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Chesapeake Fossil Shell Survey

Identifying Fossil Shell Resources via Geophysical Surveys: Chesapeake Bay Region, Virginia

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Abstract

Methodology capable of identifying fossil oyster shell (FOS) buried under several meters of sediment is needed to quantitatively assess the availability of FOS for oyster reef restoration in Virginia. Evaluated here is the feasibility of using acoustic sub-bottom seismic surveys for determining the location and quantity of buried FOS. Over 280 miles of seismic surveys and 117 cores were collected in seven regions of the Chesapeake Bay and its tributaries. Traditional methods of seismic interpretation were able to successfully identify buried FOS regions throughout the geologically complex study area. The acoustic nature of buried FOS is site specific, however, and requires groundtruthing and geologic expertise to identify in the seismic data. Buried FOS deposits range in thickness from 1 to 3 ft, are located 2 to 8 ft below the seafloor, and are comprised of 12% to 55% shell. Overall, the seven sites contain a minimum of ~877,300 ft^3 of buried FOS sediment, of which a minimum of ~288,000 ft^3 is shell material. Although a purely quantitative assessment of acoustic data is possible, it is empirical and must be tuned from site to site. Ultimately, it is recommended that a combination of geologic digitizing and quantitative assessment be used to identify buried FOS regions in future seismic studies.

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Preface

This study was conducted for the U.S. Army Corps of Engineers, Norfolk District, under Project 1FGD21, Fossil Shell Survey. The technical monitor was Jennifer R. Armstrong.

The work was performed by the Coastal and Hydraulics Laboratory (CHL) during the period April 2013 to December 2013. The report was prepared under the direction of Dr. Jeff Waters, Chief of the Coastal Observations and Analysis Branch; Dr. Ty Wamsley, Chief of the Flood and Storm Protection Division; Dr. Edmond Russo, Deputy Director; and José E. Sánchez, Director of CHL.

At the time of publication of this report, COL Bryan S. Green was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
knots	0.5144444	meters per second
microns	1.0 E-06	meters
miles (nautical)	1,852	meters
miles (U.S. statute)	1,609.347	meters
miles per hour	0.44704	meters per second
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters
square miles	2.589998 E+06	square meters

1 Introduction

In the Chesapeake Bay, increased harvesting of oysters in the wake of European colonization has significantly reduced the abundance of oysters compared to their historic extent (Rothschild et al. 1994; Kirby 2004; Lotze et al. 2006; Schulte et al. 2009), though an exact measurement of area of oyster bed lost has not been quantitatively determined for the entire region (Smith et al. 2005). The depletion of oysters, among other concerns, reduces an ecosystem's ability to maintain water quality at historic levels and reduces available habitat for other organisms. Restoring oyster reefs is currently under the guidance of the Virginia Marine Recourse Commission (VMRC) and the U.S. Army Corps of Engineers, Norfolk District (NAO). Fossil oyster shell material (FOS), frequently found buried by sediment below the modern seafloor, is considered to be the most successful substrate for restoring and/or creating oyster reefs as other substrates tend to be less successful either in terms of spat recruitment and/or reef growth (Hobbs 1988; Hargis and Haven 1999; Nestlerode et al. 2007). Although VMRC has historically provided the location of buried FOS suitable for dredging, it is no longer confident of the location and quantity of useable shell for future projects. A robust methodology that allows rapid and accurate mapping of buried FOS is needed to support future oyster restoration goals.

Previous attempts to identify FOS buried under the seafloor have involved first identifying exposed oyster reef mapped on historical charts and subsequently groundtruthing the mapped regions using lead line, chains, poles, or other seabed penetration methods to feel for FOS preserved under the seafloor (Moore 1910; Hargis and Haven 1999; Smith et al. 2001). This type of historical groundtruthing, however, is time consuming, expensive, and risks missing FOS not mapped on the available historical charts. Smith et al. (2001) evaluated several acoustic technologies, including sub-bottom profiling systems, sidescan sonar, and acoustic seabed classification systems (ASCS) in an attempt to determine the most reliable methodology to assess both the quality and the quantity of FOS resources. Their results suggested that ASCS provided the most accurate results for mapping existing oyster beds on the seafloor, though it should be noted that ASCS was not able to provide any estimates of buried FOS. In 2003, Smith et al. used Edgetech and Datasonic CHIRP sub-bottom systems to characterize the geologic features associated with existing oyster habitat to identify geologic processes affecting modern oyster bed formation and succession at four sites in the Chesapeake Bay.[1] Smith et al (2003) did not attempt to map buried FOS, however, but focused their study on better delineating potential geologic controls (sediment type, topography) that appeared to influence the location of modern oyster beds, which they identified via sidescan sonar. More recently, Allen et al. (2005), using a Klein 2260NV dual-frequency sidescan sonar, successfully mapped the extent of exposed oyster beds in nearshore Louisiana, but no attempt was made in that study to identify buried FOS as a potential oyster restoration resource. Smith et al. (2005) utilized a Quester Tangent side-scan sonar, with a limited seabed penetration range of ~0.8–2 in., to identify near-surface FOS, but this methodology was limited both in its ability to assess the total thickness of FOS where it exceeds a few inches, as well as in identifying FOS resources buried under more than a few inches of sediment. Ultimately, a more robust methodology, capable of identifying FOS potentially buried under several feet of sediment, is needed to quantitatively assess the availability of FOS for current and future oyster reef restoration needs in the Chesapeake Bay region of Virginia. In addition, current interpretation of seismic reflection data requires a skilled geologist or geophysicist with extensive experience analyzing the seismic data line by line and hand digitizing the reflection data as needed. This methodology, while standard, increases the time and expense associated with the project. Accordingly, the project explored more automated methods of identifying and mapping the acoustic signature of buried FOS regions.

[1] CHIRP sub-bottom seismic systems use a range of acoustic frequencies generated as a single pulse (a *chirp*) to allow greater resolution of shallow geologic features under the seafloor.

2 Methods

2.1 Horizontal and vertical datums

The horizontal reference system for the entire project is NAD83, VA State Plane South, U.S. feet. For the James River and Rappahannock River sites, Real-Time Kinematic (RTK) GPS data were provided by a KeyNet GPS remote radio link, and all horizontal and vertical corrections were made in real time using Hypack Oceanographic v.12.0.0.1. Vertical data are referenced to NAVD88, U.S. feet. RTK-GPS was unfortunately not available via radio link along the more remote regions of the Eastern Shore near the border between Maryland and Virginia (Tangier Sound and Pocomoke Sound study sites), and the two sites were too far from land to allow a remote RTK-GPS system to be used. Accordingly, at these sites data were collected using differential GPS for horizontal positioning via Hypack, and local tide gauges were used to reference the vertical soundings to mean lower low water (MLLW).

2.2 Geophysical surveys

Selected survey locations were determined by U.S. Army Engineer District, NAO, using the best available historic data, expertise in oyster life history and habitat requirements, and past experience in oyster reef restoration (Figure 1). NAO used existing data from past surveys that include information taken from Baylor (1894), Winslow (1882), Moore (1910), Haven et al. (1981), and local expert knowledge at the District. In addition to historical significance, these locations are also found near or adjacent to current active reefs, public grounds, private leases, and past restoration sites in the upper and lower James River, Rappahannock River, and Tangier and Pocomoke Sounds.

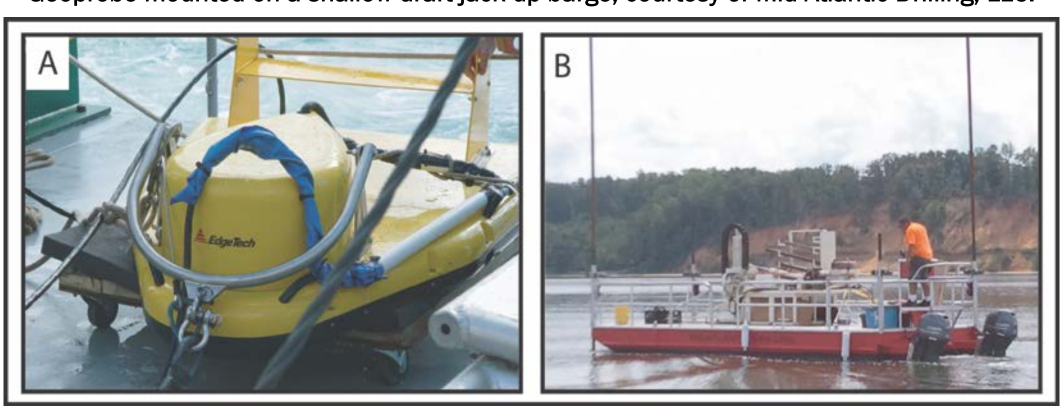
Over 280 miles of geophysical data, including single-beam bathymetry data as well as high-resolution seismic reflection data, were collected in May–August of 2012 and used to image the sub-bottom character of the study sites. The survey was conducted using an U.S. Army Corps of Engineers Field Research Facility vessel, the *R/V Barlowe*, a 27 ft Boston Whaler with a forward cabin and a shallow draft of < 2 ft. The echosounder transducer was mounted on the stern of the vessel and the sub-bottom profiler was towed along the starboard stern, out of the wake zone. Note that the small vessel size and shallow draft were critical for safely navigating shallow regions of the study sites. However, the size of the vessel made handling the sub-bottom towfish (out-of-water weight of ~500 lb with cable) very challenging under even optimal conditions.

Figure 1. Location of the primary study sites in the greater Chesapeake Bay region, VA.

Bathymetry was measured using a Knudsen echosounder interfaced with a TSS-120 heave sensor, which allowed for real-time correction of vessel motion during data acquisition. Hypack Oceanographic Software (v.12.0.0.1) was used to collect the bathymetry, RTK-GPS, and motion sensor data and relate all soundings to NAD83. For the James River and Rappahannock River sites, bathymetry data were processed, referenced to NAVD88, and corrected for tides using Fathomax and then de-spiked using IVS Fledermaus Professional (V.7.3.2c). For the Tangier Sounds and Pocomoke Sounds sites, bathymetry data were processed and referenced to MLLW using Hypack and then de-spiked in Fledermaus. Bathymetric maps were gridded using krigging in Golden Software Surfer (v. 8.0).

Seismic reflection (sub-bottom) data were collected using an EdgeTech Chirp 512i (Figure 2 [A]). The 512i system is designed for shallow coastal research, and its high-frequency and multipulse abilities allow for high resolution (average resolution of 4-20 in.) of shallow (< 75 m) reflection surfaces. Navigation data were provided by Hypack software. Vertical data are referenced to depth below the seafloor. Seismic reflection data were processed using Chesapeake Technology SonarWiz 5 (V5.05.0023), and continuous and noncontinuous reflectors were identified and digitized, as was the seafloor reflection surface. Heave is apparent in the seismic profiles because no swell filter was applied during acquisition or postprocessing. Digitization of the reflectors was visually estimated through the heave for both the seafloor and sub-bottom reflection surfaces by one person to limit the subjective differences that may arise when others participate in digitizing. Seismic reflection amplitudes with two-way travel time were also output at one of the reference sites (Tyler's Beach) to test whether a purely numerical approach could be used to map the distribution of FOS in lieu of a trained digitizer. Sediment thicknesses were calculated by subtracting the digitized sub-bottom reflector depths from the seafloor depths along the digitized lines. These data allowed a multidimensional approach in mapping not only the alongshore and cross-shore variability of the seafloor and the surface sediment but also the vertical variability of the underlying strata. Maps showing seafloor depths relative to bathymetry were gridded using krigging in Surfer, and the digitized locations of buried FOS were plotted as a post map over the bathymetric maps.

Figure 2. Sub-bottom analysis hardware. (A) EdgeTech Chirp 512i Sub-Bottom Profiler; (B) Geoprobe mounted on a shallow-draft jack-up barge, courtesy of Mid-Atlantic Drilling, LLC.



2.3 Sediment samples

Interpretation of the CHIRP sub-bottom record requires groundtruthing with sediment cores. To this end, 117 locations distributed over the seven main sites were selected for geoprobe coring (Tables A-1 and A-2, Appendix). Samples were collected using a 4 in. diameter Geoprobe core sampler rig, capable of collecting 4 ft long core sections, mounted on a 37 ft shallow-draft jack-up barge (Figure 2[B]). A cased geoprobe rod was pounded into the seafloor in 4 ft sections to identify the vertical structure of sediment type characterizing each coring site. Total core length collected at any individual site depended on the depth of the reflection surfaces being groundtruthed. At any individual borehole, once sufficient sediment was collected to the depth below the seafloor required to groundtruth the geophysical record, coring efforts were terminated.

The 4 in. geoprobe casings allowed for easy penetration into the seafloor with a minimal amount of disturbance but did limit the total amount and size of shell material that was ultimately recovered. The technique thus potentially underestimates the amount of oyster shell in FOS regions. To address the impact this potential sampling limitation had on the type of shell recovered, samples from active oyster beds, as mapped by VMRC, were collected using this same methodology to compare the type of shell recovered from modern beds versus that recovered from FOS. Field descriptions were recorded and subsamples of each different substrate sampled were preserved for further laboratory analysis.

In the laboratory, the field descriptions were refined to allow the identification of dominant sedimentary units at each site, details of which are found in the Appendix (Tables A-1 and A-2). To provide a first-order estimate of FOS quantity and type, an estimate of percent shell was determined by first selecting and weighing a representative subsample of FOS sediment. The shell material was then separated from the sediment matrix by gently washing the sediment off of the shell using a standard (0.197 in.; no. 35) sand-sized sieve. The remaining shell was described and weighed, allowing a first-order estimate of the weight percentage shell of the sediment sample to be calculated (Table A-3, Appendix). Note that shell fragments smaller than ~0.197 in. were sometimes lost in the washing process, leading to a potential underestimation of shell percentage in any given sample.

2.4 Calculating the area and percent shell of buried FOS regions

Buried FOS regions were identified using the sediment cores to interpret the sub-bottom data. The acoustic signature of a cored FOS region was identified for each region and digitized on the sub-bottom line using SonarWiz 5. This same acoustic signature was then digitized throughout the entire study site. To avoid inadvertently overestimating the area of a buried FOS region, care was taken to digitize individual buried FOS regions rather than lumping multiple small FOS regions together with non-oyster shell regions during the digitizing process (Figure 3). The digitized oyster bed reflection surfaces were then exported as .csv files and gridded using a weighted moving average (5 ft 3 weight) in Fledermaus. This allowed the extrapolation of the digitized surface over the visual footprint of the EdgeTech chirp on the seafloor. The total area of the digitized surface (ft^2) was calculated using Fledermaus, and only regions with data were included in the area calculation. An average thickness of oyster shell based on the core data for a given site was used to generate a volume of FOS (ft^3). The total percent shell was then calculated by multiplying the volume of FOS by the average percent shell for each study region (Table A-3, Appendix). This technique only includes FOS physically digitized from seismic lines and does not include FOS that might extend between adjacent survey lines (Figure 4). All FOS area and volume estimates provided in this report thus potentially underestimate the actual FOS area and volume in any one region. Given that the overall goal of this study was to assess if buried FOS regions could be identified and mapped acoustically, rather than to attempt to quantitatively account for all buried FOS in the study regions, a conservative estimate based on acoustically mapped regions alone was considered to be more appropriate for this report.

Figure 3. Example of a seismic line from McKan's Bay showing multiple, small FOS regions separated by gas-rich muddy sediment. The purple line indicates the digitized seafloor. The yellow and orange lines represent digitized FOS regions identified by coring and extrapolation, respectively. The small blue and yellow vertical rectangle in the yellow digitized FOS region shows the location and stratigraphy of a sediment core.

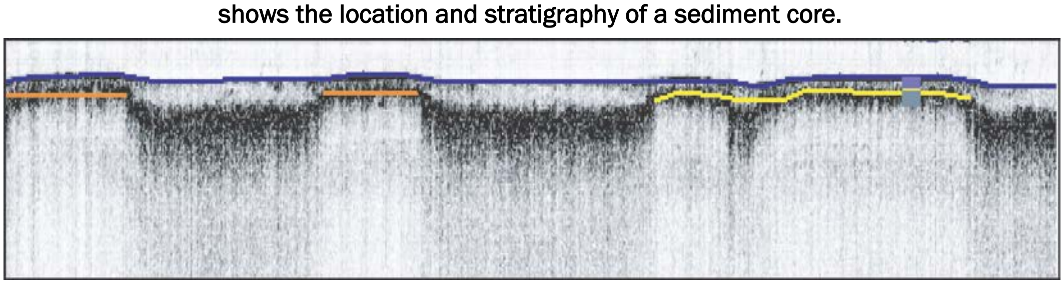
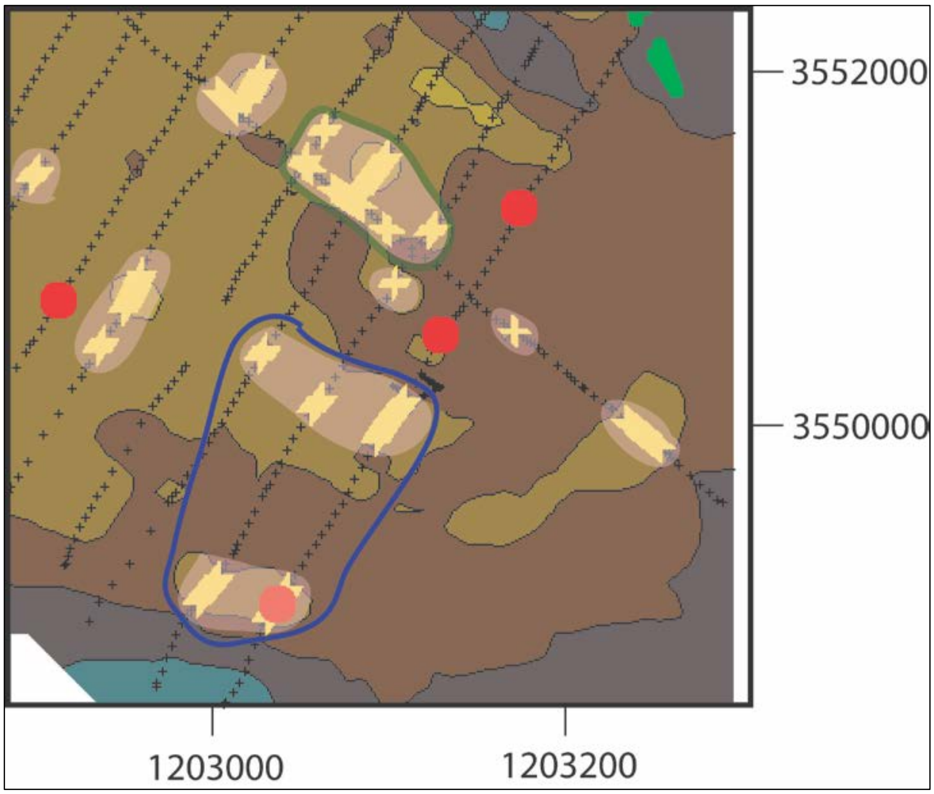


Figure 4. Plausible interpretation of reef complexes based on seismic data for McKan's Bay, VA. Seismic tracklines are represented by black x's and digitized FOS regions are represented by yellow x's. Interpreted reef complexes are shaded in pink. The green outline shows an example of digitized reefs appearing on one or more adjacent seismic lines and should be interpreted to be the same reef. The blue outline highlights an example of where digitized reefs are separated on the same seismic line by gaps of mud or other geology and should thus not be interpreted to be part of one large reef complex.



