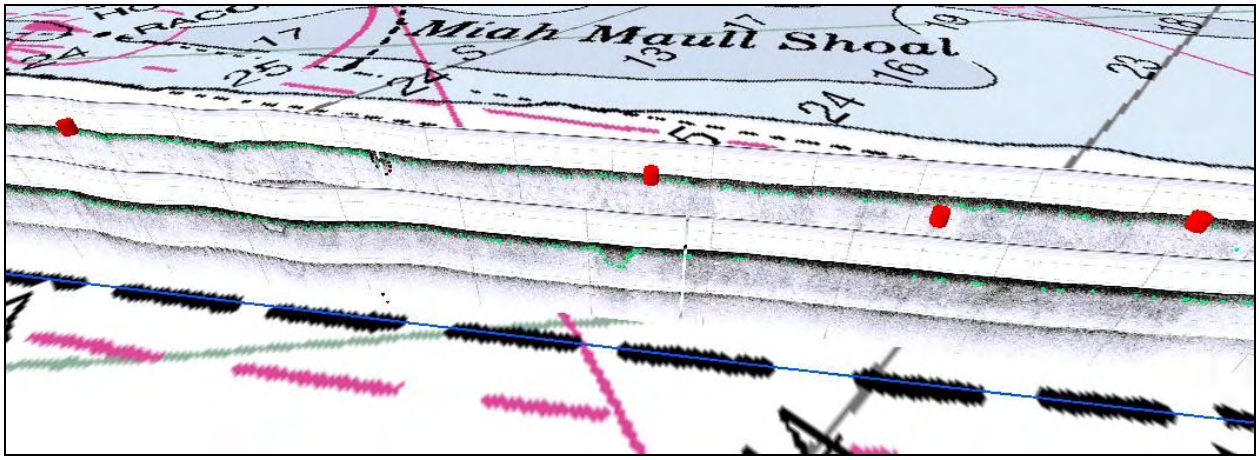
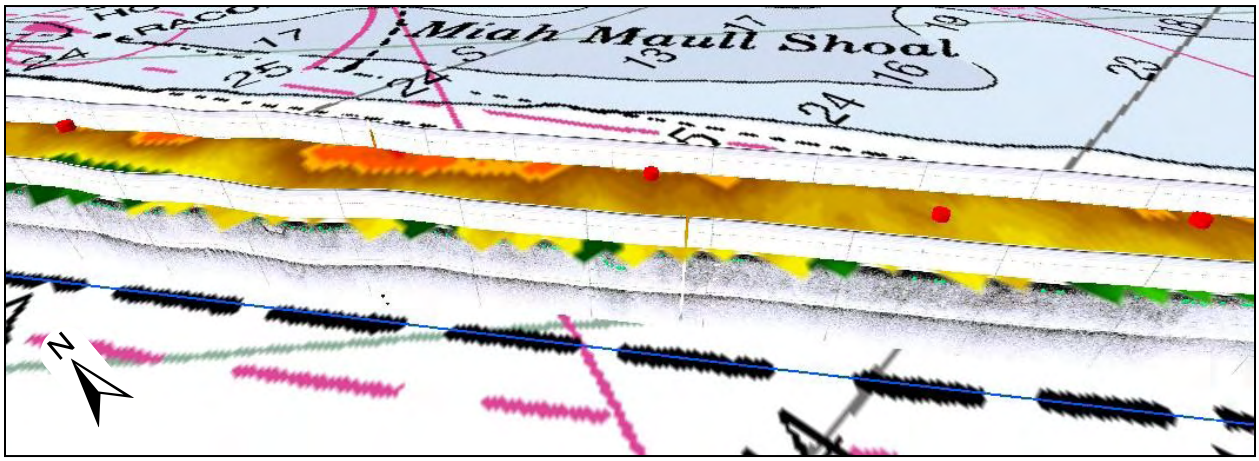


b)

Figure 44. a) Vertical curtains of chirp sub-bottom profiles for the north central extent of sub-reach E5, core DRV-76 shown at right (red cylinders) and core DRV-67 shown at left(red cylinder). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the north central extent of sub-reach E5. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

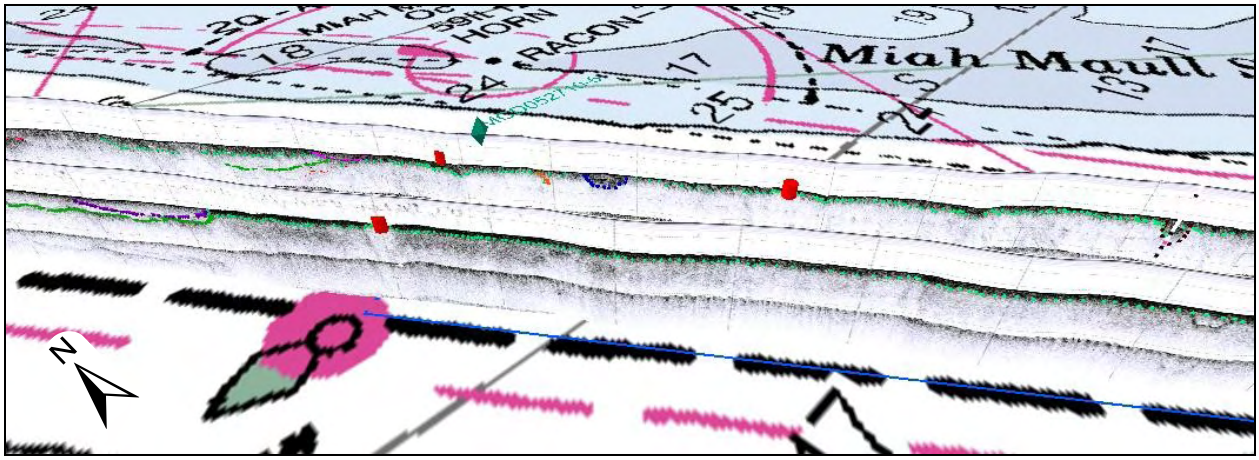


a)



b)

Figure 45. a) Vertical curtains of chirp sub-bottom profiles for the northern extent of sub-reach E5 (cores contained in view are (from right to left; red cylinders)): DRV-67, DRV-21, DRV-66, and DRV-65). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the northern extent of sub-reach E5. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).



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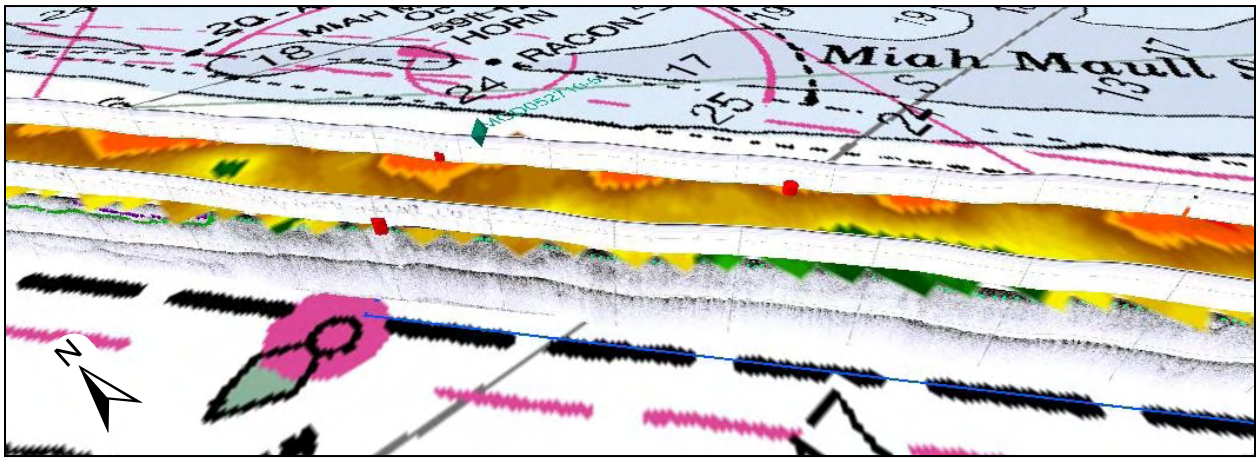


b)

Figure 46. a) Vertical curtains of chirp sub-bottom profiles for the northern boundary of sub-reach E5 (cores contained in view at center are (from right to left; red cylinders): DRV-65, DRV-75, and DRV-20). Also shown is grab sample MC052710-6 (green diamond), adjacent to DRV-75. b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the northern boundary of sub-reach E5. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

have similar abundances of silts and clays (4.2%, 2% and 4.1% for DRV-67, DRV-21 and DRV-66, respectively) and granules and gravels (16.9%, 23.5% and 24.7% for DRV-67, DRV-21 and DRV-66, respectively) (Figure 47, Appendix B). The distributions of the other grain sizes vary considerably between these three cores. The fine to very fine sand abundances are 6% (DRV-21), 8.8% (DRV-67) and 29.7% (DRV-66); percentages of medium sands are 16.4% (DRV-66), 26% (DRV-21) and 50% (DRV-67); and very coarse to coarse sands have concentrations of 14.3% (DRV-67), 25.1% (DRV-6)6 and 42.5% (DRV-21) (Figure 47, Appendix B).

As identified in sub-reach E6, the bottom sediment grain size distribution can skew composite samples if the locations of the cores are not representative of the sample area. This is also of concern in sub-reach E5. Of particular note in this sub-reach is the discrepancy between the visual descriptions of the top composite sediments and the results from sieve analyses. The descriptions are based on visual examination of the core intervals by a trained observer and the grain size relative abundances are derived from passing selected samples through a series of sieves and measuring the distribution of sediments as a function of grain size.

Examples of the discrepancies include the visual description of sample S1 from core DRV-67as “orange/tan fine sand, little gravel, little medium sand, trace coarse sand, trace silt/clay”; while the relative grain size abundances from the sieve analyses are 16.9% granules and gravel, 14.3% coarse and very coarse sand, 50.9% medium sand, 8.8% fine sand and very fine sand, and 4.2% silts and clays (Appendix B). Similarly, the top sample from core DRV-21 is described as “ light red brown medium to fine sand with scattered gravel”; while the grain size percentages are 23.5% granules and gravel, 42.5% coarse and very coarse sand, 26% medium sand, 6% fine sand and very fine sand, and 2% silts and clays. DRV-66’s top sample is “gray fine sand, some medium sand, little gravel, trace coarse sand, trace silt/clay”; but grain sizes are reported as 24.7% granules and gravel, 25.1% coarse and very coarse sand, 16.4% medium sand, 29.7% fine sand and very fine sand, and 4.1% silts and clays (Appendix B).

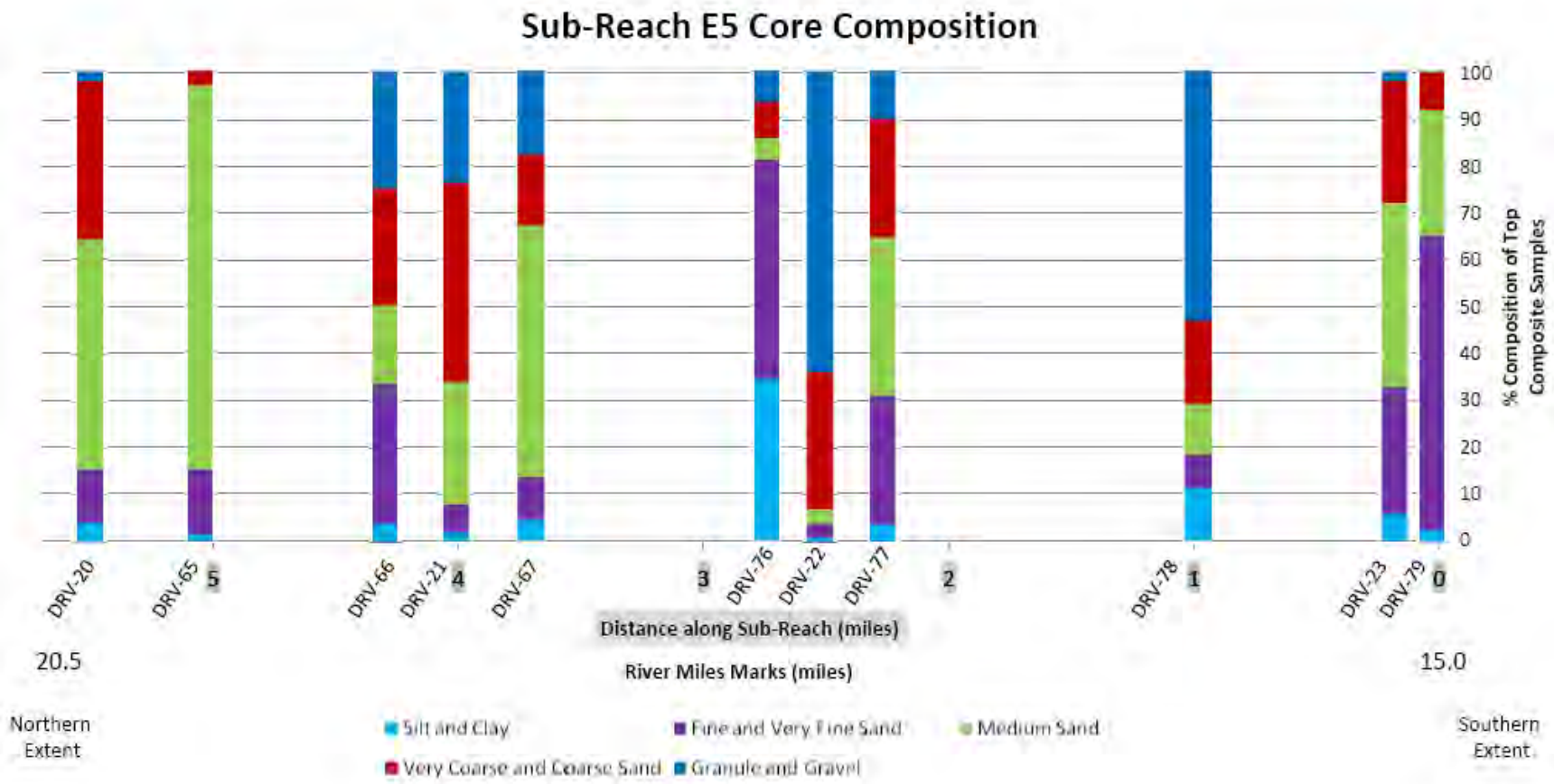


Figure 47. Graph of the top composite samples grain size composition verses the distance of cores locations along sub-reach E5.

Based on observations from grab samples that have been obtained during the Delaware Bay Benthic Mapping Project and on familiarity with the nature of sediments within the navigation channel, it is suspected that in this sub-reach there are areas where there is a relatively thin layer of very coarse sands to granules and gravels on the bottom that overlie the finer-grained medium to smaller sands, silts and clays that comprise the remainder of the top composite samples. In the sieving analyses, this upper, thin coarse layer is being essentially "over-sampled" and the grain size relative abundances based on the sieving results are skewed toward these coarser grained sediments.

The presence of a thin layer of coarser-grained bottom sediments overlying finer-grained sands is supported by results from cores DRV-65 R1 and DRV-20 that are located 1.4 km (0.75 nm) and 2.2 km (1.18 nm) to the north of DRV-66, respectively. The top sample from DRV-65 R1 (S1 0.4-5.0 ft) is 0% granules and gravel, 3% coarse and very coarse sand, 81.6% medium sand, 13.6% fine sand and very fine sand, and 1.8% silts and clays. The uppermost sample from DRV-20 (1.1-5.0 ft) is 2% granules and gravel, 33.5% coarse and very coarse sand, 49% medium sand, 11.5% fine sand and very fine sand, and 4% silts and clays (Appendix B). In both of these cores the uppermost 0.4 and 1.1 ft were not sampled. Note that especially with core DRV-65 when the uppermost layer is not sampled, the distribution of sediments is towards smaller-grained medium and fine sands vs. gravels and granules and very coarse to coarse sands. To further validate this observation, it would be necessary to have grain-size analyses from samples of the uppermost sediments. There is however, a core log description of the upper 1.1 ft of core DRV-20 as a "black sandy-gravel, medium to fine sand grains, and light grey silt clay", which would support the presence of a coarser-grained top sediment layer.

Similar to recommendations made for sub-reach E6, additional coring data also needs to be collected through sub-reach E5 especially to better constrain the spatial extent of the coarsest-grained deposits in the sub-reach. Specifically, several additional cores need to be collected in the general vicinity of DRV-78 to determine the extent of the extremely coarse results (53.01% granules and gravels, 17.75% coarse and very coarse sands) found in that core. In the more southern portion of the sub-reach, cores

are also needed to better understand the transitions in sediment grain sizes between DRV-23 to DRV-78 and DRV-78 to DRV-77 with close attention given to sediments that occur within and outside the paleochannels that were observed in the chirp sub-bottom profiles (Figure 47).

Within the middle section of sub-reach E5, additional coring needs to be conducted to further examine the extreme variability that exists in the distribution of grain sizes between cores DRV-77, DRV-22, and DRV-76. Cores should be collected between these cores and along the western portion of the navigation channel, adjacent to DRV-22, to evaluate the lateral variability of the coarse-grained bottom sediments (Figures 36 and 47). Moving toward the northern portion of the sub-reach, additional cores are needed between cores DRV-76 and DRV-67 to determine the impact that the cut and fill sequences, as imaged by the chirp sub-bottom profiling have on sediment-grain sizes in this area (Figures 44 and 47).

The northernmost section of sub-reach E5 needs to be further examined in detail, as cores DRV-65 and DRV-20 do not sample the uppermost bottom sediments for their grain-size distribution. The presence of an uppermost thin layer of coarse-grained sediments overlying finer-grained sands to silts and clays must be confirmed for this section of the sub-reach. There is also a large discrepancy in grain size distribution at the boundary of this sub-reach with sub-reach E4. Core DRV-75 in sub-reach 4, only 240 m (800 ft) east of DRV-20, contains a dramatically different grain size distribution with 90.87% silts and clays, and only 1.51% granules and gravel, 2.25% coarse and very coarse sand, 0.78% medium sand and 4.59% fine sand and very fine sand (Appendix B, Figure 35). This large discrepancy needs to be better understood.

II. Sub-Reaches E4 and E3

Sub-reaches E4 and E3 comprise the central portion of the Reach E section of the PD-ACOE navigation channel deepening project. Sub-reach E4 (stations 432+200 to 421+700) and E3 (stations 421+700 to 390+200) sediments will be pumped into the Kelly Island CDF once the containment berm is completed. This dredging prism would

incorporate the top of all 8 existing cores (through sub-reaches E4 and E3), with depths of inclusion of 2.0 ft of core DRV-75, 3.4 ft of core DRV-74, 0.6 ft of core DRV-19, 1.1 ft of core DRV-73, 2.4 ft of core DRV-18, 0.1 ft of core DRV-72, 1.1 ft of core DRV-71 and 2.5 ft of core DRV-17 (GBA, 2010). The volume of material to be dredged from E4 is estimated to be 252,064 cy (10% of the total Reach E dredge volume) and E3 has an estimated volume of 580,243 cy (23% of the total Reach E dredge volume) (Appendix D).

Two cores were collected within E4 (in 2001 by Alpine) and six cores were collected within E3 (1n 1991 and 2001 by Ocean Survey, Inc and Alpine). In this investigation's acoustic survey, 10.6 km (5.7 nm) of Roxann and chirp tracklines with one grab sample were collected within the E4 sub-reach; 33 km (17.8 nm) of tracklines with four sediment grab samples were collected for sub-reach E3 (Figures 48 to 51).

Since both sub-reaches E4 and E3 are to be pumped within the CDF, a detailed description of the sediment distributions within these sub-reaches is not necessary. In general, sub-reach E4 is very fine grained. The top samples from the two cores (DRV-75 (S1 0.5–2.0 ft) and DRV-74 (S1 0.0–5.0 ft)) in the sub-reach have 90.87% and 86.5% silts and clays, respectively. In addition, DRV-75 S1 has 1.51% granules and gravel, 2.25% coarse and very coarse sand, 0.78% medium sand, 4.59% fine sand and very fine sand; DRV-74 S1 has 0.27% granules and gravel, 5.94% coarse and very coarse sand, 2.88% medium sand, 4.41% fine sand and very fine sand (Appendix B, Figure 48, Figure 52).

There is a pronounced difference in the grain size distributions between sub-reaches E5 and E4 with E4 having much finer grained sediments. This is due in part to the sampling, or lack thereof, of the surficial layer of generally coarse-grained sediments in the top composite cores. For example, DRV-75 does not have a surficial sample (core grain size analyses starts at a depth of 0.5 ft), therefore it does not include the bottom coarse-grained sediments in its grain size analyses. The presence of the thin layer of coarse-grained sediments at the bottom is confirmed by the Roxann sediment classification map for the sub-reach (Figure 49). This coarser sediment cover was not sampled in the grain size analysis of core DRV-75.

