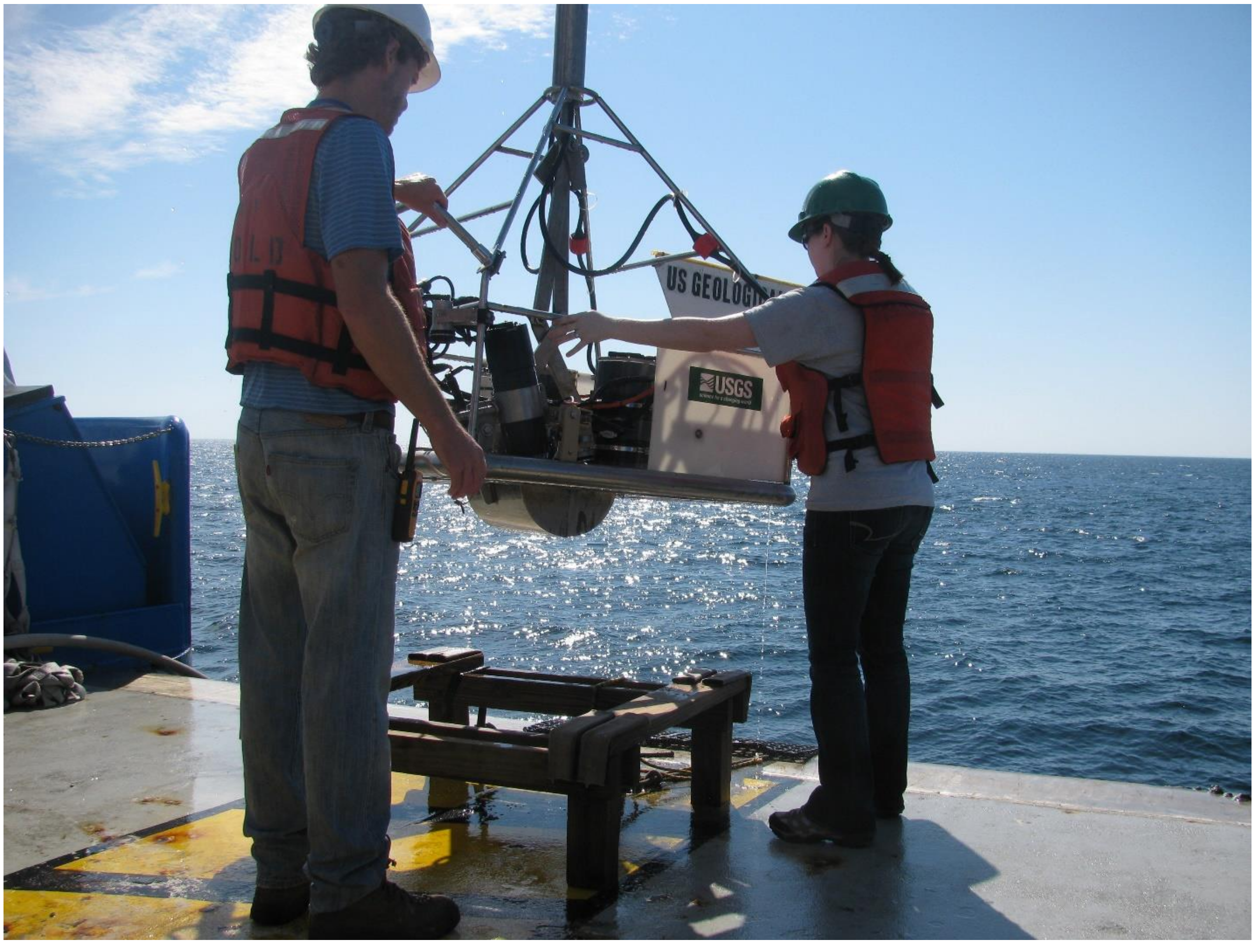

Executive Office of Energy and Environmental Affairs
Massachusetts Office of Coastal Zone Management

SEDIMENT AND GEOLOGY – Workgroup Report

2020 Massachusetts Ocean Management Plan Review

November 6, 2020

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SECTION ONE: Workgroup Membership

Regional Sediment Resource Management

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Workgroup Lead's Acknowledgement:

I would like to thank all the members of the 2020 workgroup. Without their input and expertise this report would not be as comprehensive, detailed, and informative as it is. For this review, we welcomed new members Ken Cirillo, Chris Hatfield, Greg Robbins, and Steve Wolf to the group. I appreciate their commitment to reviewing the report, their expertise, and their fresh eyes. As in past reports, the contributions of Walter Barnhardt and the staff at the U.S. Geological Survey (USGS) are invaluable, and their input forms the bedrock (no pun intended) of the report. The cooperative agreement between CZM and the USGS for the collection of data pertaining to mapping the seafloor of Massachusetts' coastal waters is one of the most important and productive agreements I have had the pleasure to be associated with. I would also like to thank Lisa Berry Engler, CZM's Director for her leadership and direction of both CZM and the 2020 Ocean Management Plan update. Her steady hand on the tiller has been vital to the agency and the Plan. I would also like to thank Todd Callaghan, CZM's Marine Science Specialist for his expertise, input, and willingness to discuss issues related to seafloor mapping. I also appreciated his direction of the survey of potential offshore sand excavation sites. He is truly one of the most accomplished scientists that I have been associated with throughout my career. And finally, I would like to thank Dan Sampson. Without his GIS and data management expertise, his general knowledge of all things seafloor related, his enthusiasm for collecting the data and making this report the best it could be for the citizens of the Commonwealth, his calm demeanor, and sense of humor, this report update would not be possible. Thank you, Dan, and thanks to all.

SECTION TWO: Introduction and Mission

The Massachusetts Oceans Act of 2008 required the creation of a comprehensive ocean management plan (Plan) for Massachusetts waters by December 2009. The foundation of the Plan was the identification of management areas within state waters with specific siting and performance standards established to protect existing natural resources as well as commercial and recreational uses. Twelve habitat types were determined to be Special, Sensitive, or Unique (SSU) natural resources deserving of protection and were mapped for the Plan using the best data available at that time. The 12 SSU resources mapped in the Plan are:

- North Atlantic right whale core habitat
- Humpback whale core habitat
- Fin whale core habitat
- Roseate Tern core habitat
- Special concern (Arctic, Least, and Common) tern core habitat
- Long-tailed Duck core habitat
- Leach's Storm-Petrel important nesting habitat
- Colonial waterbirds important nesting habitat
- Hard/complex seafloor
- Eelgrass
- Intertidal flats
- Important fish resource areas

The preparation of the 2009 Hard/Complex Seafloor SSU and the Surficial Sediment Characterization maps were accomplished through the establishment of the Sediment and Geology (S&G) Workgroup, whose mission was to identify existing, specific spatial data that characterize the physical and chemical properties of sediment in the planning area and/or that locate and quantify sediment types to be employed in any proposed regional sediment management plans. These data are used to assist with the siting and review of projects in the coastal zone that propose to remove and use sediment beneficially or whose location requires specific sediment types. These data are also used to prioritize sediment uses and needs, assisting resource managers and the public in evaluating sediment management activities.

In 2014, the Plan was updated and over 30,000 additional data points were added to the Massachusetts Office of Coastal Zone Management (CZM)/Massachusetts Division of Marine Fisheries (DMF) surficial sediment database. Additional high-resolution backscatter, bathymetry, and sub-bottom profiling data were also collected through the continuation of the seafloor mapping cooperative between CZM and the U.S. Geological Survey (USGS). Analysis and ground truthing of these data, along with the interpretation and inclusion of over 10,000 seafloor images, allowed for a significant improvement in the accuracy of the maps.

The Oceans Act requires that the Plan be reviewed at least every five years. In 2020, the S&G Workgroup was charged with updating the Hard/Complex Seafloor SSU map and to investigate the following:

- Identify any new data to add to or change the spatial extent of SSU resource areas from what was mapped in the 2014 ocean plan.
- Characterize notable trends in the condition of resources and uses covered in the Baseline Assessment (contained in Volume II of the 2009 ocean plan).
- Reveal any new science that might advance the characterization of the ocean planning area.
- Review the steps toward addressing the science and data priorities in the 2009 and 2014 ocean plan and making recommendations for priority research and data acquisitions to be included in the 2020 ocean plan.

In this document, items listed under "*Near-term Actions for the 2021 Ocean Plan Update*" were incorporated into the updated maps presented. Those items listed under "*Long-term Actions for Future Ocean Plan Updates*" need further research prior to inclusion into subsequent ocean plan revisions.