3 Results

A brief description of the nature and distribution of buried FOS and surrounding geologic framework is provided for each study region. With two exceptions, buried FOS was embedded in a muddy matrix (clay with varying amounts of silt) and was found overlying similarly muddy sediments. The two exceptions included one of seven FOS samples at Tyler's Beach and the single sample of FOS from the "Moke" region of Pocomoke Sound. Both of these samples are characterized by FOS embedded in muddy sand. At Tyler's Beach, the sandy FOS was found overlying a sand unit. Sandy FOS at Moke did overlie the more common muddy sediment (Table A-1, Appendix).

3.1 McKan's Bay, Rappahannock River

Located in the Rappahannock River just north of Urbana, VA, McKan's Bay is a shallow embayment just south of the main Rappahannock river channel. Depths range from -5 to -19 ft NAVD88 as shoals along the southwestern portion of the site gradually deepen to the northeast towards the main river channel (Figure 5). Twenty-six miles of sub-bottom data groundtruthed by 12 cores indicate that overall the region is muddy (clay with varying amounts of silt) with varying amounts of buried FOS, regions of gas, and laminated sequences. Buried FOS has a distinctive acoustic signature and appears as a dark, distinct reflection surface raised on average 4–8 ft above the surrounding reflection surfaces (Figure 6) and at water depths ranging from -10 to -18 ft NAVD88. The seafloor directly overlying the buried FOS is also slightly elevated (0.5–2 ft) above the surrounding seafloor. Gas is the other dominant acoustic reflector at McKan's Bay and appears as a dark, more diffusive layer and is not associated with elevation of the overlying seafloor (Figure 6). In the western and southern region of the site, little to no gas is observed. A small region of the south-central portion of McKan's Bay is dominated by laminated reflection surfaces constrained by an old paleochannel (Figures 5, 6). These acoustic surfaces correspond to alternating layers of muddy sand and sandy mud found in the corresponding sediment core (Tables A-1 and A-2, Appendix). Of the 12 cores collected at the McKan's Bay site, 7 contained buried FOS. Individual shell pieces at this site average just less than 1 in. in length and were fairly consistent in size throughout the samples. Based on these seven samples, the mapped buried FOS at McKan's Bay averages 1 ft in thickness, and 30%

of the FOS sediment by weight is shell. The total mapped volume of the buried FOS from the sub-bottom data indicates McKan's Bay contains a minimum of 93,100 ft^3 of FOS, of which at least 27,800 ft^3 is shell material.

Figure 5. McKan's Bay bathymetry (NAVD88). Seismic tracklines are shown in gray, and core sites are plotted as red circles. Digitized buried FOS beds are plotted as yellow x's. Track lines shown in Figure 6 are noted as A-A', B-B', and C-C'.

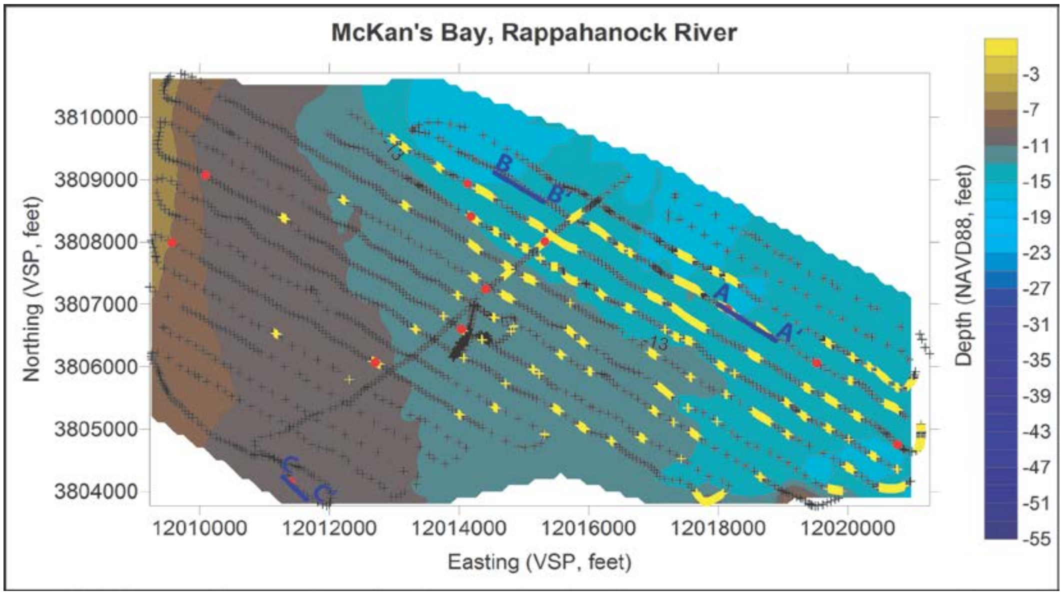
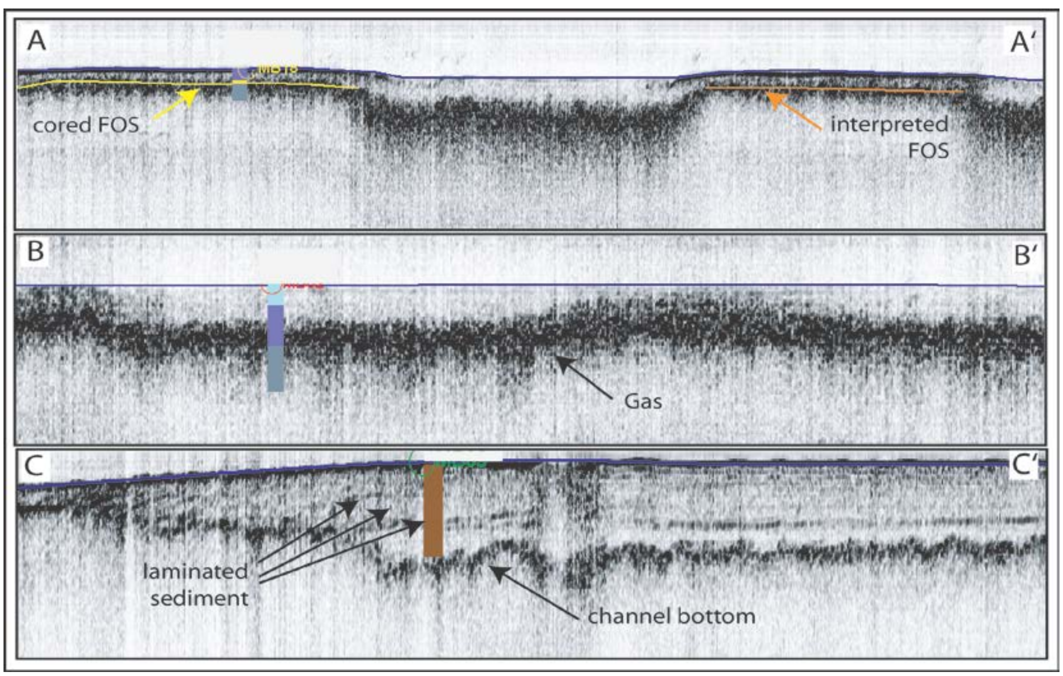


Figure 6. Characteristic acoustic signatures of McKan's Bay. The seafloor reflection surface has been digitized as purple lines. Rectangles represent sediment cores, and core log data are available in Appendix. Upper Panel: A-A'–buried FOS sediment (cored and interpreted) surrounded by gas-rich mud. Middle Panel: B-B'–muddy sediment with abundant gas. Lower Panel: C-C'–laminated channel sequence.



3.2 Tyler's Beach, Upper James River

Located in the upper James River just north of Smithfield, VA, most of the Tyler's Beach site is a relatively flat shoal located east of the main James River channel. A shallow channel runs across the northwestern portion of the region, and nearly all buried oyster shell is found on the flat region located south-east of this channel at depths ranging from -5 to -10 ft NAVD88 (Figure 7). Water depths range from -34 ft in the channel to -4 ft along the shoals. Thirty-five miles of sub-bottom data groundtruthed by 18 cores indicate that the region is dominantly muddy with significant pockets of gas at depths of 10–20 ft below the seafloor. Buried FOS has a distinctive acoustic signature similar to that observed at McKan's Bay, appearing as a dark, distinct reflection surface raised, on average, 3–7 ft from the surrounding reflection surface (Figure 8). The seafloor immediately above the buried FOS is also raised in relief by an average of ~1–3 ft from the surrounding seafloor. The other dominant acoustic reflector is gas. Gas appears as a dark, more diffuse layer and is not characterized by higher overlying seafloor topography (Figure 8). Overall, the buried FOS is patchy. Sections of buried FOS along any one seismic line are separated by pockets of gas-rich mud, and mapped gaps between FOS regions where mapped on a specific line are accurate. As it is uncertain if FOS is present in the gassy regions, those areas were not included in the total FOS area calculations. A small portion of the eastern edge of the study site is characterized by laminated reflection surfaces that correspond to alternating layers of mud and muddy sand in the sediment cores (Figures 7, 8). Of the 18 cores collected at Tyler's Beach, 7 included buried FOS. Individual shell pieces at this site average 1.3 in. in length, and shell pieces were fairly consistent in size in each sample. Based on these seven samples, the buried FOS at Tyler's Beach averages 2.7 ft thick and contains ~34% shell. The total mapped volume of the buried FOS from the sub-bottom data indicates Tyler's Beach contains a minimum of 310,950 ft^3 of FOS, of which at least 105,700 ft^3 is shell material.

Figure 7. Tyler's Beach bathymetry (NAVD88). Seismic tracklines are shown in gray, and core sites are plotted as red circles. Digitized buried FOS beds are plotted as yellow x's.

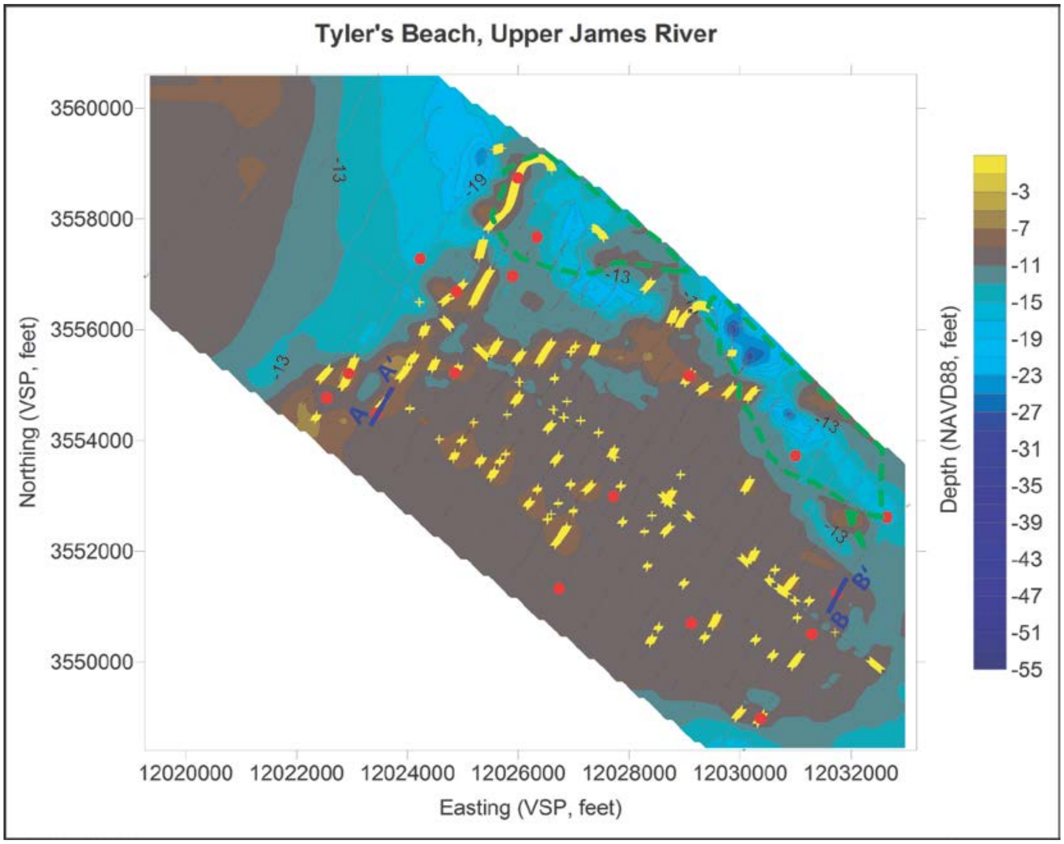
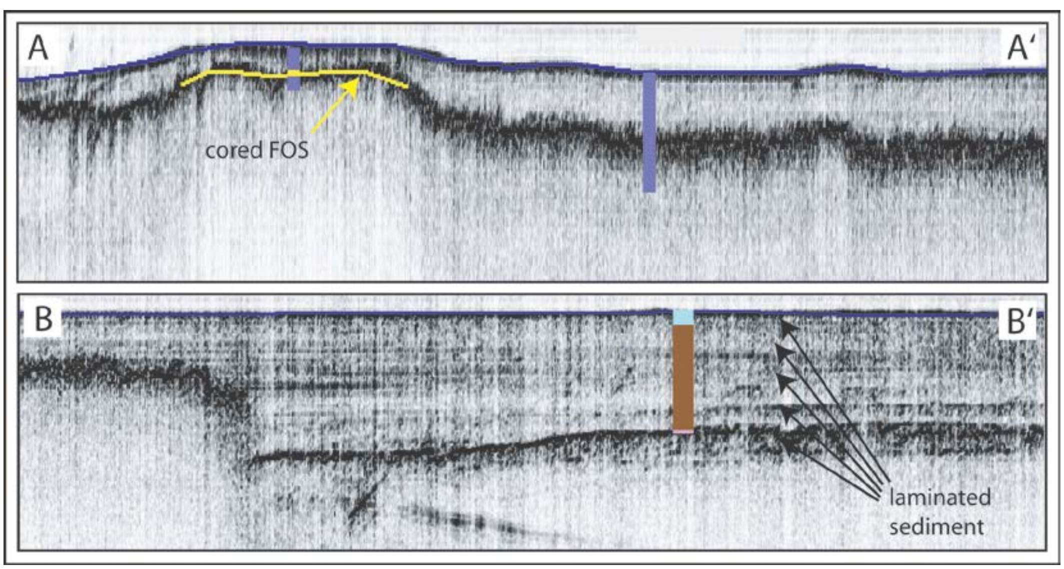


Figure 8. Characteristic acoustic signatures of Tyler's Beach. The seafloor reflection surface has been digitized as purple lines. Rectangles represent sediment cores, and core log data are available in Appendix. (A) Buried FOS sediment (digitized yellow line) surrounded by gas-rich mud; (B) Laminated sediment.



3.3 Tribell Shoals, Upper James River

Located in the upper James River along the edge of Hog Island and near Kingsmill, VA, the Tribell Shoals site includes shoals on either side of the main James River channel. Sub-bottom data indicate that buried FOS regions are limited in extent to the shoals in the lower third, southeastern edge of the site, northeast of the river channel (Figure 9) at depths ranging from -9 to -19 ft NAVD88. The only sub-bottom line collected on the shoal on the southwestern side of the river channel did not show any evidence of buried oyster beds. Note that the planned survey lines at Tribell Shoals did not initially extend into the shoals north and east of the main river channel but instead extended over the entire river channel (depths in excess of -37 ft NAVD88). Tyler's Beach was the last site to be surveyed, and based on the shoal-dominated locations of most of the buried FOS regions mapped at the other study sites, a decision was made in the field to drop the survey lines originally planned in the James River main channel. Lines were instead extended inshore across the shoals, potentially increasing the amount of FOS mapped in this region. Unfortunately, inclement weather prevented the complete mapping of this shoal region leading to a possible underestimation of FOS resources at this site.

Over 23 miles of sub-bottom data coupled with 14 cores indicate that most of Tribell Shoals is either muddy sand or mud with multiple and widespread pockets of gas (Figure 10). Similar to Tyler's Beach, buried FOS regions were elevated above the surrounding reflection surfaces by ~2–6 ft, and the overlying seafloor was also elevated by up to 3 ft above the surrounding seafloor. Modern oyster reefs were mapped in this region, and a core was collected on one of these reefs to compare how the coring methodology sampled oyster shell in a region of known shell size and density (Figure 10). Of the 14 cores collected at Tyler's Beach, 2 included buried FOS, and 3 samples of buried FOS were collected between the 2 cores. Individual shell pieces at this site average 1.3 in. in length, and shell pieces were fairly consistent in size in each sample. Based on these three samples, the buried FOS at Tyler's Beach averages 2.5 ft thick and contains ~36% shell (Table A-1, Appendix). The total mapped volume of the buried FOS from the sub-bottom data indicates Tyler's Beach contains a minimum of 48,000 ft^3 of FOS, of which at least 17,500 ft^3 is shell material.

Figure 9. Tribell Shoals bathymetry (NAVD88). Seismic tracklines are shown in gray, and core sites are plotted as red circles. Digitized buried FOS beds are plotted as yellow x's.