The major change that occurs along sub-reach E4 is the presence of a large cut and fill sequence that starts approximately 400 m (1,300 ft) and 200 m (650 ft) north of cores DRV-20 and DRV-75, respectively. This feature trends north over a distance of approximately 900 to 1,200 m (2,950 to 3,900 ft) reaching a maximum depth of 5 m (16 ft) below the bottom (Figure 53). The sediments associated with the cut and fill sequence are finer-grained and the sub-bottom profiles are characterized by six to nine different irregular to planar reflection events within the interval of 1 to 5 m (3 to 16 ft) beneath the bottom (Figures 53 and 54).

Sub-reach E3 contains coarser deposits than those found in E4, with a marked change in the sub-surface grain size distribution occurring between cores DRV-74 (in the northern portion of sub-reach E4) and DRV-19 (1 km (0. 6 nm) north of DRV-7 in sub-reach E3). The top composite sample in DRV-19 (0.0–2.1 ft) contains 47% fine sand and very fine sand with 28% medium sand and 9% coarse and very coarse sand, 1% granules and gravel and 15% silts and clays (Appendix B, Figure 54).

Three (DRV-18, DRV-72 and DRV-71) of the other five cores in sub-reach E3 all located near the Elbow of Cross Ledge (Figure 50) have very similar grain size distributions with predominantly medium to fine to very fine sands. DRV-18 (sample 0.0-4.1 ft) has 35% fine sand and very fine sand with 38% medium sand and 26% coarse and very coarse sand, 1% granules and gravel and 4% silts and clays; DRV-72 (sample 0.0-5.0 ft) has 34.27% fine sand and very fine sand with 39.58% medium sand, 7.41% coarse and very coarse sand, 0.04% granules and gravel and 16.75% silts and clays; and DRV-71 (S1 0.0-4.3ft) has 25% fine sand and very fine sand with 52% medium sand, 28% coarse and very coarse sand, 3.99% granules and gravel and 2% silts and clays (Appendix B, Figures 50 and 54).

The two remaining cores (DRV-73 and DRV-17) within sub-reach E3 contain considerably coarser sediments in the top composite samples (Appendix B, Figure 54). Core DRV-73 (S-1, 0.0-3.0 ft, located 300 m (980 ft) north of DRV-19) is 57.97% coarse and very coarse sand with 1.53% granules and gravel, 27.27% medium sand, 5.54% fine sand and very fine sand and 7.69% silts and clays (Appendix B). Core DRV-

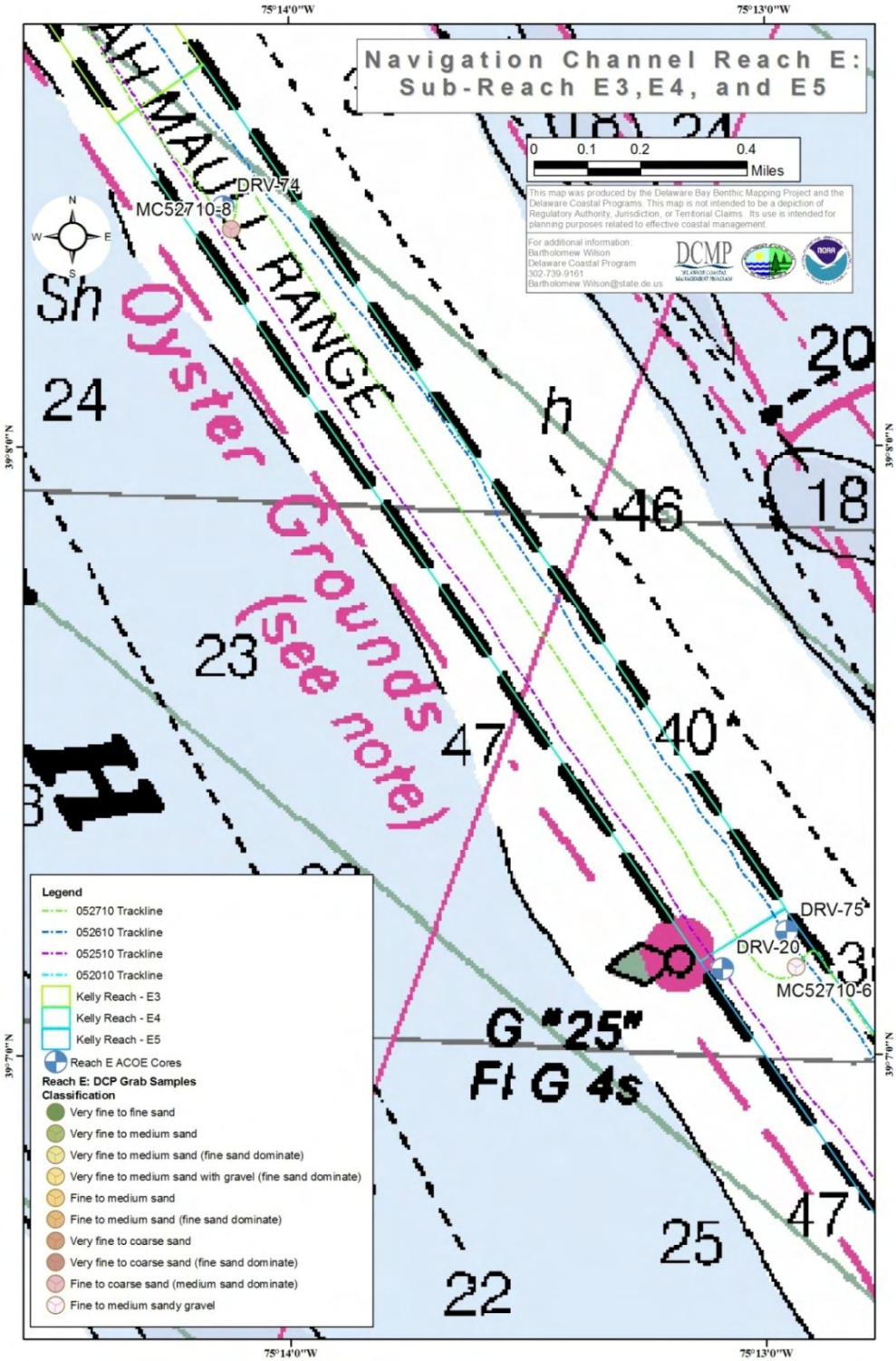


Figure 48. Map of tracklines, grab samples, and core locations within sub-reach E4.

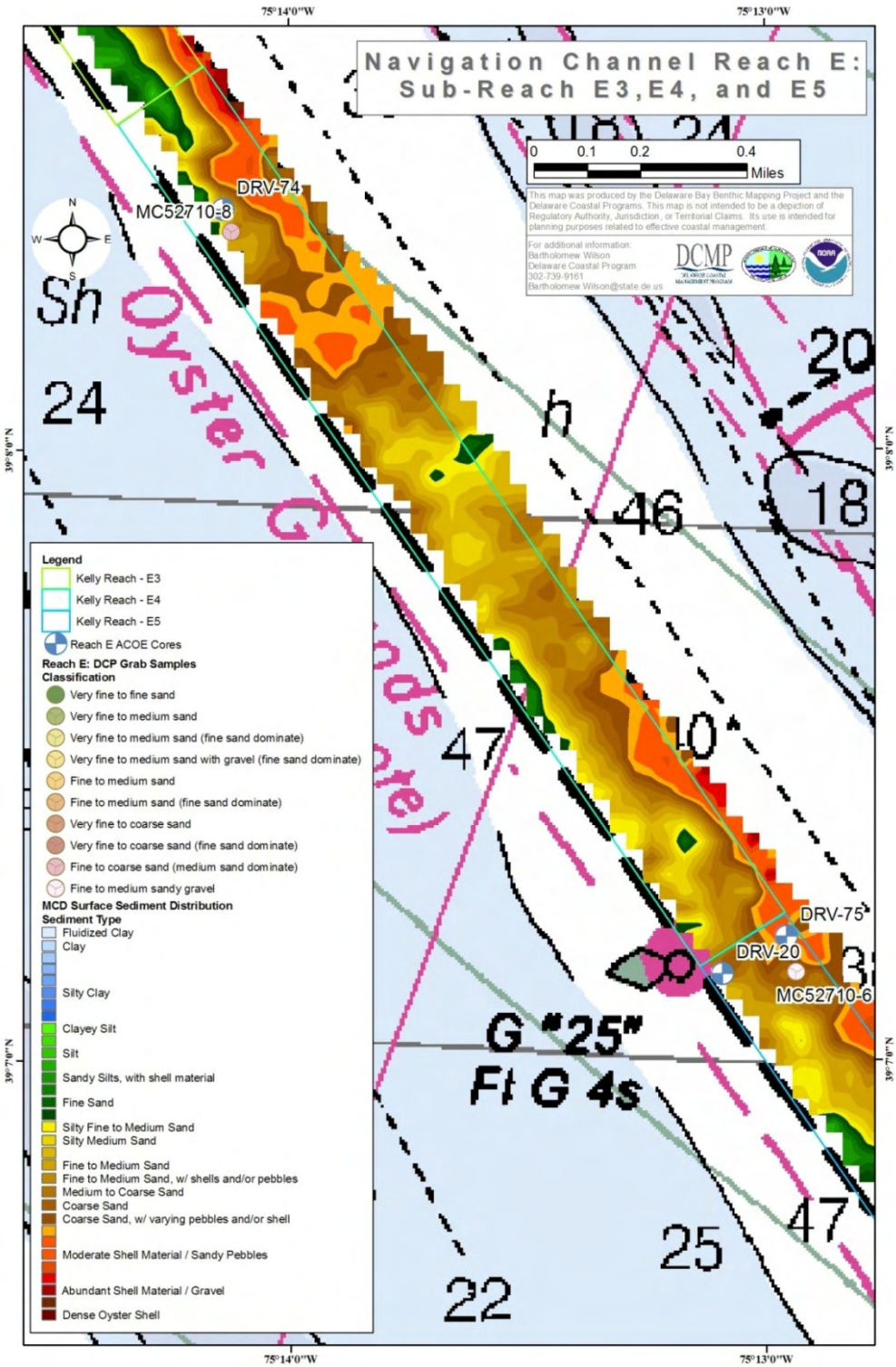


Figure 49. Roxann seabed classification map of sub-reach E4.

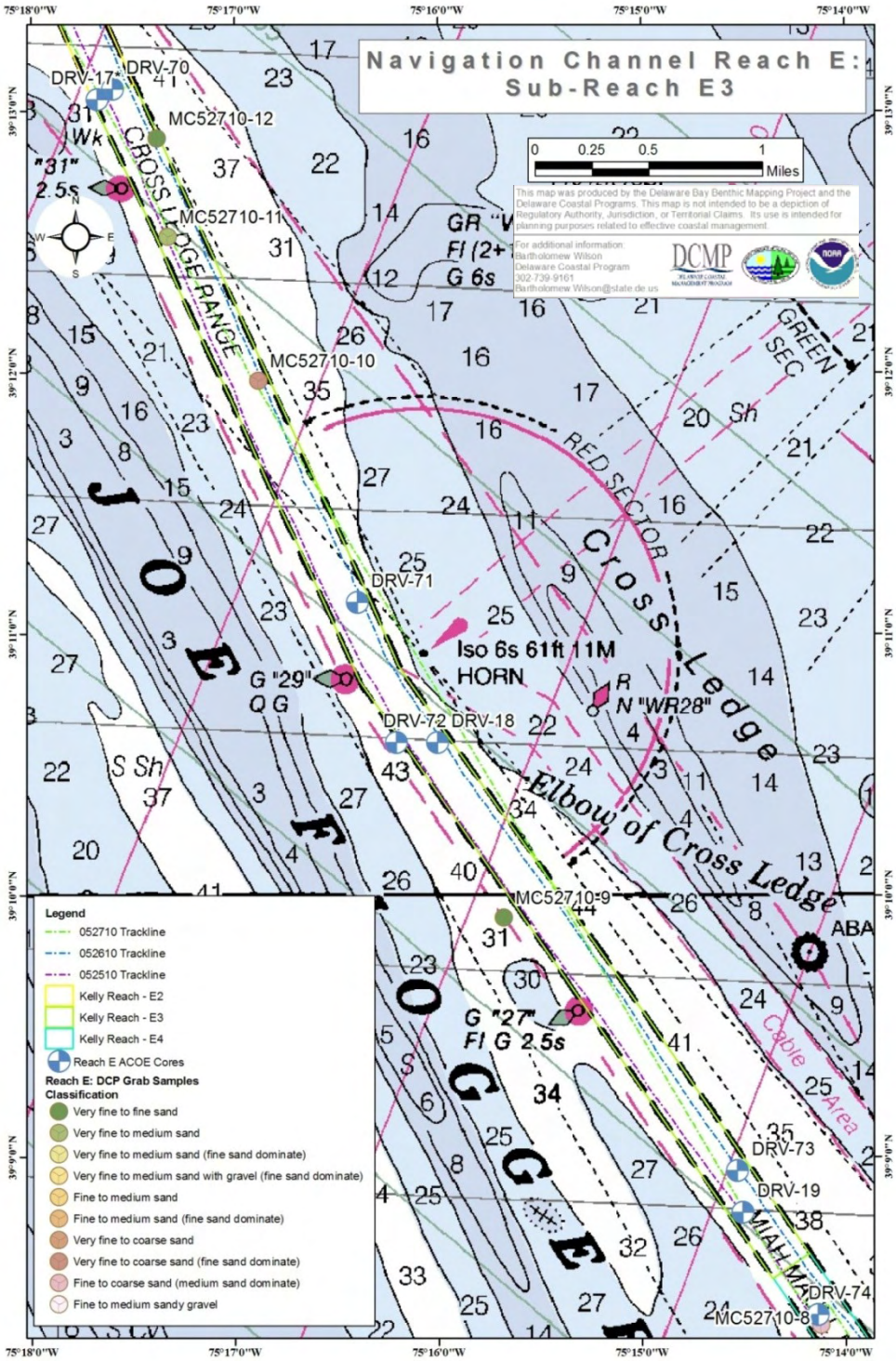


Figure 50. Map of tracklines, grab samples, and core locations within sub-reach E3.