SECTION THREE: Data Sources and Recommendations

Discussions with work group members were used to establish a list of recommendations to CZM to assist in updating the existing ocean plan as well as keeping the science behind the ocean plan current. Recommendations from the workgroup have been divided into three sections based upon the classes of mapped products: Hard/Complex Seafloor, Surficial Sediment, and Potential Sand Extraction Areas. These sections are presented after a general discussion of the seafloor characteristics in Massachusetts waters.

General Characterization of the Seabed in Massachusetts Waters

As described in the 2015 Ocean Management Plan, the geology of the seabed in Massachusetts waters is highly heterogeneous. An overview of the seabed geology with respect to sediment resources, discussed during a workshop with CZM and USGS in August 2013, and updated in 2020 follows.

In the north, the seafloor is predominantly sandy with few rocky areas, though more rock occurs closer to Cape Ann. Seismic-reflection surveys have identified areas of thick (up to nine meters) sand and mixed sand/gravel deposits. Many of these deposits are relatively close to shore, particularly in the Plum Island area. There is a need for more detailed subsurface sampling (coring) in this area in order to assess the resource potential of these deposits. Seismic Data and core samples show that nearshore areas of western Massachusetts Bay and Cape Cod Bay are rockier with considerably less sandy material, though deeper regions farther from shore are generally characterized by thicker sections of sandy to muddy sediment. There are potential sand resources in western Massachusetts Bay that also need additional geophysical characterization, including coring and grain size analyses to determine the texture and volume of the sediment deposits. This region is generally characterized by older glacial deposits (coarser sands). There also appear to be beach-compatible sand deposits close to shore near Hull and Duxbury.

Cape Cod Bay's geology and shape were largely established by the Laurentide Ice Sheet and the incursion of ocean waters as the ice retreated. Underlying the seafloor of Cape Cod Bay are a series of moraines, glacial lake deposits, and more-recent fluvial and estuarine sediments. The modern seafloor is mostly smooth and flat consisting of finer-grained sediment (e.g., muddy sand, sandy mud). In a few locations, such as Fishing Ledge, glacial and older geology outcrops at the seafloor. Toward the shorelines, sediment texture becomes coarser grained. Sand bedforms are present in the southern portion of Cape Cod Bay. More detailed information about this region will become available as the seafloor mapping data collected in 2019 are analyzed further.

Buzzards Bay is a semi-enclosed basin with a fairly flat seafloor, with more rocky topography toward the mouth (southwest). Post-glacial drainage channels incised into Pleistocene outwash deposits are infilled with muddy estuarine fill and capped by Holocene fine-grained marine deposits. The central part of the basin is predominantly mud with margins that are sandy. Minimal existing cores reveal potential Pleistocene and Holocene sand resources. The post-glacial sediment may include Holocene sand but could also include estuarine deposits (mixed benefit material) – e.g., the deposit could be 20 meters thick but contain only two to three meters of surficial sand. Holocene marine sand is likely to be well sorted; Pleistocene outwash is likely to contain some gravel mixed with sand and/or mud. An evaluation of sand thickness using isopach (sediment thickness) maps derived from seismic-reflection data as a guide to coring should be conducted in this area. There appears to be a significant sand deposit (approximately six meters thick) north of Cuttyhunk Island.

In Vineyard Sound, most of the cores collected by Oldale and others did not penetrate through the sand layer. Some small wedges of sand are located near shorelines. There are several sand shoals in Vineyard Sound where sediment can reach 12 meters in thickness. These features generally overlie ridges of coarser grained glacial material. Vineyard Sound differs from Buzzards Bay in that the post-glacial drainage surface is exposed over much of the seabed. Waves and tidal flow have reworked, and continue to rework, these sediments in places forming armored beds of winnowed gravel. Hedge Fence, Squash Meadow, Middle Ground, and L'Hommedieu shoals are relatively thick localized source of sand. There are also several thin, mobile barchan dunes northwest of the main shoal areas. These sources may be self-maintaining (re-generate), allowing for the removal for nourishment purposes (depending on how much sand is removed, more analysis of sediment transport processes is needed). Sand waves in this area may migrate up to 10 meters per month (but not the underlying bank; the feature itself is stable). The tidal currents are very strong here and the stratigraphy is complex. In Vineyard Sound, swath bathymetry reveals several meters of relief. The backscatter data show large bodies of coarse grain material oriented in a north-south direction along the southwestern tip of Martha's Vineyard. Termed "sorted bedforms," these features are indicative of a highly mobile, high-energy environment. The USGS collected data in 2013 in a small area just north of Nantucket. There are several areas of natural gas within five to 10 meters of the seafloor; likely related to the presence of buried, organic rich material or estuarine deposits. Based on backscatter data, it is not likely that significant quantities of sand resources are located in the area just north of Nantucket.

Hard/Complex Seafloor

Hard/complex seafloor is seabed characterized singly or by any combination of hard seafloor, complex seafloor, artificial reefs, biogenic reefs, or wrecks and obstructions. Hard seafloor is seabed characterized by exposed bedrock or concentrations of boulder, cobble, or other similar hard bottom distinguished from surrounding unconsolidated sediments. Complex seafloor is a morphologically rugged seafloor characterized by high variability in bathymetric aspect and gradient. Biogenic reefs and man-made structures, such as artificial reefs, wrecks, or other functionally equivalent structures, may provide additional suitable substrate for the development of hard bottom biological communities.

CZM characterizes sediment using the Wentworth (1922) scale and the Barnhardt et al. (1998) classification scheme. The Wentworth scale is used to define the grain-size ranges for mud, sand, gravel, cobble, and boulder. Sediment data are then classified using the Barnhardt classification scheme (Figure 1), where the four corner classes (rock [R], gravel [G], sand [S], and mud [M]) have ≥90% of that particular sediment type. For the composite classes, the first letter is the majority grain-size component of the seafloor sediment and the second letter is the minority component. In the Barnhardt scheme, rock is characterized as cobble and larger (>64 mm) under the Wentworth scale. For the 2014 ocean plan, sediment data classified as rock (R), rock with gravel (Rg), rock with sand (Rs), or rock with mud (Rm) were mapped as hard seafloor. Therefore, when sediment is collected via a grab or other physical sampling devices, hard bottom is present when the dominant grain-size class (by volume) is >64 mm. When a sample is collected remotely via bottom photographs, hard bottom is present when sediment >64 mm is the spatially dominant sediment class in the field of view.

The workgroup recommended the following actions related to the update of the Hard/Complex Seafloor map:

Near-term Actions for the 2021 Ocean Plan Update

- Incorporate the following new or updated data:
  - Updated CZM/DMF sediment database
  - USGS interpreted sediment maps (published and unpublished data in review)
  - Artificial reefs
  - Board of Underwater Archaeological Resources' recreational shipwreck sites designated as "exempted sites" (member sites of the National Oceanic and Atmospheric Administration [NOAA]/U.S. Department of the Interior [DOI] National System of Marine Protected Areas) with 100-meter radius buffer around each wreck
  - Automated Wreck and Obstruction Information System (AWOIS) with 100-meter radius buffer around each wreck and obstruction

Long-term Actions for Future Ocean Plan Updates

- Investigate the importance of and develop shapefiles for additional biogenic reefs (e.g., mussels, oysters, *Crepidula*, worms) and incorporate into Hard/Complex Seafloor map if appropriate or categorize separately with the same protections afforded Hard/Complex Seafloor.
- Continue collection and interpretation of bathymetry data, backscatter data, and sub-bottom profiling (areas presently mapped using high-resolution bathymetry and backscatter data are presented in Figure 2).

After responding to the Work Group's recommendations, which involved acquiring data and performing additional analyses, CZM brought its proposed SSU updates to the Science Advisory Council (SAC) for additional feedback. CZM's draft proposed updates to SSU areas integrate the most recently available data with the recommendations of resource experts on the Work Group, as well as the SAC.

Discussion

The 2009 Hard/Complex Seafloor map was created by combining three data sources. First, a statewide bathymetry dataset was created by combining the highest resolution bathymetric datasets available and then calculating rugosity, a measure of bathymetric heterogeneity. Highly rugose areas were then combined with seafloor delineated as hard bottom in USGS interpreted seafloor maps. Finally, the combination of these two datasets was added to points coded as hard bottom in the CZM/DMF sediment database. The resultant map was representative of hard/complex bottom, in that it was based upon the highest resolution data available. Additional data sources have been identified and/or became available for both the 2014 update and the 2020 update to the ocean plan.