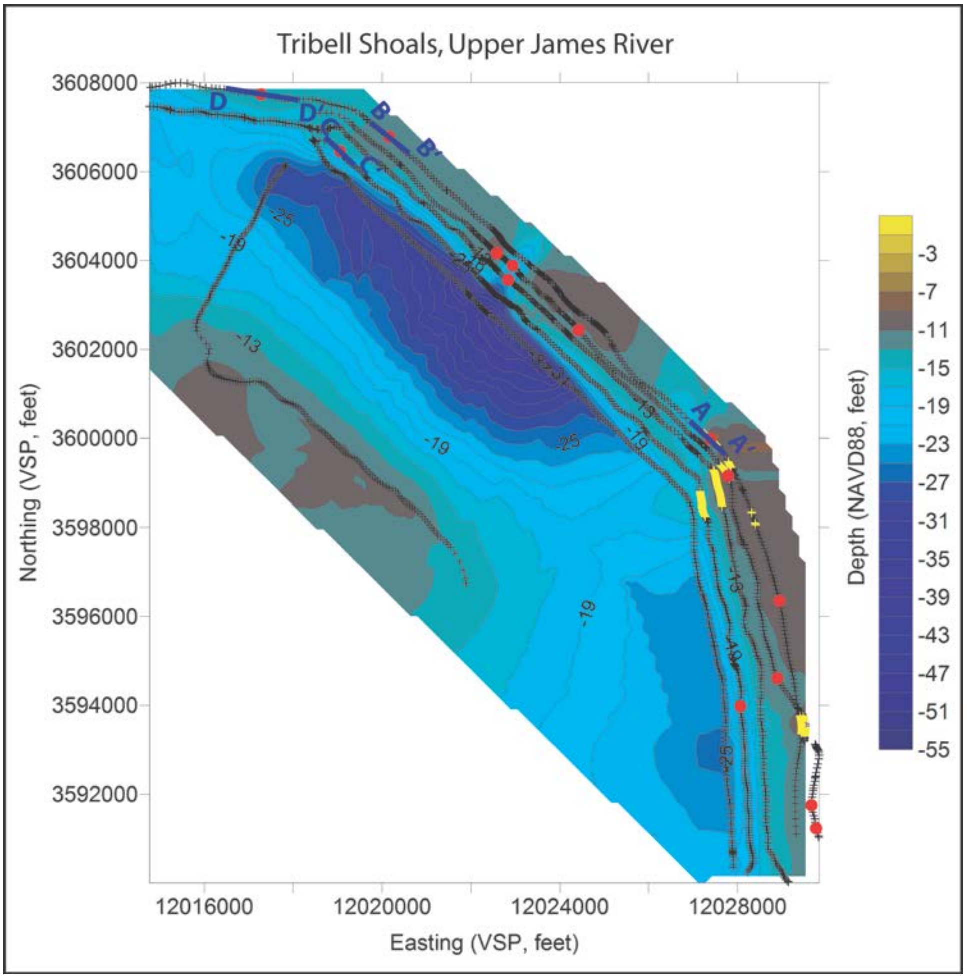
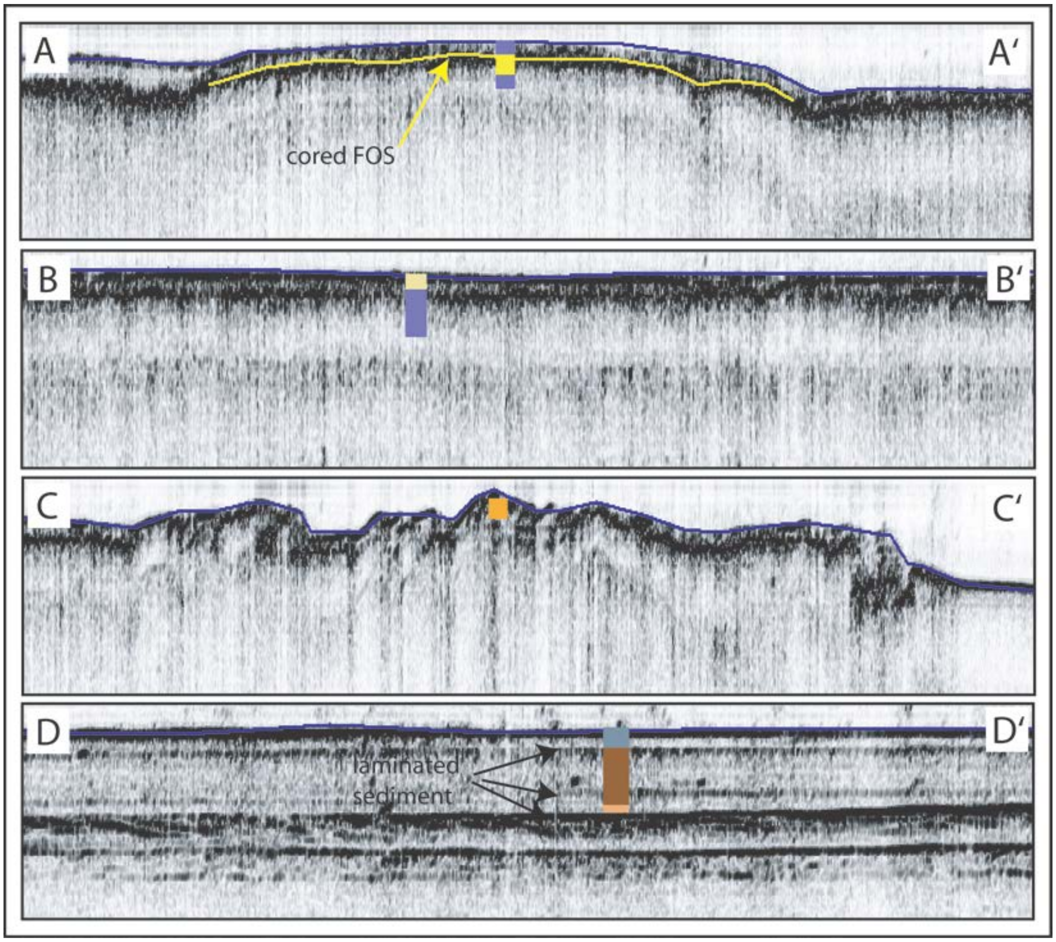


Figure 10. Characteristic acoustic signatures of Tribell Shoals. The seafloor reflection surface has been digitized as purple lines. Rectangles represent sediment cores, and core log data are available in Appendix. (A) Buried FOS sediment (digitized yellow line) surrounded by gas-rich mud; (B) Silty sand overlying stiff mud; (C) Modern oyster reef; (D) Laminated sediments.



3.4 Nansemond Flats, Lower James River

Located in the south side of the lower James River, just east of the Monitor-Merrimack Bridge Tunnel, Nansemond Flats is a broad, flat region with the old Nansemond River channel (depths up to -19 ft, NAVD88) extending into the southeastern portion of the site (Figure 11). The extreme southwestern portion of the planned survey region was not surveyed due to presence of an old, partially submerged pier (Figure 12a). Sub-bottom data indicate that buried FOS is present primarily along the shallow, flat regions of the site, in water depths of -11 to -13 ft NAVD88. Some buried FOS is located, however, in the deeper region of the old Nansemond River Channel (at depths up to -19 ft, NAVD88). Overall, ~65 miles of sub-bottom data and 13 cores show Nansemond Flats to be comprised both of laminated sediment, and muddy sediment, with varying and widespread regions of gas (Figure 13). The number and depth of laminations decrease from southeast to northwest.

Buried FOS in the more southern region of the site is characterized by a sharp, dark reflection surface, with little to no laminated sediments above it and none below it, that masks out the adjacent laminated reflectors (Figure 13). The buried FOS is not elevated above surrounding reflection surfaces, nor is the seafloor raised above it. In the middle and northwestern portion of the site, the acoustic signature of buried FOS is more similar to that seen in the upper James in that the buried FOS is elevated above the surrounding reflection surfaces (Figure 13). The seafloor overlying the buried FOS is not, however, elevated above buried FOS, and the FOS reflection surface is not as sharp and distinct as it was in the upper James and Rappahannock River sites (Figures 6, 7, 10, 13). The non-FOS portion of Nansemond Flats is dominated by a dark reflection surface which represents a classic transgressive shell hash exposed both at the surface and at depths of up to 6 ft below the seafloor (Figure 13). The shell hash reflection surface is patchy in distribution and can easily be mistaken for buried FOS in the seismic lines. In hand sample, the transgressive hash is comprised of coarse fragments of multiple types of shell, including clams, mussels, and oysters, and is easily distinguished from intact FOS. Care must be taken to distinguish the two surfaces in the seismic record where there are no sediment cores. Distinguishing characteristics include the following: (1) shell hash frequently has other reflection surfaces overlying it while buried FOS does not; (2) shell hash does not mask out adjacent laminated reflectors in the southeastern portion of the site while FOS does; and (3) in the northwest region of the site, the shell hash reflection surface is not elevated above the adjacent reflection surfaces while the FOS reflection surface is elevated. Of the 13 cores collected at Nansemond Flats, 5 included buried FOS. Individual shell pieces at this site average ~1 in. in length, and shell pieces showed significant variation in size in each sample. Based on these five samples, the buried FOS at Nansemond Flats averages 1 ft thick and contains ~35% shell (Appendix). The total mapped volume of the buried FOS from the sub-bottom data indicates Tyler's Beach contains a minimum of 205,200 ft^3 of FOS, of which at least 72,650 ft^3 is shell material.

Figure 11. Nansemond Flats bathymetry (NAVD88). Seismic tracklines are shown in gray, and core sites are plotted as red circles. Digitized buried FOS beds are plotted as yellow x's.

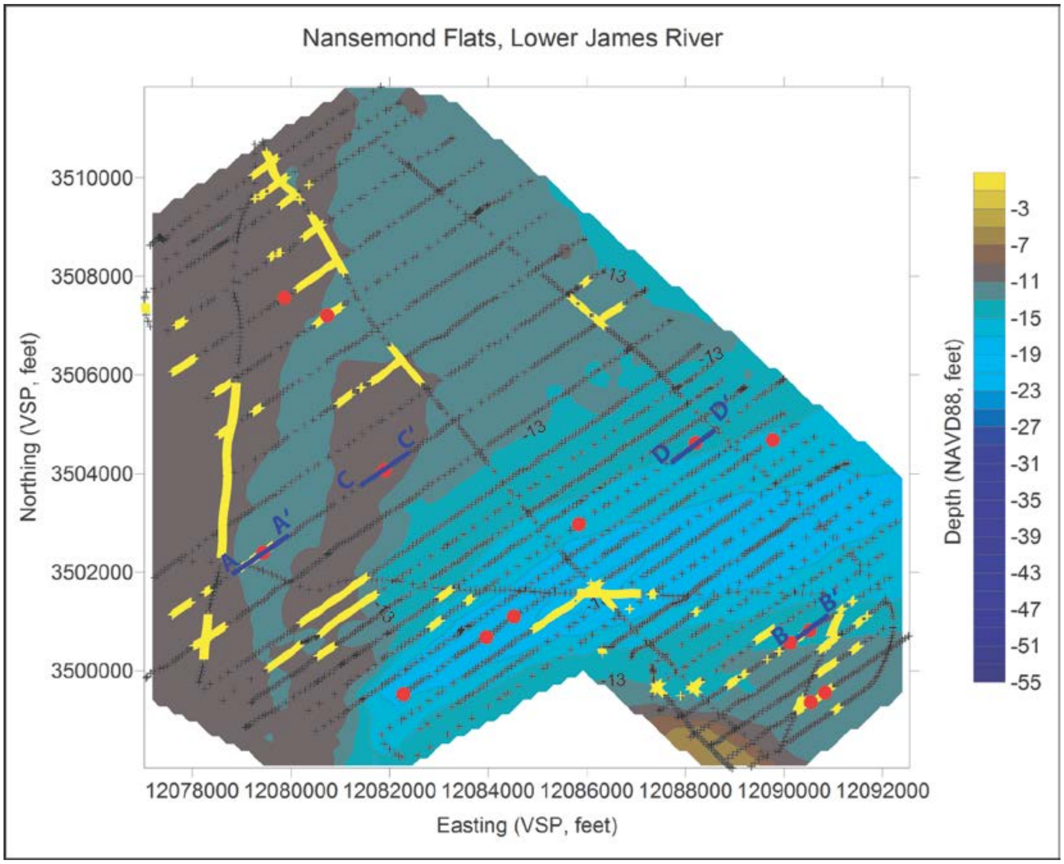


Figure 12. Structures limiting surveying in the lower James River. (A) Old pier structures blocking the southwestern portion of Nansemond Flats; (B) Net and pole structures limiting access to the southern and northern regions of Craney NIT 1.

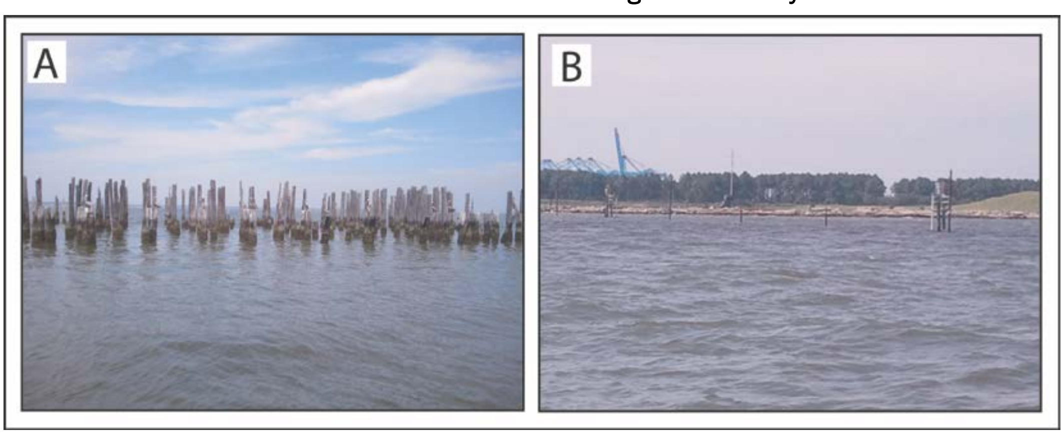
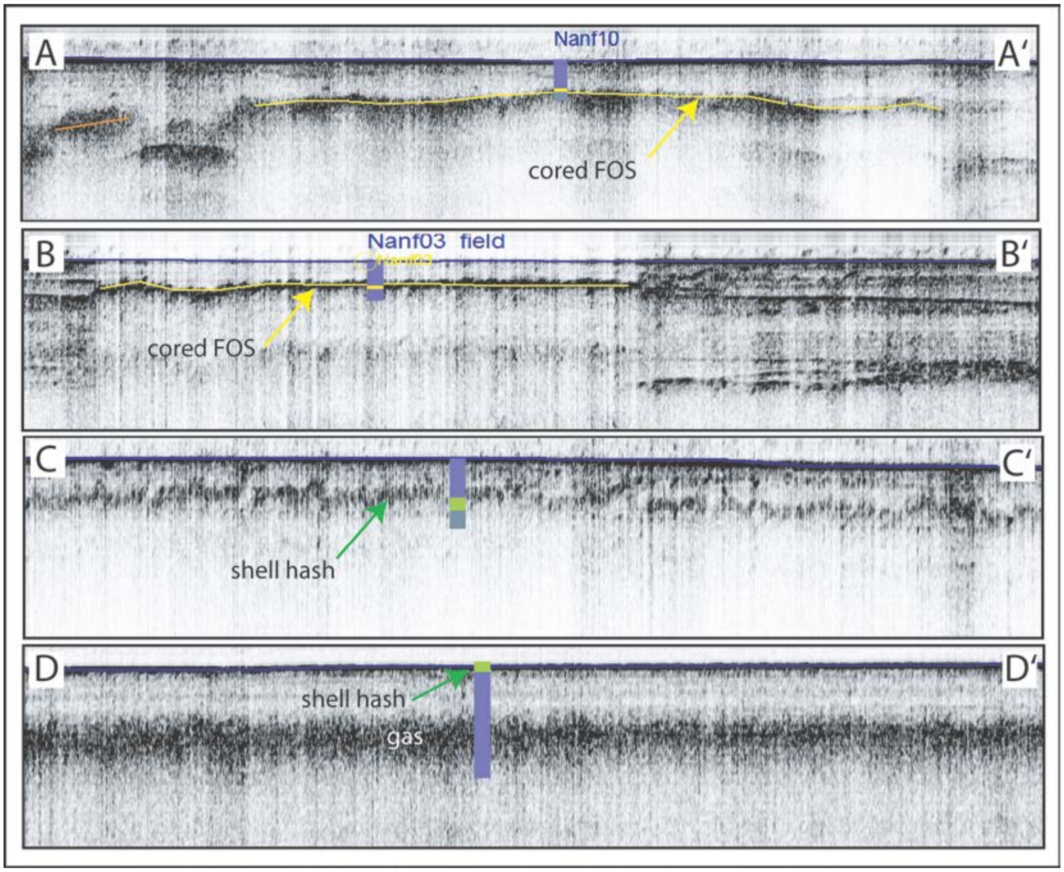


Figure 13. Characteristic acoustic signatures of Nansemond Flats. The seafloor reflection surface has been digitized as purple lines. Rectangles represent sediment cores and core log data are available in Appendix. (A) Buried FOS sediment (digitized yellow line) elevated above the surrounding reflection surfaces; (B) Buried FOS sediment masking adjacent laminated sediment; (C) Buried shell hash; (D) Surface shell hash overlying muddy, gassy sediment.



3.5 Craney Island, Lower James River

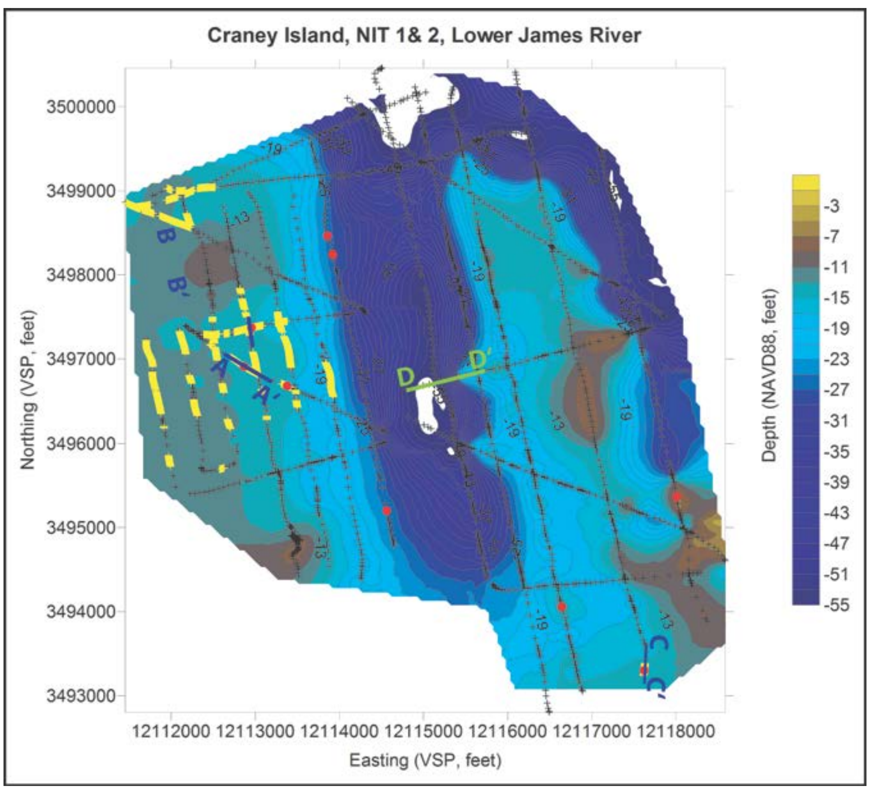
The study regions around Craney Island were broken into three separate sub-regions: NIT 1, NIT 2, and NIT 3 (Figure 14). For ease of explanation, NIT 1 and 2 will be presented separately from NIT 3.