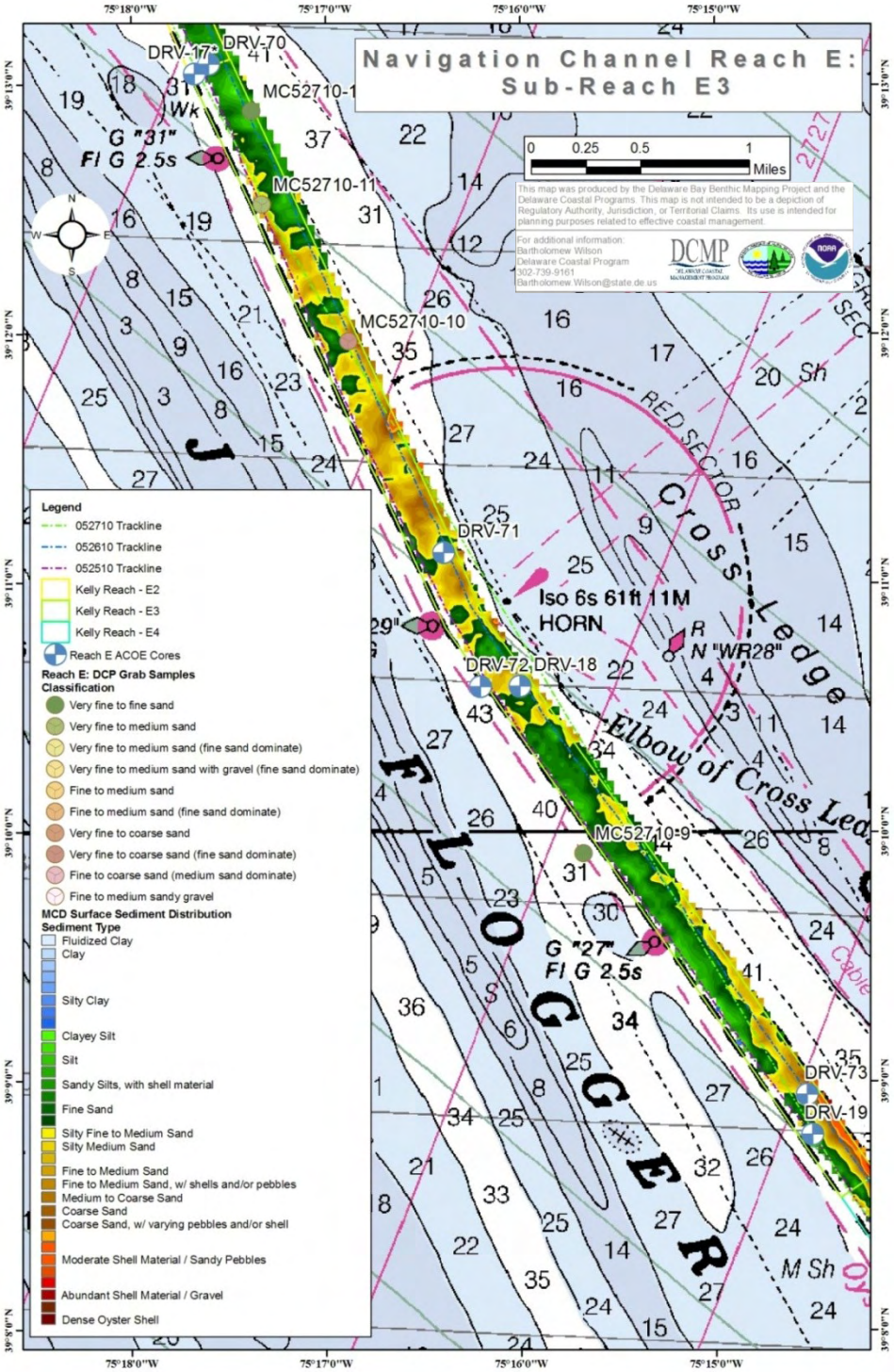


Figure 51. Roxann seabed classification map of sub-reach E3

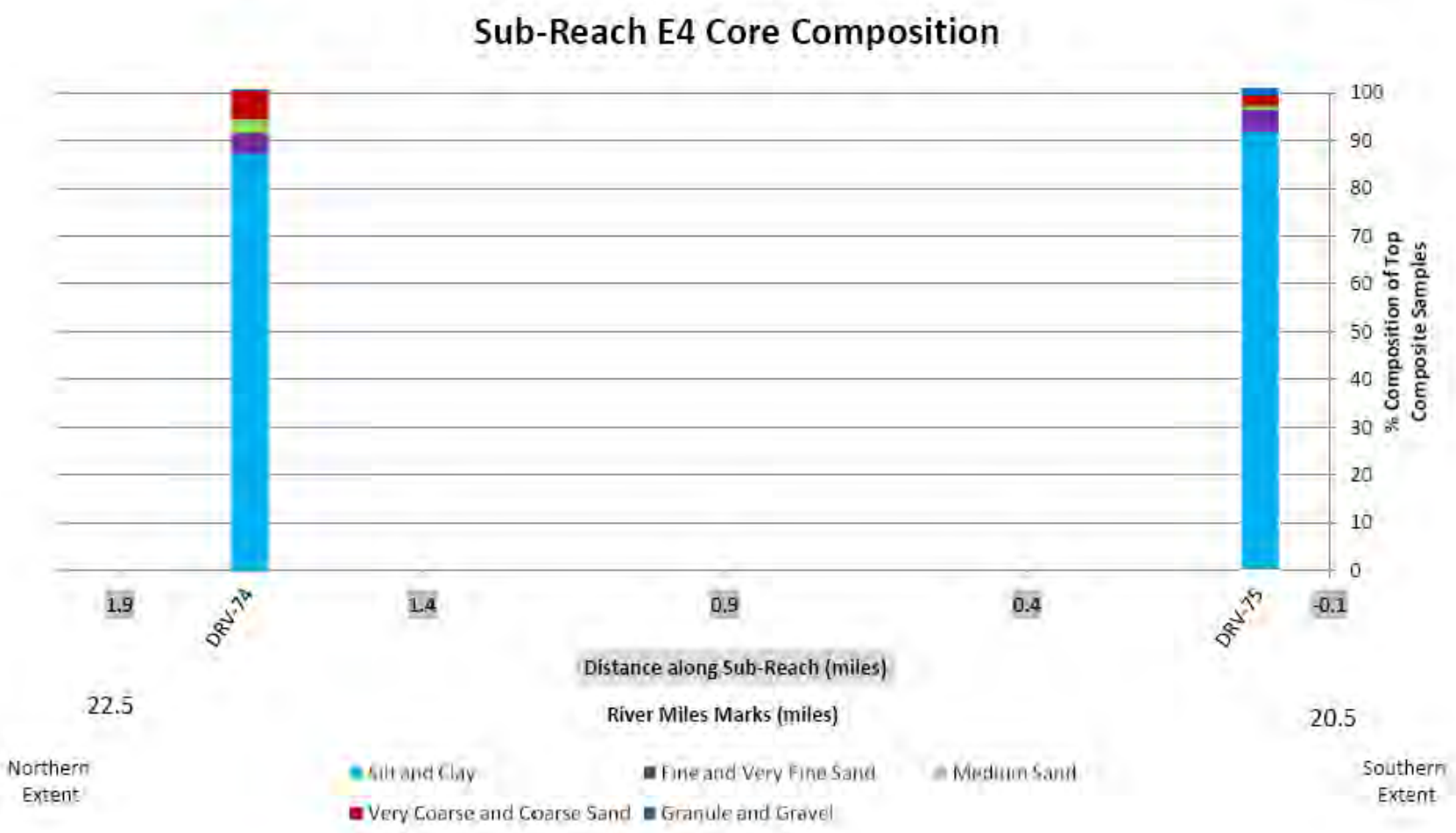


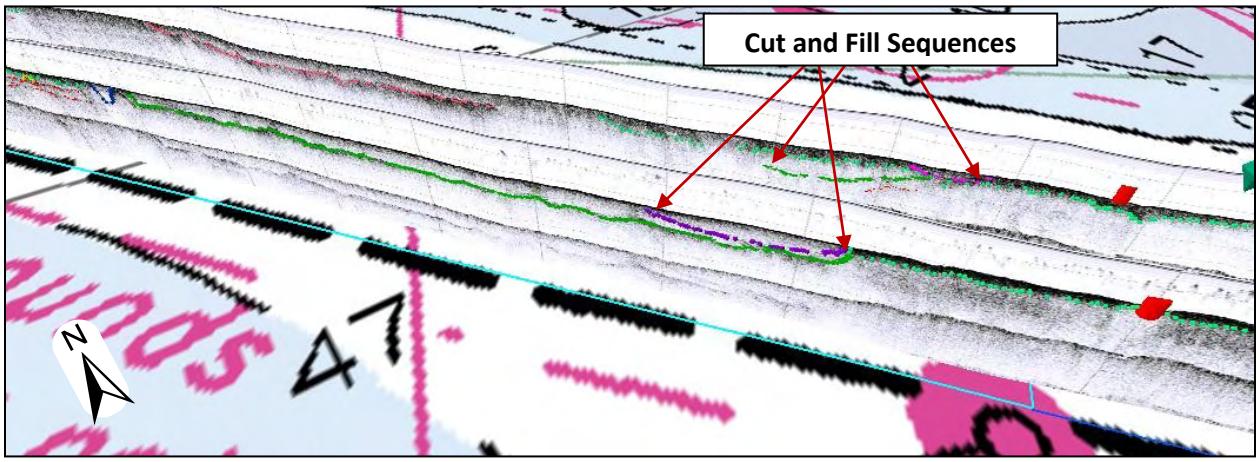
Figure 52. Graph of the top composite samples grain size composition verses the distance of cores locations along sub-reach E4.

17 (sample 0.0–1.2 ft, at the northern boundary of sub-reach E3 and 4.8 km (2.4 nm) north of DRV-71) contains even coarser sediments with 50% granules and gravel, 17% coarse and very coarse sand, 21% medium sand, 10% fine sand and very fine sand and 2% silts and clays (Figure 50, Appendix B). The differences in grain size between cores DRV-73 and DRV-19 do correlate with changes in the sub-bottom sediments as constrained by the chirp data. Core DRV-73 is located within a cut and fill structure, while core DRV-19 is outside of the cut and fill structure and is characterized in the sub-bottom by a series of planar reflectors (Figure 55b).

Cores DRV-18, DRV-72, DRV-71 to DRV-70 (in sub-reach E2) correlate very well with similar distributions of sediment grain sizes (Figures 54 and 56, Appendix B). However in between cores DRV-71 and DRV-70, core DRV-17 with its much coarser-grained sediments indicates a significant variation in the bottom sediments. Unfortunately Roxann and chirp data were not collected directly over the DRV-17 core site, but the Roxann map suggests that there is a small coarser patch of sediments extending toward the western margin of the navigation channel (just north of cores DRV-17 and DRV-20) that could be indicative of the coarser-grained sediments of DRV-17 (Figures 51 and 57b). The chirp sub-bottom collected between DRV-17 and DRV-70 shows a near bottom (~0.5 m to 1 m deep) reflector that could represent a change from coarser bottom deposits into finer-grained sub-bottom deposits that appear to dominate the sub-surface of sub-reach E3 and the southern (or northern) extent of sub-reach E4 (Figures 54, 56, and 57a).

III. Sub-Reach E2

Sub-reach E2 is the northernmost sub-reach to contribute dredged sediments to the proposed Kelly Island CDF. The dredging prism for sub-reach E2 incorporates the top of thirteen of the fourteen cores, with depths of inclusion of: 1.2 ft of core DRV-70, 0.1 ft of core DRV-68-R2, 3.8 ft of core DRV-64, 1.8 ft of core DRV-63, 0.5 ft of core DRV-62, 2.6 ft of core DRV-61, 0.1 ft of core DRV-88, 3.8 ft of core DRV-60, 1.0 ft of core DRV-87, 1.8 ft of



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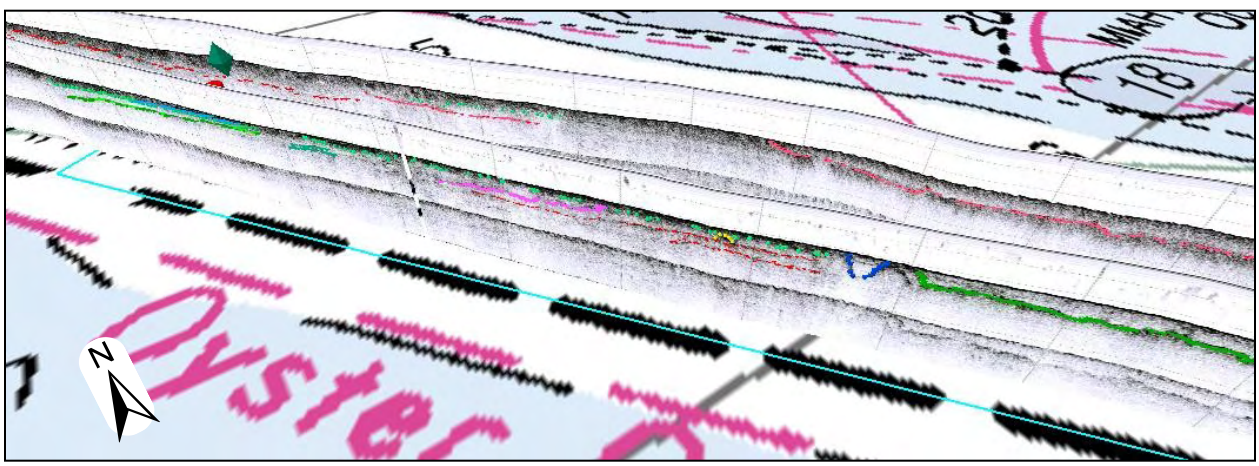


b)

Figure 53. a) Vertical curtains of chirp sub-bottom profiles for the southern boundary of sub-reach E4 (cores contained in view at right are (red cylinders): DRV-20 (in E5) and DRV-75). b) Vertical curtains of chirp sub-bottom profiles for the northern boundary of sub-reach E4 (core and grab sample contained in view at far left are: DRV-74 (red cylinder) and MC052710-8 (green diamond)). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

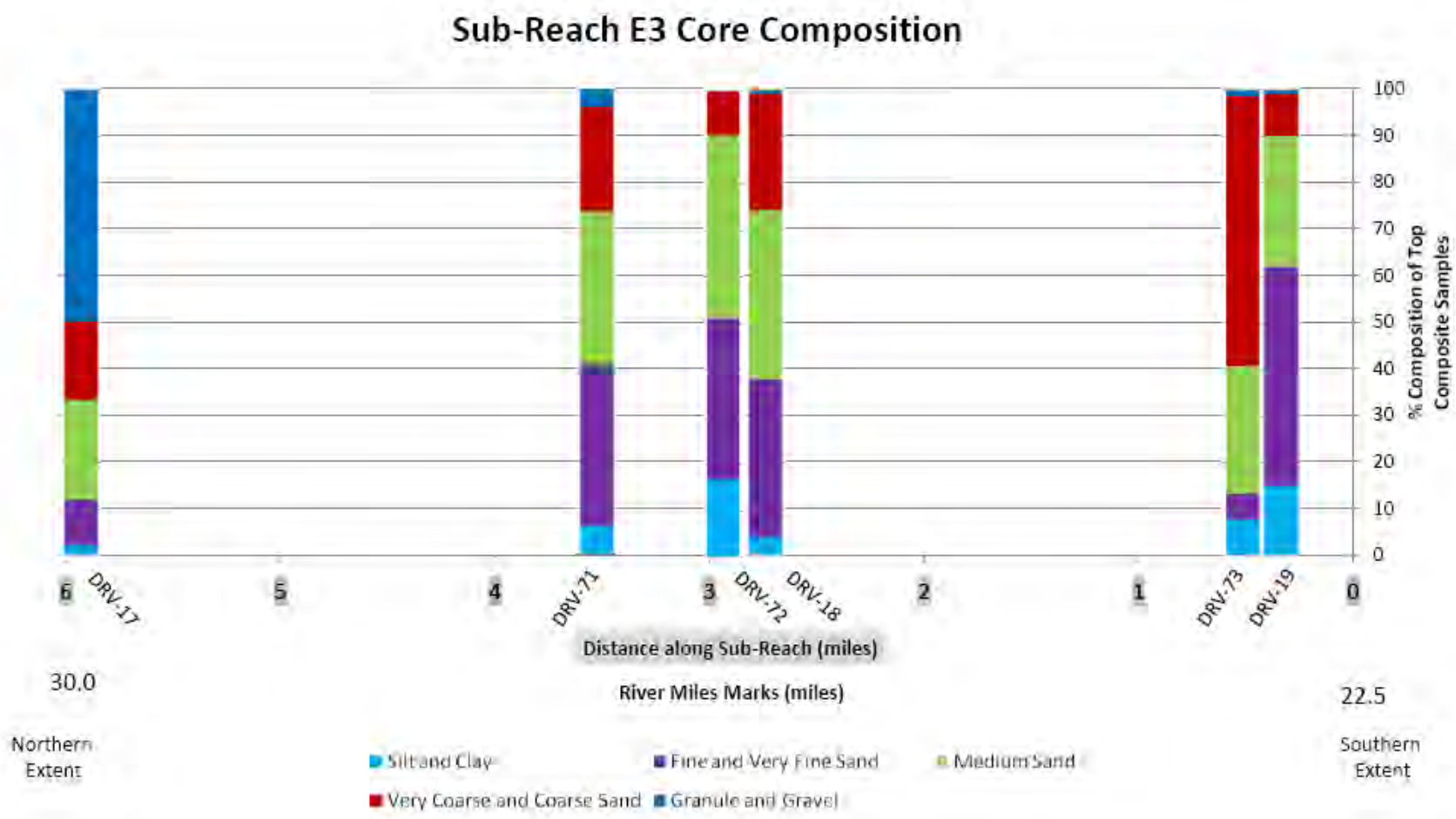
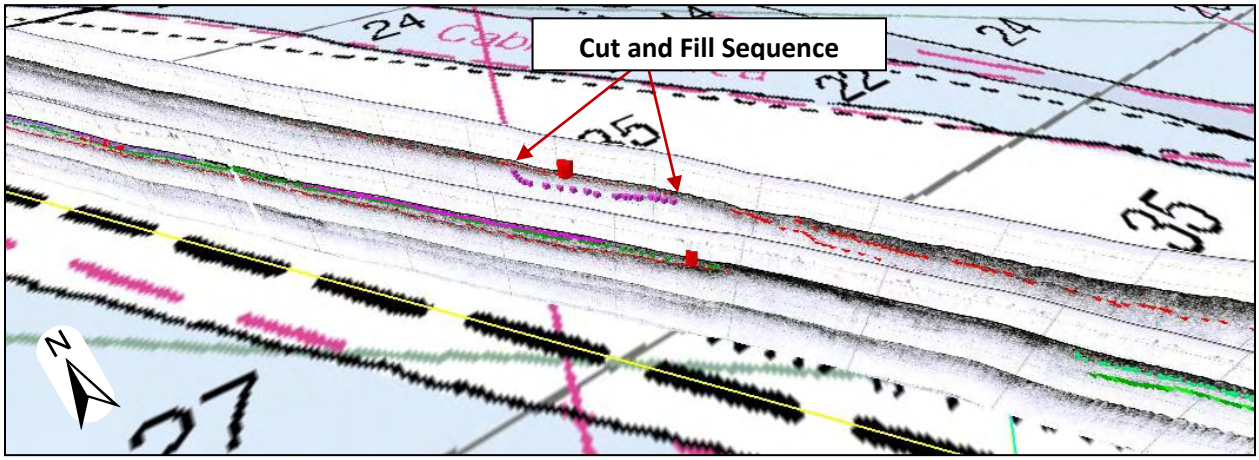


Figure 54. Graph of the top composite samples grain size composition verses the distance of cores locations along sub-reach E3.



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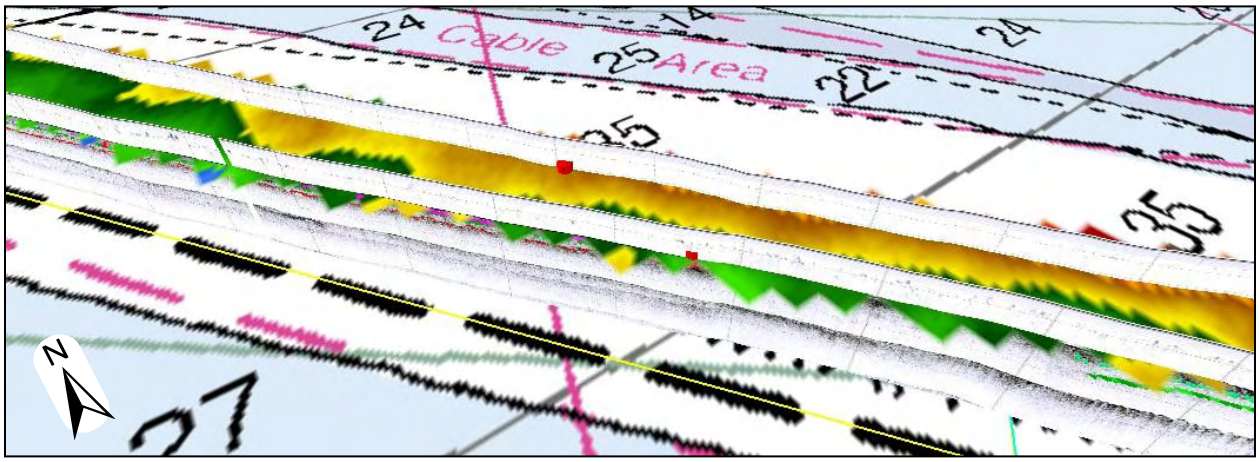


b)

Figure 55. a) Vertical curtains of chirp sub-bottom profiles for the southern boundary of sub-reach E3 (cores contained in view at center are (red cylinders): DRV-19 (right core) and DRV-73(left core)). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the southern boundary of sub-reach E3. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

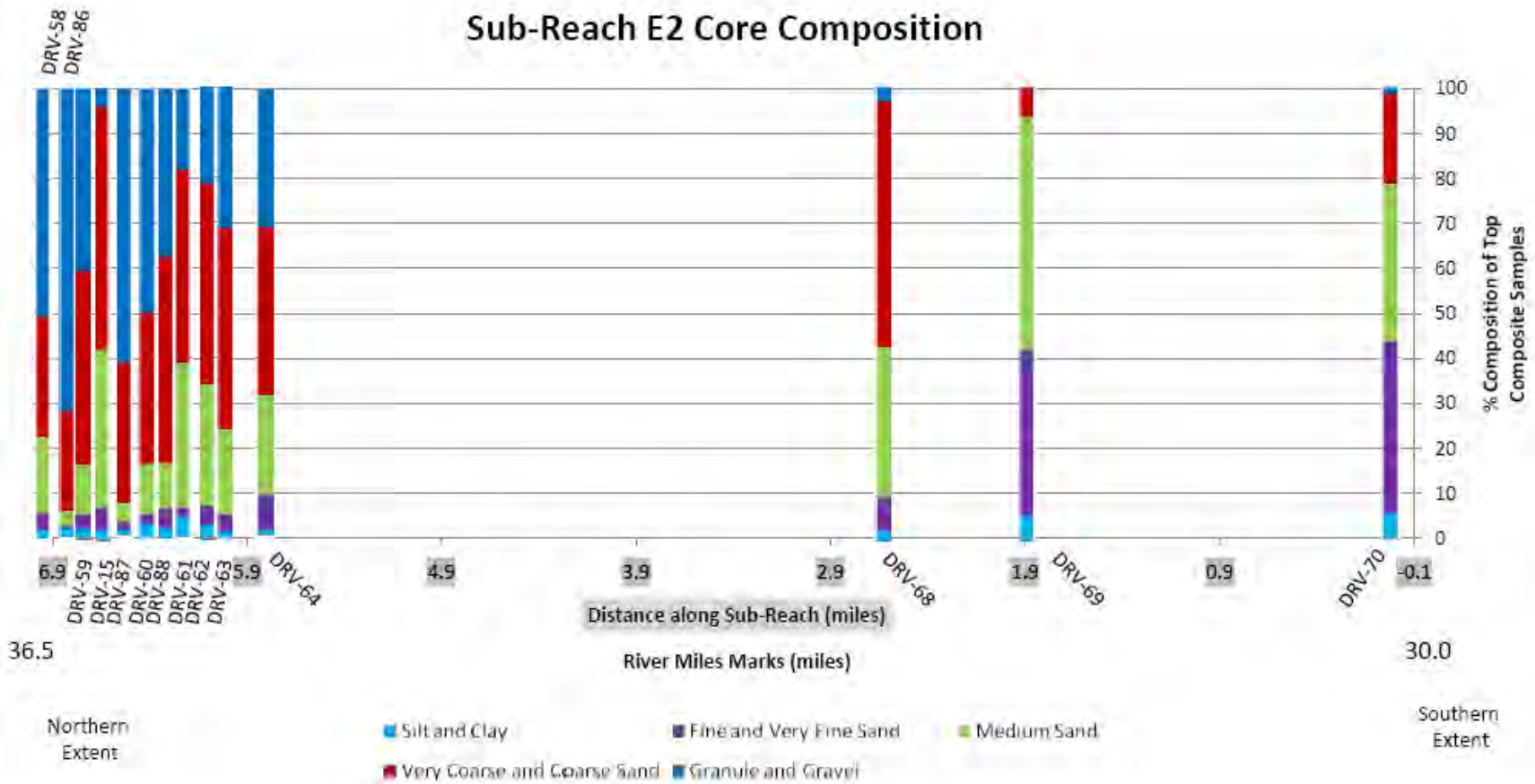
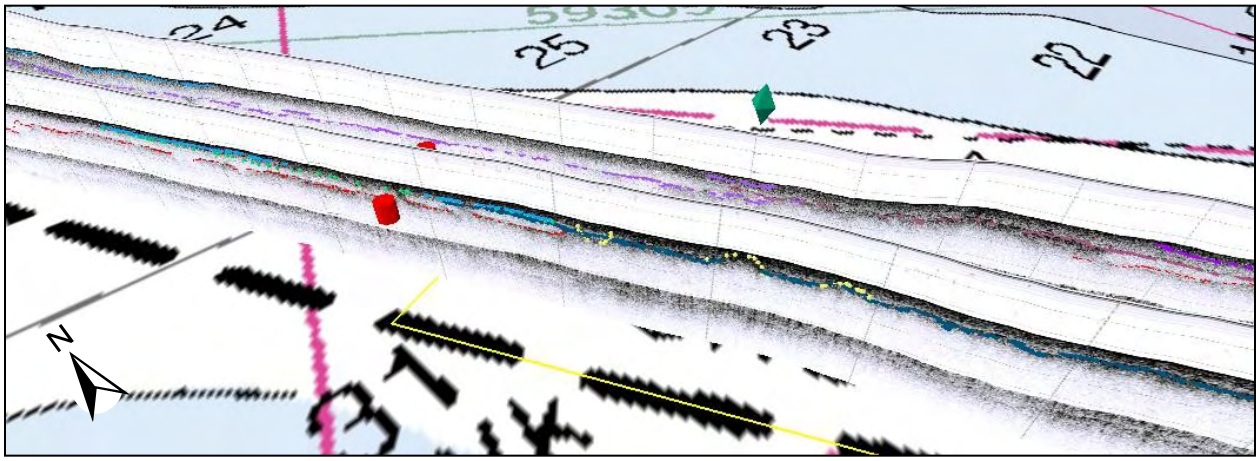
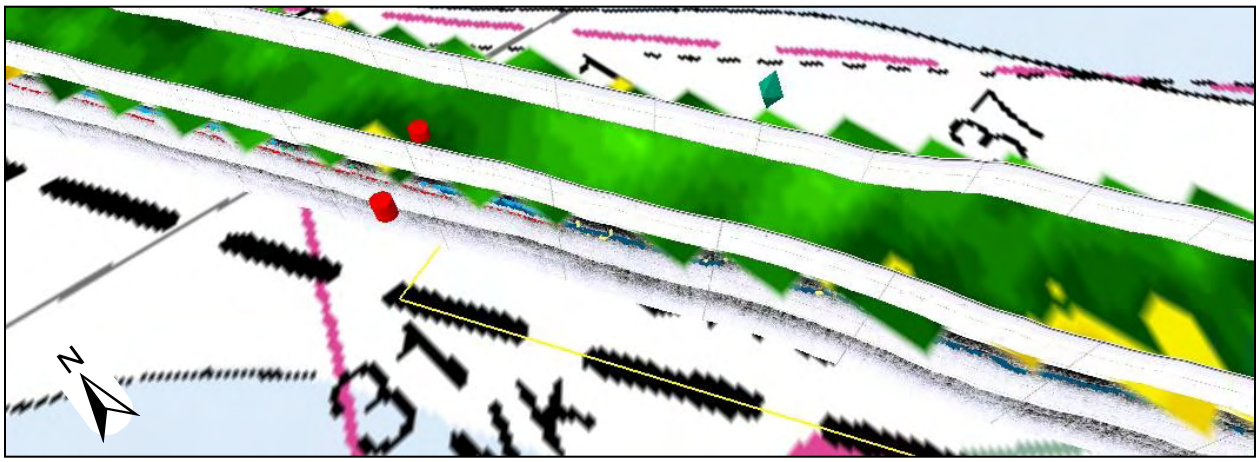


Figure 56. Graph of the top composite samples grain size composition verses the cores locations distance along sub-reach E2.



a)



b)

Figure 57. a) Vertical curtains of chirp sub-bottom profiles for the northern boundary of sub-reach E3 (cores contained in view at left center are (red cylinders): DRV-17 (lower left core) and DRV-70 (upper core in sub-reach E2)). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the northern boundary of sub-reach E3. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

core DRV-15, 1.3 ft of core DRV-59, 1.2 ft of core DRV-86 and 1.7 ft of core DRV-58 (GBA, 2010).