The Hard/Complex Seafloor map presented in the 2009 ocean plan covered a total of 904 km^2, or 16% of the planning area (Table 1). In the updated 2014 map, including artificial and biogenic reefs, wrecks, and obstructions, this area changed to cover a total area of 756 km^2, or 14% of the planning area. This was a 16% reduction in Hard/Complex Seafloor, the result of additional data points, increased accuracy, and refined mapping. Hard seafloor using updated 2014 data covered 578 km^2

and complex seafloor (including hard areas) covered 364 km^2, 10% and 7% of the ocean planning area, respectively. The complex seafloor was further separated into complex hard bottom (192 km^2, 53% of complex seafloor) and complex soft bottom (171 km^2, 47% of complex seafloor). Complex seafloor [defined as areas of high rugosity, with rugosity calculated from 10x10-meter resolution bathymetry data using the ArcGIS Vector Ruggedness Measure tool, based on an algorithm developed by Sappington et al. (2007) with a 9x9-cell neighborhood size] contains diverse benthic communities in some places. An analysis of 8,911 bottom photographs taken within the planning area was conducted by CZM biologist Adrienne Pappal on select groups and taxa with the percentage of prevalence in the original and final revised Hard/Complex Seafloor SSU areas. Percentages were calculated by dividing the number of photos with the group/taxa identified within the given Hard/Complex seafloor area by the number of photos with the group/taxa in the ocean planning area. As an example, hard/complex areas contain approximately 78% of soft corals observed in the photos, while only 62% are covered by hard seafloor alone. Overall, there was an average of 9% more photos containing the select taxa when including hard and complex areas rather than just hard bottom.

The 2020 Hard/Complex seafloor map was updated following generally the same methods employed in the 2014 update (i.e. including artificial and biogenic reefs, wrecks, and obstructions), with the mapped area changing to cover a total area of 744 km^2, or 13% of the planning area. This amounts to a 2% reduction in Hard/Complex Seafloor as compared to the 2014 report, the result of additional data points, increased accuracy, refined mapping, and the elimination of islands from the seafloor calculations. Hard seafloor using updated 2020 data covered 561 km^2 and complex seafloor (including hard areas) covered 385 km^2, 10% and 7% of the planning area, respectively. The complex seafloor was further separated into complex hard bottom (201 km^2, 52% of complex seafloor) and complex soft bottom (185 km^2, 48% of complex seafloor). Separate maps identifying hard seafloor, complex seafloor, artificial and biogenic reefs, and wrecks and obstructions were prepared (Figures 3 thru 6), along with a combined Hard/Complex Seafloor SSU map (Figure 7). Additionally, a map depicting the locations of areas identified as mussel reefs is presented in Figure 8.

Surficial Sediment

In addition to the Hard/Complex Seafloor maps, the workgroup also recommended the following updates to the Surficial Sediment map.

Near-term Actions for the 2021 Ocean Plan Update

- Incorporate the following new data:
    - New and older USGS interpretations some of which are refined with the CZM/DMF sediment database;
    - Available sediment data for areas adjacent to state waters out to 10 nautical miles from mean high water.

Long-term Actions for Future Ocean Plan Updates

- Develop regional sediment transport data.
- Continue to research sediment data for areas adjacent to state waters for inclusion in future mapping efforts.

Discussion

Figure 9 illustrates the sediment sample locations used to create the Surficial Sediment map. The Surficial Sediment map (Figure 10) contains newly incorporated, high-resolution data, including new USGS interpreted seafloor sediment maps, Massachusetts Department of Environmental Protection (MassDEP) wetlands sandy beach and rocky shore delineations, older USGS interpreted sediment maps, and an updated version of the CZM/DMF sediment database used in the 2009 and 2014 Ocean Plan. As part of the CZM-USGS Seafloor Mapping Cooperative, USGS continues work initiated in 2009 to delineate areas of similar seafloor sediment texture for much of Massachusetts marine waters by qualitatively analyzing acoustic backscatter (which can be used to estimate the seafloor hardness), bathymetry (which can be used to characterize rough and smooth topographies that are associated with rocky and finer sediments, respectively), surficial geologic and stratigraphic interpretations of seismic-reflection profiles, sediment samples, and bottom photographs.

In addition to the sediment map in the planning area, the two maps prepared for the 2014 ocean plan that carry this mapping beyond state waters and into adjacent federal waters were further refined. Figure 11 incorporates the available data from the CZM/DMF sediment database out to a distance of 10 nautical miles. Using this source, the confidence in data beyond 10 nautical miles was low, and therefore not included. The map presented in Figure 12 employs the data presented in the updated Surficial Sediment map, the updated Surficial Sediment to 10 Nautical Miles map, and data obtained from the USGS Continental Margin Mapping (CONMAP) Program. These data are useful during the siting and review of projects entering the state from federal waters and may also be useful for locating possible sand extraction sites outside of state waters.

The confidence key associated with the Surficial Sediment map was developed using four data confidence levels: low, medium, high, and very high.

- **Low** = low confidence Thiessen polygons and 1:1M scale USGS CONMAP[1]
- **Medium** = medium confidence Thiessen polygons
- **High** = high confidence Thiessen polygons and older USGS sediment interpretations[2]
- **Very High** = new USGS sediment interpretations[3] and MassDEP Wetlands[4]

[1] CONMAP data (Poppe et al. 2005) were used only outside the planning area
[2] Knebel and Circe 1995; Rendigs and Knebel 2002; Poppe et al. 2006; Poppe et al. 2007
[3] Pendleton et al. 2013 and unpublished data in review
[4] Mapped at 1:12,000, used to extract sandy beaches and rocky intertidal shores

Thiessen polygons were created from the CZM/DMF sediment database. The sediment data within contains a spectrum of quality, therefore CZM developed a "Data Quality Index" to quantify the variability in data confidence based on sample age, sampling device, and analytical technique.

Age Quality Values	Sampling Device Quality Value	Analytical Technique Quality Value
2000-present = 12	Grab = 4	Laboratory = 2
1985-1999 = 11	Photo = 4	Visual = 1
1960-1984 = 7	Core = 3	
Pre-1960 = 1	Dredge = 2	
	Lead Line = 1	

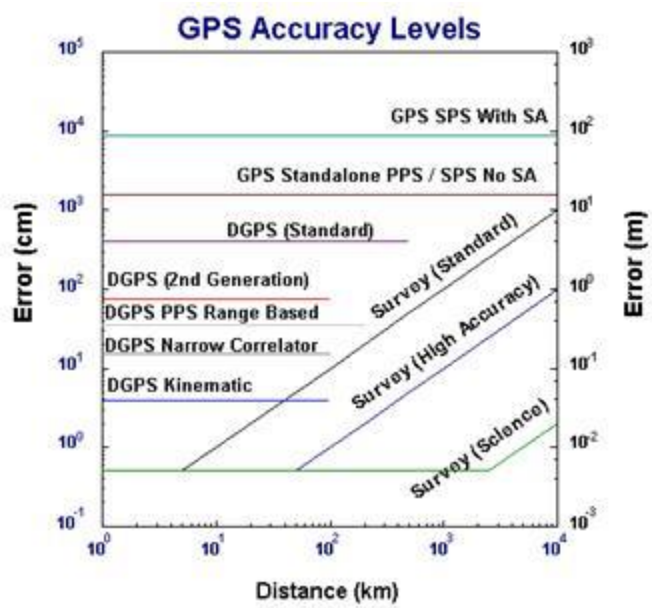
Data Quality Index $\boldsymbol{I} = ((A/12) + (S/4) + (N/2))$ where,
A is age quality value of the sample
S is sampling device
N is analytical technique

I values range from 0.83 to 3, the higher the number equating to a higher confidence in the data. The range was divided into quartiles yielding three confidence levels and attributed accordingly.

High > 2.46 (highest quartile)
Med 1.37 to 2.46 (middle two quartiles)
Low < 1.37 (lowest quartile)

The age quality value is based on the inferred technology used to locate the point.

Global Positioning System (GPS)
From the Naval Postgraduate School, http://www.oc.nps.edu/oc2902w/gps/gpsacc.html:



Per this table, the accuracy of:
GPS with Selective Availability (SA) is ±100 m
GPS after May 1, 2000 is ±12.6 m
Differential Global Positioning System (DGPS) is ±2 m

LORAN-C
"The distinction between absolute and repeatable accuracy is the most important one to understand. With the correct application of ASF's and within the **coverage area** defined for each chain, the absolute accuracy of the Loran system varies from between 0.1 and 0.25 nautical miles."[1,2]

Pre-LORAN
We presume a variety of different navigational techniques were used in the pre-LORAN era, hence we have no way to assign an approximate accuracy value. Some of the values are, however, reported as latitude-longitude pairs with two decimal places. Two decimal places can span up to 1.1 km (1,100 m).

Using the above information, CZM assigned the following Age Quality Values.

Year Range		**Approx. accuracy**	**Age Quality Value**
2000-present	DGPS	±2 m	12
1985-1999	GPS with SA	±100 m	11
1960-1984	LORAN-C	±463 m	7
Pre-1960	various	±1,100 m	1

Age Quality Values are derived from distances on the ground measured in 100 m intervals. When ranked each 100 m represents one ordinal number so that 2 m = 12, 100 m = 11 (12 - 1), 463 m = 7 (12 - 5 where 5 is 4.63 rounded), etc.