3.5.1 Craney Island NIT 1 and 2

The Craney Island NIT 1 and 2 sites are both located on the eastern side of Craney Island and encompass the shallow flats adjacent to Craney Island, the Elizabeth River main channel, and the shoals to the east of the Elizabeth River, including the region immediately off of the Norfolk loading docks (Figures 14, 15). Only the middle portion of NIT 1 was surveyed due to the presence of several nets in the northern and southern section of the study site (Figure 12b). Over 22 miles of sub-bottom data and 14 cores indicate that, with one exception, buried FOS is limited to NIT 1.

Figure 14. Location of Craney Island subregions NIT 1, 2, and 3.

Figure 15. Craney Island NIT 1 and 2 bathymetry (NAVD88). Seismic tracklines are shown in gray, and core sites are plotted as red circles. Digitized buried FOS beds are plotted as yellow x's.



In NIT 1, unlike the rest of the James River sites, the buried FOS is not only patchy but also characterized by a broken, irregular reflection surface (Figure 16A) and found primarily in water depths of -12 to 17 ft NAVD88. The reflection surface is slightly elevated (1 to 3 ft) from the adjacent reflection surface in some locations but not in others. NIT 1 was also the only site surveyed for the entire project that showed possible multiple layers of buried FOS (Figure 16B). Depth to the first layer of FOS from the seafloor ranged from 3 to 7 ft, and depth from the upper layer of FOS to the possible lower layer ranged from 5 to 12 ft. Mud with minor, patchy pockets of gas was found overlying the upper FOS layer, lying between the two FOS layers, and underlying the lower FOS layer (Figure 17). The lower layer of FOS was only cored once and was slightly less thick than the average FOS thickness for the rest of NIT 2 (0.5 ft vs. 1 ft, respectively). The percent shell was too small to sample in the lower FOS layer but averaged 35% in the upper layer. Given the acoustic similarity of the upper and lower FOS layers, it is likely that the percent shell in the lower FOS layer is similar to that of the upper FOS layer and was simply not sampled effectively during the study.

Figure 16. Characteristic acoustic signatures of Craney Island, NIT 1. The seafloor reflection surface has been digitized as purple lines. Rectangles represent sediment cores and core log data are available in Appendix. (A) Single layer of buried FOS (digitized yellow and orange lines) overlying gas-rich muddy sediment; (B) Two layers of buried FOS (digitized yellow and orange lines) with gas-rich mud overlying both layers and underlying the lower FOS layer.

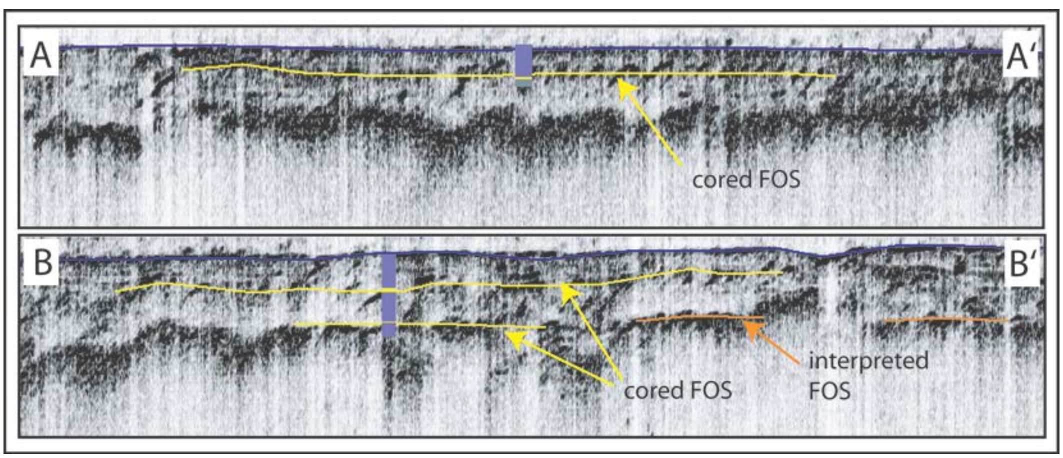
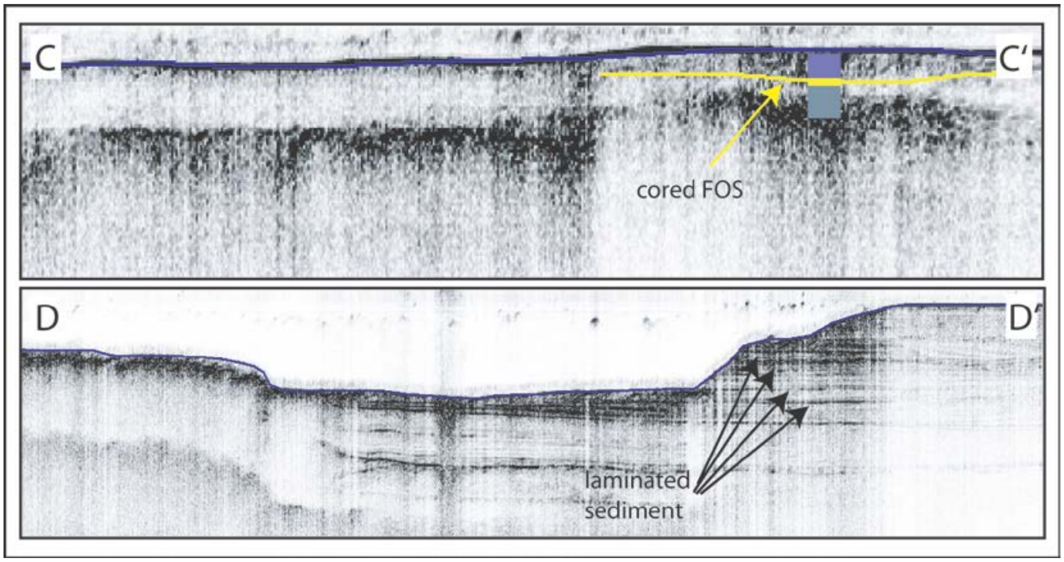


Figure 17. Characteristic acoustic signatures of Craney Island, NIT 2. The seafloor reflection surface has been digitized as purple lines. Rectangles represent sediment cores and core log data are available in Appendix. (A) Buried FOS (digitized yellow line) in the far southern region of the site surrounded by gas-rich mud; (B) Laminated sediments in the main Elizabeth River channel transitioning to muddy sediment along the shoal.



The sub-bottom of NIT 2 was dominated by multiple reflection surfaces indicating laminated sediment in the Elizabeth River channel that transitioned into muddy sediment with widespread patches of gas at depths shallower than -19 ft NAVD88 (Figure 17). Only one area of buried FOS was mapped in NIT 2, a small area (~70 ft horizontal extent) near the far north edge of the region at a depth of -16 ft NAVD88. Buried FOS was not mapped in either of the two adjacent seismic lines. The reflector was similar to the signature of the buried FOS in northern Nansemond Flats, a more diffuse reflection surface raised up from the adjacent reflection surfaces and with a flat overlying seafloor (Figures 13, 17). Note that the buried FOS was mapped at the farthest southern extent of the seismic line, and an obvious southern edge was not seen, suggesting that this bed might be larger than the available data suggest. The buried FOS was 1.5 ft thick and contained 42% shell that averaged ~1 in. in size.

To estimate the mapped volume of buried FOS in Craney NIT 1 and 2, the area and FOS sediment data from the single bed mapped in NIT 1 and the upper FOS layer mapped in NIT 2 were combined. The lower FOS layer in NIT 2 could not be included given the limited sampling of that layer. In addition, nearly one-third of the planned survey region in NIT 2 was inaccessible due to pound nets and other structures, and much of this inaccessible region was adjacent to the buried FOS-rich region of NIT 2.

Although these two limitations inevitably resulted in a potentially large underestimation of the total buried FOS at NIT 2, the goal of this study was not an absolute quantification of buried FOS at NIT 2, and thus a more conservative estimate was considered appropriate. Combining NIT 1 and the upper FOS of NIT 2 yields a total volume of buried FOS of 39,600 ft^3 of FOS, of which at least 13,750 ft^3 is shell material.

3.5.2 Craney Island NIT 3

The Craney Island NIT 3 site is located along the northern edge of Craney Island almost entirely along the edge of the lower James River (water depths of -15 to -33 ft NAVD88; Figure 18). Despite collecting over 27 miles of sub-bottom data as well as 16 cores, no buried FOS beds were found at this site. The eastern and western portions of NIT 3 are dominated by gas-rich mud which transitions into more laminated sediment in the middle portion of the site (Figures 18, 19). The eastern portion of NIT 3 also contains a patchy, dark reflection surface that is slightly (<1 ft) raised above surrounding reflection surfaces, though the seafloor remains flat immediately overlying these surfaces (Figure 19). Although they are similar in appearance to buried FOS mapped at Nansemond Flats and Craney NIT 1, multiple sediment cores indicate that at NIT 3, these reflection surfaces are comprised of stiff, silty sand rather than buried FOS. This region exemplifies the importance of using sediment cores to groundtruth seismic reflection data to avoid accidently interpreting a reflection surface as buried FOS simply because it looks acoustically similar to FOS in other regions.

Figure 18. Craney Island NIT 3 bathymetry (NAVD88). Seismic tracklines are shown in gray, and core sites are plotted as red circles.

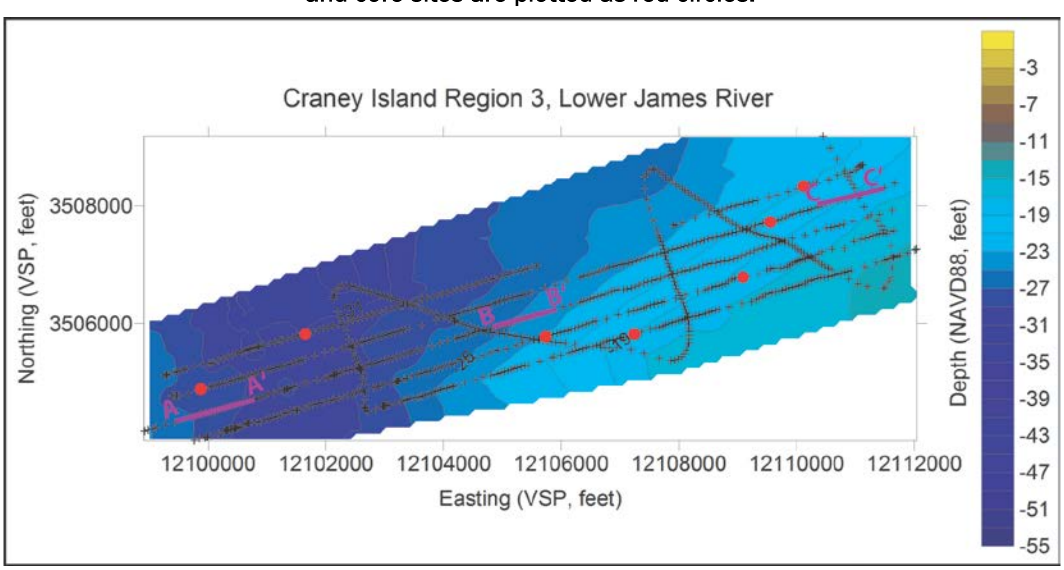
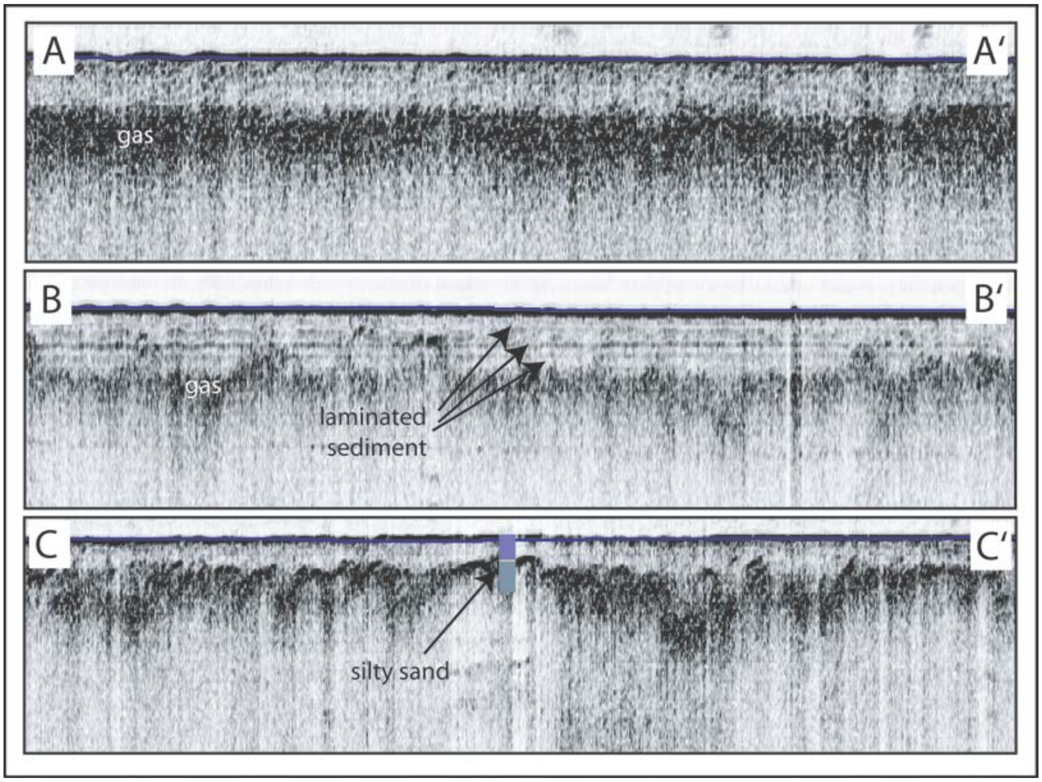


Figure 19. Characteristic acoustic signatures of Craney Island, NIT 3. The seafloor reflection surface has been digitized as purple lines. Rectangles represent sediment cores and core log data are available in Appendix. (A) Muddy sediment with widespread gas characterizing the eastern and western portions of the site; (B) Laminated sediment characterizing the middle portion of the site; (C) Acoustic signature of the stiff silty sand found in the eastern portion of the site.



3.6 Tangier Sound, Chesapeake Bay

The Tangier Sound study site is located in the upper Chesapeake Bay near the border of Virginia and Maryland (Figure 1). The site includes a portion of the shoals along the western edge of the channel between Tangier and Smith Islands to the west and the Fox Island region to the east (Figure 20). Water depths range from -8 to -19 ft MLLW along the shoals and rapidly deepen eastward to over -40 ft with increasing distance into the channel proper. Sub-bottom data indicate that buried FOS is limited to the northern third of the site in water depths ranging from -13 to -19 ft. Overall, 36 miles of sub-bottom data groundtruthed by 18 cores show the northern third of Tangier to be comprised primarily of mud with minor pockets of gas and laminations of muddy sand and mud. Buried FOS is characterized by a sharp, dark reflection surface with no laminations either above or below it (Figure 21). Approximately half of the buried FOS appears raised slightly (<1 ft) relative to the reflection surfaces adjacent to the beds.

Figure 20. Tangier Sounds bathymetry (MLLW). Seismic tracklines are shown in gray, and core sites are plotted as red circles. Digitized buried FOS beds are plotted as yellow x's.