The coarse-grained sediments of this sub-reach are proposed to be used in the construction of the outer (seaward) portion of the containment berm. From previous work, the PD-ACOE has determined that this sub-reach contains the coarsest sediments within Reach E (Appendix D). Fourteen vibracores have been collected (in 1991, 1999, 2001, and 2004) in sub-reach E2, and this data was integrated with the 39 km (21.1 nm) of Roxann and chirp tracklines and three grab samples that were collected during this investigation to characterize the sub-reach (Figures 58 and 59, Appendices B and D).

The southern portion of sub-reach E2 appears to be a continuation of the sediment grain size trends, as characterized by cores DRV-18, DRV-72 and DRV-71, that extend from the central section of sub-reach E3 from near the Elbow of Crossledge feature (Figures 54 and 56). This fine to medium sand dominated deposit continues through E2, as shown by the composite sample from core DRV-69 (S1 2.5 ft–5.0 ft) that is located approximately 3.5 km (1.87 nm) to the north of DRV-70. The sample is 51.3% medium sand and 36.27% fine sand and very fine sand with 0.09% granules and gravel, 6.49% coarse and very coarse sand and 5.89% silts and clays (Figure 56, Appendix B). The upper 2.5 ft of DRV-69 was not sampled for its grain size distribution and its core log description is “sand with silt: poorly graded, silt, with trace fine sand and fine gravel; and sand with silt: poorly graded fine to coarse sand with gravel” (Appendix B).

Based on the Roxann sediment classification map, the bottom sediments along the southern portion of the sub-reach are slightly finer-grained sandy silts and fine sands than the sediments sampled in the composite cores. The Roxann data shows a change to coarser sediments approximately 1.6 km (0.89 nm) from the boundary with E3 (Figures 59 and 60). The chirp sub-bottom data in the lower portion of the E2 sub-reach show a continuation of near-bottom and deeper planar to irregular reflections that were seen in the central to northern portions of sub-reach E3 (Figures 61 and 62). To the north, less of these reflections are observed when the coarser bottom sediments start to occur (Figures 61-65).

In place of the near-bottom and deeper planar features, the chirp data, in association with the coarser-grained bottom sediments, is characterized by a high-amplitude bottom reflection. This high-amplitude reflection is indicative of acoustic energy being reflected at the bottom boundary with the coarse-grained sediments, and/or the void spaces within the near-bottom sediments being filled with naturally-occurring gases. Cores DRV-69 and DRV-68 were collected in this area and indicate that the bottom sediments are dominated by silty fine to medium sand to coarse sand with varying amounts of pebbles and/or shell, with several large distinct sandy pebble to gravel deposits (Figures 59 and 60).

The coarse sediment cover continues to the north of cores DRV-69 and DRV-68, extending beyond the northern portion of the E2 sub-reach and through sub-reach E1 (Figure 59). The top composite samples of all but one (DRV-58) of the remaining twelve cores confirms this sediment distribution with cores DRV-68 thru DRV-58 being dominated by coarse to very coarse sands and granules and gravel (Figure 56, Appendix B). For example, the top composite sample of DRV-68 (S-1 0.0 -4.5 ft) that is located 1.4 km (0.75 nm) northwest of DRV-69 is 3.22% granules and gravel, 54.24% coarse and very coarse sand, 33.03% medium sand, 7.16% fine sand and very fine sand and 2.45% silts and clays (Figure 56, Appendix B).

As within sub-reach E5, there is some question as to the overall thickness of the coarse-grained bottom sediments. The core log description of DRV-68 is “sand: poorly graded, fine to medium sand, wet, loose sub-angular to sub-rounded grains, dark yellow brown” (Appendix B). This suggests that the coarse-grained sediments occurring on the bottom do not extend very far into the sub-bottom. The coarse bottom sediment thickness may also vary laterally across the channel. This variability is not documented in sufficient detail by the existing Reach E core logs (Appendix B). The possible variability significantly impacts estimates of the amount of coarser-grained sediments (coarse sands to gravels) that could potentially be dredged and hence the total volume of coarse sediments that could be available for construction of a berm. A more detailed assessment, through additional coring and bottom grab sampling is needed to determine the lateral thickness and extent of the coarser-grained bottom sediment

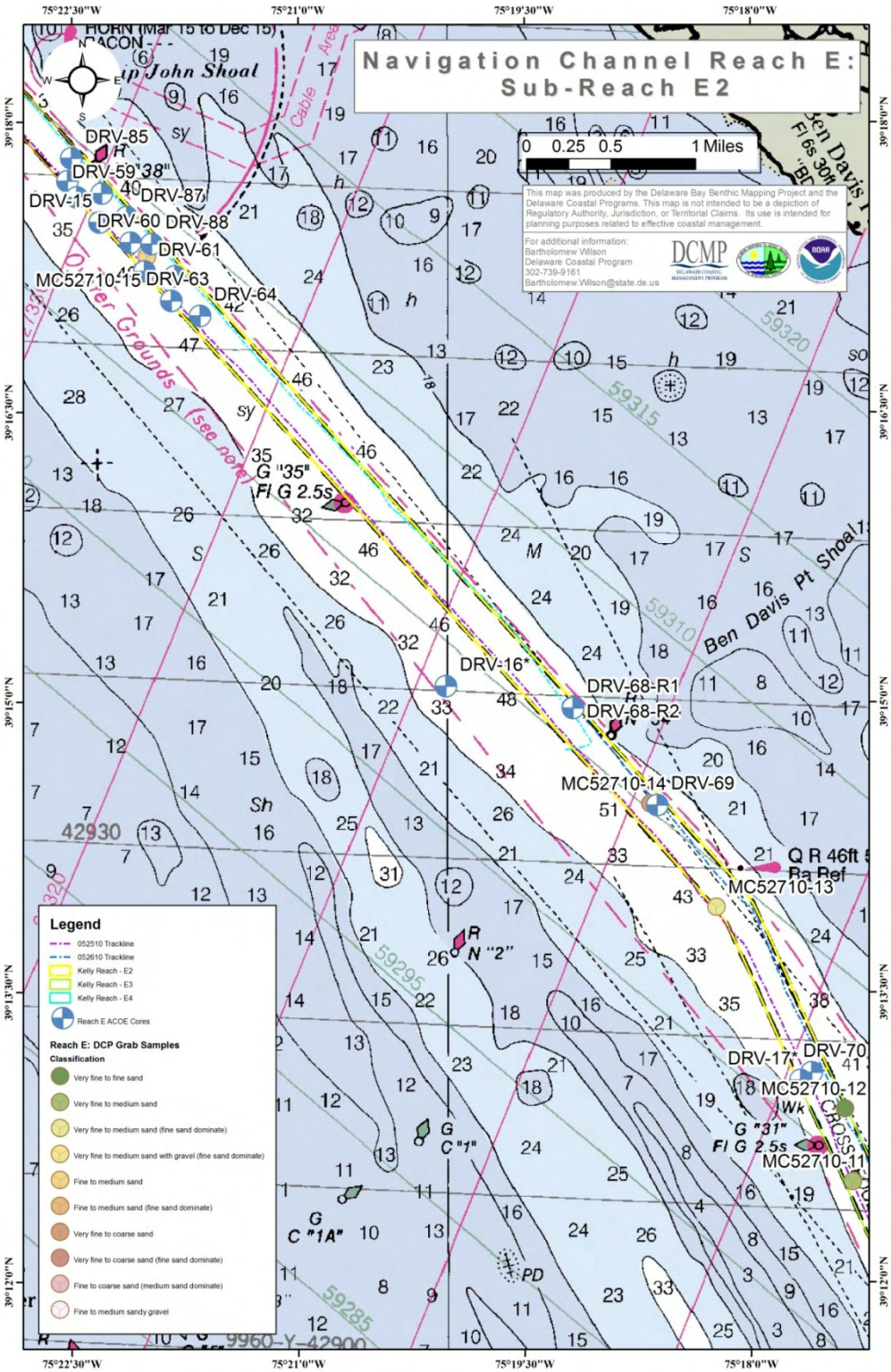


Figure 58. Map of tracklines, grab samples, and core locations within sub-reach E2.

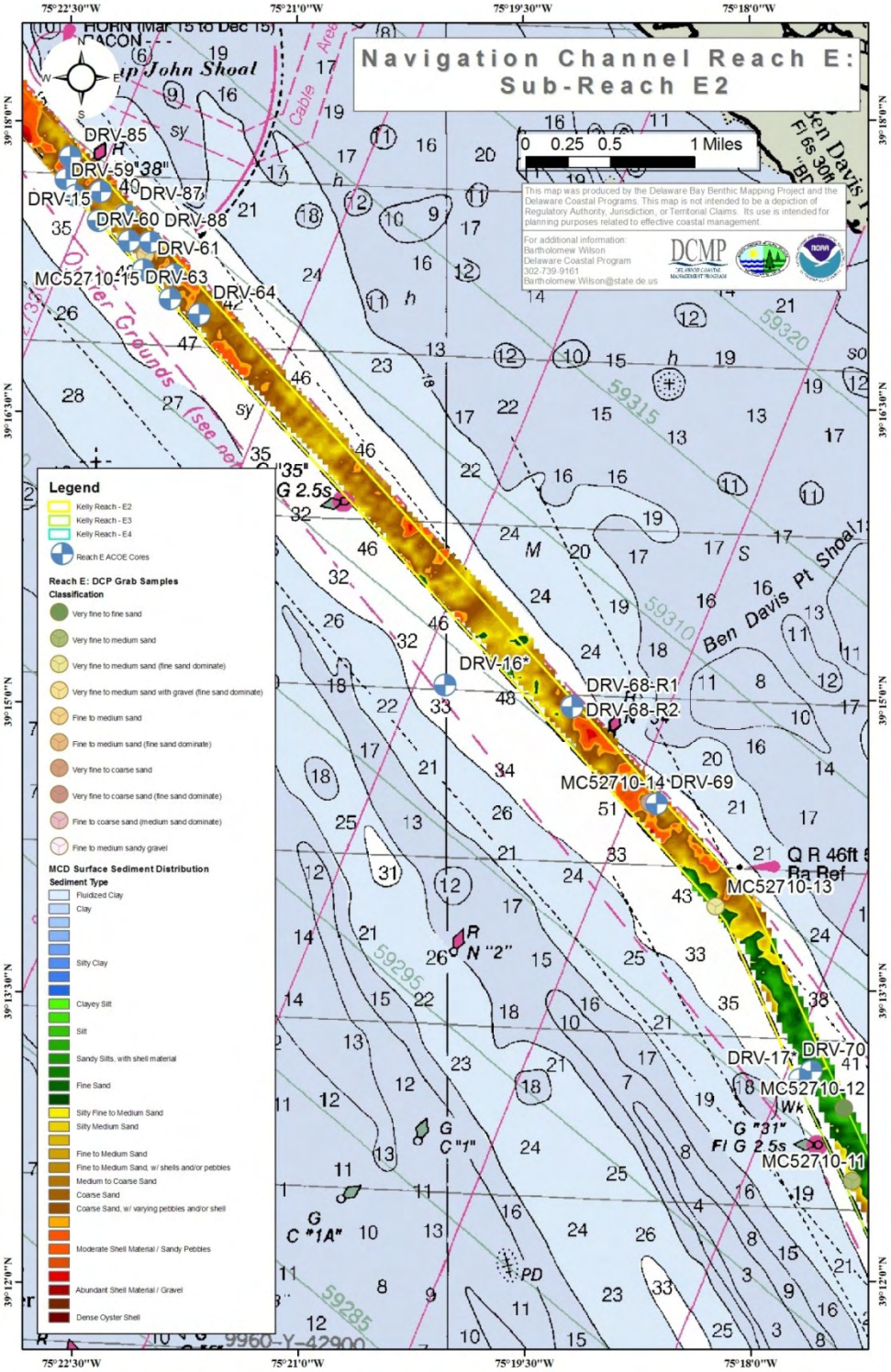


Figure 59. Roxann seabed classification map within sub-reach E2.

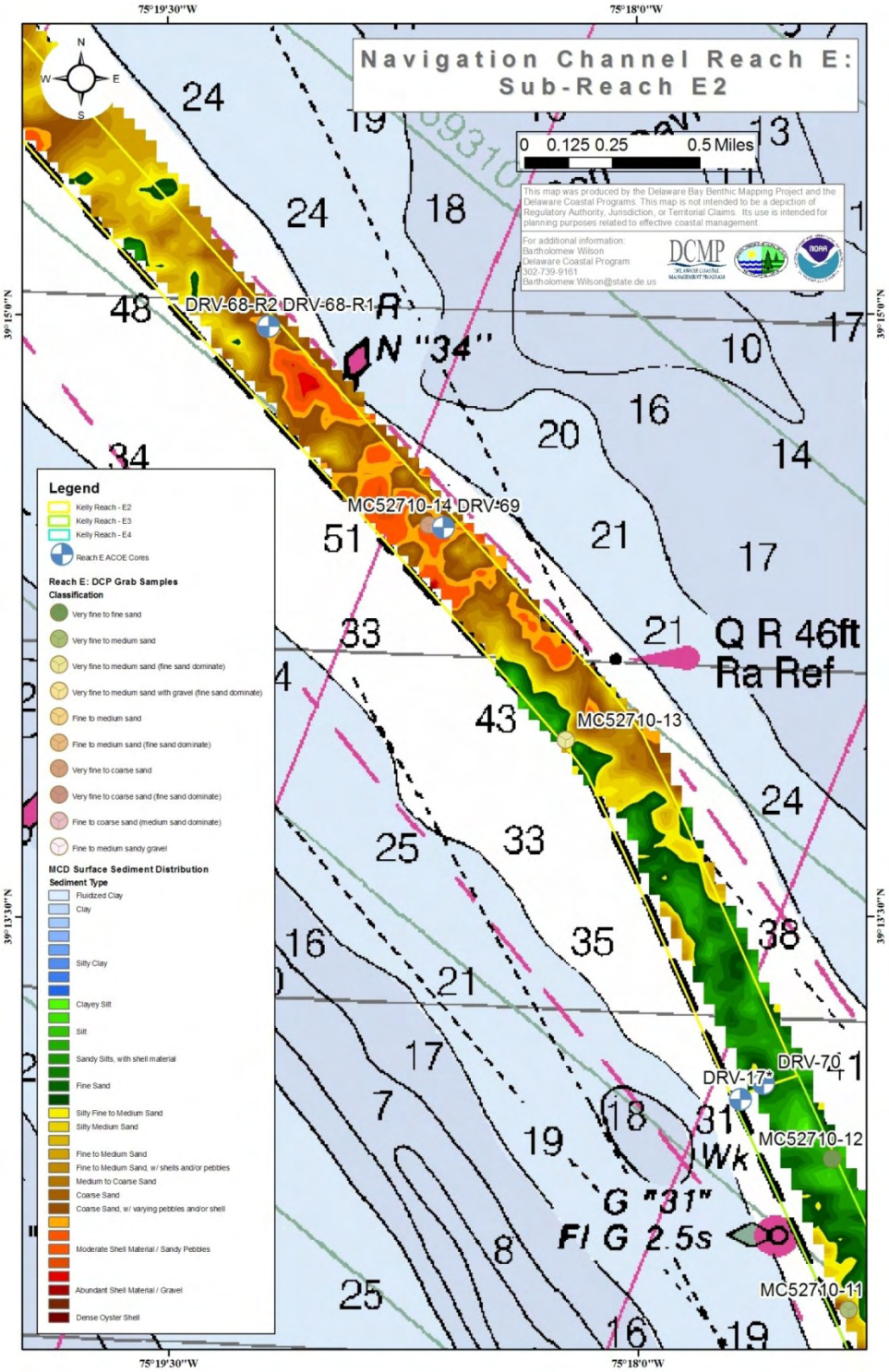


Figure 60. Roxann seabed classification map within the southern extent of sub-reach E2.

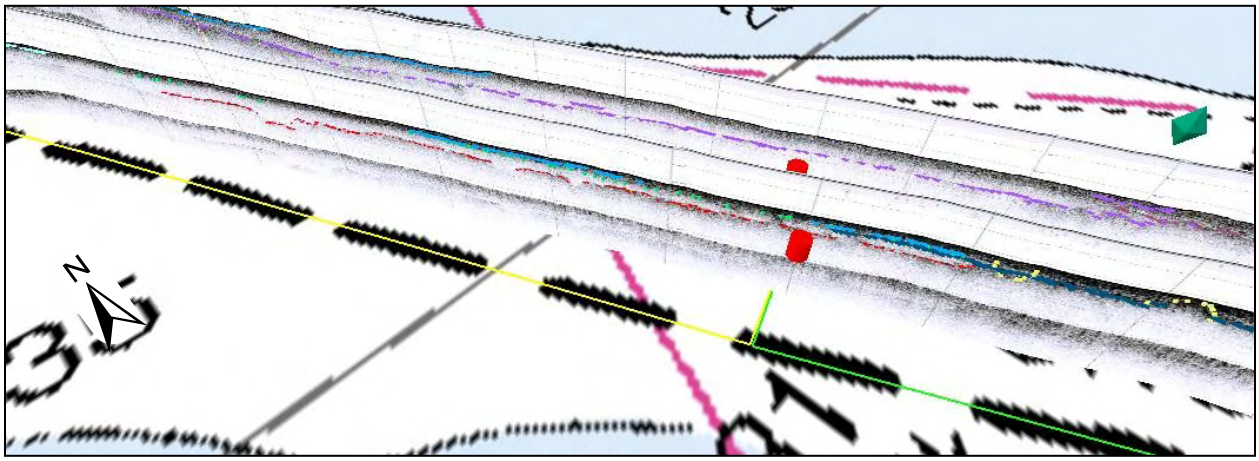


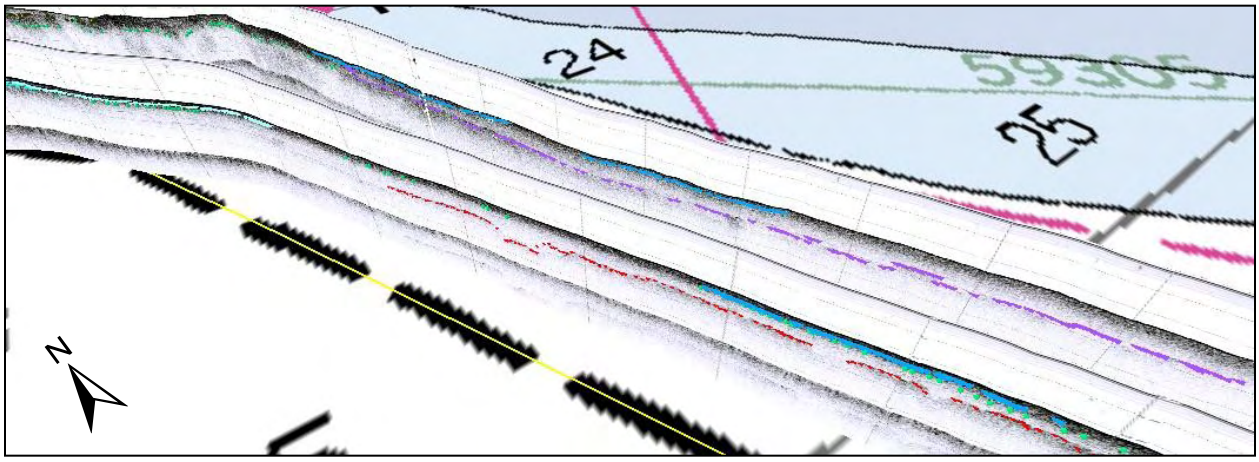
Figure 61. Vertical curtains of chirp sub-bottom profiles for the southern boundary of sub-reach E2 and northern boundary of sub-reach E3 (cores contained in view at right center are (red cylinders): DRV-17 (lower right core in sub-reach E3) and DRV-70 (upper core in sub-reach E2)). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

cover. This will enable a more representative evaluation to be made of the grain size distributions for the sub-reach E2 sediments.