Potential Sand Extraction Areas

The workgroup recommended the preparation of the following maps and actions related to potential sand extraction areas:

Near-term Actions for the 2021 Ocean Plan Update

- Incorporate the following new data:
    - APTIM report and BOEM/State Geologist data into database;
    - Available core locations and data attributes into the potential sand extraction map;
    - Existing nearshore disposal sites.

Long-term Actions for Future Ocean Plan Updates

- Continue to research sediment data for state and adjacent federal waters, including the addition of core sample analysis for potential sand extraction sites.
- Incorporate sub-bottom profiling and coring data from studies conducted prior to CZM-USGS Seafloor Mapping Cooperative.

1 http://msi.nga.mil/MSISiteContent/StaticFiles/NAV_PUBS/APN/Chapt-12.pdf

2 0.25 nautical miles = 463 meters

- Overlay all sub-bottom data and sediment core data from available sources to identify additional deposits of beach compatible sand.
- Develop a map of surficial sediments overlain by available coring information showing the depth of beach compatible sand to create isopach maps.
- Map existing beach nourishment sites and conduct needs assessment for beach nourishment.
- Use existing sediment grain size data to match potential sand resources with receiving beaches.
- Consider moving forward with developing a better understanding of the issues and possible impacts of using the sand extraction sites.

Discussion

The investigation and characterization of marine sand deposit areas was identified as a top science priority in the 2015 ocean plan and as a key recommendation by the 2015 Massachusetts Coastal Erosion Commission. The 2015 ocean plan identified nine potential offshore sand resource areas in Commonwealth waters, and five of these nine areas were selected for further study including geophysical characterization, grab sampling, and coring to establish grain size and the thickness/volume of sand, as well as video/photo assessment of the seafloor to generally characterize biotic resources. The data gathered can be used in part to determine the general compatibility and suitability of the study areas for use as potential borrow sites for nourishment of nearby beaches. In addition, the video/photo data collected during this study can be used to help identify the location and presence of biotic resources. The project was limited only to the investigation and characterization work described below. It was not associated with any specific nourishment proposal or project and does not represent an assessment or endorsement of the feasibility of any potential proposal or project. Any potential proposal or project to extract sand from these potential sites will have to complete more detailed assessments of the potential sand sources, further characterize the biological resources, and complete all required state, federal, and local environmental review and permitting.

Several maps are presented. The first map, Figure 13, shows the locations of sites that have been investigated for the possibility of sand extraction for use in beach nourishment projects. These potential sources of sand were identified using both the sub-bottom profiling results and sediment core analysis. This map also presents the sites that were investigated as part of the preliminary characterization of offshore sand conducted in 2017 and described above. Sediment disposal locations utilized for the placement of dredged material are presented in Figure 14. These sites, often used for the disposal of sand from channel dredging projects, may be sources of significant volumes of sand available for beach nourishment. Further investigation is required. Figure 15 marks the locations of sediment cores collected in and adjacent to the planning area. These data come from various sources and represent preliminary characterizations for those sites. To determine the extent of any possible sand resources for use in shoreline protection and beach nourishment needs, additional data collection and analysis must be performed, including subsurface cores, grain-size analysis, and sub-bottom profiling to determine the volume and type of sediment present and their compatibility with existing beach sediment. In addition, the environmental impacts of mining these potential sand sources would need to be assessed. Figure 16 represents the areas of seismic (sub-bottom) profiling data collected in and adjacent to state waters. This work has been significantly expanded since 2015. Figures 17, 18 and 19 present maps created in 1987 and 1990 showing the sediment thickness, in meters above bedrock, north of Cape Ann, in Massachusetts Bay, and in Boston Harbor. Total sediment includes Holocene, Pleistocene, and coastal plain deposits.

Preliminary Characterization of Potential Offshore Sand Resources in Selected Study Areas

As described in Appendix A, CZM contracted with Aptim Environmental & Infrastructure, Inc. (APTIM) together with CR Environmental, Inc. (CR) in 2017 to conduct a preliminary characterization of these offshore sand resources in five (5) Study Areas located offshore of Massachusetts. The project consisted of an historic data review, collection of 20 vibracores, up to 4-meters long, collection of 25 surface grab samples, collection of towed video footage of the seafloor, and sediment analysis.

The first phase of the project consisted of a desktop study, consisting of an extensive search for previous geophysical and geotechnical investigations conducted within the five (5) Study Areas. For the desktop study APTIM utilized historic geophysical (sidescan sonar, bathymetric and seismic sub-bottom) data along with historic geotechnical data (surface grab samples and vibracores) and photographs of the seafloor provided by the USGS and CZM to narrow down areas of potential sand for this investigation. In areas with limited raw geophysical and geotechnical data, APTIM relied on historic reports prepared for The Division of Mineral Resources State of Massachusetts, The Commonwealth of Massachusetts Department of Natural Resources Division of Mineral Resources, the USGS, and other references provided by CZM.

After reviewing the available data, APTIM, CR, and the Massachusetts Office of Coastal Zone Management discussed the proper allocation of vibracore samples, surface grab samples and video collection efforts. The field investigation consisted of the collection of five (5) vibracores in Study Area 1 offshore of the Merrimack River, four (4) vibracores in Study Area 2 offshore of Nantasket Beach, three (3) vibracores in Study Area 3 offshore of Duxbury Bay, three (3) vibracores in Study Area 4 offshore of Sandwich, five (5) vibracores in Study Area 5 offshore of Cuttyhunk along with five (5) surface grab samples in each of the Study Areas and enough towed video transects to generally characterize the bottom type and habitat. The vibracores were collected between September 15, and October 5, 2017, while separate offshore operations to collect the surface grab samples and towed video data were conducted between August 2 and November 9, 2017.

Upon the completion of field investigations, vibracores and surface grabs samples were sent to APTIM's geotechnical laboratory for description and analysis. Vibracores were processed to determine sedimentary properties by strata in terms of thickness, color, texture (grain size), composition and presence of clay, silt, sand, gravel, or any other identifying features. Samples from individual layers were extracted for grain size distribution analysis. Surface grab samples were also described and processed for grain size. Results from the vibracore analysis were correlated to the available seismic sub-bottom data (where available) to create isopach maps of sediment thickness of the potential sand resources in each of the Study Areas to determine an estimated sand volume available. Video transects were analyzed in real time for habitat type, sediment composition, observed fauna (epibenthic/nekton), and their relative abundance. Table 2 provides a breakdown of the investigation results per Study Area (also described below). These results include either the range of the average thickness of these deposits, ± one standard deviation, or the average thickness not shown as a range (for areas without historic seismic sub-bottom data), shown as a discrete value representing the average thickness of that sand deposit as logged in the newly collected vibracores within that specific Study Area. The volumes shown are the actual calculated estimated volumes in

m^3 rounded to the nearest 10,000 m^3. The rounded m^3 volume value was then converted to cubic yards and rounded to the nearest 100 cubic yards.

For Study Area 1, the dominant substrate type was low relief sand waves with some coarse grain sands and pebbles in the troughs. Dominant fauna included juvenile sea scallops, lobster, mysid shrimp, and amphipods. A total of 37 lobsters were observed on 85% of the collected transects. Dominant fish included winter flounder (16) and sculpin (18). An estimated preliminary volume of 99,730,000 m^3 (130,442,000 cy) of potential sand resources was identified throughout Study Area 1.

For Study Area 2, the bottom substrates were highly variable, ranging from flat sand, mud to sand waves, pebble-cobble, and partially buried or dispersed boulders. Dominant invertebrates included sea scallops, rock crabs, and sand dollars. The dominant fish observed was cunner with 62 observations. The Massachusetts OMP Study Area 2 was broken down into three (3) Study Areas (2A, 2B, and 2C). Interpretation of historic seismic sub-bottom data correlated to the vibracores results from this project indicated preliminary estimates of potential sand resource volumes of 3,600,000 m^3 (4,708,600 cy) in the Study Area 2A. Recent backscatter and high-resolution bathymetric data within Study Area 2B indicate the presence of surficial gravels as well as high relief ledges, likely rocky in nature, crossing portions of the Study Area. As a result, little or no potential sand resource volume is expected in Study Area 2B. Based on historical surficial backscatter data indicating limited surficial sands, Study Area 2C was narrowed down to a smaller area with an estimated preliminary volume of 3,600,000 m^3 (4,708,600 cy) of potential sand resources.