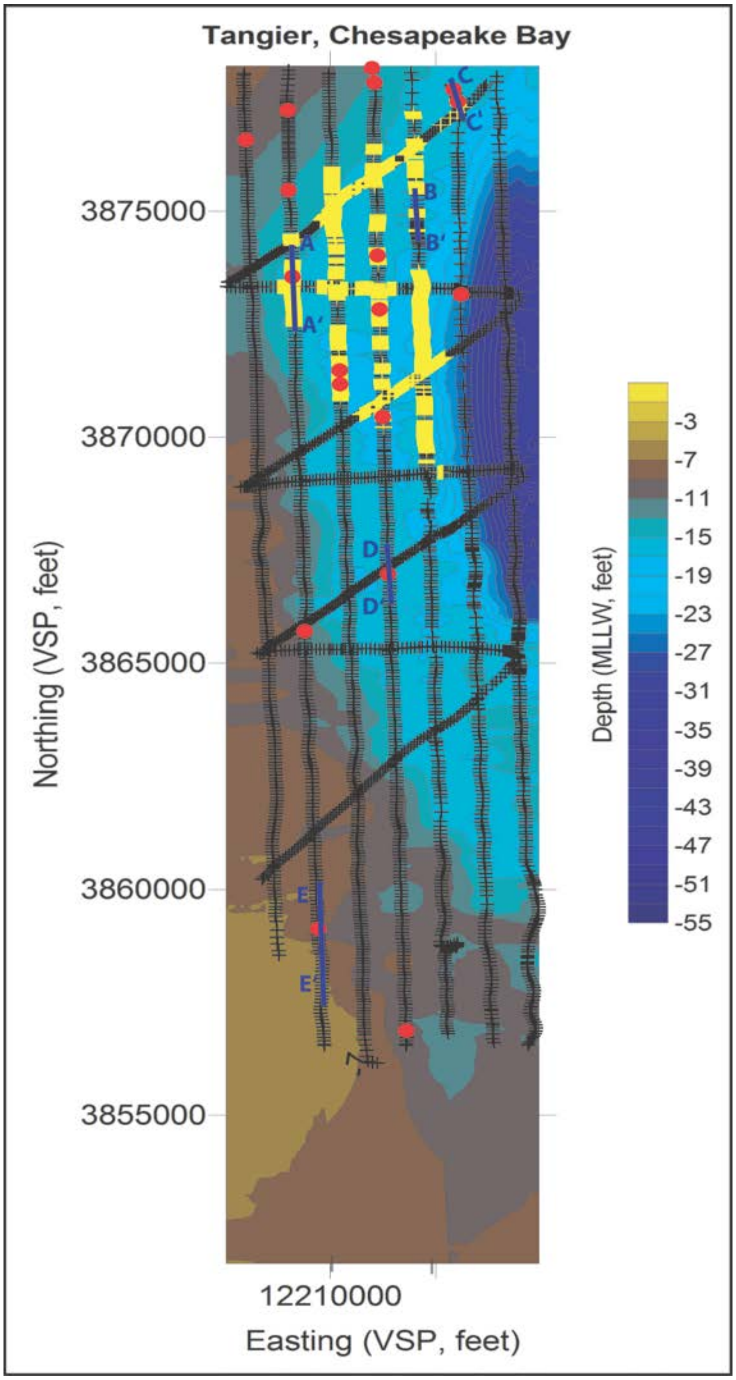
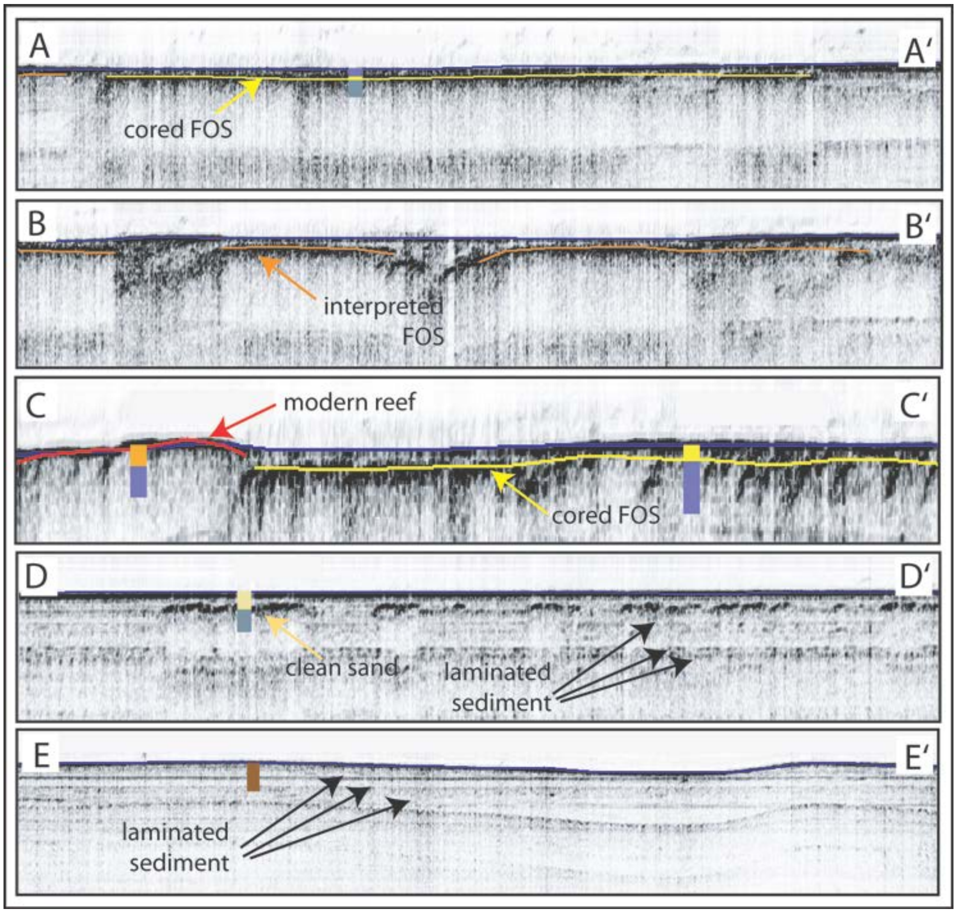


Figure 21. Characteristic acoustic signatures of Tangier. The seafloor reflection surface has been digitized as purple lines. Rectangles represent sediment cores and core log data are available in Appendix. (A) Buried FOS sediment (cored) surrounded by mud; (B) Interpreted buried FOS elevated slightly from the surrounding reflection surfaces; (C) Modern reef (red line) adjacent to buried FOS; (D) Clean sand surrounded by and overlying laminated sediment; (E) Laminated sediment (southern two-thirds of study site).



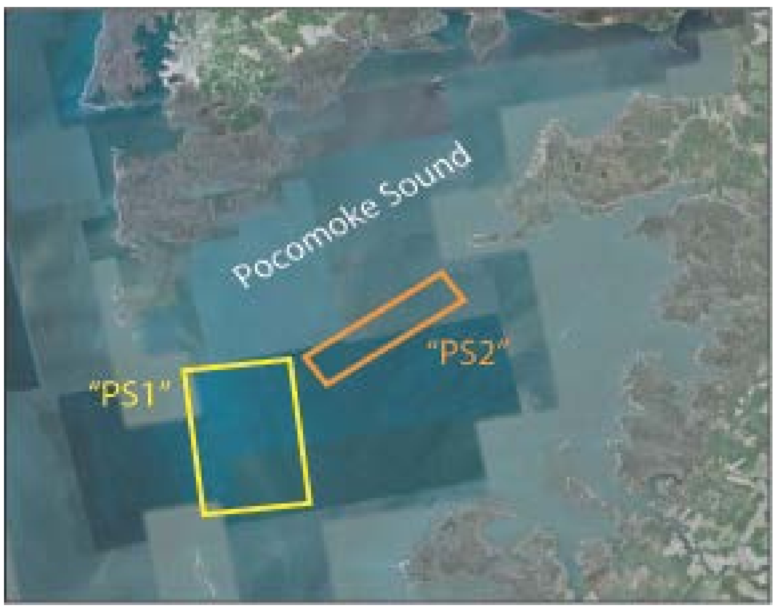
A discontinuous layer of sand (~6 ft thick) is also present in the northern region and looks very similar acoustically to the buried FOS (Figure 21). Overall, the sand tends to be more discontinuous than the buried FOS, is never elevated above the surrounding reflection surfaces, and often other reflection surfaces are visible below the sand layer, aiding in distinguishing sand from FOS in this region. Modern shell beds were also observed in the northern third of Tangier immediately adjacent to several buried FOS beds (Figure 20). The remainder of the site is characterized by extensive laminations of muddy sands and clays, as well as a few preserved channel sequences and discontinuous layers of coarse-grained shell hash (Figure 20). Of the 18 cores collected at Tangier, 6 of them included buried FOS. Individual shell pieces at this site average 0.8 in. in length and shell pieces showed significant variation in size in each sample (~0.3 to 1.3 in.).

Based on these six samples, the buried FOS at Tangier averages 1.5 ft thick and contains ~28% shell. The total mapped volume of the buried FOS from the sub-bottom data indicates Tangier contains a minimum of 175,550 ft^3 of FOS, of which at least 49,650 ft^3 is shell material.

3.7 Pocomoke Sound, Chesapeake Bay

The study region in the greater Pocomoke Sound was broken into two separate subregions: PS1 and PS2 (Figure 22). For ease of explanation, PS1 will be presented separately from PS2.

Figure 22. Location of the PS1 and PS2 regions of the Pocomoke Sound study site.



3.7.1 PS1 Region – Pocomoke Sound

Water depths at the PS1 portion of Pocomoke Sound range from -3 ft to -9 ft MLLW along the western shoals and gradually deepen to up to -13 ft MLLW in the deeper sounds to the east (Figure 23). Despite collecting over 41 miles of sub-bottom data and 12 cores, no buried FOS regions were mapped in the PS1 region. Overall, muddy sediment in the shallower, northwestern portion of the site gave way to laminated sediments which dominated the rest of the region (Figure 24). Several extensive buried channel sequences were noted at this site as well (Figure 24). Although no FOS was mapped here, a single bed of buried clam shell (0.5 ft thick; ~25% shell) was found near the center of the study site (Figures 23, 24). The buried clam shell bed was less than 550 ft in length, was buried at a depth of ~6 ft from the seafloor, and was not mapped in either adjacent survey line. Similar to the acoustic signature of Craney Island NIT 3, several sub-bottom reflection surfaces, including the buried clam shells, could be mistaken for buried FOS under casual observation. This region highlights the need for sediment cores to groundtruth data, as the acoustic nature of buried FOS is site-specific and cannot simply be extrapolated from one region of the Chesapeake Bay and its tributaries to another (Figure 25).

Figure 23. Bathymetry of the PS1 region of Pocomoke Sounds (MLLW). Seismic tracklines are shown in gray, and core sites are plotted as red circles.

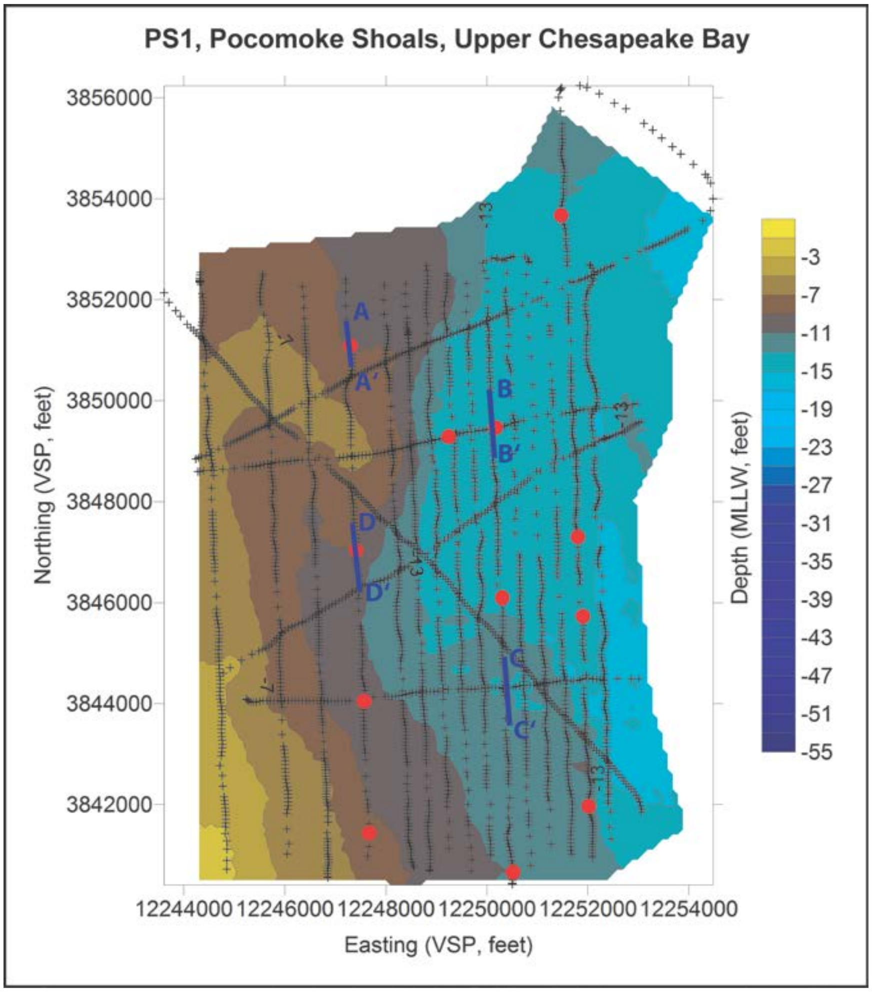


Figure 24. Characteristic acoustic signatures of the PS1 region of Pocomoke Sound. The seafloor reflection surface has been digitized as purple lines. Rectangles represent sediment cores and core log data are available in Appendix. (A) Mud; (B) Laminated sediment; (C) Laminated sediment including extensive buried channel sequences; (D) Buried clam shell as determined via sediment cores.

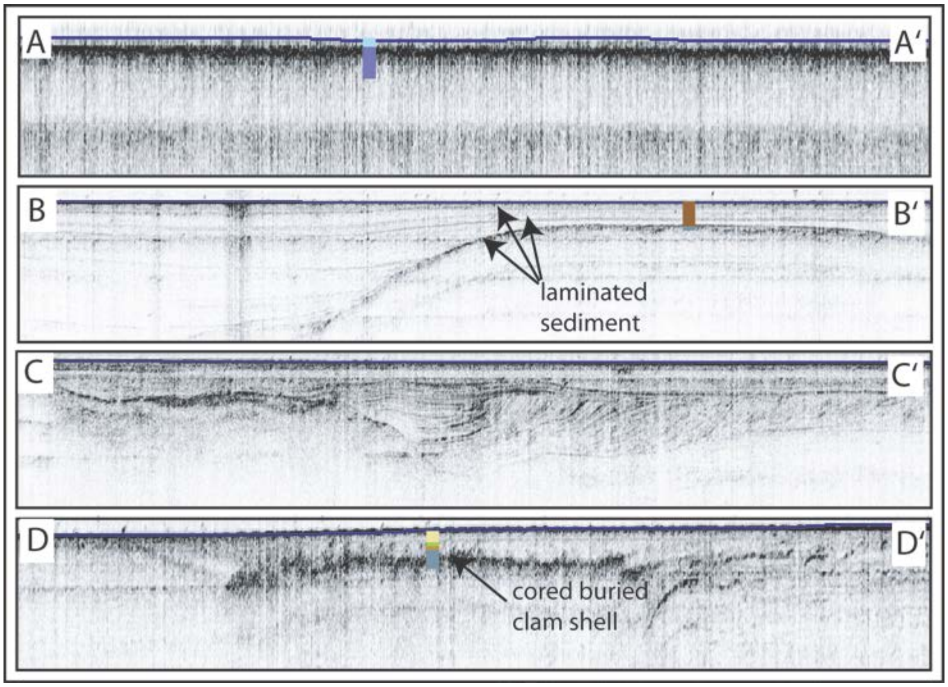
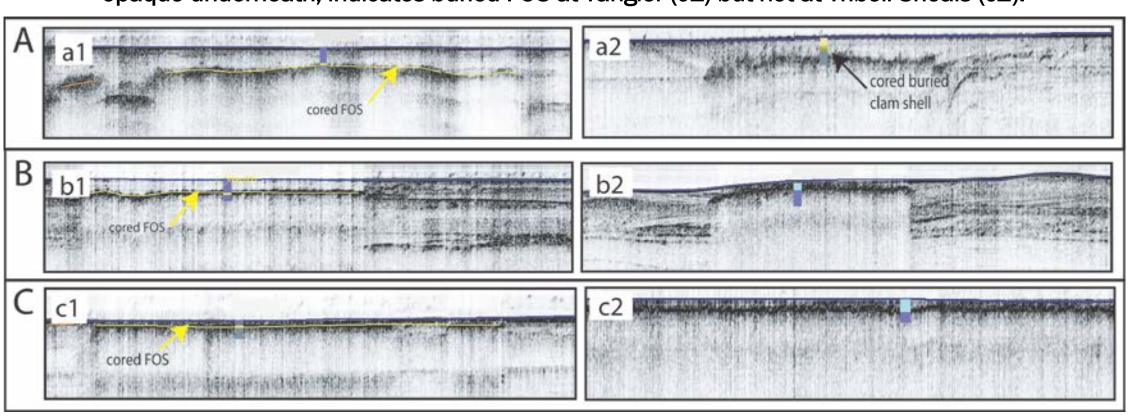


Figure 25. Similar seismic reflection data indicating either buried FOS or no FOS depending on study site. The seafloor reflection surface has been digitized as purple lines. Cored FOS sites are digitized as yellow lines. Rectangles represent sediment cores, and core log data are available in Appendix. (A) Acoustic reflector is smudged, slightly elevated relative to the surrounding reflection surfaces, and opaque underneath. Indicates buried FOS in northern Nansemond Flats (a1) but not in PS1, Pocomoke Sound (a2), although the Poco example is characterized as buried clam shell; (B) Acoustic reflector is sharp, dark, and masks adjacent and underlying laminated reflectors. Indicates buried FOS at Nansemond Flats (b1) but not at Tyler's Beach (b2); (C) Flat-lying, near-surface acoustic reflector, which is sharp, dark, and opaque underneath, indicates buried FOS at Tangier (c1) but not at Tribell Shoals (c2).



3.7.2 PS2 Region – Pocomoke Sound

In contrast to PS1, the survey lines for the PS2 region were mostly found in deeper water (maximum water depth of -21 ft MLLW). The only shoals were seen in the south-southeastern portion of the site, and shoal -depths ranged from -5 to -11 ft MLLW (Figure 26). Thirty-one miles of survey lines groundtruthed by 13 cores indicated one small bed of buried FOS along the edge of the southeastern shoal (Figure 26). The buried FOS was similar in character to that mapped in the southern region of Nansemond Flats, where a sharp, dark reflection surface masks out laminated sediments adjacent and underlying it, but neither the reflection surface nor the seafloor are elevated (Figures 13, 27). In addition, the FOS at PS2 is comprised of a sandy, not muddy, matrix, though it does overlie a unit of mud, similar to the FOS cored throughout the greater study area (Tangier Sounds and James and Rappahannock Rivers). The rest of PS2e is acoustically similar to the PS1 and Tangier Sound sites, with multiple reflection surfaces indicating laminated sediments as well as a few buried channels in most of the deeper water transitioning to primarily muddy sediment on the shoals (Figure 27). Of the 13 cores collected at PS2, only 1 included buried FOS. Individual shell pieces in this sample averaged 0.6 in. in length, and shell pieces showed little variation in size. Based on this single sample, the buried FOS at PS2 is 0.5 ft thick and contains ~12% shell. The total mapped volume of the buried FOS from the sub-bottom data indicates PS2 contains a minimum of 4,900 ft^3 of FOS, of which at least 600 ft^3 is shell material.

Figure 26. Bathymetry of the PS2 region of Pocomoke Sounds (MLLW). Seismic tracklines are shown in gray, and core sites are plotted as red circles. Digitized buried FOS beds are plotted as yellow x's.