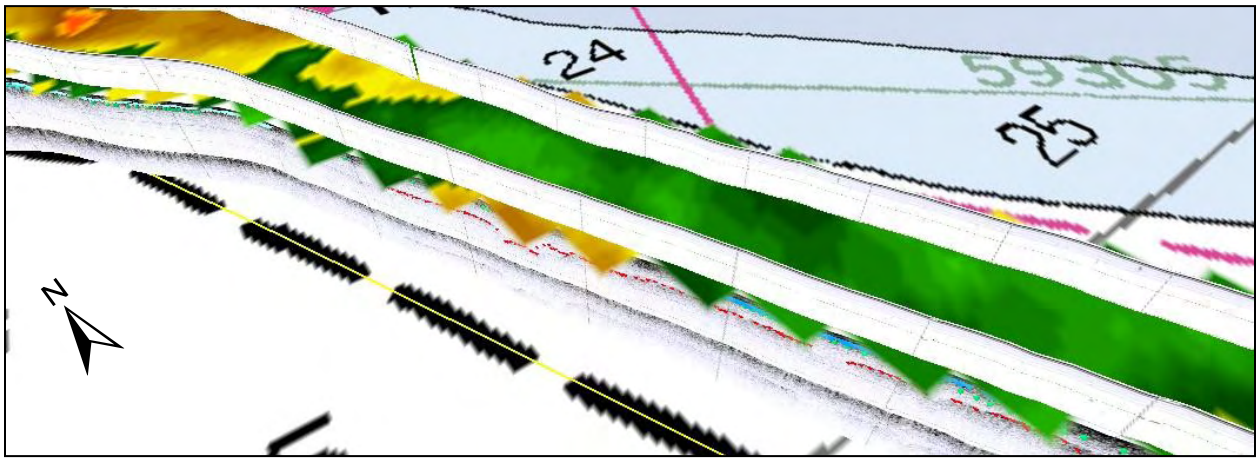
To the north of DRV-68, there is a 5.9 km (3 .18 nm) sampling gap in cores until DRV-64 (Figure 59). As shown by the Roxann map, the interval between these cores is dominated by coarse sediment cover, similar to that seen in the vicinity of cores DRV-69 and DRV-68. However, there are noticeably fewer patches of sandy pebbles to gravels (Figure 59). The chirp sub-bottom data for this interval, changes from a high amplitude bottom reflection, with little acoustic energy penetration into the sub-bottom, to a lower amplitude, yet still strong, bottom reflection with numerous shallow to intermediate depth reflections (~0.5 to 5 m (1.6 to 16 ft) beneath the bottom; Figures 66 through 70). Further to the north, continuous reflections that show top lap of the bottom (i.e., occur at the bottom, trend downward into the sub-surface flatten out with depth) are observed (Figures 67 and 68).

Shown in Figures 68 and 69 by a reflection identified in purple is another toplapping feature that ranges in depth from 0.0 to 3.5 m (11.5 ft). This reflection trends to the northwest for a distance of approximately 1.0 km (0.54 nm). Near its end, it is underlain by an additional reflector (also shown in purple) that appears to represent a cut and fill sequence that can be correlated with a similar feature (as shown by the orange reflector) that is observed in the sub-bottom on the western margin of the navigation channel (Figure 69). The appearance of the cut and fill sequence on the western margin of the navigation channel marks the return of sub-bottom reflections along this side of the channel. A high amplitude bottom reflection and a deeper event (shown in green) is observed extending northward approximately 3.2 km (5.5 nm) to the end of the sub-reach (Figures 69-73).

Further to the north in the chirp sub-bottom profiles, both the eastern and western sides of the navigation channel are dominated by a high-amplitude bottom reflection with only minor features observed in the sub-bottom. With the strong bottom reflection, it is likely that most of the acoustic energy was reflected at the bottom with little penetration into the sub-surface (Figures 71-73). As discussed earlier, a high-



a)



b)

Figure 62. a) Vertical curtains of chirp sub-bottom profiles for the southern region of sub-reach E2 (north of DRV-70 and south of DRV-69). b) Vertical curtain chirp-profile with overlay of Roxann seabed classification for the southern region of sub-reach E3. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

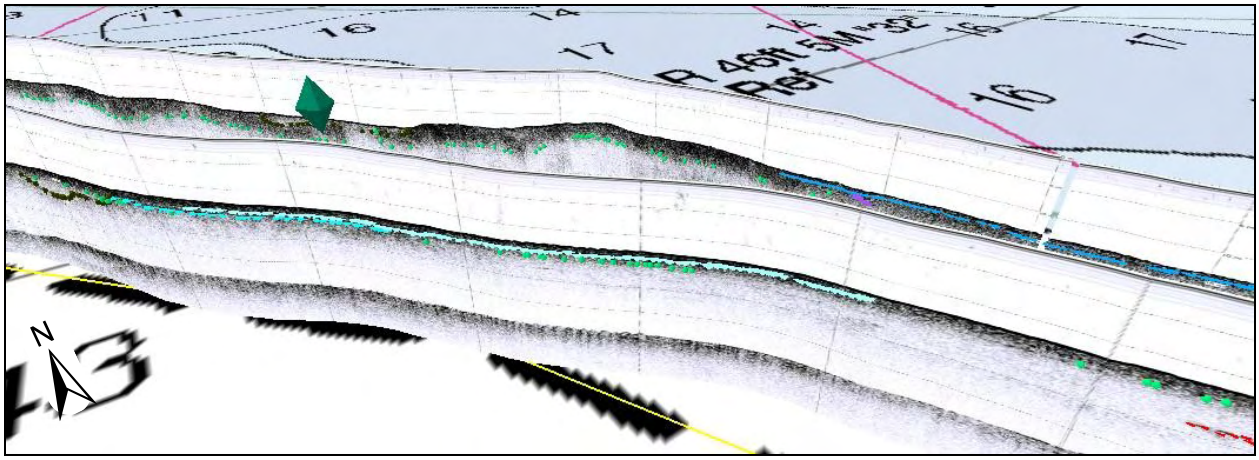


Figure 63. Vertical curtains of chirp sub-bottom profiles for the southern region of sub-reach E2 (north of DRV-70 and south of DRV-69), grab sample MC052710-13 (green diamond). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

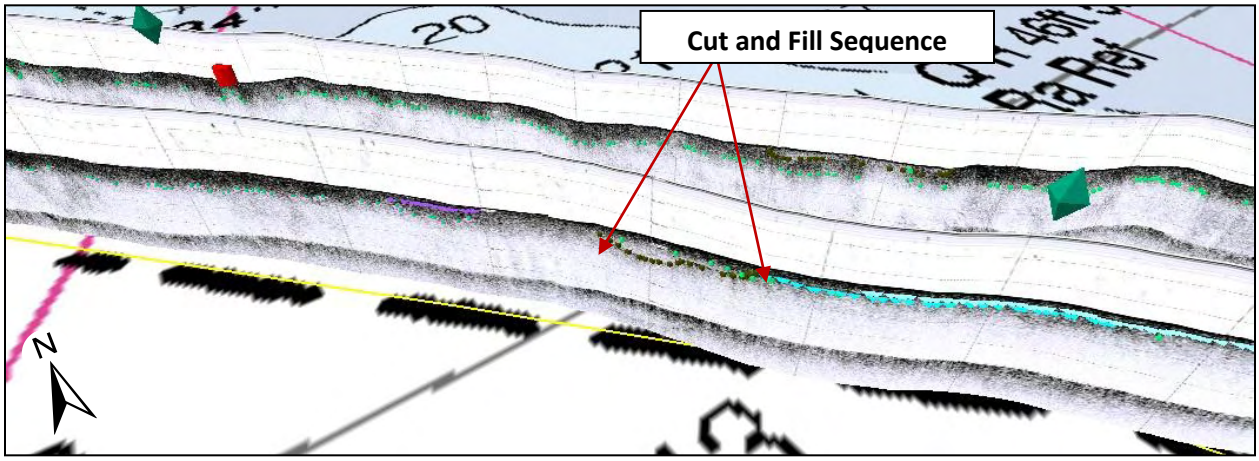


Figure 64. Vertical curtains of chirp sub-bottom profiles for the southern region of sub-reach E2 (core DRV-69 (red cylinder) shown at far left and grab sample MC052710-13 (green diamond at right) and MC052710-14 (green diamond at far left, adjacent to DRV-69)). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

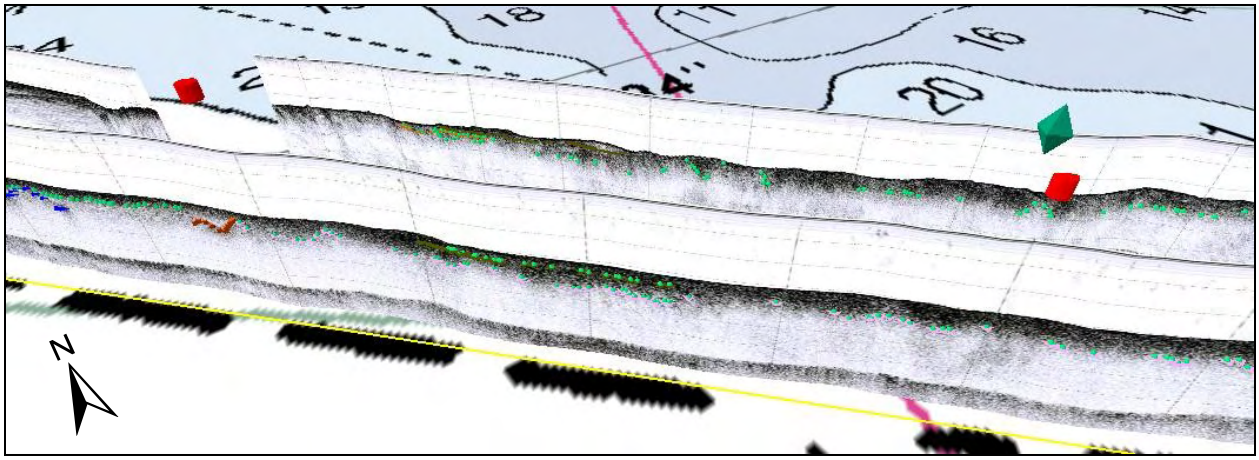


Figure 65. Vertical curtains of chirp sub-bottom profiles for the south central region of sub-reach E2 (shown are cores DRV-69 (red cylinder, at far right) and DRV-68 R2 (red cylinder, at far left) and MC052710-14 (green diamond at far right, adjacent to DRV-69)). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

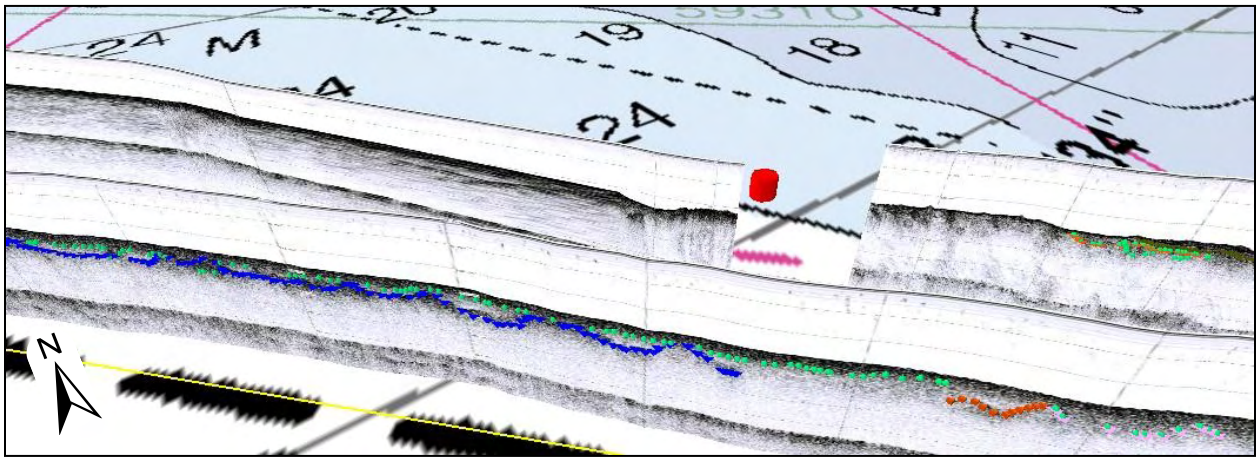


Figure 66. Vertical curtains of chirp sub-bottom profiles for the central region of sub-reach E2 (shown are core DRV-68 R2 (red cylinder, at center)). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

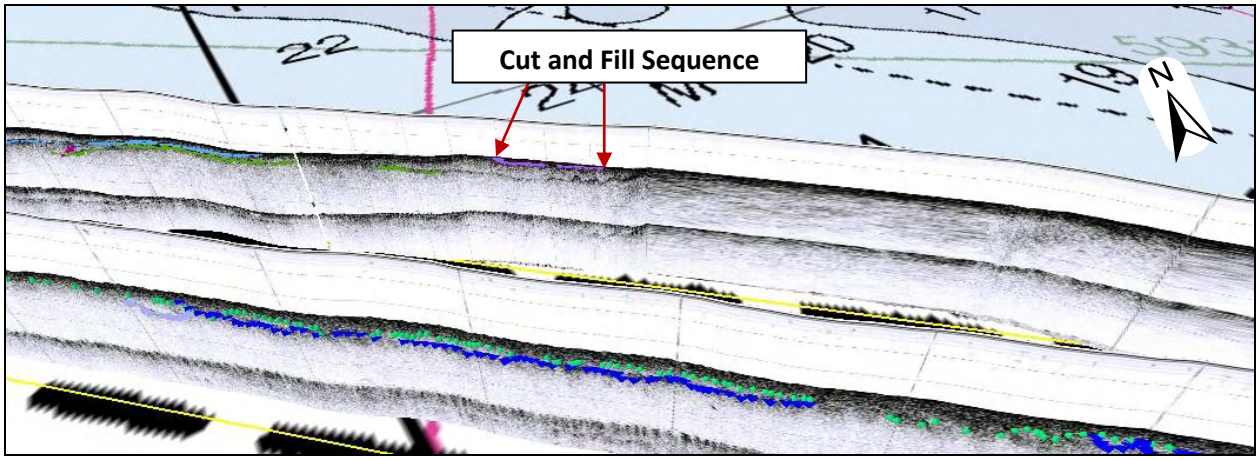


Figure 67. Vertical curtains of chirp sub-bottom profiles for the central region of sub-reach E2 (area is to the north of Figure 66). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

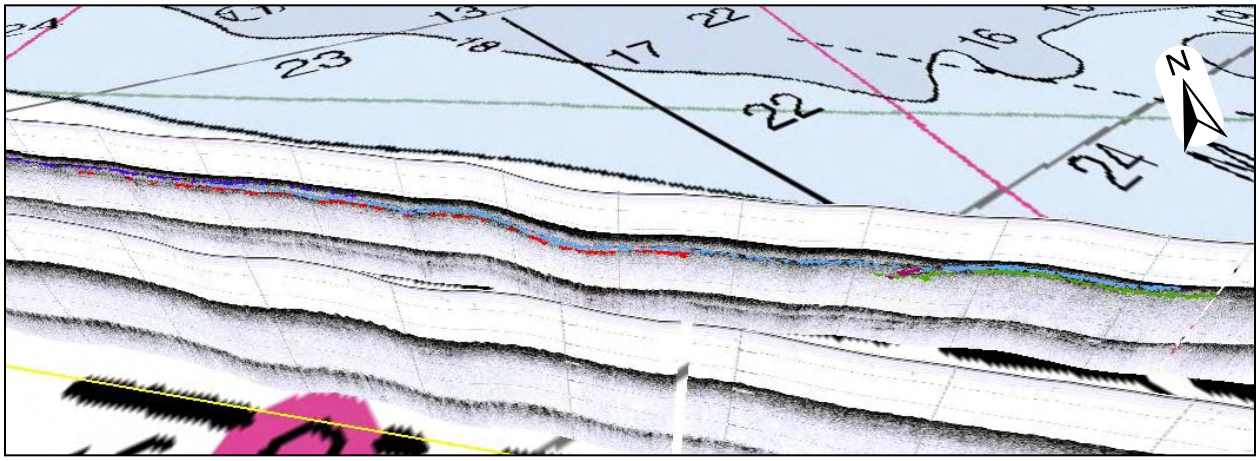


Figure 68. Vertical curtains of chirp sub-bottom profiles for the north central region of sub-reach E2 (area is to the north of Figure 67). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

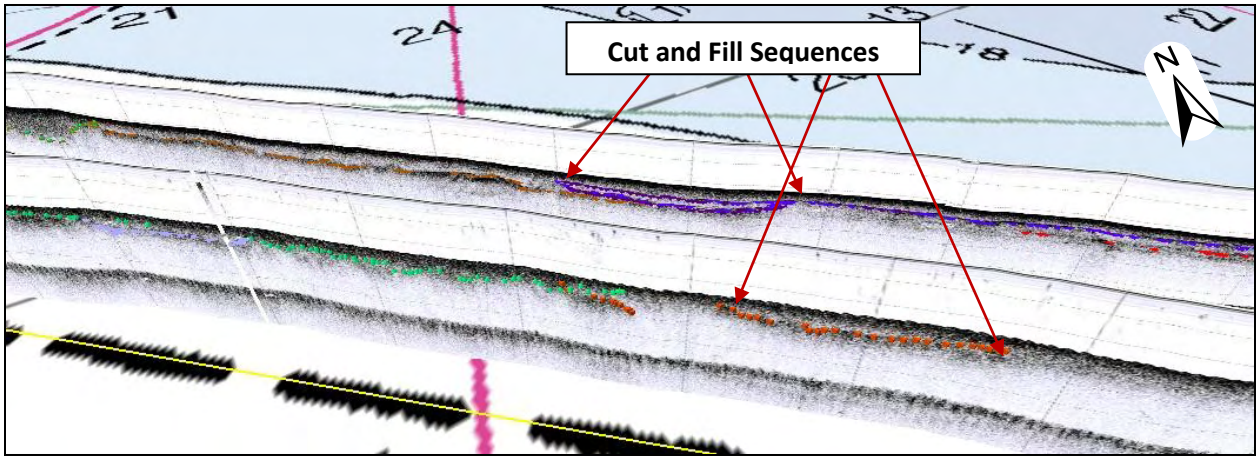


Figure 69. Vertical curtains of chirp sub-bottom profiles for the northern region of sub-reach E2 (area is to the north of Figure 68, and just south of core DRV-64). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

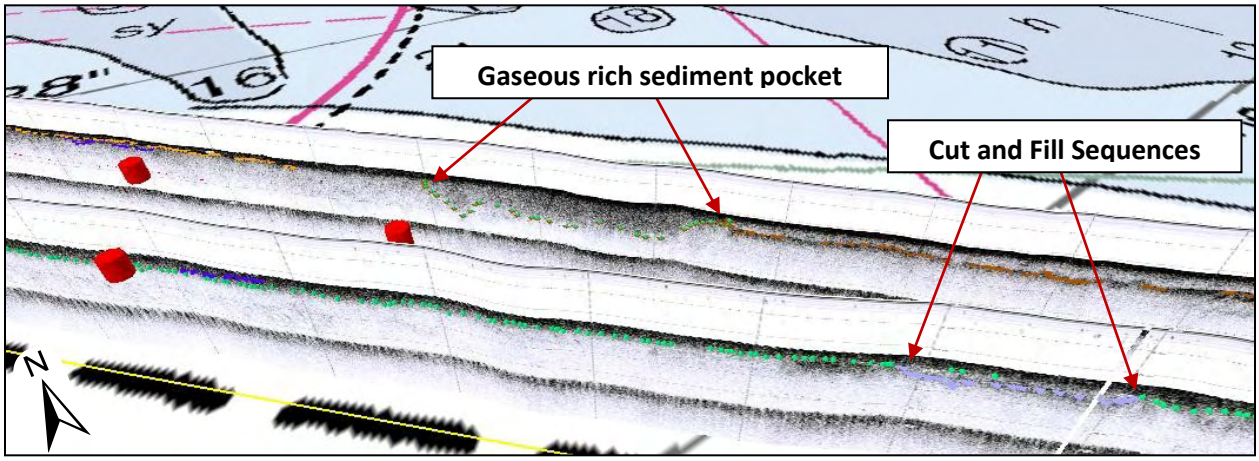


Figure 70. Vertical curtains of chirp sub-bottom profiles for the northern region of sub-reach E2 (cores shown at left are (from right to left): DRV-64, DRV-63 (lower core at left), and DRV-62 (upper core at left)). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

amplitude bottom reflection could result from the presence of gases within the pores of the sediments and/or coarse sediment grain sizes. This northern 4.3 to 5.4 km (2.3 to 2.9 nm) of sub-reach E2 has a distinctly different bottom reflection than the area to the south between cores DRV-68 and DRV-64.