Offshore of Duxbury Bay, the bottom substrate at Study Area 3 was primarily flat sand, mud with limited observations of pebble-cobble bottom, and occasional shell aggregate bottom. Dominant invertebrates were mysid shrimp and sand dollars. Commercial species observed included 17 observations of rock crabs and nine lobsters. The dominant fish species at Study Area 3 off Duxbury Bay included red hake (33), winter flounder (15) and sculpin (12). The Massachusetts OMP Study Area 3 was broken down into two Study Areas (3A and 3B). Interpretations of the historic sidescan sonar data in Study Area 3A indicate that the surface is likely mostly sand; therefore, in order to determine the potential volume of sand, an average thickness value was calculated from the isopach and used as a general representation of the entire Study Area 3A, yielding an estimated preliminary volume of 46,940,000 m^3 (61,395,200 cy) of potential sand resources. The isopach in Study Area 3B was clipped to the Interpreted Sandy Area polygon to avoid areas that appear to have a hard bottom/rock outcrop. The total estimated preliminary volume of Study Area 3B is 46,000,000 m^3 (60,165,700 cy) of potential sand resources.

Offshore of Sandwich, the habitat type at Study Area 4 was primarily flat sand and mud except for sand waves with coarser sand east of the Cape Cod Canal. Occasional biogenically structured bottom (burrows and mounds) was also observed. A limited amount of pebble-cobble bottom was observed, and some rock disposal material was observed in the Cape Cod Canal Offshore Dredged Material Disposal Site. Dominant fauna included sand dollars that were abundant at all of nine sandy bottom transects. The dominant fauna on the silty/sand sediment at the Disposal Site were mysid shrimp. Counts of the commercial species included 40 rock crabs, 20 winter flounder, and 10 lobsters. Study Area 4 was divided into two Study Areas, 4A and 4B. Study Area 4B was considered, but not included for additional geotechnical data collection as it is designated as a USACE/EPA Offshore Dredge Material Disposal Site and can likely be initially characterized via historic dredging records. The estimated preliminary volume in Study Area 4A is estimated to be 51,670,000 m^3 (67,581,800 cy) of potential sand resources. Given the fact that no seismic sub-bottom data were available for this area, it is impossible to know the exact nature and full extent of the deposit without additional design-level data.

For Study Area 5, offshore of Cuttyhunk, the bottom substrate was primarily flat sand/mud, with occasional exceptions of observed sand waves and partially buried and dispersed boulders. The dominant invertebrate at eight of the 10 transects were two species of hermit crabs. Fish species observed at Study Area 5 included 21 red hake and one winter flounder. Study Area 5 was broken down into two Study Areas (5A and 5B). Sand deposits in Study Area 5A are associated with a shoaling feature with an estimated preliminary volume of 54,470,000 m^3 (71,244,100 cy) of potential sand resources. Study Area 5B contains a thin (approximately 1.4 m (4.27 ft) thick) sand layer overlaying a paleochannel complex likely filled with clays and silts yielding an estimated preliminary volume of approximately 7,460,000 m^3 (9,757,300 cy) of potential sand resources.

In total, a preliminary, reconnaissance-level estimate of approximately 313,470,000 m^3 (410,003,400 cy) across all five Study Areas was identified. These are preliminary volumes of potential sand resources based on widely spaced reconnaissance-level geotechnical data and varying levels of geophysical data coverage. Actual borrow area design would require additional, design-level geotechnical and geophysical data collection in order to accurately and fully characterize these sand deposits, account for environmental and cultural resources, determine compatibility of the potential sand resource with the recipient beach, evaluate dredgeability of the sand resource, and design permit plans and specifications (including dredge cuts) for a final borrow area.

In addition to this work and as described in Appendix B, the Massachusetts Geological Survey and the University of Massachusetts established a cooperative agreement with the Bureau of Ocean Energy Management (BOEM) in 2014 to characterize 18 public beaches that are threatened by erosion or have important infrastructure that is at risk and to provide a better understanding of the frequency of major erosion and overwash events at selected beaches by coring and dating the individual storm event layers within overwash fans. Although the beaches selected for study are landward of the ocean management planning area, the assessment of these beaches and the determination of nourishment needs and characteristics dovetails with the APTIM study presented above. Although there is still much work that would need to be completed prior to the potential excavation of the identified sand sites, the data presented in Appendix B show a clear need for sand sources to be identified and evaluated. It is not clear that sand obtained through navigational dredging projects can meet the present and future need for beach nourishment sand.

Topographic beach and dune profiles and grain size analyses were completed for 18 public beaches that are threatened by erosion, have important infrastructure that is at risk or are in communities with no active coastal management plan. The purpose of this work was to fully characterize the beaches so that beach-compatible material could be identified in off-site sources. A total of 234 topographic profiles (winter and summer combined) surveyed normal to the beaches plus 889 sediment samples and 86 pebble counts (winter and summer combined) were collected and analyzed for the following beaches: 1) Barges Beach, Gosnold, East and Horseneck Beaches, Westport, Low and Miacomet Beaches, Nantucket, Surf Beach, Falmouth, Town Beach, Oak Bluffs (also referred to as Pay and Inkwell beaches) and Sylvia State Beach, Oak Bluffs and Edgartown during August/September 2014 and March, 2015; and, 2) Humarock Beach, Scituate, Nahant Beach, Nahant, Nantasket Beach, Hull, Peggotty Beach, Scituate, Plum Island, Newbury and Newburyport, Long Beach, Plymouth (referred to as Plymouth), Revere Beach, Revere, Long Beach, Rockport (referred to as Rockport), Fieldston/Brant Rock Beach, Marshfield (collectively referred to as

Marshfield hereafter) and Salisbury Beach, Salisbury during August/September, 2015 and March, 2016. Sediment samples/pebble counts were collected at low tide, mid tide, and high tide positions, the berm crest and dune, if present. Between two and 10 profiles were surveyed at each beach, depending on the length of the beach, using a Topcon GTS 210 total station and/or a real time kinematic Trimble R8 Global Navigation Satellite System (GNSS) connected to the cellular network. Spacing between profiles ranged from 80 to 600 meters.

Reported results indicate that increased wave activity during winter strips sand from the intertidal zone. At cobble (till- and moraine-dominated) beaches (Horseneck, East, Barges, Town, Humarock, as well as parts of Nantasket, Peggotty, Marshfield and Plymouth) removal of a summer veneer of sand reveals larger grains below but little appreciable change in profile, whereas at finer-grained sandy beaches (outwash-dominated or extensive barrier beaches) significant loss of berm was observed (Low, Miacomet, Salisbury, and Plum Island). Less berm loss is noted as the deposits become progressively coarser (e.g., Sylvia, Oak Bluffs-Edgartown; Surf, Falmouth). Results of this work will be used to help determine which beaches can or will be nourished with sand from an offsite source.

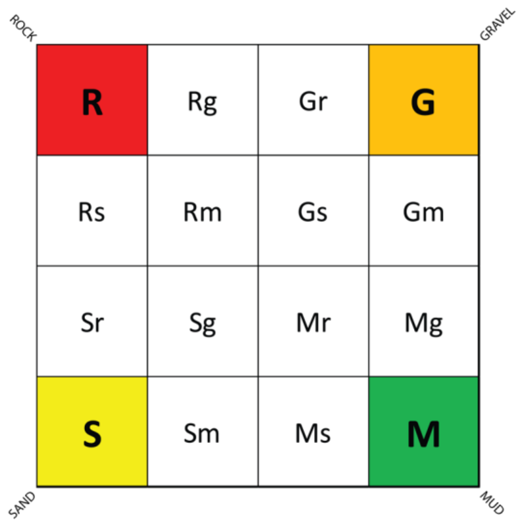
A second objective of this work was to core backbarrier ponds at selected sites to obtain a record of overwash deposits corresponding to intense past storms and provide an estimate of the frequency of major events. Coring was completed at Miacomet Pond, Nantucket, East Beach, Westport, Bartlett Pond, Plymouth, Cambourne Pond, Rockport, and a marsh behind Short Beach in Winthrop. However, only Bartlett Pond yielded a usable record suitable for analysis. Work on the core from Bartlett Pond reveals continuous long-term overwash deposits going back as far as 1000 years ago. Analysis of the Bartlett Pond cores show several major storm events that can be linked directly to historic storm events back to 1723. Furthermore, these large events appear to be associated with extra-tropical cyclones (sometimes called nor'easters), not tropical cyclones (hurricanes). This contrasts with the south-facing shores of Massachusetts where large storm tides are dominated by tropical cyclones. These results point to the importance of considering all the differences in coastal conditions (tidal ranges, different storm populations, etc.) in assessing the return period of flood events. Furthermore, information gained from these historic and sedimentary records also seem to suggest an underassessment of the recurrence interval of large flood events in the Boston area. Results emphasize the value in combining sedimentological, modeled, and historical records of early historical floods for improving these assessments. Methods and results are presented in Appendix B.