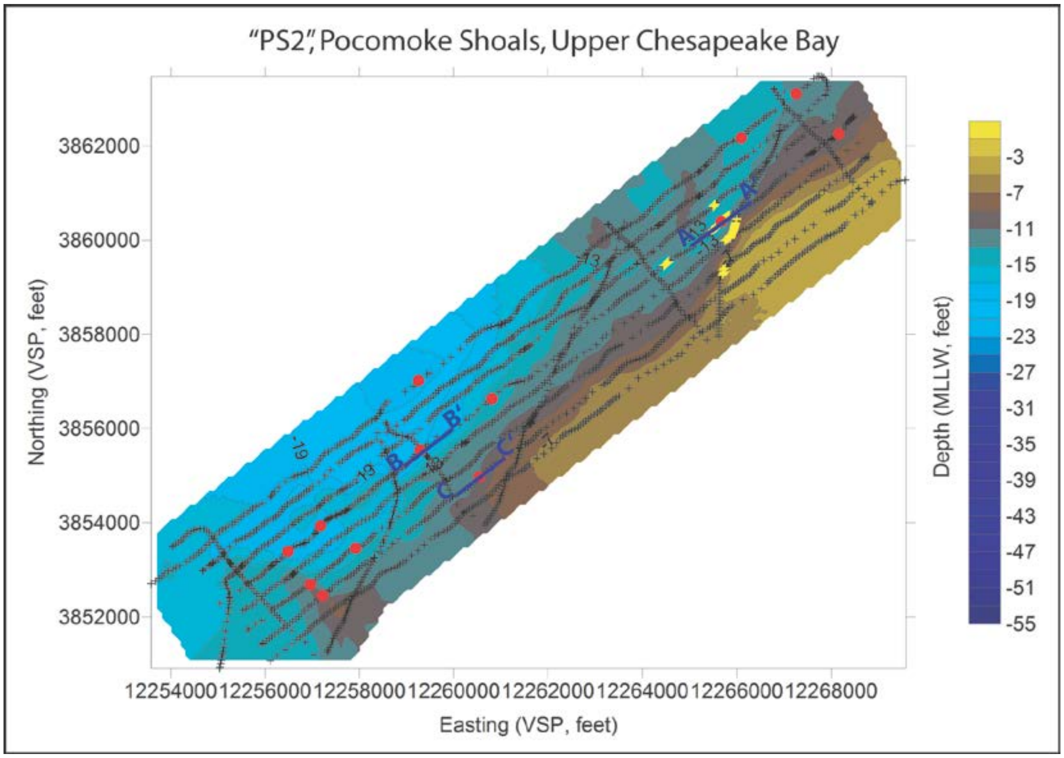
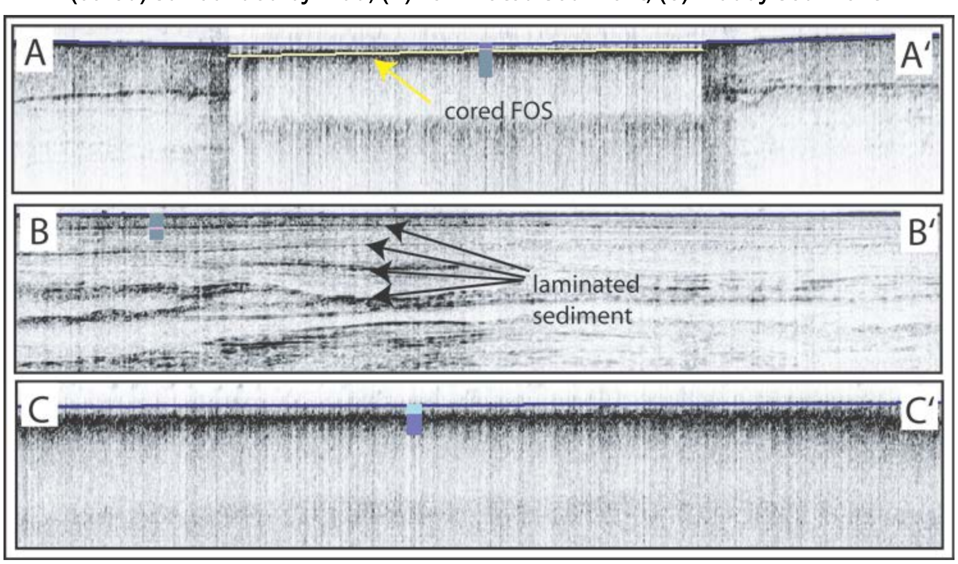


Figure 27. Characteristic acoustic signatures of PS2 region of Pocomoke Sound. The seafloor reflection surface has been digitized as purple lines. Rectangles represent sediment cores, and core log data are available in Appendix. (A) Buried FOS sediment (cored) surrounded by mud; (B) Laminated sediment; (C) Muddy sediment.



4 Discussion

Arguably, the biggest limitation inherent in the methodology used for the seismic analyses is that identifying and digitizing FOS and non-FOS regions require the expertise of a skilled geologist or geophysicist familiar with the processing of seismic data. Interpreting seismic reflection data traditionally entails (1) visual examination of every seismic line collected, (2) interpretation of the reflection surfaces using sediment core data, and (3) hand digitization of pertinent reflection surfaces. This method is not only time consuming, but the knowledge needed to properly interpret the both the geophysical data and the sediment cores requires years of training and familiarity with a wide range of seismic reflection data. The interpretations are also subjective in that, where acoustic signatures of buried FOS and non-FOS are very similar, the distinction between them must be made by an individual’s best judgment. Note that proper training and experience yields very robust and defendable seismic interpretations. However, to possibly expand on the methodology to allow interpretation to be made by less-experienced individuals, this study developed a first-order quantitative methodology for identifying buried FOS in seismic reflection data at one site, Tyler’s Beach, in the upper James River.

The seismic amplitude of FOS regions consistently showed the highest spikes in amplitude at depths consistent with the depth to the FOS as indicated by the seismic profiles and the sediment cores. An FOS example from Tyler’s Beach is shown in Figure 28. The upper panel shows seismic amplitude plotted against two-way travel time, which serves as a rough approximation of depth below the seafloor. The highest amplitude in this location (~12000) is found at -3 msec, with comparatively low amplitudes above and below the spike (Figure 28). The lower panel shows the location of the actual ping used to generate the amplitude plot on the relevant seismic line. The only strong reflection surface seen at this location is the buried FOS layer, the top of which is interpreted to start ~3 ft below the seafloor (Figure 28). The presence of gas in muddy sediment, however, also generated a strong spike in amplitude (~13000; Figure 29), similar to that associated with buried FOS. In addition, changes in stratigraphy, such as alternating layers of muddy sand and soft mud, generated spikes in amplitude of the same strength or higher as spikes associated with buried FOS and/or gas (Figure 30). Ultimately, there was no clear relationship between the total weight percent shell at a specific site and the seismic amplitude of the layers below the seabed at Tyler’s Beach (Figure 31).

Figure 28. Seismic amplitude vs. sub-bottom image for buried FOS region. (A) Amplitude vs. travel time (proxy for depth); (B) Exact location of seismic ping (red vertical line) from which amplitude data in (A) are extracted. Red arrow indicates the distance between the seafloor and the FOS reflection surface as calculated using SonarWiz. Rectangle indicates location of sediment core (data available in Appendix).

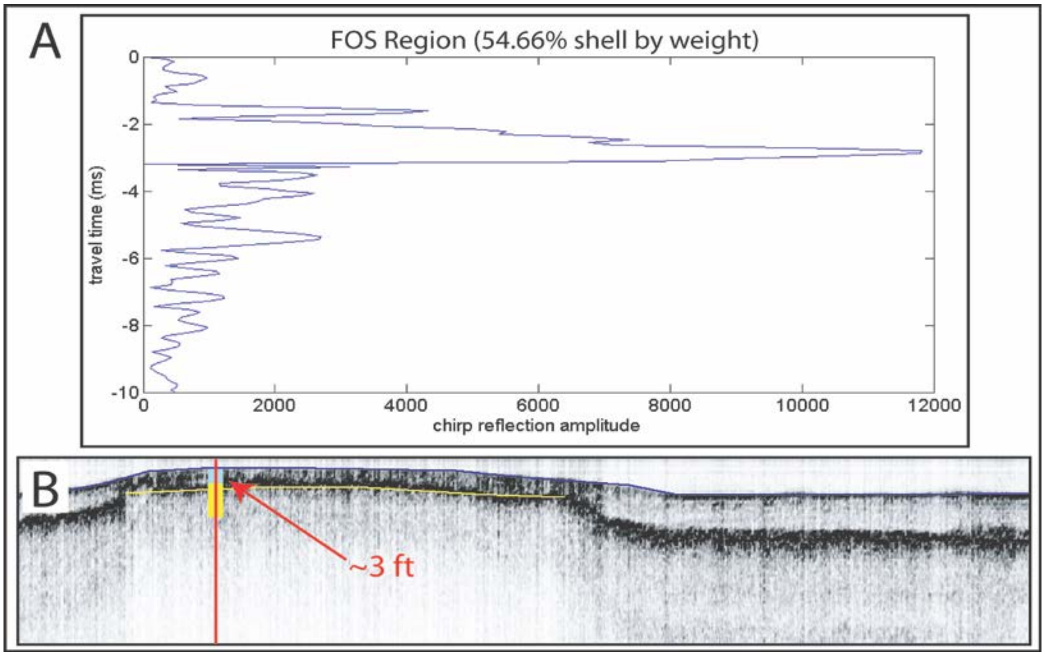


Figure 29. Seismic amplitude vs. sub-bottom image for gas-rich region. (A) Amplitude vs. travel time (proxy for depth); (B) Exact location of seismic ping (red vertical line) from which amplitude data in (A) are extracted. Yellow and orange digitized lines indicate cored and interpreted FOS regions, respectively. Red arrow indicates distance between the seafloor and the top of the interpreted gas-rich reflection surface as calculated using SonarWiz. Rectangle indicates location of sediment core (data available in Appendix).

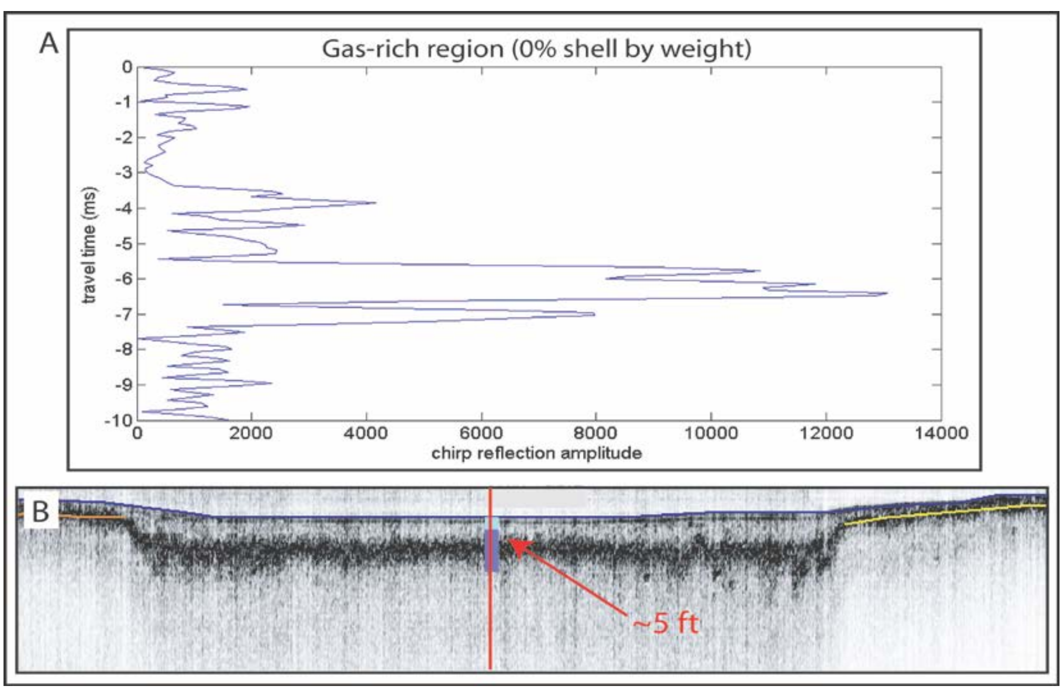


Figure 30. Seismic amplitude vs. sub-bottom image for laminated region. (A) Amplitude vs. travel time (proxy for depth); (B) Exact location of seismic ping (red vertical line) from which amplitude data in (A) are extracted. Rectangle indicates location of sediment core (data available in Appendix). Red arrow indicates the total distance between the seafloor and each subsequent reflection surface, at the location of the red vertical line and plotted in (A), as calculated using SonarWiz. Yellow box indicates region digitized in SonarWiz; (C) Seismic line plotted in (B) but with individually digitized reflection surfaces plotted as black lines in SonarWiz and interpreted to be interlaminated mud and muddy sands.

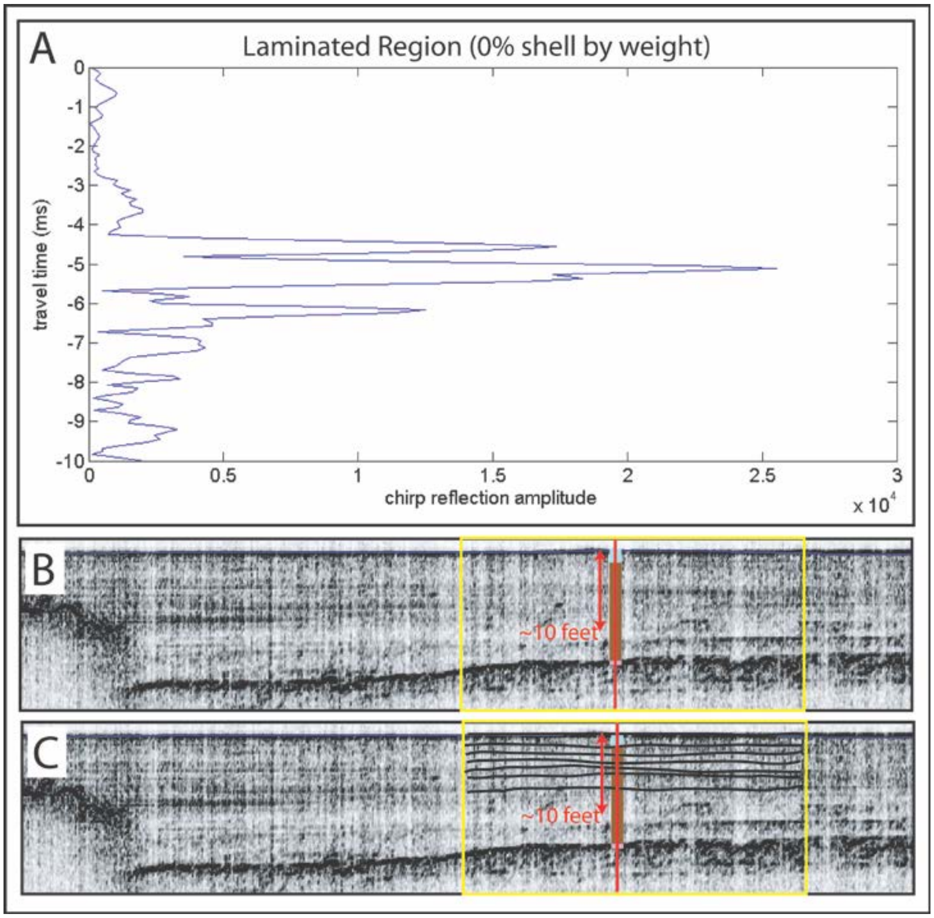
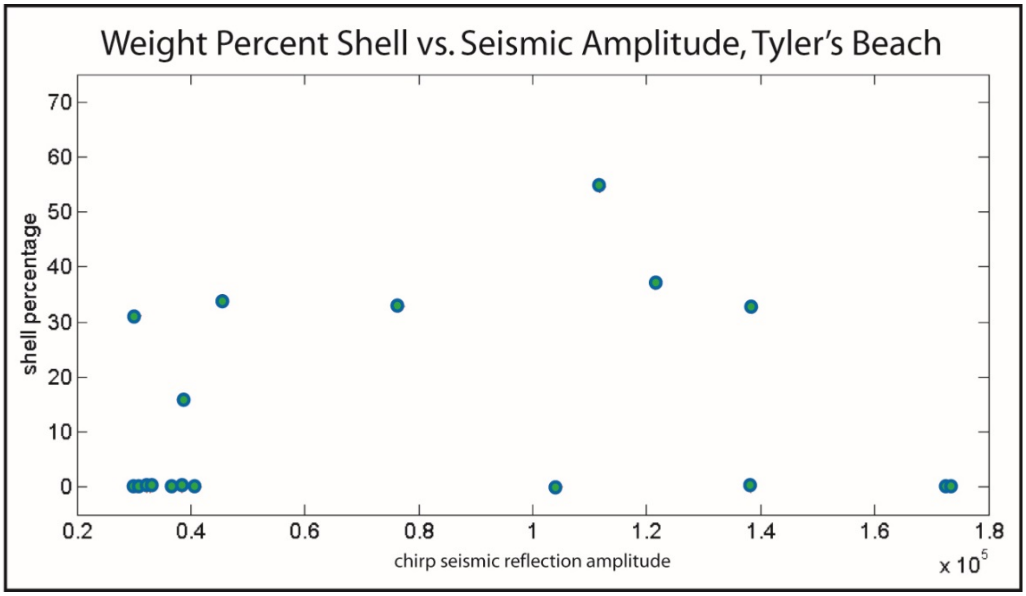


Figure 31. Total weight percent shell vs. seismic amplitude for Tyler's Beach.

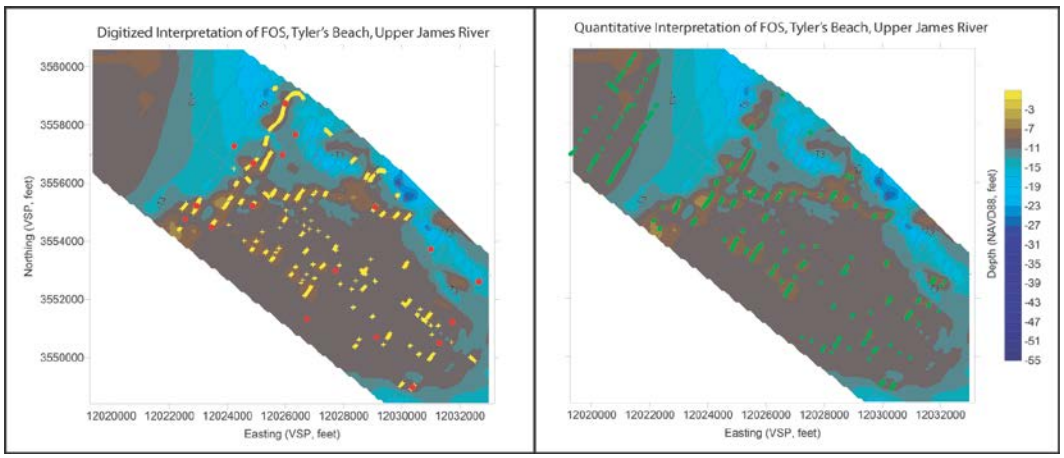


Nevertheless, a quantitative identification of buried FOS was still obtainable for Tyler's Beach by empirically adjusting the search algorithms used for the region. Regions were identified as FOS from the seismic data alone by finding areas that (1) had high reflection amplitudes at the top of the shell-seabed interface (Figure 31), (2) decreased in depth below the seafloor (i.e., raised mound above the seafloor; Figure 28), and (3) had a greatly attenuated reflection amplitude below the FOS reflection surface.