It can be concluded from the chirp data, in parallel with the Roxann map, that the bottom and near bottom sub-surface sediments are distinctly different in composition between these two areas. Thus, the eleven cores collected at the northernmost end of sub-reach E2 and core DRV-68 are not good proxies to characterize the sediments of the sub-reach between DRV-68 and DRV-64. This region will need to have additional cores collected to better determine the bottom and sub-bottom sediment grain size distribution in this portion of the sub-reach (Figure 59).

The eleven cores in the northernmost extent of sub-reach E2 were collected in 1991, 1999, and 2004 (Figure 74, Appendix B). They are clustered within a length of the sub-reach of approximately 1.8 km (1 nm). All of the cores are dominated by the gravel and granule and coarse sand to very coarse sand grain size fractions (Figure 56). The southernmost of these cores, DRV-64, in its composite sediment sample (S1 0–4.8 ft) contains 30.9% granules and gravel and 37.6% coarse and very coarse sand with 22.35% medium sand, 7.95% fine sand and very fine sand and 1.2% silts and clays. As with other cores from Reach E, there is somewhat of a discrepancy between the grain size analyses results and the core log descriptions. For DRV-64, the description for the sampled interval is “brown/orange, medium sand, some fine sand, some gravel, trace coarse sand, trace silt/clay (Appendix B). Once again, it appears as if in the visual description of the composite sediment logs, the abundance of the larger-sized grains is underestimated.

The discrepancy continues for the cores in this portion of the sub-reach. The composite sample (S1 0-4.5 ft) for core DRV-63 has 31.2% granules and gravel, 44.8% coarse and very coarse sand with 18.8% medium sand, 4.1% fine sand and very fine sand and 1.1% silts and clays with a core log description of “orange/tan medium sand, some gravel, some fine sand, trace coarse sand, trace silt/clay”(Figure 56; Appendix B). The composite samples of seven of the nine remaining cores within sub-reach E2

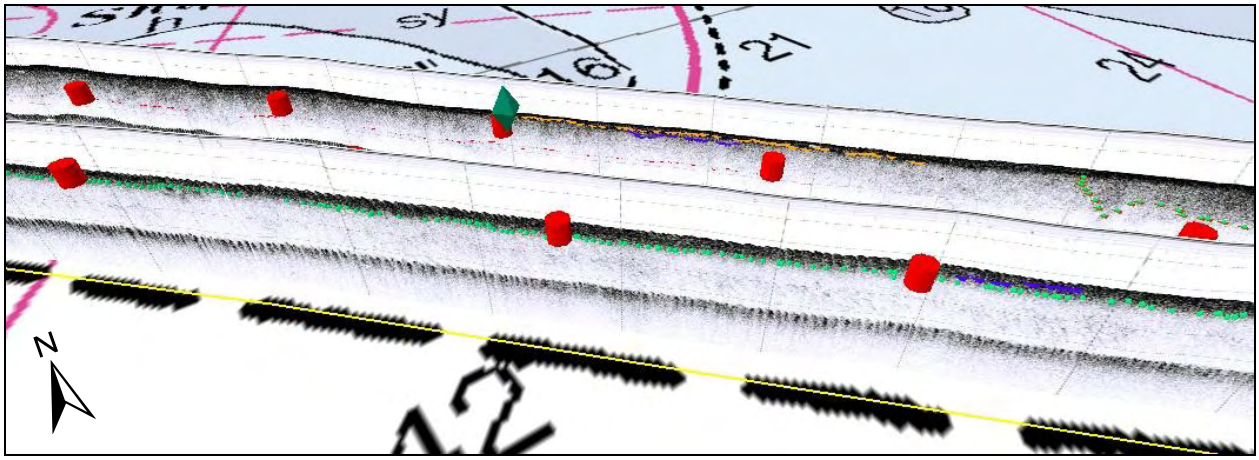


Figure 71. Vertical curtains of chirp sub-bottom profiles for the northern region of sub-reach E2 (cores shown at left are (from right to left): DRV-64 (far right) , DRV-63 (lower core at right), DRV-62 (upper core at right center), DRV-61 (lower core at center), DRV-88 (upper core at center), DRV-60 (to the lower left of DRV-88, but obscured by lower vertical curtain), DRV-87 (upper core at left center), DRV-15 (lower core at far left), and DRV-59 (upper core at far left). Also shown is grab sample MC052710-15 (green diamond at center), adjacent to DRV-88. The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

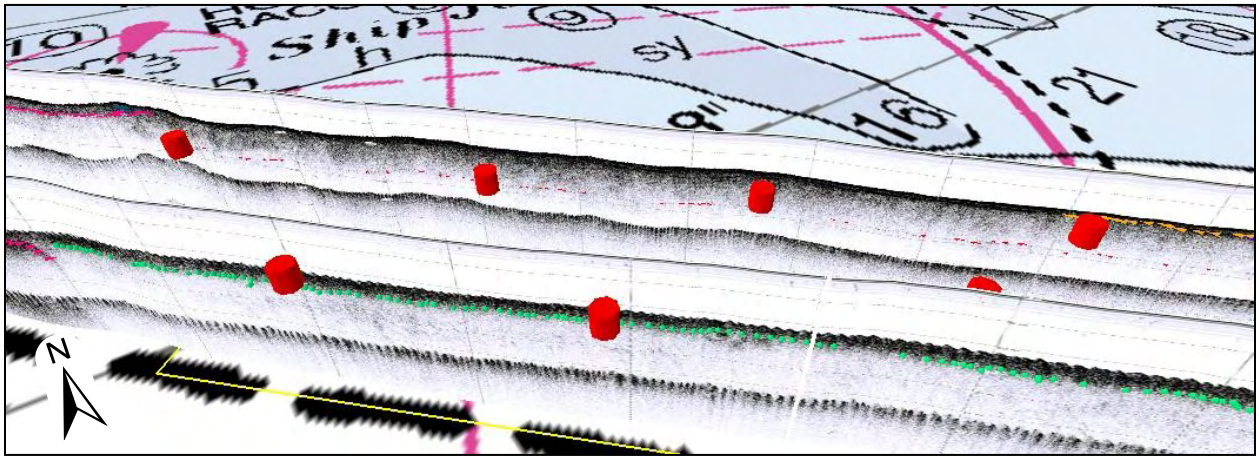


Figure 72. Vertical curtains of chirp sub-bottom profiles for the northern region of sub-reach E2 (cores shown at left are (from right to left): DRV-88 (upper core at right), DRV-60 (to the lower left of DRV-88), DRV-87 (upper core at right center), DRV-15 (lower core at center), DRV-59 (upper core at left center), DRV-86 (lower core at left), DRV-58 (to the left of DRV-86, but obscured by lower vertical curtain), and DRV-85 (top core to left, in sub-reach E1). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

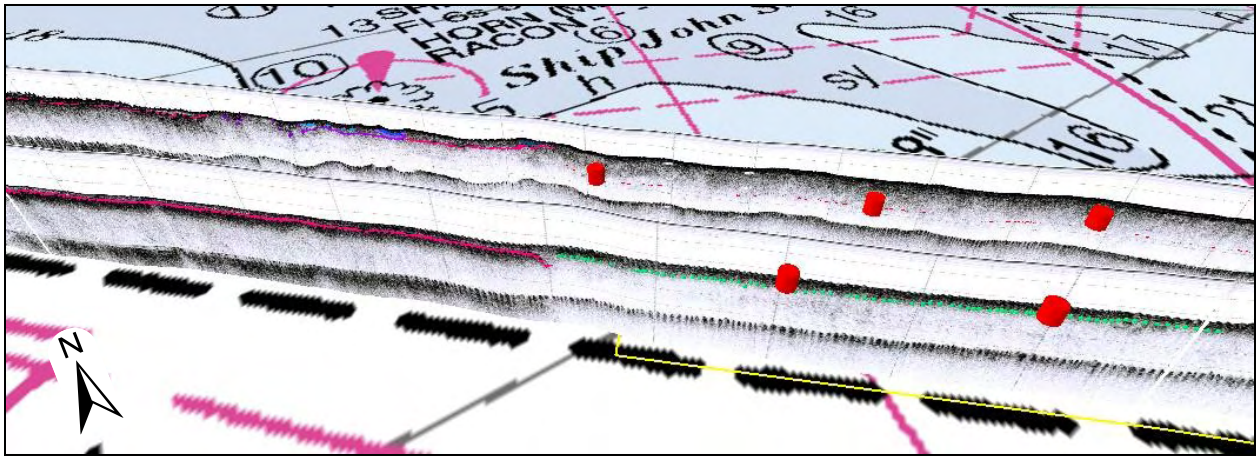


Figure 73. Vertical curtains of chirp sub-bottom profiles for the northern region of sub-reach E2 (cores shown at left are (from right to left): DRV-87 (upper core at right), DRV-15 (lower core at right), DRV-59 (upper core at right center), DRV-86 (lower core at right center), DRV-58 (to the left of DRV-86, but obscured by lower vertical curtain), and DRV-85 (top core to center, in sub-reach E1). The distances between vertical lines are ~150 m (490 ft), and horizontal lines are ~5 m (16 ft).

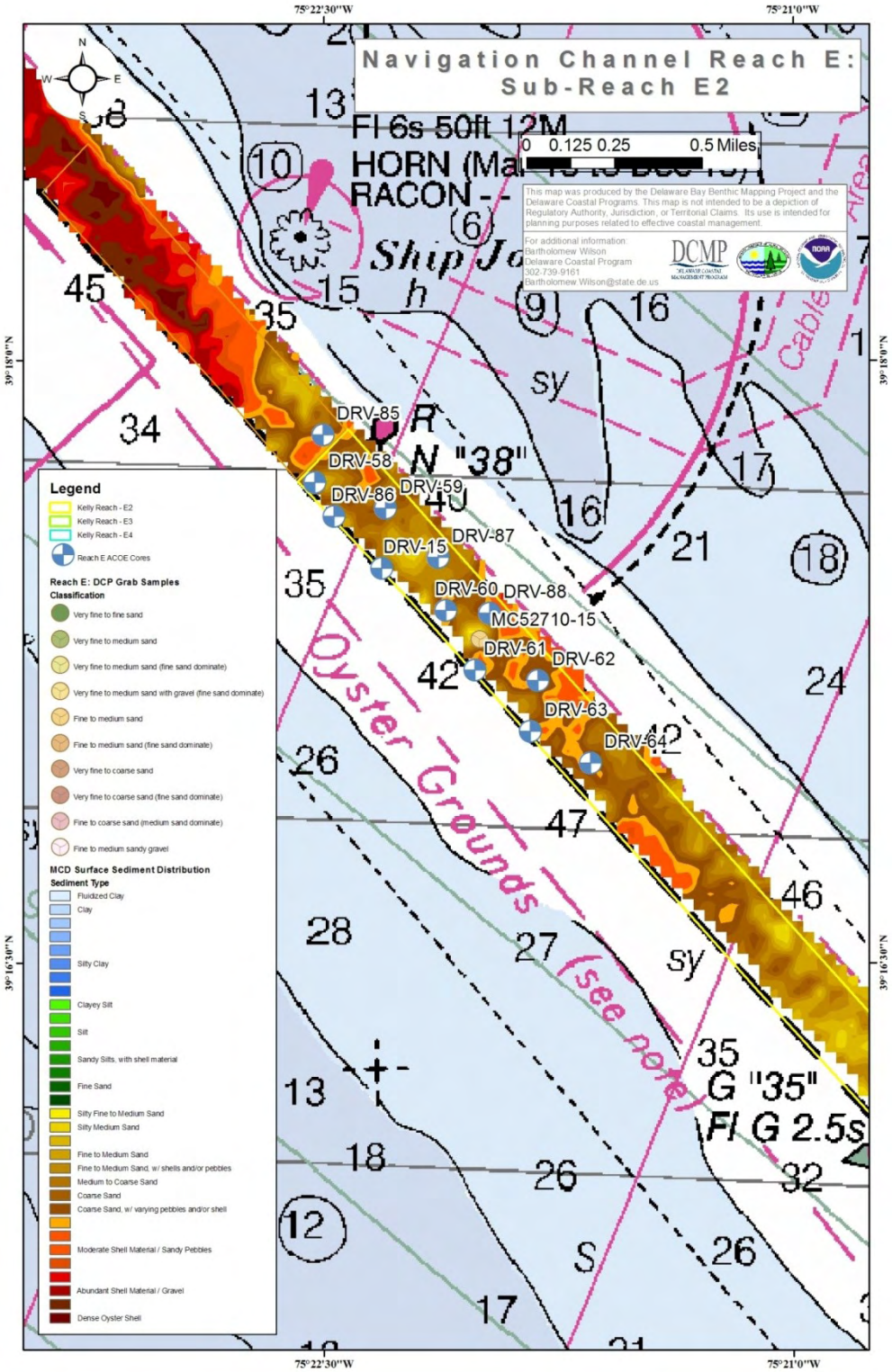


Figure 74. Roxann seabed classification map within the northern extent of sub-reach E2, and southern extent of E1.

composite samples of seven of the nine remaining cores within sub-reach E2, DRV-62, DRV-61, DRV-88, DRV-60, DRV-87, DRV-59 and DRV-58 contain the same disparities between the grain size data and the core log descriptions (Figures 56; Appendix B).

The two cores that have more closely matched composite sample grain size results and corresponding core log descriptions are cores DRV-15 and DRV-86 (Appendix B). The composite sample (0–3.4 ft) from DRV-15 has 4% granules and gravel, 54% coarse and very coarse sand with 35% medium sand, 5% fine sand and very fine sand and 2% silts and clays with a core log description of “coarse to fine sand” (Appendix B). The composite sample (S-1 0-2 ft) from DRV-86 is 71.9% granules and gravel and 22.3% coarse and very coarse sand with 3.25% medium sand, 0.75% fine sand and very fine sand and 1.8% silts and clays with a core log description of “brown, gray gravel, some medium sand, little coarse sand, trace fine sand, trace silt/clay” (Appendix B).

These eleven cores (from DRV-64 to DRV-58) correlate with the Roxann bottom sediment map in indicating that this 2.1 km (1.1 nm) interval of sub-reach E2 is dominated by a surficial gravel deposit that varies laterally and vertically in its percent grain-size composition and thickness (Figure 56). As described earlier for sub-reach E5 and an interval of sub-reach E-2 to the south, this variation makes it difficult to accurately determine the total volume of gravels to coarse sand that would be removed by dredging. Descriptions from the core logs, integrated with the reflection events from the chirp sub-bottom profiles, suggest that the underlying sub-surface sediments are considerably finer grained, and until the bottom coarser-grained sediment cover can be better quantified in its lateral and vertical extent the total composition of sub-reach E2 cannot be accurately determined. Hence, the availability of this material to be used in the CDF construction cannot be fully quantified with a high-level of confidence.

IV. Discussion

The purpose of this study is to assess the grain size distribution of sediments in Reach E that are proposed to be removed through the Main Channel Deepening Project of the Delaware River and Bay. It is the assertion of the PD-ACOE that the dredged sediments from Reach E can be used as a beneficial resource by the State of Delaware. This data review and acoustic investigation was implemented to validate the results presented by the PD-ACOE for the State of Delaware Wetlands and Subaqueous Lands Permit as to the suitability of the sediments for coastal construction and beach restoration.

There are seven sub-reaches within Reach E. Sub-reaches E6 and E7 of the lower Main Channel Deepening Project extend from the southern portion of the proposed maintenance region, starting at approximate channel station 512+000, northward to channel station 461+000. The sediment dredged from this reach (~ 1.6 mcy) are proposed to be used as fill for the Broadkill Beach nourishment. This project has been authorized to reduce coastal and storm damage along the community of Broadkill Beach and provide horseshoe crab spawning habitat (EA, 2009). According to the 2009 Environmental Assessment (EA) and Appendix H of the State of Delaware Permit, the Broadkill Beach plan consists of a 100-foot wide berm at an elevation of +8 ft NGVD.

The selected plan has the following components (EA, 2009):

- A berm extending seaward 100 ft from the design line. The beachfill extends from Alaska Avenue southward for 13,100 linear ft. Tapers of 1,000 ft extending from the northern project limit and 500 ft extending from the southern project limit brings the total project length to 14,600 linear ft.
- On top of the berm lies a dune with a top elevation of +16 ft NGVD and a top width of 25 ft. The berm face is to be constructed at a slope of 15:1, which extends from the foot of the dune to below the mean low water mark (-1.5 ft NGVD 29; Figure 75).

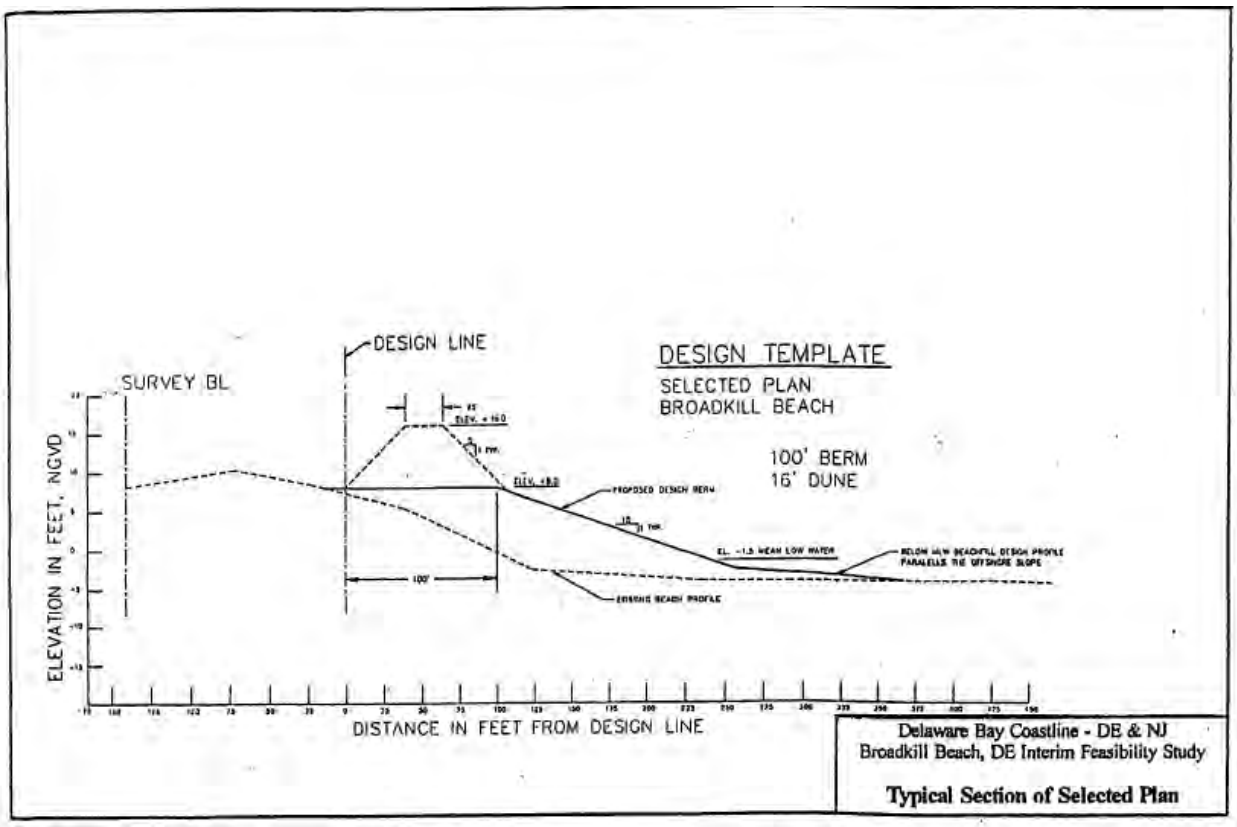


Figure 75. Generalized cross-section of the proposed Broadkill Beach nourishment project (EA, 2009).