Bottom Type	2009 Plan Area (% of Planning Area)	2014 Update Area (% of Planning Area)	2020 Update Area (% of Planning Area)	% Change (2014 vs. 2020)
Hard/Complex	904 km^2 (16%)	756 km^2 (14%)	744 km^2 (13%)	-2%
Hard	308 km^2 (6%)	578 km^2 (10%)	561 km^2 (10%)	-3%
Complex	755 km^2 (14%)	364 km^2 (7%)	385 km^2 (7%)	5%
- Complex Hard	160 km^2 (3%)	192 km^2 (3%)	201 km^2 (4%)	4%
- Complex Soft	596 km^2 (11%)	171 km^2 (3%)	185 km^2 (3%)	8%

Table 1. Area covered by Hard/Complex Seafloor SSU in the ocean management planning area.

Region	Study Area	Average Grain Size (mm)	Average Silt %	Average Sand Thickness (m)	Area of Isopach (m^2)	Estimated Volume of Isopach (m^3)	Estimated Volume of Isopach (cy)
Merrimack River	1	0.30	2.50	1.76 to 3.84	35,665,334	99,730,000	130,442,000
Nantasket Beach	2A	0.11	11.75	2.54 to 4.18	1,070,310	3,600,000	4,708,600
	2B			No cores or	grabs	collected	
	2C	0.11	12.28	2.67	1,348,929	3,600,000	4,708,600
Duxbury Beach	3A	0.17	1.69	0.84 to 5.68	14,398,272	46,940,000	61,395,200
	3B	0.16	10.59	0.71 to 4.55	17,497,037	46,000,000	60,165,700
Sandwich	4A	0.23	2.68	3.38	15,286,265	51,670,000	67,581,800
	4B			No cores or	grabs	collected	
Cuttyhunk	5A	0.19	4.66	1.61 to 7.33	12,180,335	54,470,000	71,244,100
	5B	0.17	6.49	0.76 to 2.04	5,338,989	7,460,000	9,757,300

Table 2. Summary of preliminary characterization of offshore sand resources in selected study areas (Aptim Environmental & Infrastructure, Inc. and CR Environmental, Inc., 2018).



Rock	Rock with gravel	Gravel with rock	Gravel
Rock with sand	Rock with mud	Gravel with sand	Gravel with mud
Sand with rock	Sand with gravel	Mud with rock	Mud with gravel
Sand	Sand with mud	Mud with sand	Mud

Figure 1. Barnhardt classification scheme (Barnhardt and others, 1998) used to classify sediments.

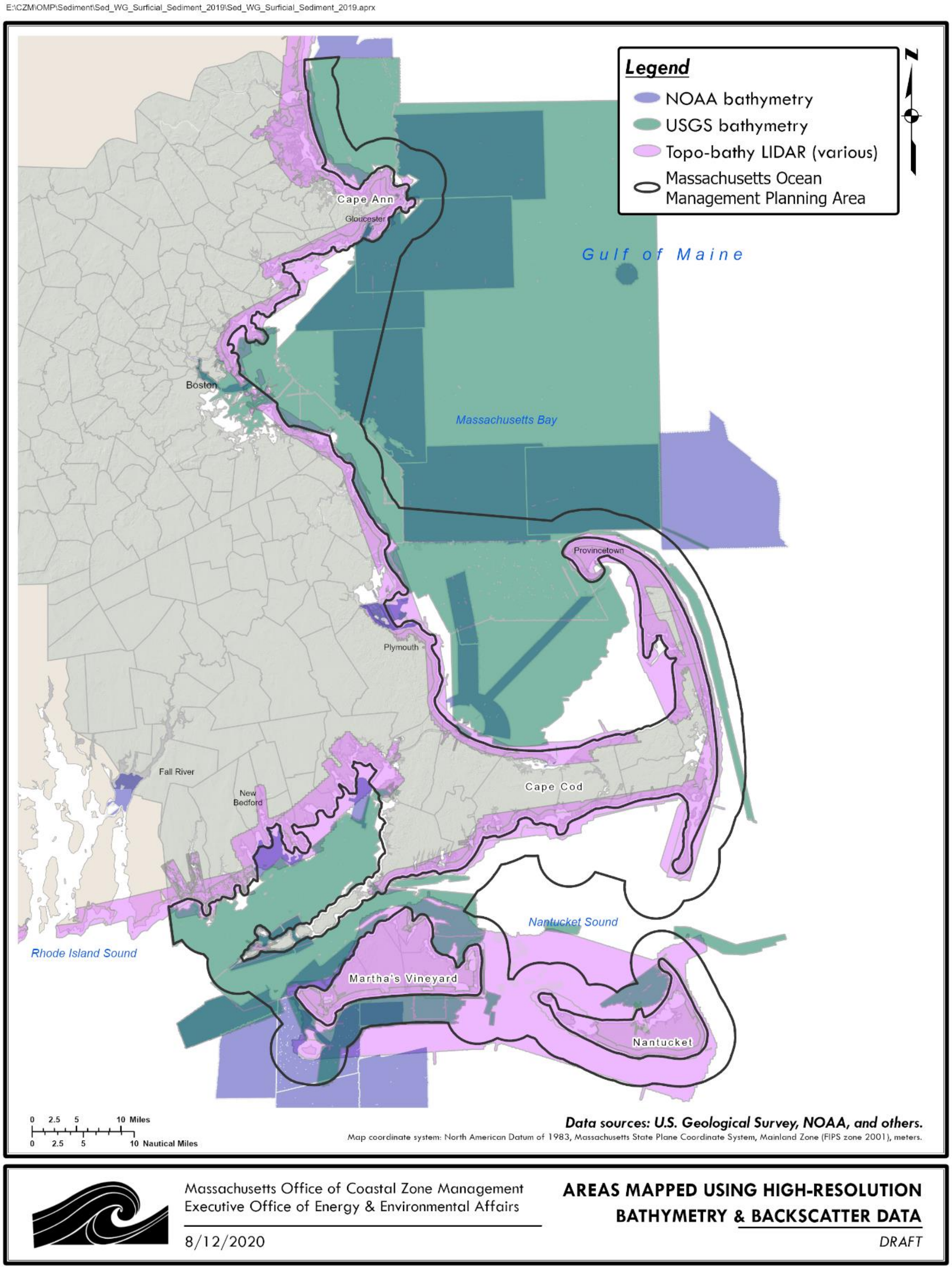


Figure 2. Seafloor mapped using high-resolution bathymetry and backscatter data.