To quantify how well the Matlab quantification method identified shell when present, the total number of FOS digitized points entered by hand were compared to the total number of FOS digitized points created via Matlab. For this exercise, the hand-digitized locations of FOS were held as *true*. If a Matlab-identified FOS location was found within 100 m (~330 ft) of a hand-digitized FOS location, the Matlab location was identified as a true FOS location. Where Matlab identified FOS but hand digitization did not, the Matlab location was flagged as a false positive. Where Matlab failed to identify FOS compared to the hand-digitized locations, the location was noted to be a false negative.

The Matlab method generated significantly more FOS-digitized locations (2775 points) than generated via hand digitization (439 points) because (1) Matlab identified a point as FOS or not FOS every 100 m (~330 ft) along a given seismic line and (2) the Matlab method includes incorrect FOS locations. In contrast, the hand-digitization method generates a FOS point at a random, and usually larger, spacing interval and does not generate any points at non-FOS locations. Of the 2775 Matlab-generated FOS locations, 400 points were determined to be false positives, meaning Matlab incorrectly identified FOS where it was not, 14% of the time. Likewise, Matlab did not identify FOS within 100 m (~330 ft) of 138 digitized FOS locations, meaning Matlab missed FOS locations 5% of the time. Overall, 79% of the Matlab-identified FOS locations were verified as *correct* compared to the hand-digitization method. From these empirical-based rules, a post map of buried FOS was generated for Tyler's Beach using the Matlab algorithms. Overall, the location and water depth of mapped FOS regions were very similar using the quantitative method to those mapped via hand digitizing (Figure 32).

Figure 32. Digitized (yellow x's) vs. quantitative (green x's) interpretations of buried FOS locations at Tyler's Beach.



The greatest difference between the two methods was in the far northwest corner of the site. Here, the Matlab method indicated substantial FOS regions. Core and seismic data, however, indicate this region is characterized by gas-rich mud, and no buried FOS regions were found using traditional methods. The gas-rich seismic reflection surface in this region, however, was found much closer to the seafloor, similar to the depth to buried FOS, which might account for the error in the quantitative method. Although a simple relationship between seismic amplitude and the presence of buried FOS was not found, the results suggest that empirically tuning a general search algorithm to the geologic characteristics of a specific site yields defensible results and potentially reduces the amount of time-consuming hand digitization needed to interpret a region.

5 Conclusions

- Over 230 miles of acoustic sub-bottom (seismic) data and 117 sediment cores were collected in seven regions of the Chesapeake Bay and its tributaries to develop a field observational approach for identifying buried oyster shell.
- Field techniques are ultimately challenging and must be undertaken by an experienced geophysical surveyor. Although seismic data are collected with off-the-shelf equipment and software, experience in collecting seismic data is critical for correctly setting the various acquisition parameters to ensure accurate mapping of the FOS in a given region. In addition, the combination of small vessel size (to allow access to shallow regions) and heavy seismic equipment requires a crew with extensive small-boat, shallow-water experience.
- Traditional methods of seismic interpretation were able to successfully identify buried FOS regions throughout the geologically complex study area.
- The acoustic nature of buried FOS is site specific and requires groundtruthing and geologic expertise to identify in the seismic data.
- Buried FOS regions range from 1 to 3 ft in thickness, are located from 2 to 8 ft below the seafloor and are comprised of 12% to 55% shell.
- Overall, the seven sites contain a minimum of ~877,300 ft^3 of buried FOS sediment, of which a minimum of 287,650 ft^3 is shell material. These values should be considered minimum estimates, however, due to the following factors:
  - Shell area is based on mapped area only and does not include any area of FOS likely found between mapped FOS regions on adjacent survey lines.
  - Percent shell is based on a weight percentage of recovered shell, and shell material was not assessed for quality or suitability for future reef building efforts.
  - The methodology used to collect the sediment samples likely undersampled the total shell material present in a FOS region, resulting in an underestimate of total available shell at a given site.
- The methodology for this study, both geophysical and coring, was designed to quantify the shallow (usually within ~15 ft from the surface) extent of FOS at all of the sites. It is possible that the FOS at any one site is much thicker than described here. Additional sub-

bottom surveys using different acoustic frequencies supported by deeper coring efforts could quantify the total deep (within 30 to 50 ft of the surface) extent of buried FOS at any one site.

- A purely quantitative assessment of acoustic data is possible but empirical and must be tuned from site to site.
- It is recommended that a combination of geologic digitizing and quantitative assessment is used to identify buried FOS regions in future seismic studies. In addition, final interpretations should be reviewed by an independent expert or panel of experts.

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Appendix

This appendix contains sediment data in the form of three tables used in the preparation of this report.

Table A-1. Core data for all sites. Core IDs include letter designations for each site and the core number. Letter designations are as follows: MB = McKan's Bay; TB = Tyler's Beach; TS = Tribell Shoals; CRNY = Craney Island (includes NIT 1, 2, 3); NF = Nansemond Flats; TANG = Tangier; PO = "Poco" Pocomoke Sounds; MK = "Moke" Pocomoke Sounds. Descriptions of the sediment units are provided in Table A-2. Shaded rows indicate cores with positively identified fossil shell material. ** Indicates cores where oyster shell was sampled more than once in the core, and an average of the core's weight percent oyster shell was used to calculate the volume of buried fossil oyster shell at that site.

Core ID	Lat		Lon		Units	Thick (ft)	Shell + Sed (g)	Shell (g)	% all shell	% oyster shell	Shell Description / Notes
MB01	37	45.83	76	38.90	FLUID MUD	2.5	0.00	0.00	0.00	0.00	n/a
					OYSTER MUD	1.3	27.80	6.31	22.68	22.68	Oyster, largest ~1.5 cm, fairly uniform range of sizes
					MUD	16	0.00	0.00	0.00	0.00	n/a
					STIFF MUD	18	0.00	0.00	0.00	0.00	n/a
MB02	37	45.68	76	38.63	FLUID MUD	2	0.00	0.00	0.00	0.00	n/a
					MUD	2	0.00	0.00	0.00	0.00	n/a
					OYSTER MUD	0.5	32.76	6.10	18.62	18.62	Oyster, largest ~1.5 cm, most pieces are very tiny
					MUD	7.5	0.00	0.00	0.00	0.00	n/a
					STIFF MUD	8	0.00	0.00	0.00	0.00	n/a
MB03	37	46.21	76	40.57	FLUID MUD	3	0.00	0.00	0.00	0.00	n/a
					MUD	12	0.00	0.00	0.00	0.00	n/a
					STIFF MUD	8	0.00	0.00	0.00	0.00	n/a
MB05	37	46.17	76	39.73	MUD	12	0.00	0.00	0.00	0.00	n/a
MB09	37	45.41	76	40.32	LAMINATED	15	0.00	0.00	0.00	0.00	n/a
MB10	37	46.02	76	39.48	MUD	5	0.00	0.00	0.00	0.00	n/a
					OYSTER MUD	1	25.71	8.76	34.07	34.07	Oyster, largest ~2 cm, most pieces are smaller
					STIFF MUD	3	0.00	0.00	0.00	0.00	n/a
MB11	37	45.79	76	39.75	MUD	3	0.00	0.00	0.00	0.00	n/a
					OYSTER MUD	1	29.07	9.11	31.33	31.33	Oyster, largest ~2 cm, fairly uniform size range
					MUD	8	0.00	0.00	0.00	0.00	n/a
MB12	37	46.05	76	40.69	MUD	3	0.00	0.00	0.00	0.00	n/a
					STIFF MUD	9	0.00	0.00	0.00	0.00	n/a
MB15	37	45.90	76	39.68	MUD	8	0.00	0.00	0.00	0.00	n/a
MB18	37	45.46	76	38.37	MUD	3	0.00	0.00	0.00	0.00	n/a

Core ID	Lat		Lon		Units	Thick (ft)	Shell + Sed (g)	Shell (g)	% all shell	% oyster shell	Shell Description / Notes
					OYSTER MUD	1	33.67	10.36	30.78	30.78	Oyster, largest ~1.5 cm, fairly uniform size range
					STIFF MUD	4	0.00	0.00	0.00	0.00	n/a
MB20	37	46.09	76	39.72	MUD	3	0.00	0.00	0.00	0.00	n/a
					OYSTER MUD	1	26.65	8.68	32.57	32.57	Oyster, largest ~2 cm, fairly uniform size range
					STIFF MUD	4	0.00	0.00	0.00	0.00	n/a
MB25	37	45.71	76	40.04	FLUID MUD	3	0.00	0.00	0.00	0.00	n/a
					OYSTER MUD	2	18.46	7.17	38.85	38.85	Oyster, largest ~2 cm, fairly uniform size range
					MUD	10	0.00	0.00	0.00	0.00	n/a
TB01	37	3.66	76	37.14	FLUID MUD	3	0.00	0.00	0.00	0.00	n/a
					LAMINATED	21	34.74	6.42	18.47	0.00	mostly *chesapectins;* some very old, friable oyster
					GRAVEL	1	0.00	0.00	0.00	0.00	n/a
TB02	37	3.54	76	37.24	MUD	16	0.00	0.00	0.00	0.00	n/a
TB03	37	3.29	76	37.43	MUD	3	0.00	0.00	0.00	0.00	n/a
					OYSTER MUD	1	27.76	10.28	37.02	37.02	Oyster, largest ~3 cm, fairly uniform size range
					MUD	2	0.00	0.00	0.00	0.00	n/a
TB04	37	3.88	76	39.94	FLUID MUD	2.5	0.00	0.00	0.00	0.00	n/a
					STIFF MUD	8	0.00	0.00	0.00	0.00	n/a
TB05	37	4.07	76	37.28	FLUID MUD	2.5	0.00	0.00	0.00	0.00	n/a
					MUD	7	0.00	0.00	0.00	0.00	n/a
TB06	37	3.58	76	37.68	FLUID MUD	2.5	0.00	0.00	0.00	0.00	n/a
					MUD	7	0.00	0.00	0.00	0.00	n/a
TB07	37	3.69	76	38.17	FLUID MUD	5.5	0.00	0.00	0.00	0.00	n/a
					MUD	5	0.00	0.00	0.00	0.00	n/a
TB08	37	3.96	76	37.96	MUD	9.5	0.00	0.00	0.00	0.00	n/a
TB09	37	4.32	76	37.67	MUD	5.5	0.00	0.00	0.00	0.00	n/a
					OYSTER MUD	1.5	33.87	10.57	31.22	31.22	Oyster, largest ~2.5 cm, fairly uniform size range
					MUD	6.5	0.00	0.00	0.00	0.00	n/a
TB10	37	4.93	76	38.28	MUD	4.5	0.00	0.00	0.00	0.00	n/a
					OYSTER MUD	3	57.89	19.01	32.84	32.84	Oyster, largest ~3 cm, fairly uniform size range
					STIFF MUD	4	0.00	0.00	0.00	0.00	n/a
TB11	37	4.22	76	38.83	FLUID MUD	3.5	0.00	0.00	0.00	0.00	n/a
					MUD	7	0.00	0.00	0.00	0.00	n/a
TB12	37	4.60	76	38.51	MUD	3.5	0.00	0.00	0.00	0.00	n/a

Core ID	Lat		Lon		Units	Thick (ft)	Shell + Sed (g)	Shell (g)	% all shell	% oyster shell	Shell Description / Notes
					OYSTER MUD	2	35.22	11.88	33.74	33.74	Oyster, largest ~3 cm, fairly uniform size range
					MUD	6	0.00	0.00	0.00	0.00	n/a
TB13	37	4.74	76	38.22	MUD	14	0.00	0.00	0.00	0.00	n/a
					OYSTER SAND	2	47.05	7.42	15.78	15.78	Oyster, largest ~3.5 cm, fairly uniform size range
					CLEAN SAND	4	0.00	0.00	0.00	0.00	n/a
TB14	37	4.68	76	38.67	MUD	10.5	0.00	0.00	0.00	0.00	n/a
TB15	37	4.37	76	38.93	MUD	2	0.00	0.00	0.00	0.00	n/a
					OYSTER MUD	1.5	30.02	9.81	32.68	32.68	Oyster, largest ~1.5 cm, fairly large size range
					STIFF MUD	2.5	0.00	0.00	0.00	0.00	n/a
TB16	37	4.27	76	39.01	FLUID MUD	3	0.00	0.00	0.00	0.00	n/a
					MUD	10	0.00	0.00	0.00	0.00	n/a
TB17	37	4.62	76	38.32	MUD	7.5	0.00	0.00	0.00	0.00	n/a
TB18	37	4.35	76	38.52	FLUID MUD	1	0.00	0.00	0.00	0.00	n/a
					MUD	2	0.00	0.00	0.00	0.00	n/a
					OYSTER MUD	7	45.63	24.94	54.66	54.66	Oyster, largest ~6 cm, very large size range
TS01	37	12.41	76	38.81	MOD OYSTER	3	41.24	33.77	81.89	81.89	Oyster, largest ~3 cm, large size range
TS02	37	12.37	76	38.74	MUD	5	0.00	0.00	0.00	0.00	n/a
TS03	39	12.12	76	38.81	FLUID MUD	2	0.00	0.00	0.00	0.00	n/a
					MUD	6	0.00	0.00	0.00	0.00	n/a
TS04	37	11.57	76	37.76	STIFF MUD	1	0.00	0.00	0.00	0.00	n/a
					OYSTER MUD	2	73.21	23.84	32.56	32.56	Oyster, largest ~3 cm, large size range
TS05	37	10.82	76	37.55	FLUID MUD	4	0.00	0.00	0.00	0.00	n/a
					MUD	3	0.00	0.00	0.00	0.00	n/a
TS06	37	10.25	76	37.38	STIFF MUD	3	0.00	0.00	0.00	0.00	n/a
					LAMINATED	8	0.00	0.00	0.00	0.00	n/a
					CLEAN SAND	1.3	0.00	0.00	0.00	0.00	n/a
TS07	37	10.72	76	37.72	MUD	6	0.00	0.00	0.00	0.00	n/a
					SILTY SAND	1.5	0.00	0.00	0.00	0.00	n/a
					STIFF MUD	2	0.00	0.00	0.00	0.00	n/a
TS08	37	13.02	76	39.88	MUD	8	0.00	0.00	0.00	0.00	n/a
TS09	37	12.85	76	39.29	SILTY SAND	2	0.00	0.00	0.00	0.00	n/a
					MUD	6	0.00	0.00	0.00	0.00	n/a
TS10 **	37	11.70	76	37.84	MUD	2	0.00	0.00	0.00	0.00	n/a
					OYSTER MUD	3	31.92	11.83	37.06	37.06	Oyster, largest ~3 cm, fairly uniform size range
							18.74	7.45	39.74	39.74	Oyster, largest ~3 cm, large size range
					MUD	2	0.00	0.00	0.00	0.00	n/a

Core ID	Lat		Lon		Units	Thick (ft)	Shell + Sed (g)	Shell (g)	% all shell	% oyster shell	Shell Description / Notes
TS11	37	11.10	76	37.53	MUD	5	0.00	0.00	0.00	0.00	n/a
					SILTY SAND	1	0.00	0.00	0.00	0.00	n/a
					STIFF MUD	4	0.00	0.00	0.00	0.00	n/a
TS12	37	12.31	76	38.76	MUD	2.5	0.00	0.00	0.00	0.00	n/a
					SHELL HASH	3.5	0.00	0.00	0.00	0.00	n/a
					MUD	4	0.00	0.00	0.00	0.00	n/a
TS13	37	10.72	76	37.72	FLUID MUD	2	0.00	0.00	0.00	0.00	n/a
					MUD	6	0.00	0.00	0.00	0.00	n/a
TS14	37	12.80	76	39.52	MUD	9	0.00	0.00	0.00	0.00	n/a
CRNY01	36	55.93	76	22.98	FLUID MUD	4	0.00	0.00	0.00	0.00	n/a
					MUD	6	0.00	0.00	0.00	0.00	n/a
					LAMINATED	6	0.00	0.00	0.00	0.00	n/a
CRNY02	36	56.22	76	21.35	FLUID MUD	2	0.00	0.00	0.00	0.00	n/a
					MUD	9	0.00	0.00	0.00	0.00	n/a
CRNY04	36	55.78	76	23.34	MUD	9	0.00	0.00	0.00	0.00	
					OYSTER SAND	0.3	14.48	1.58	10.91	10.91	Only 1 oyster shell in sample, 1.5 cm long
					STIFF MUD	3	0.00	0.00	0.00	0.00	
CRNY05	36	56.32	76	21.23	FLUID MUD	3	0.00	0.00	0.00	0.00	n/a
					MUD	9	0.00	0.00	0.00	0.00	n/a
CRNY07	36	56.06	76	23.34	MUD	5	0.00	0.00	0.00	0.00	n/a
					SILTY SAND	0.2	0.00	0.00	0.00	0.00	n/a
					STIFF MUD	6	0.00	0.00	0.00	0.00	n/a
CRNY08	36	55.91	76	22.14	MUD	11	0.00	0.00	0.00	0.00	n/a
					SILTY SAND	0.4	0.00	0.00	0.00	0.00	n/a
					STIFF MUD	3.6	0.00	0.00	0.00	0.00	n/a
CRNY09	36	55.91	76	21.83	MUD	9	0.00	0.00	0.00	0.00	n/a
CRNY10	36	54.39	76	20.61	FLUID MUD	1.5	0.00	0.00	0.00	0.00	n/a
					OYSTER MUD	2	24.71	9.37	37.92	37.92	Oyster, largest ~3cm, large size range
					OYSTER MUD		30.00	14.31	47.68	47.68	Mostly oyster, largest ~2.5 cm, fairly uniform size range, one clam shell found
											Average of two percentages used for plot
					STIFF MUD	4	0.00	0.00	0.00	0.00	n/a
CRNY11	36	54.42	76	20.72	MUD	6	0.00	0.00	0.00	0.00	n/a
					OYSTER MUD	0.5	0.00	0.00	0.00	0.00	Shell content too small to sample
					STIFF MUD	1.5	0.00	0.00	0.00	0.00	n/a
CRNY12	36	54.64	76	20.49	MUSSEL SAND	2	29.41	3.51	11.92	0.00	Mussel shells, largest ~2 cm
					STIFF MUD	5	0.00	0.00	0.00	0.00	n/a
CRNY13	36	54.67	76	20.51	FLUID MUD	1	0.00	0.00	0.00	0.00	n/a
					MUD	14	0.00	0.00	0.00	0.00	n/a
CRNY14	36	54.14	76	20.37	MUD	6	0.00	0.00	0.00	0.00	n/a
					SILTY SAND	4	0.00	0.00	0.00	0.00	n/a
					STIFF MUD	2	0.00	0.00	0.00	0.00	n/a
CRNY15	36	54.50	76	20.70	MUD	7	0.00	0.00	0.00	0.00	n/a