A reference grain size distribution was needed to assess what impact the nourishment would have on the existing and post-nourishment grain size distribution of Broadkill Beach. The current grain size composition of the beach face at Broadkill Beach, as expected, was determined to be highly dependent upon the vertical position along the foreshore and backshore. Surface sediment samples were collected on August 9th, 2010 by Delaware Coastal Program personnel from four transects perpendicular to the beach face, with three samples (low-beach, mid-beach, and high-beach) in each transect. These samples were used to determine a baseline summer condition for mean grain size of the beach (Figure 76).

The low-beach samples were collected on the low tide terrace, above the mean low water level, in the surf zone (i.e., region of beach where the breaking of waves occurs). The mid-beach samples were collected on the beach face, approximately just below mean high water level, in the swash zone (i.e., region of up-rush and backwash onshore after an incoming wave has broken). The high-beach samples were collected along the backshore (i.e., area of beach extending from the limit of high water foam lines to dunes, affected by waves only during severe storms) on the berm to the water side of the toe of the dune.

The low-beach samples (BK1 L thru BK4 L) are predominately coarse in nature with mean grain size fractions of 38.28% gravel and 46.28% very coarse sand and coarse sand with 6.83% medium sand, 8.68% fine and very fine sand and 0% silt and clays (Appendix E). The mid-beach samples (BK1 M thru BK4 M) contained a mean grain size fraction of 1.8% gravel, 15.53% very coarse sand and coarse sand, 30.28% medium sand, 52.38% fine and very fine sand and 0% silt and clays (Appendix E). The high-beach samples (BK1 H thru BK4 H) have a mean grain size fraction of 0.55% gravel, 2.0% very coarse sand and coarse sand, 26.4% medium sand, 71.05% fine and very fine sand and 0% silt and clays (Appendix E).

The grain size distribution for the samples can be further aggregated into the foreshore (swash and surf zones; low- and mid-beach samples) and backshore (high-beach samples) environments. The foreshore contained a mean grain size distribution fraction of 20.04%

Figure 76. Sample sites on the beach at Broadkill Beach.

gravel, 30.9% very coarse sand and coarse sand, 18.55% medium sand, 30.53% fine and very fine sand and 0% silt and clays (Appendix E). The backshore contained a mean grain size fraction of 0.55% gravel, 2.0% very coarse sand and coarse sand, 26.4% medium sand, 71.05% fine and very fine sand and 0% silt and clays (Appendix E). As expected due to wave action, the foreshore is considerably coarser than the backshore. It is the foreshore grain size composition that would have the greatest impact on the potential resiliency of the beach to wave action and, due to their location, on the habitat of spawning horseshoe crabs.

The ASMFC Fishery Management Plan for Horseshoe Crab (1998) recommends that the grain size of the sand placed on a beach undergoing re-nourishment should be consistent with the grain sizes that already exist within the spawning habitat at that beach. Thus, the material at a “beneficial use” site should be similar in grain size to that at the beach in question. Smith et al. (2002), in a review of horseshoe crab habitat, concluded that the source of sediment for beach nourishment should be chosen to reflect a coarse-grained estuarine beach. They suggested that the material should have a gravel sub-fraction and have a mean sediment size of 0.35 to 0.50 mm in the sand fraction (Smith et al., 2002). Botton et al. (1994) noted that the grain size of beaches that had the greatest horseshoe crab spawning concentrations in Delaware Bay were from 0.6 to 0.8 mm, with a median grain size of 0.7 mm (Brady and Schrading, 1996). Penn and Brockmann (1994) found that fine-grained, poorly drained sediments impeded horseshoe crab egg development and that eggs placed in coarse well-drained sediments were prone to desiccation.

Based on the analyses of sediment samples from the available cores in Reach E, the average grain size abundance from sub-reaches E6 and E7 was 1.41% gravel (0.91% without DRV-25), 27.3% very coarse sand and coarse sand (21.41% without DRV-25), 36.68% medium sand (37.74% without DRV-25), 31.27% fine and very fine sand (36.49% without DRV-25) and 3.87% silt and clays (5.74% without DRV-25; Figure 32, Appendix B).

Note that core DRV-25 was considered to be an anomaly in that it contained an extremely high coarse-grained sediment fraction (5% granules and gravel and 64%

coarse and very coarse sand), that was not reflected in any of the other eight cores collected in these sub-reaches.

A comparison between the average grain size abundance for these sub-reaches to the existing foreshore sediments at Broadkill Beach indicates that there is not a good match between these sediments. The sediments measured at the Broadkill Beach foreshore are 20.04% gravel, while the material to be dredged from sub-reaches E6 and E7 (including DRV-25) contain only 1.41% gravel. The highest percentage grain size bins for the potential dredge material would be medium grained sand (36.68%, PD-ACOE sieve samples have a grain size of 0.25 mm to 0.42 mm), fine and very fine sand (31.27%, PD-ACOE sieve samples have a grain size of 0.074 mm to 0.25 mm), and very coarse and coarse sand (27.3%, PD-ACOE sieve samples have a grain size of 0.074 mm to 0.25 mm; Appendix B). The mean grain size of these highest percentage sediments would be ~0.30 to 0.35 mm, with a small gravel fraction (Appendix D).

The poor match in the gravel fraction, coupled with the low mean grain size (~0.30 to 0.35 mm) estimated for the material to be dredged, does not meet the requirements set by the ASMFC Fishery Management Plan for Horseshoe Crab that the placed material should be consistent with the existing sediments at the beach. Of particular concern in the mismatch between sediments is the finer-grained nature of the dredged sediments that are to be placed on Broadkill Beach. This concern is summarized in Penn and Brockmann (1994) that fine-grained, poorly drained sediments impede horseshoe crab egg development. This in part is why the results from both Smith et al. (2002) and Botton et al. (1994) suggest that average grain sizes on the order of 0.35 to 0.70 mm are optimal for spawning habitat for the crabs.

A beach that is constructed of material that is too fine would likely experience rapid erosion of the placed material during storm or large fetch wave events. Wright and Short (1982) found that finer grained sediments tend to result in lower foreshore profiles (i.e., lower slope angle), with these beaches tending to be less stable during wave events when the wave height to wavelength (H/L) ratio begins to exceed 0.01 (Figure 77). Conversely, beaches with coarser grained sediments tend to have a steeper profile and maintain their stability at much higher H/L ratios.

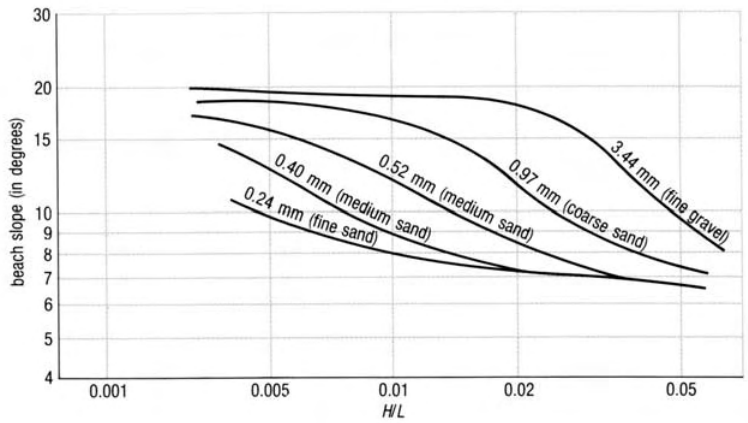


Figure 77. Diagram of the beach profile gradient resulting from several sediment grain size and exposure to different wave height to wavelength (H/L) ratios (Wright and Short, 1982).

According to ACOE projections, the mean grain size of the placement material is expected to be 0.3 mm (d-50; Appendix D), and because the beach replenishment is planned for September to December, the beach will equilibrate to the fall/winter higher wave activity by adjusting to a lower slope beach profile. Under the increased wave activity of the winter season, it would be expected that higher proportions of the emplaced material will become mobile and entrained in the tidal and cross-shore currents and transported, and eventually deposited, elsewhere in the coastal system, most likely in the nearshore region.

The potential negative impacts that could result from larger quantities of sediment becoming mobile and deposited in the nearshore are unclear. The eroded fill sediment could create a variable thickness cover over portions of the Delaware Bay bottom. Existing sessile and infaunal macro-invertebrates could be covered and unable to excavate themselves. If these organism were unable to maneuver vertically (i.e., sessile organisms) or burrow upward fast enough, then it would be likely that they would perish. As an example in proximity to Broadkill Beach, the tube-building polychaete *Sabellaria vulgaris* is abundant in the nearshore and considered essential fish habitat (EFH) for many commercial and recreation fisheries. Because *Sabellaria vulgaris* is sessile, it would be unable to excavate itself out of a sediment cover of thickness greater than 2.5 to 5 cm (1 to 2 in) and would perish at these sites.

There has been an implicit assumption in the discussion above that the averages obtained from only nine cores are spatially and vertically representative of the sediments that are present within sub-reaches E6 and E7. As recommended earlier in the results section, additional coring needs to be conducted within sub-reach E6 to better determine sediment grain sizes. In particular, it was advised that additional cores be collected within the vicinity of core DRV-25 to constrain its anomalous results. Also, cores are needed to fill in the existing 6.7 km (3.6 nm) gap between cores DRV-26 and DRV-82.

Sub-reaches E5 through E1 are the central and northern portions of Reach E extending from channel stations 461+300 to 351+200. The sediment to be dredged from these sub-reaches (2.48 mcy) is proposed to be used in the construction of a confined disposal facility (CDF) adjacent to Kelly Island (located along Delaware Bay in central

Kent County, Delaware). The CDF's berm, or offshore dike, that is to be used to contain the finer grained materials (from sub-reaches E1, E3, and E4) is proposed to be constructed from material to be dredged from sub-reaches E2 and E5 (EA, 2009; Figure 78, Appendix D). The PD-ACOE estimates the mean grain size (d-50) of sub-reaches E5 and E2 to be 0.7 mm and 1.0 mm, respectively (Appendix D).

A coarser sediment distribution for the berm construction greatly benefits the overall sustainability of the project design, especially given this region's high rate of coastal erosion (e.g., Kraft et al., 1992). If finer-grained sediments were used in the construction, the berm's ability to resist storm wave activity would be reduced. Finer grained deposits will not only erode and be transported offshore, but the foreshore will begin to equilibrate by reducing its slope, which could result in increased wave run-up and sediment movement. Any structures built into the shoreface (e.g., timber groins) would then destabilize more readily as the finer-grained sediments would shift around them. This in turn would necessitate more frequently than scheduled re-nourishment. A catastrophic berm failure could result if any larger storm surges (i.e. as the result of a Nor'easter) impacted the CDF prior to a needed nourishment event. Given these scenarios, it is important to as accurately as possible constrain the grain size distributions in sub-reaches E5 and E2, as they are the sediments that are key to the stable construction of the CDF berm.

Based on the review of the existing PD-ACOE core data and the analysis of the Roxann bottom sediment map and chirp sub-bottom profiles that were collected during this investigation, a number of concerns exist about the current ability to accurately define the distribution of grain sizes for the key sub-reaches E5 and E2. These concerns are discussed below.

Grain Size Discrepancies between Composite Sample Analyses and Core Log Descriptions

There are several documented instances where the grain size distribution data does not match the core log descriptions for the corresponding samples. These discrepancies make it difficult to confidently evaluate how representative the grain size

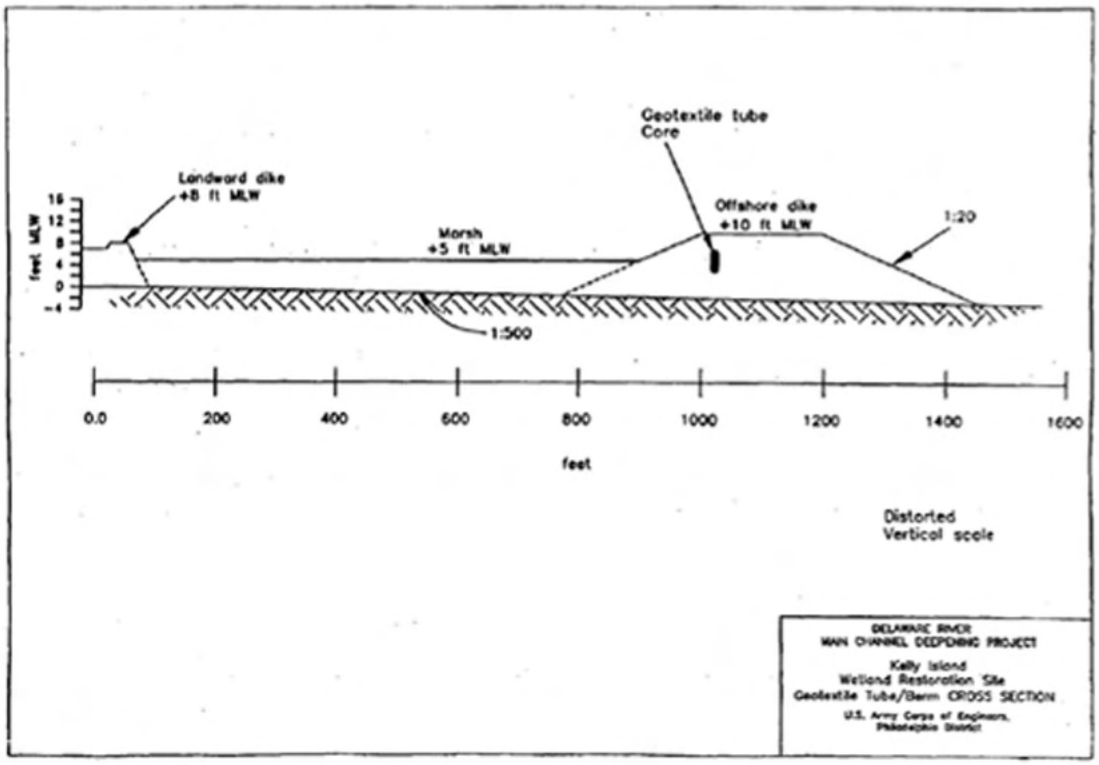


Figure 78. Cross-section of the proposed Kelly Island confined disposal facility (EA, 2009).

distributions, as determined from the analyses, are for the deposits that are proposed to be dredged and subsequently used for coastal construction. The major differences between the grain size distribution analyses and the visual description of the cores occurs in the central and northern portions of Reach E, where the sediments tend to be coarser-grained. No obvious discrepancies were identified in the southern sub-reaches E6 and E7 where the sediments were dominantly finer grained sandy silts and fine sands.

Sub-reach E5, in the central portion of Reach E, has four cores that have significant disparities between the sample grain size fraction distributions and the core log descriptions. These four cores (DRV-78, DRV-67, DRV-21 and DRV-66 R1) have a common discrepancy in that the core log descriptions are of a fine sand to medium sand (with scattered to some gravel), yet the grain size distributions show much coarser-grained deposits (Appendix B). DRV-78, described as sand with silt and some gravel, was found to be 53.01% gravel and granules and 17.75% very coarse and coarse sand in the grain size analysis. Similarly, DRV-67, a fine sand, little gravel, little medium sand and trace coarse sand in the core log description, was 16.92% gravel and granule, 14.3% very coarse and coarse sand and 50.9% medium sand. DRV-21, a medium to fine sand with scattered gravel, had 23.5% granule and gravel, 42.5% very coarse to coarse sand and 26% medium sand. DRV66 R1 was described as fine sand, some medium sand, little gravel and trace coarse sand and in the grain size analysis had 24.7% gravel and granule and 25.1% very coarse to coarse sand.

It should be noted that there are two cores (DRV-65 1 and DRV-20) in the northern portion of sub-reach E5 where there is good correlation between the core log descriptions and the grain size distribution results, but these cores do not have in their sampling for grain size the surficial bottom sediments. Core DRV-65 R1 did not sample the 0.0 to 0.4 ft interval in the core and DRV-20 has no sample for the interval between 0.0 and 1.1 ft.

It appears that the types of sediments based on the analysis of core samples for their percentages of sediments of a given grain size are skewed toward the coarser-grained sediments. That is, it is likely that the surficial bottom sediments, which are dominated by coarser-grained gravels and granules to very coarse and coarse sands

have been over-sampled relative to the underlying finer grained medium to fine to very fine sands. It is noted in the Roxann map that there is a surficial layer of coarser-grained sediment that is overlying the finer-grained sub-bottom sediments. It is the cores DRV-65 R1 and DRV-20, that did not sample for grain size analyses this surficial cover, that show the closest match between core log descriptions and the measured sediment grain-size distributions.

The surficial bottom cover and underlying deposits should have been separated when the samples were collected for sieve analysis. Unfortunately, core sections were homogenized together (forming composite sections) unless the stratum (or deposit) exceeded a thickness of 6 in (Duffield Associates Inc., 1999 and 2005). It was stated in sieve analyses conducted by SAIC (2001) that, “In several cases a sample collected and analyzed from a discrete depth interval was representative of a larger depth interval based on field classification.” As an example, for core DRV-69 the results from sample S1 (collected from the 2.5 to 5.0 ft interval) was used to represent the grain size distribution of the entire 0.0 to 5.0 ft interval.

Based on observations from grab samples and results from the Delaware Bay Benthic Mapping Project, the coarser-grained surficial bottom sediment deposits are likely in some areas to be at most only 5-10 cm (several inches thick). They are also highly variable in their thickness and in their lateral distribution. Thus if they are oversampled either by placement of the cores (preferentially, not by intention, in areas where the coarse-grained bottom sediments are located) or by including them in an unrepresentative sample of the sediments within the core, the grain size results would over-estimate their presence. The total volume of coarse material (granules, gravel, very coarse sand and coarse sand) throughout Reach E is predominantly the result of variable surficial bottom deposits of these grain sizes. In an attempt to more accurately characterize the distribution of grain sizes within the proposed dredge material, it is necessary to segregate the surficial deposits and the underlying subsurface deposits into their respective grain size fractions and consider the volumes of these two different types of deposits.

Similar discrepancies between grain size distributions from sieving analyses and core log descriptions are present in eleven of the fourteen cores of sub-reach E2 (DRV-

70, DRV-68, DRV-64, DRV-63, DRV-62R1, DRV-61R1, DRV-88R2, DRV-60, DRV-59, DRV-86 and DRV-58). This sub-reach contains the coarsest surface sediment cover (over the largest extent and with the most sandy pebble to gravel bars) of all the sub-reaches, so it is not a surprise that the majority of the cores had these discrepancies. Of the remaining three cores in the sub-reach, DRV-69 did not have the 0.0 to 2.5 ft included in the composite sample thus the surficial bottom deposits were not included and the core log description and grain size results correlated), DRV-87 was collected only from 0.0 to 1.1 ft so the composite sample did accurately reflect the presence of coarser bottom sediments, and DRV-15 correlated well with its coarse and medium sand dominated distribution.

Given the results from the grain size analyses and the overall general lack of correlation with the core log descriptions, it is likely that sub-reach E2 has also been characterized with grain sizes that are coarser than those actually present, especially within the sub-surface. This portion of Reach E is proposed to be used to construct the top berm and beach face of the Kelly Island CDF, so it is critical that the estimate of the grain-sizes for this sub-reach be as accurate as possible for the engineering of these features. It is of concern that it appears as if the percentages of coarser-grained sediments in this sub-reach are overestimated. The grain size distributions and the volume calculations of the various sediments for this sub-reach need to be recalculated and reanalyzed given the evidence of the overestimation of the coarser-grained fraction.