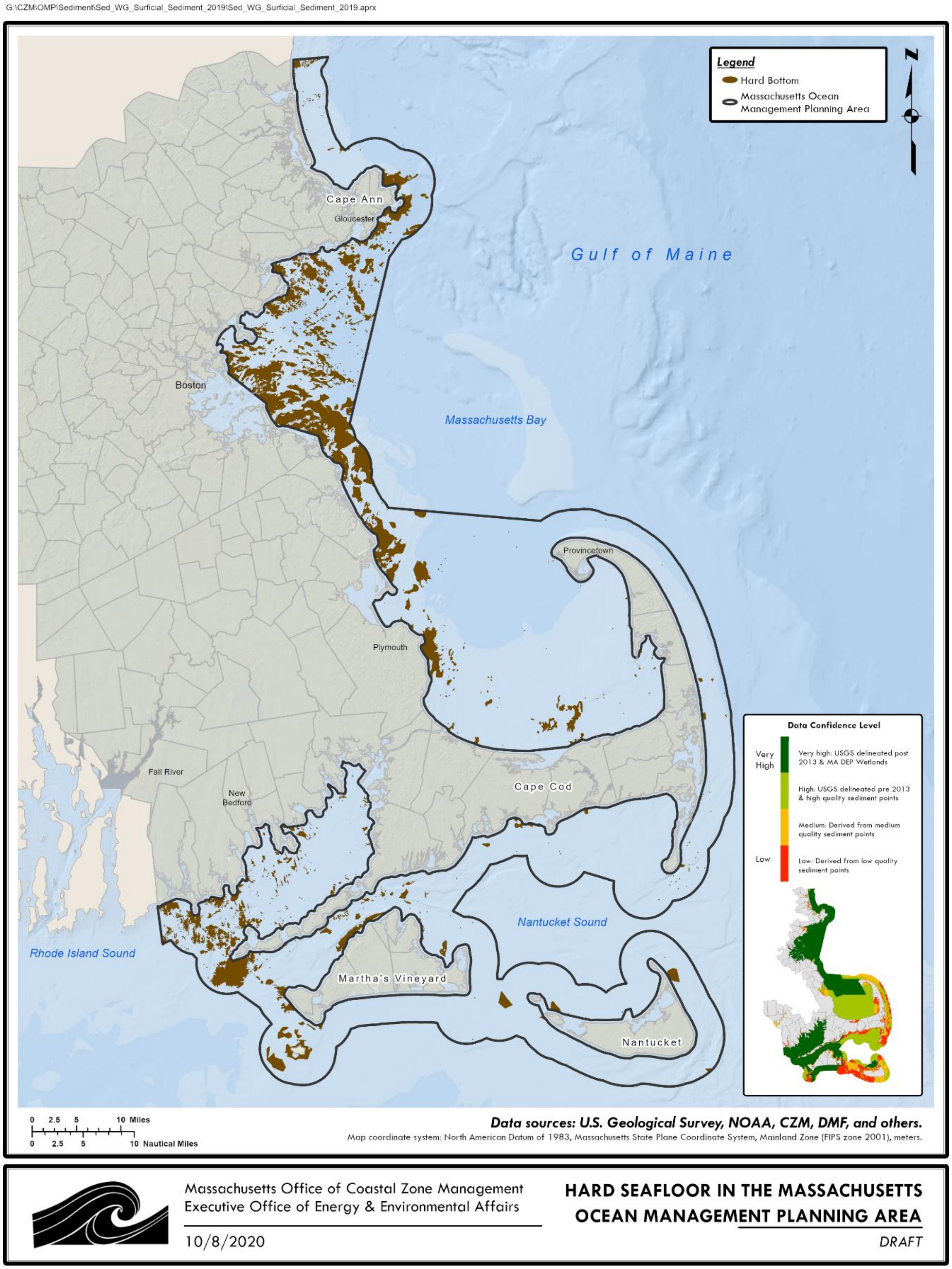


Figure 3. Hard seafloor in the ocean management planning area.

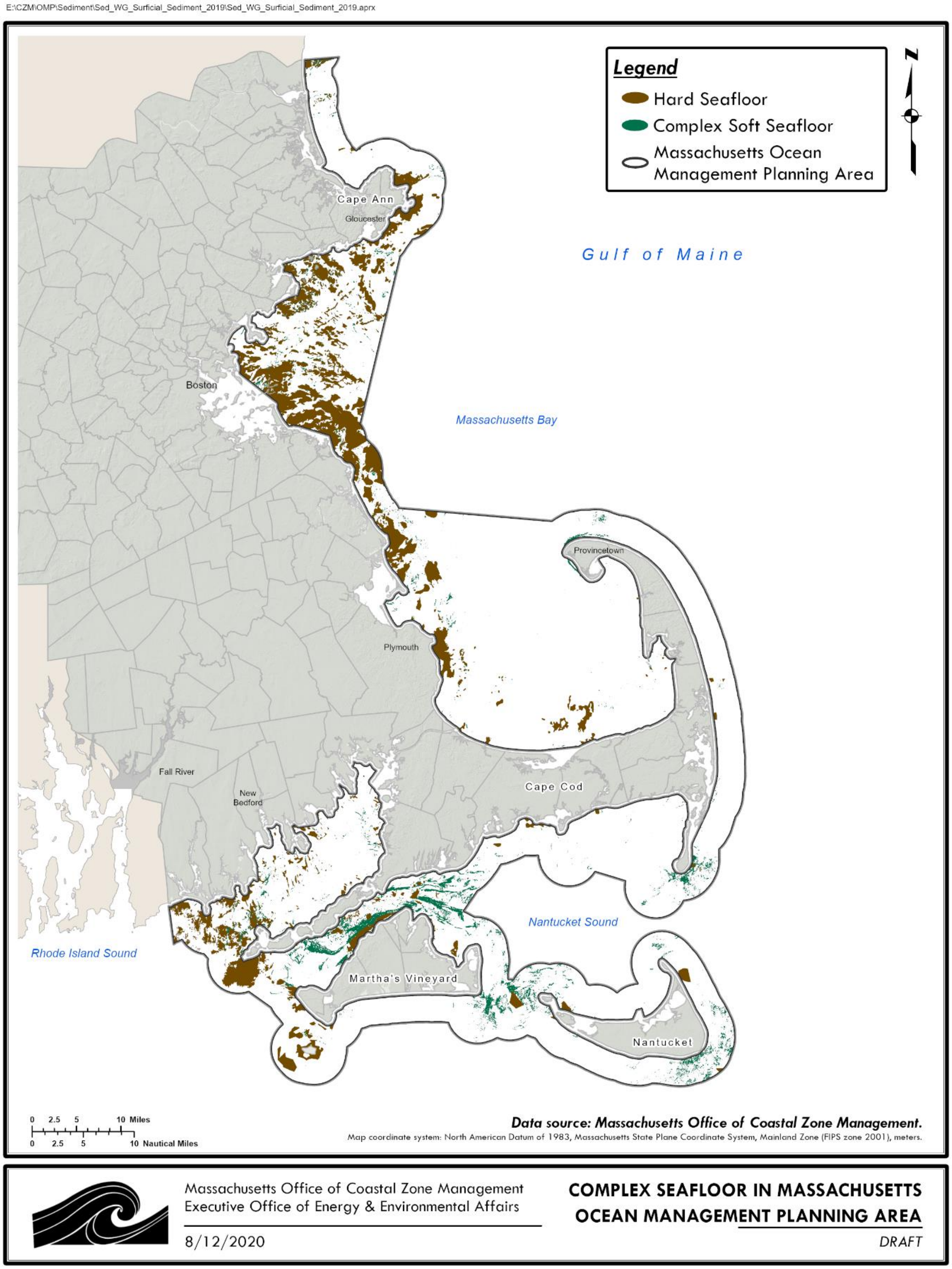


Figure 4. Complex seafloor in the ocean management planning area.

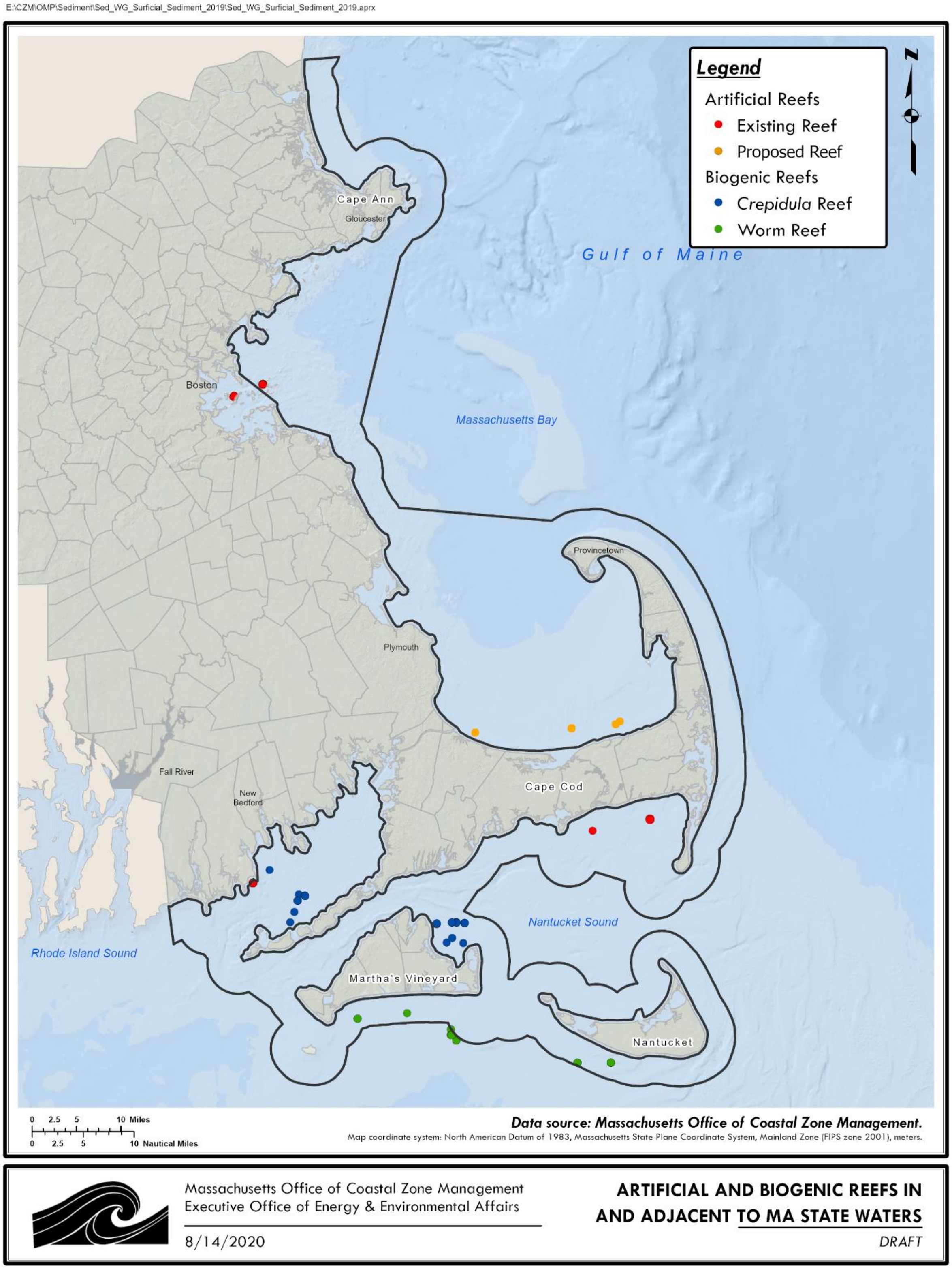


Figure 5. Artificial and biogenic reef sites in and adjacent to state waters.