Core ID	Lat		Lon		Units	Thick (ft)	Shell + Sed (g)	Shell (g)	% all shell	% oyster shell	Shell Description / Notes
					OYSTER MUD	1	0.00	0.00	0.00	0.00	Shell content too small to sample
					MUD	6	0.00	0.00	0.00	0.00	n/a
					OYSTER MUD	0.5	0.00	0.00	0.00	0.00	Shell content too small to sample
					MUD	3	0.00	0.00	0.00	0.00	n/a
CRNY17	36	53.81	76	19.76	MUD	4.5	0.00	0.00	0.00	0.00	n/a
					OYSTER MUD	1.5	39.20	16.55	42.23	42.23	Oyster, largest ~2.5 cm, fairly uniform size range
					MUD	5.5	0.00	0.00	0.00	0.00	n/a
CRNY18	36	54.15	76	19.67	SILTY SAND	7	0.00	0.00	0.00	0.00	n/a
CRNY19	36	53.84	76	19.95	MUD	13.5	0.00	0.00	0.00	0.00	n/a
NF01	36	55.11	76	25.36	MUD	4.5	0.00	0.00	0.00	0.00	n/a
					OYSTER_MUD	1	33.25	15.29	45.99	45.99	Oyster, largest ~3 cm, very large size range. Some small shell lost
					MUD	5	0.00	0.00	0.00	0.00	n/a
NF02	36	55.15	76	25.28	MUD	8	26.84	3.06	11.41	11.41	Very little oyster recovered, most smaller than 2 cm
					SILTY_SAND	1	0.00	0.00	0.00	0.00	n/a
					STIFF_MUD	4	0.00	0.00	0.00	0.00	n/a
NF03	36	54.94	76	25.36	MUD	6	0.00	0.00	0.00	0.00	n/a
					OYSTER_MUD	1			N/A	0.00	shell sample was not saved
					MUD	3	0.00	0.00	0.00	0.00	n/a
NF04	36	54.91	76	25.29	MUD	5	0.00	0.00	0.00	0.00	n/a
					OYSTER_MUD	1	29.77	13.34	44.81	44.81	Oyster, largest ~3 cm, very large size range; some small shell lost
					STIFF_MUD	4	0.00	0.00	0.00	0.00	n/a
NF05	36	55.79	76	25.42	MUD	15	0.00	0.00	0.00	0.00	n/a
NF06	36	55.22	76	26.52	FLUID_MUD	3	0.00	0.00	0.00	0.00	n/a
					MUD	15	0.00	0.00	0.00	0.00	n/a
NF07	36	55.15	76	26.63	FLUID_MUD	3.5	0.00	0.00	0.00	0.00	n/a
					MUD	13	0.00	0.00	0.00	0.00	n/a
NF08	36	54.96	76	26.97	FLUID_MUD	4	0.00	0.00	0.00	0.00	n/a
					MUD	7	0.00	0.00	0.00	0.00	n/a
NF09	36	55.72	76	27.05	MUD	7.5	0.00	0.00	0.00	0.00	n/a
					SHELL HASH	2.5	0.00	0.00	0.00	0.00	Sample saved - classic coarse-grained shell hash
					STIFF_MUD	3.5	0.00	0.00	0.00	0.00	n/a
NF10	36	55.46	76	26.97	MUD	5	0.00	0.00	0.00	0.00	n/a
					OYSTER_MUD	1	25.85	11.92	46.12	46.12	Oyster, largest ~3 cm, very large size range; some small shell lost
					STIFF_MUD	4	0.00	0.00	0.00	0.00	n/a

Core ID	Lat		Lon		Units	Thick (ft)	Shell + Sed (g)	Shell (g)	% all shell	% oyster shell	Shell Description / Notes
NF11	36	55.52	76	27.23	SHELL HASH	2	0.00	0.00	0.00	0.00	Sample saved - classic coarse-grained shell hash
					MUD	20	0.00	0.00	0.00	0.00	n/a
NF12	36	55.78	76	25.74	MUD	7	0.00	0.00	0.00	0.00	n/a
					STIFF_MUD	7	0.00	0.00	0.00	0.00	n/a
NF13	36	56.24	76	27.26	MUD	5.5	0.00	0.00	0.00	0.00	n/a
					OYSTER_MUD	1.2	36.57	10.49	28.67	28.67	Oyster, largest ~2 cm, very large size range; some small shell lost
					STIFF_MUD	2	0.00	0.00	0.00	0.00	n/a
NF14	36	56.30	76	27.44	MUD	5	0.00	0.00	0.00	0.00	n/a
					STIFF_MUD	8					
TANG01	37	56.83	75	58.54	STIFF MUD	3	0.00	0.00	0.00	0.00	n/a
					MUD	7	0.00	0.00	0.00	0.00	n/a
TANG02	37	56.77	75	58.53	MUD	8	0.00	0.00	0.00	0.00	n/a
TANG03	37	56.15	75	58.54	OYSTER MUD	2	39.37	5.92	15.03	15.03	Oyster, largest ~1 cm, fairly uniform size range
					MUD	4	0.00	0.00	0.00	0.00	n/a
TANG04	37	55.95	75	58.53	MUD	2	0.00	0.00	0.00	0.00	n/a
					OYSTER MUD	1.5	22.46	4.16	18.53	18.53	Oyster, largest ~2.5 cm, large size range
					STIFF MUD	6	0.00	0.00	0.00	0.00	n/a
TANG05	37	54.98	75	58.54	SILTY SAND	4	0.00	0.00	0.00	0.00	n/a
					SHELL HASH	1	11.75	0.55	4.67	0.00	Mostly small hash with one large (2 cm) clam shell fragment
					CLEAN SAND	6	0.00	0.00	0.00	0.00	n/a
TANG06	37	55.55	75	58.54	MUD	2	0.00	0.00	0.00	0.00	n/a
					OYSTER MUD	1	24.30	5.33	21.95	21.95	Oyster, largest ~1.5 cm, some variation in size range
					SULFUR MUD	8	0.00	0.00	0.00	0.00	n/a
TANG07	37	53.32	75	58.52	STIFF MUD	9	0.00	0.00	0.00	0.00	n/a
TANG08	37	53.66	75	58.86	SHELL HASH	1	9.89	0.53	5.41	0.00	Mostly small clam hash
					STIFF MUD	9	0.00	0.00	0.00	0.00	n/a
TANG09	37	54.78	75	58.87	LAMINATED	10	0.00	0.00	0.00	0.00	n/a
TANG10	37	56.07	75	58.87	MUD	2	0.00	0.00	0.00	0.00	n/a
					OYSTER MUD	1	28.74	11.91	41.45	41.45	Oyster, largest ~2 cm, large size range
					STIFF MUD	4	0.00	0.00	0.00	0.00	n/a
TANG11	37	56.39	75	58.88	SULFUR MUD	1	0.00	0.00	0.00	0.00	n/a
					MUD	9	0.00	0.00	0.00	0.00	n/a
TANG12	37	56.68	75	58.87	SILTY SAND	2	0.00	0.00	0.00	0.00	n/a

Core ID	Lat		Lon		Units	Thick (ft)	Shell + Sed (g)	Shell (g)	% all shell	% oyster shell	Shell Description / Notes
					SHELL HASH	0.3	14.32	2.69	18.80	18.80	Mostly small hash with one large (3 cm) clam shell fragment & 1 large (2 cm) oyster fragment
					STIFF MUD	5	0.00	0.00	0.00	0.00	n/a
TANG13	37	55.99	75	58.21	SULFUR MUD	2.5	0.00	0.00	0.00	0.00	n/a
					STIFF MUD	7	0.00	0.00	0.00	0.00	n/a
TANG14	37	56.75	75	58.22	MUD	21	0.00	0.00	0.00	0.00	n/a
TANG15 **	37	56.70	75	58.20	SHELL HASH	0.5	12.09	7.81	64.62	64.62	Shell hash mixed with oyster shell, largest ~1.5 cm, large size range
					OYSTER MUD	2.5	20.39	7.99	39.18	39.18	Oyster, largest ~2 cm, large size range
					MUD	3	0.00	0.00	0.00	0.00	n/a
TANG16	37	56.58	75	59.04	MUD	2	0.00	0.00	0.00	0.00	n/a
					SILTY SAND	8	0.00	0.00	0.00	0.00	n/a
TANG17	37	55.68	75	58.70	OYSTER MUD	2	23.21	6.67	28.74	28.74	Oyster, largest ~2 cm, large size range
					MUD	6	0.00	0.00	0.00	0.00	n/a
TANG18	37	55.73	75	58.70	MOD OYSTER	2.5	23.06	9.81	42.54	42.54	Oyster, largest ~2.5 cm, large size range
					MUD	3.5	0.00	0.00	0.00	0.00	n/a
P01	37	52.21	75	51.10	CLEAN SAND	5	0.00	0.00	0.00	0.00	n/a
P02	37	51.54	75	51.10	SILTY SAND	3	0.00	0.00	0.00	0.00	n/a
					SHELL HASH	0.5	0.00	0.00	0.00	0.00	Hash too small to sample
					CLAM MUD	0.5	19.52	4.92	25.21	0.00	Mostly clam-like (*Isonogmen*?), largest ~2.5 cm, fairly uniform size range
					STIFF MUD	3	0.00	0.00	0.00	0.00	n/a
P03	37	51.05	75	51.08	LAMINATED	12	0.00	0.00	0.00	0.00	n/a
P04	37	50.61	75	51.08	SILTY SAND	1.5	0.00	0.00	0.00	0.00	n/a
					CLEAN SAND	4	0.00	0.00	0.00	0.00	n/a
					GRAVEL	1	0.00	0.00	0.00	0.00	n/a
P05	37	51.90	75	50.71	MUD	20	0.00	0.00	0.00	0.00	n/a
P06	37	51.93	75	50.51	MUD	10	0.00	0.00	0.00	0.00	n/a
P07	37	50.68	75	50.18	SILTY SAND	0.3	0.00	0.00	0.00	0.00	n/a
					BACONS CASTLE	8	0.00	0.00	0.00	0.00	n/a
P08	37	51.30	75	50.18	FLUID MUD	1.5	0.00	0.00	0.00	0.00	n/a
					MUD	5	0.00	0.00	0.00	0.00	n/a
P09	37	51.56	75	50.19	FLUID MUD	2.5	0.00	0.00	0.00	0.00	n/a
					MUD	6	0.00	0.00	0.00	0.00	n/a
P10	37	52.61	75	50.22	FLUID MUD	2	0.00	0.00	0.00	0.00	n/a
					MUD	7	0.00	0.00	0.00	0.00	n/a
P11	37	50.49	75	50.50	LAMINATED	10	0.00	0.00	0.00	0.00	n/a
					STIFF MUD	2	0.00	0.00	0.00	0.00	n/a

Core ID	Lat		Lon		Units	Thick (ft)	Shell + Sed (g)	Shell (g)	% all shell	% oyster shell	Shell Description / Notes
P12	37	51.36	75	50.51	MUD	3.5	0.00	0.00	0.00	0.00	n/a
					SILTY SAND	0.3	0.00	0.00	0.00	0.00	n/a
					MUD	6	0.00	0.00	0.00	0.00	n/a
MK01	37	53.95	75	46.70	STIFF MUD	5	0.00	0.00	0.00	0.00	n/a
					GRAVEL	1	0.00	0.00	0.00	0.00	n/a
					STIFF MUD	4	0.00	0.00	0.00	0.00	n/a
MK02	37	53.65	75	47.23	MUD	1.5	0.00	0.00	0.00	0.00	n/a
					OYSTER SAND	0.5	8.87	1.11	12.46	12.46	Oyster, largest ~1.5 cm, mostly small, fairly uniform size range
					STIFF MUD	7	0.00	0.00	0.00	0.00	n/a
MK03	37	53.05	75	48.26	MUD	3.5	0.00	0.00	0.00	0.00	Hash too small to sample
					SHELL HASH	4	0.00	0.00	0.00	0.00	n/a
MK04	37	52.88	75	48.58	FLUID MUD	3	0.00	0.00	0.00	0.00	n/a
					MUD	6	0.00	0.00	0.00	0.00	n/a
MK05	37	52.63	75	49.04	MUD	3	0.00	0.00	0.00	0.00	n/a
					CLEAN SAND	4	0.00	0.00	0.00	0.00	n/a
MK06	37	52.45	75	49.18	MUD	6	0.00	0.00	0.00	0.00	n/a
					GRAVEL	0.3	0.00	0.00	0.00	0.00	One large clam shell (3 cm); rest is gravel
					CLEAN SAND	5	0.00	0.00	0.00	0.00	n/a
MK07	37	54.09	75	46.89	MUD	3	0.00	0.00	0.00	0.00	n/a
					CLEAN SAND	4	0.00	0.00	0.00	0.00	n/a
MK08	37	53.94	75	47.13	MUD	8	0.00	0.00	0.00	0.00	n/a
MK09	37	53.13	75	48.58	FLUID MUD	2	0.00	0.00	0.00	0.00	n/a
					MUD	6	0.00	0.00	0.00	0.00	n/a
MK10	37	52.38	75	49.03	CLEAN SAND	7	0.00	0.00	0.00	0.00	n/a
MK11	37	52.55	75	48.88	CLEAN SAND	6	0.00	0.00	0.00	0.00	n/a
					BACONS CASTLE	6	0.00	0.00	0.00	0.00	n/a
					GRAVEL	0.5	0.00	0.00	0.00	0.00	includes iron concretions in gravel fraction
MK12	37	52.55	75	48.88	SILTY SAND	3	0.00	0.00	0.00	0.00	n/a
					GRAVEL	2	0.00	0.00	0.00	0.00	n/a
MK13	37	52.43	75	49.10	CLEAN SAND	6	0.00	0.00	0.00	0.00	n/a

Table A-2. Description of the sedimentary units used in Table A-1.

Unit ID	Description
MUD	Includes soft clay with varying amounts of silt and occasional minor fine sand
FLUID MUD	Includes fluid mud measurements determined from both acoustic signatures and sediment samples
STIFF MUD	Includes very stiff clay with varying amounts of silt and occasional minor fine sand
SULFUR MUD	Includes black, sulfur-rich clay with varying amounts of silt, no shell
OYSTER MUD	Includes oyster shell in a MUD matrix (may be soft or stiff)
OYSTER SAND	Includes oyster shell imbedded in a dominantly sandy matrix (with varying amounts of silt/clay)
MOD OYSTER	Includes OYSTER MUD or OYSTER SAND collected on a modern oyster bed
CLEAN SAND	Includes fine-coarse sand, usually well sorted, with occasional minor silt
SILTY SAND	Includes silty-fine sand with varying amounts of clay
LAMINATED	Includes lamented muddy sands and mud (lumped as one unit)
BACONS CASTLE	Includes yellowish sand with fine ribbons/laminae of reddish-pink clay or light green clay indicative of the Bacon's Castle or Windsor Formations
GRAVEL	Includes dominantly gravel (usually rounded) sediment with varying amounts of clean sand and/or muddy sand
SHELL HASH	Includes poorly sorted fine-coarse muddy sand with abundant coarse shell hash
MUSSEL SAND	Includes sandy mussel beds (at surface or buried)
CLAM MUD	Includes muddy clam beds (at surface or buried)

Table A-3. Values used to approximate the amount buried fossil shell material at each site.

Site	Kilometers of Survey Lines	Number of Samples (Cores)	Average Thickness (ft)	Average Weight % Shell	Approximate Buried FOS (ft^3)	Approximate Buried Shell (ft^3)
McKan's Bay	43	32 (12)	1	30	93,100	27,800
Tyler's Beach	56	40 (18)	2.7	34	310,950	105,700
Tribell Shoals	36	31 (14)	2.5	36	48,000	17,500
Craney, NIT 1 and 2	36	31 (14)	1	35	39,600	13,750
Craney, NIT 3	43	41 (16)	n/a	---	---	---
Nansemond Flats	104	34 (13)	1	35	205,200	72,650
Tangier Sounds	58	38 (18)	1.5	28	175,550	49,650
"Poco" Pocomoke	67	24 (12)	n/a	---	---	---
"Moke" Pocomoke	50	27 (13)	0.5	12	4,900	600

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12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Methodology capable of identifying fossil oyster shell (FOS) buried under several meters of sediment is needed to quantitatively assess the availability of FOS for oyster reef restoration in Virginia. Evaluated here is the feasibility of using acoustic sub-bottom seismic surveys for determining the location and quantity of buried FOS. Over 280 miles of seismic surveys and 117 cores were collected in seven regions of the Chesapeake Bay and its tributaries. Traditional methods of seismic interpretation were able to successfully identify buried FOS regions throughout the geologically complex study area. The acoustic nature of buried FOS is site specific, however, and requires groundtruthing and geologic expertise to identify in the seismic data. Buried FOS deposits range in thickness from 1 to 3 ft, are located 2 to 8 ft below the seafloor, and are comprised of 12% to 55% shell. Overall, the seven sites contain a minimum of ~877,300 ft^3 of buried FOS sediment, of which a minimum of ~288,000 ft^3 is shell material. Although a purely quantitative assessment of acoustic data is possible, it is empirical and must be tuned from site to site. Ultimately, it is recommended that a combination of geologic digitizing and quantitative assessment be used to identify buried FOS regions in future seismic studies.

15. SUBJECT TERMS

Chesapeake Bay, Chirp Sub-Bottom, Fossil Oyster Shell, Geoprobe, Geophysical surveys, Historical oyster beds, Oyster restoration

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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