It is recommended that if undisturbed halved sections of the cores still exist, they should be re-sampled to determine a representative grain size distribution for the surficial bottom sediments and for the sub-surface deposits. The thicknesses of the bottom sediments should be reported and included in the volume calculations. If the cores no longer exist, a detailed sampling effort should be undertaken to collect cores throughout Reach E that are located, based on the Roxann bottom sediment map and the chirp sub-bottom profiles, to give the most representative coverage in terms of both the surficial bottom sediments and the sub-surface deposits. This entails adding sites to fill in data gaps between the previously collected cores and constraining areas where significant lateral variations in the grain size fractions are observed in the Roxann map.

It is also important that the cores that are collected are sampled along their entire length. For example, cores DRV-65 R1, DRV-75 and DRV-69 did not have samples from their surficial intervals varying from missing the upper 0 to 0.4 ft (DRV-65R1), 0 to 0.5 ft (DRV-75) and 0 to 2.5 ft (DRV-69). This affects the reported sediment grain size distributions because a portion of the sediments that would be removed in dredging was not included in calculations for determining a composite sample.

Data Gaps in Core Locations

Some of the existing gaps in the distribution of the current cores will need to be sampled in order to get a better representation of the lateral variability and trends in the grain size distributions. Cores DRV-25 (sub-reach E6), DRV-78 (sub-reach E5), DRV-77 (sub-reach E5), DRV-22 (sub-reach E5), DRV-76 (sub-reach E5), and DRV-17 (sub-reach E3) all illustrate that the sub-bottom (and composite bottom deposits) can vary considerably in their grain size fraction content when compared to their neighboring cores. Some of this variability may be explained by the influence of the surficial bottom sediments skewing the entire composite sample results, but it should not be ruled out that many of these cores may represent gradational, or rapid, transitions in sub-surface grain sizes. Additional cores are needed between these cores to constrain the observed variability.

The 6.7 km (3.6 nm) gap between DRV-26 and DRV-82 (sub-reach E6) needs to be sampled to detail the changes in the very fine to fine sand and very coarse to coarse sand fraction through this interval (Figure 32). In sub-reach E5, several core gaps mark dramatic changes in the subsurface grain size composition, with the gaps between DRV-23 to DRV-78 to DRV-77 highlighting a large change in the gravel and granule fraction that needs to be further examined (Figure 47). Several cores should also be collected through the DRV-77, DRV-22, and DRV-76 portion of this sub-reach to constrain the dramatic variations that exist between these cores, which could be due either to sub-surface changes or the effect of the bottom sediment fraction on the composite sample. Additional cores should also be collected in the gaps between cores DRV-76 to DRV-67 and DRV-66 to DRV-65 to document the changes in the sub-surface

sediments between these clusters of cores with similar grain size compositions (Figure 47).

Along Reach E on the chirp sub-bottom profiles, many paleochannels were identified. Due to their in-fill, which is of different sediment type than the surrounding sediments, they may mark major changes in sub-surface grain size distributions. It is expected that paleochannel in-fill sediments are generally finer-grained (i.e., fine sands to silts to clays). In areas where paleochannels have been identified, further coring is needed within, and outside, the channels to better constrain the sub-surface grain sizes.

In the transition between sub-reach E2 and E3, there is a dramatic change in the composite sample grain size fraction between DRV-17 (sub-reach E3) and DRV-70 (sub-reach E2) which necessitates additional cores to be collected between them to evaluate this dramatic change (Figure 54 and 56). At least one to two additional cores should be collected between DRV-70 and DRV-69 in sub-reach E2 to fill in the 3.5 km (1.9 nm) gap between them. Also in this sub-reach, there is a significant change in the grain size fraction composition between cores DRV-69 and DRV-68, and a large un-sampled gap between DRV-68 and DRV-64 (a gap of 3.18 miles). It was discussed earlier in light of the importance of this sub-reach to the construction of the CDF, that additional sampling along the entire length of E2 should be undertaken. This sampling is required due to the issues associated with the skewing of the composite samples toward the coarser-grained size fraction and the discrepancies in the correlation of the core log descriptions and grain size distribution results.

Sampling Methods

The sampling methods that were used to collect and sample the cores for the grain size analyses, plays a major role in much of the discrepancies that exist between the grain size distributions based on sieving results and the core log descriptions. The 1999 report *Geotechnical Investigation: 1999 Vibracoring Along the DE River Port Mahon PED* (prepared by Duffield Associates, Inc.) and the 2005 report *Geotechnical Investigation: Vibrational Coring in the Liston Range of the Delaware River Main Channel Delaware* (prepared by Duffield Associates, Inc.) state that vibrational core or vibracore sediment samples were collected for each stratum (in the core) that exceeded

thicknesses of 6 in. As discussed earlier, the coarse sediment surficial bottom cover (lying on top of a finer grained sub-surface or substrate) does not appear to have been separated into individual samples. Thus it must be assumed that these surficial bottom sediments did not exceed thicknesses of 6 in and were included within larger intervals from which composite samples were drawn.

Employing composite samples is often used as a means of reducing the cost of sampling at a particular site. However, Mason (1983) argues that it is a useful method, but must be implemented with caution. One of the main problems with composite sampling is the loss of information and sensitivity due to dilution of the samples (Mason, 1983). Composite samples are an attempt to homogenize an interval or volume of sediment into a smaller fraction for analysis, but the bulk material observed on a macro-scale may appear to be homogenous while on a micro-scale it is quite heterogeneous (Mason, 1983).

The methods used for the mixing and sub-sampling of a composite sample are the key to adequately removing a representative sub-sample for analysis. Once homogenized, the force of gravity results in a composite sample undergoing segregation (Mason, 1983). Depending upon how well the sample was mixed, the time between mixing and sampling and the location within the composite sample where the sub-sample is removed (i.e. center or side of sample container; top, middle or bottom of sample) a gravity or segregation error may skew the grain sizes in the sub-sample toward a finer or coarser distribution than is representative of the bulk sample.

If it is desired to take a composite sample, Pitard (1989) recommends constructing a sample by taking a large number of small increments and combining them into a single sample. This sample is then reduced to an analytical subsample by splitting or some other method of volume reduction. This approach provides the benefits of the composite sample and yet avoids the problems of homogenization, etc., that one encounters with large volumes of soil (Mason, 1993; Pitard, 1989).

It is not clear from the information supplied through the available reports and EA as to what exact methods were used to select the range to be composited, how the samples were mixed (homogenous), and how sub-samples were extracted from the composite for the sediment samples available in Reach E. It is clear that a common,

pre-determined methodology was not followed and there is a lack of consistentcy between the sampling efforts. To avoid this in the future, it is recommended that all subsequent sediment sampling should follow a peer review and standardized sampling method, such as the methodology outlined for the Cape Wind Energy Project (Cape Wind Final Environmental Impact Statement (FEIS; 2010)). This methodology is described in the geotechnical sampling and analysis protocols, and a selection criteria for determining which sediments need to be submitted for bulk physical analysis were outlined as:

- If no stratification is observed throughout the length of the core, one composite sample of the core will be selected for bulk analysis.
- If sediment stratification is observed in the core, each distinct strata will be sampled in a composite fashion for subsequent analysis.

It is also recommended through the EPA sediment sampling standard operating procedure, that the top of the core (approximately 2.54 cm (1 in)) be discarded, as this possibly represents material collected before penetration of the underlying layers of concern (Mason, 1983; EPA, 2003).

The apparent lack of a standard procedure for the sediment sampling puts the top composite samples results into question about their being representative of the grain sizes of the sediments to be dredged. The surficial bottom sediment cover is always in a state of flux and readjusting to bottom current conditions. Their distribution and thickness is highly variable. It is not advisable to include them as the main source of the coarse fraction in the total volume. At present, only first-order constraints, based on the Roxann bottom sediment map integrated with the chirp sub-bottom profiles and the existing core data, can be placed on the lateral and vertical distribution of the coarse-grained bottom sediment cover. Until this coarse-grained component can be further documented and properly including in the composite sampling procedure, it is difficult to accurately estimate the total volume of each grain size fraction or mean grain size of the sub-reaches within Reach E. This makes it difficult to validate the planning or engineering for any coastal construction project that might use these sediments in a matter that would interact with normal or storm wave conditions.

It is unknown from the available information how the samples were collected from the 1991 cores and the 2001 cores described in the report *Vibracoring and Analysis of Marine Sediments : Delaware River Main Channel, Delaware* (prepared by Science Applications International Corporation). It is assumed that these efforts used the same method outline in the previous reports, especially the 2001 SAIC report. However, the 2001 SAIC report does not mention the sampling procedure in enough detail to determine if it affected the sieve grain size results and contributed to the mismatch in the core log descriptions and the measured grain size distributions. SAIC does state that, “In several cases a sample collected and analyzed from a discrete depth interval was representative of a larger depth interval based on field classification”. It is unclear in the available documentation how this was conducted and what criteria was used to determine that samples were representative of a larger sections.

An additional point of concern that exists in terms of the reporting of the sediment grain size results are the non-traditional divisions that were used by the PD-ACOE and its contractors to define sediment grain size classes. The Wentworth grain size scale is the most commonly used standard by geologists for determining the diameter of grain size classes and the corresponding US Standard Sieve Mesh # or Phi (Φ) size.

In the PD-ACOE project, the composite samples from the cores were sieved and the grain sizes were classified by size bins that do not fit the standard Wentworth grain size classes. The PD-ACOE grain size class data was constructed so that any material that passed through the #200 sieve was classified as silt or clay, while any material that was retained was classified as very fine sand. According to the Wentworth size class scheme this break occurs at the #230 sieve (Figure 79, Table 1; Folk, 1974). The differences in the two scales would result in very fine sand (as defined by the Wentworth scale) with a diameter less than 0.074 mm to 0.0625 mm being classified by the PD-ACOE as coarse silt and not as very fine sand (Figure 79; Table 1). The upper limit for the very fine sand class in the scale used by the

US Standard Sieve Mesh #		Millimeters	Microns	Phi (ϕ)	Wentworth Size Class
		4096		-12	
		1024		-10	Boulder (-8 to -12 ϕ)
		256		-8	
		128		-7	Cobble (-6 to -8 ϕ)
		64		-6	
		16		-4	Pebble (-2 to -6 ϕ)
5.00		4.00		-2	
6.00		3.36		-1.75	
7.00		2.83		-1.5	Granule
8.00		2.38		-1.25	
10.00		2.00		-1.0	
12.00		1.68		-0.75	
14.00		1.41		-0.5	Very Coarse Sand
16.00		1.19		-0.25	
18.00		1.00		0.0	
20.00		0.84		0.25	
25.00		0.71		0.5	Coarse Sand
30.00		0.59		0.75	
35.00	1/2	0.50	500	1.0	
40.00		0.42	420	1.25	
45.00		0.35	350	1.5	Medium Sand
50.00		0.30	300	1.75	
60.00	1/4	0.25	250	2.0	
70.00		0.210	210	2.25	
80.00		0.177	177	2.5	Fine Sand
100.00		0.149	149	2.75	
120.00	1/8	0.125	125	3.0	
140.00		0.105	105	3.25	
170.00		0.088	88	3.5	Very Fine Sand
200.00		0.074	74	3.75	
230.00	1/16	0.0625	62.5	4.0	
270.00		0.053	53	4.25	
325.00		0.044	44	4.5	Coarse Silt
		0.037	37	4.75	
	1/32	0.031	31	5.0	
	1/64	0.0156	15.6	6.0	Medium Silt
	1/128	0.0078	7.8	7.0	Fine to Very Fine Silt
	1/256	0.0039	3.9	8.0	
		0.0020	2.0	9.0	
		0.00098	0.98	10.0	
		0.00049	0.49	11.0	Clay
		0.00024	0.24	12.0	
		0.00012	0.12	13.0	
		0.00006	0.06	14.0	

Figure 79. The Wentworth grain size scale for sediments (Folk, 1974).

PD-ACOE is the #100 sieve while the Wentworth scale sets the upper extent to be any material that passes through the #120 sieve. All material with a diameter less than 0.149 mm to 0.125 mm, which would be considered fine sand in the Wentworth scheme, under the PD-ACOE scheme would be considered very fine sand. The fine sand class upper limit was consistent between the two schemes (#60 sieve), but as stated previously, the lower extent of this size class was truncated in the PD-ACOE scheme and lumped into the very fine sand class. The medium sand class has a consistent lower size limit but the upper limit is lower (smaller) in the PD-ACOE scheme which has the #40 sieve as the coarse sand to medium sand break, while the Wentworth scale uses the #35 sieve as that class break (Figure 79, Table 1; Folk, 1974). Thus in the ACOE scheme, sediment that was retained in the #40 sieve would be a coarse sand, where normally using the Wentworth scale sediment with diameters less than 0.50 mm to 0.42 mm would be called medium sand. The very coarse and coarse sand breaks are also lowered in the ACOE size class scheme, where the #20 sieve is the break compared to the #18 sieve in the Wentworth scheme (Figure 79, Table 1; Folk, 1974). The break between very coarse sand and the granule class remained consistent between the two schemes with the break being the #10 sieve (Figure 79, Table 1; Folk, 1974).

The issue that arises in the PD-ACOE scheme from having the lower end of the sediment classes shifted up in their grain size breaks (very fine and fine sand) and then the upper limit of the coarser end shifted down in their size classes (very coarse and coarse sands) is that there is a convergence that results in the coarse sand, medium sand and fine sand ranges being defined over a smaller range of grain diameters, while the very fine and very coarse sand classes have larger ranges in their defined grain diameters. In the Wentworth scale, the very fine sand class has range of 0.0625 mm (lower and upper limits of >= 0.0625 mm to <0.125 mm), but in the PD-ACOE scheme very fine sand has a larger range of 0.75 mm (lower and upper limits of >= 0.074 mm to <0.149 mm). The fine sand class has a range of 0.125 mm (lower and upper limit of >= 0.125 mm to <0.25 mm) for the Wentworth scale, while the ACOE scheme has a range of .101 mm (lower and upper limits of >= 0.149 to < 0.25 mm). Medium sand has a range of 0.25 (lower and upper limits of >= 0.25 to < 0.50 mm) for the Wentworth scale,

while the ACOE scheme has a range of 0.17 mm (lower and upper limits of >=0.25 mm to <0.42 mm). The coarse sand class has a range of 0.50 mm (lower and upper limits of >= 0.50 to < 1.00 mm) for the Wentworth scheme, but the ACOE of scheme has a range 0.42 mm (lower and upper limits of >= 0.42 to < 0.84 mm). The very coarse sand class has a range of 1.00 mm (lower and upper limits of >= 1.00 to < 2.00mm) for the Wentworth scale, while the ACOE scheme has a range of 1.16 mm (lower and upper limits of >= 0.84 to < 2.00 mm; Figure 79, Table 1, Folk, 1974, Appendix B).

These changes in the sediment classes may not seem to be very significant, but it is both a compounding error for misrepresenting the grain size data and illustrates the already highlighted issue with respect to utilizing non-standardized field data collection methods. The PD-ACOE sediment class scheme skews the coarser grain sediment sizes up (with the standard medium grain sand class moving into the coarse sand class and shifting the upper values of the coarse sand into the very coarse sand class). This will result in a coarsening up descriptive error associated with these three sediment classes, and therefore an artificial coarsening of the sediment sample (potential resulting in a coarser mean or d-50 grain size distribution).

The smaller-grained sediment classes will conversely have the potential to increase the amount of reported coarse silts and very fine sands (due to their defined shift towards larger grain sizes), while the medium sand and fine sand will be underrepresented (because their ranges have been reduced). All of these changes, by not using a standard broadly accepted classification scheme by geologists, complicate any attempt to compare independent or previously collected sieve data to the ACOE's grain size data. The scheme that the PD-ACOE have chosen does not support any attempts to standardize their methods with the efforts of other federal, state or academic data collection efforts that utilize the broadly accepted Wentworth scheme of sediment classification. This is an avoidable sampling methodology that hampers efforts to validate the PD-ACOE's efforts to accurately characterize the sediments for Reach E.

V. Conclusion

The data that has been provided by the PD-ACOE to the State of Delaware for the Wetland and Subaqueous Lands permit for the Main Channel Deepening Project contains numerous sampling errors and data discrepancies, and is therefore considered inadequate to allow for its usage if forming a sound decision in the process review.

- All the sediment grain size samples collected for vibracores, by the PD-ACOE and its contractors, were collected by compositing larger sections of material into a sub-sample. An artificial skewing of the grain size results occurred because of this undesired sampling scheme. Any deposits less than six in thick were not segregated, but rather included into a larger composite sample. Extremely coarse sediments dominate the surface of sub-reaches E2 and E5, and the composite samples from these reaches have erroneously coarse grain size results, which do not match core log descriptions, and are the result of not separating the surface cover sediments from the underlying deposits. The thin surface deposits are not representative of the finer grained sub-surface and should not have been included in the top composite sample, but rather segregated into their own samples for sieve analysis.

- Unorthodox grain size divisions by the PD-ACOE and its contractors, which do not match the standard Wentworth scale used by geologists, were used to calculate the grain size distributions of the sediment samples. The shifting of the grain size class ranges resulted in data that cannot easily be compared to outside sources of data and also misrepresents the grain size distribution of the sediments and therefore all d-50 or mean grain size calculations that were done based upon these numbers can be called into question.

- Large gaps exist between core locations that make it very difficult to accurately determine the trend in sub-surface grain size distributions, and exposes any calculation of the total mean grain size per sub-reach volume to errors associated with this lack of sampling. Discrepanices based on differences between visual core log descriptions and sieve analysis results and from the

Roxann bottom sediment maps and chirp sub-bottom profiles document the heterogenous nature of the sediments located within the dredging prism of Reach E. Additional cores are needed to fill in data gaps that exist in most of the sub-reaches. Additional cores need to be collected in sub-reach E6 to confirm the results that were reported by the PD-ACOE and to determine if that sub-reach needs to be completely re-sampled.

The sediment sampling errors, discrepancies in reported grain size distributions and the lack of sufficient cores have reduced the validity of the PD-ACOE's efforts to accurately characterize the sub-surface sediments for Reach E. It is the recommendation of this review that it is essential that additional cores be collected for sub-reaches E2 and E5. In that it is the only way to get reliably and accurate grain size data that can be used to assess the viability and resiliency of the proposed CDF to be created on Kelly Island.

Cores should be collected adjacent to existing locations, and over areas that were previously unsampled. These cores should be analyzed such that the coarser surface deposits should be segregated from the sub-surface sediments to obtain a more reliable estimate of subsurface sediment grain size distributions. The grain size results need to be spatially weighted through the sub-reaches to better represent the areal and vertical variation in grain-size distributions and their trends. The need for weighting is shown by the RoxAnn bottom sediment maps where several cores were located in regions of localized variability and thus were not representative of the larger area or trend in up-channel sediment distribution.

In terms of the Broadkill Beach replenishment project, the average grain size data from sub-reaches E6 and E7 was determined to have a mean grain size fraction of 1.41% gravel, while the current foreshore conditions of Broadkill Beach contain 20.04% gravel. Thus using the dredged sediment from these sub-reaches would not meet the requirements set by the ASMFC Fishery Management Plan for Horseshoe Crab that sediments to be emplaced should match existing conditions. The mean grain size of the emplaced sediments would be ~0.30 to 0.35 mm, with a very small gravel fraction, according to the PD-ACOE (Appendix D). According to Smith et al (2002) and Botton et al. (1994) these sediments would be inadequate for horseshoe crab habitat, and

because of their finer-grained nature with a very small gravel fraction, the proposed beach to be constructed would likely have a detrimental effect on horseshoe crab spawning habitat. The potential Broadkill Beach nourishment does not meet the beneficial use requirements for this project, if anything it would negatively impact the prevalence of horseshoe crab spawning habitat and impede horseshoe crab egg development.

In terms of the Kelly Island CDF, the incomplete data that was provided by the PD-ACOE does not meet the minimal lithologic and volumetric data requirements that would be necessary in the development of the engineering design for the CDF. No detailed engineering plans have been presented for the creation of the CDF creation, so it is difficult to evaluate the feasibility of this project. In considering the initial plans for the CDF, the available grain size data does not support a design that could pass a rigorous engineering and geotechnical review.

At this time, not enough valid information has been provided by the PD-ACOE to allow the State of Delaware to adequately assess the outcome of the proposed material reuse of the Reach E sediments. Not enough information has been provided to accurately predict how the Broadkill Beach nourishment and Kelly Island CDF projects will respond to the wave conditions at those locations. The material may be outside of the projects designs and expectation, which could result in the projects outcome to deviate and result in significant negative ecological impacts. Even after sediment analyses of new cores that need to be collected, it is essential that information be provided to the State of Delaware indicating that the beneficial use projects will be able to achieve their proposed purpose and not become a financial burden and/or ecological catastrophe.

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