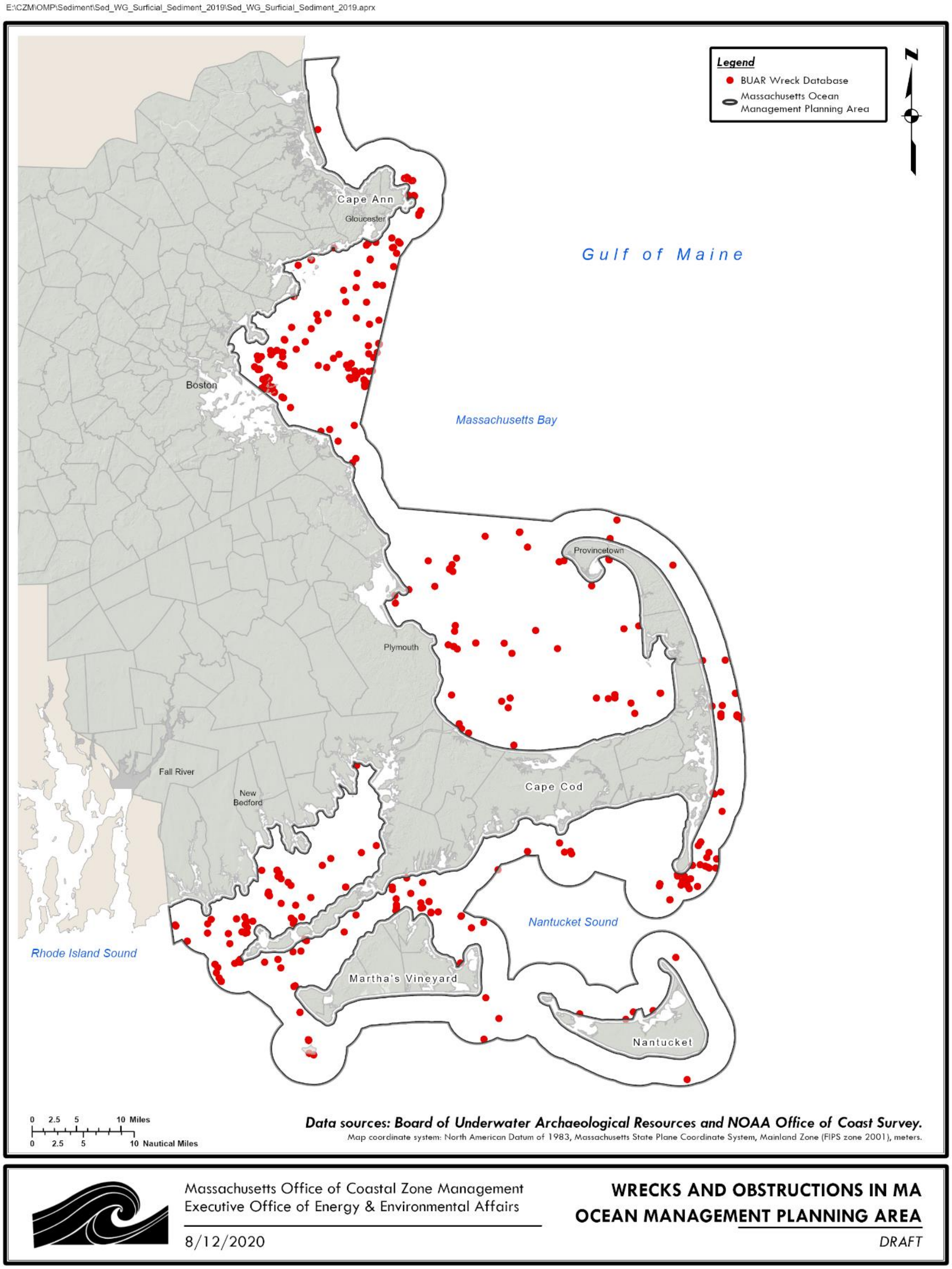


Figure 6. Wrecks and obstructions in the ocean management planning area.

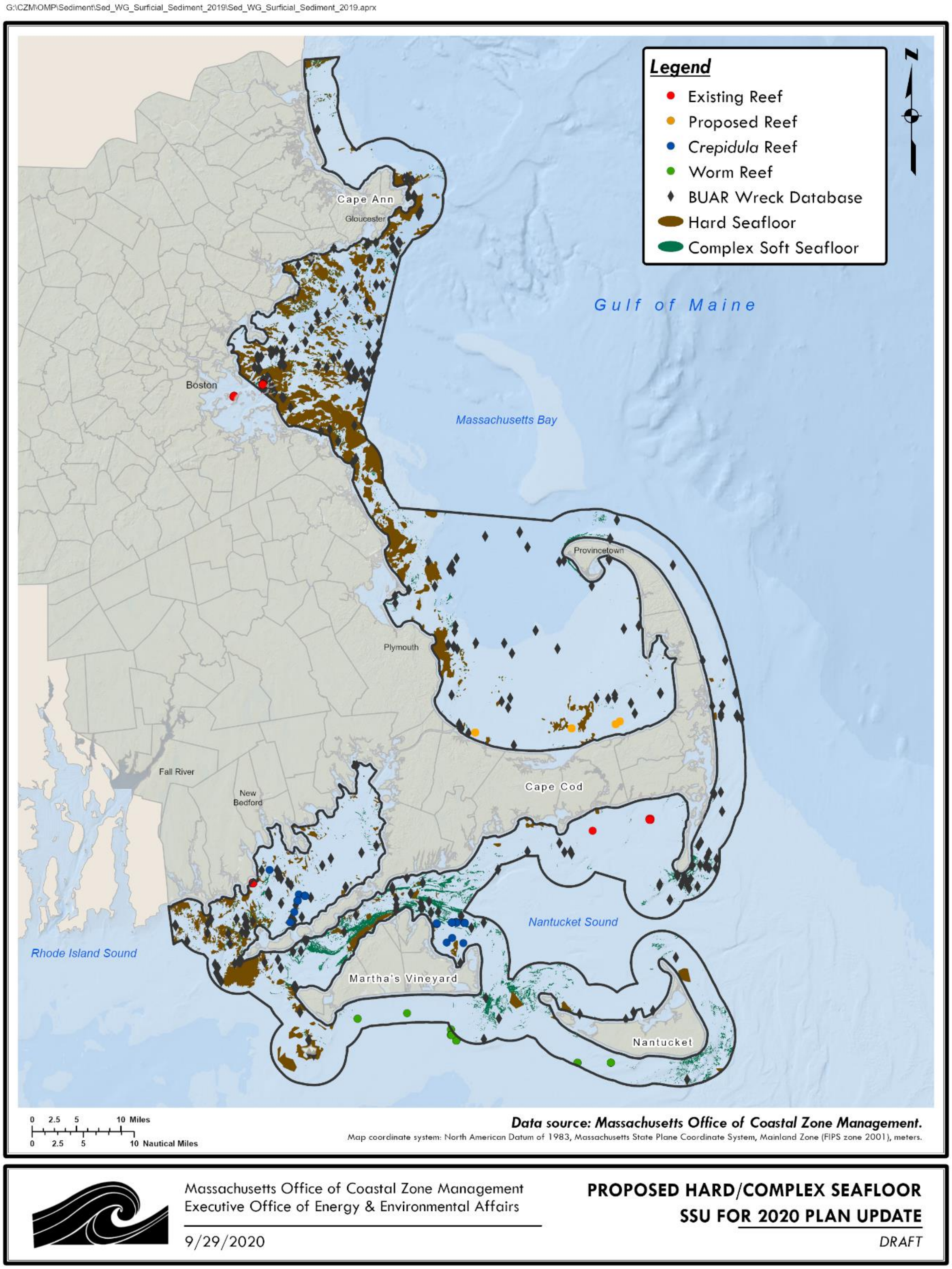


Figure 7. Hard/complex seafloor SSU in the ocean management planning area, including artificial reefs, biogenic reefs, wrecks, and obstructions.

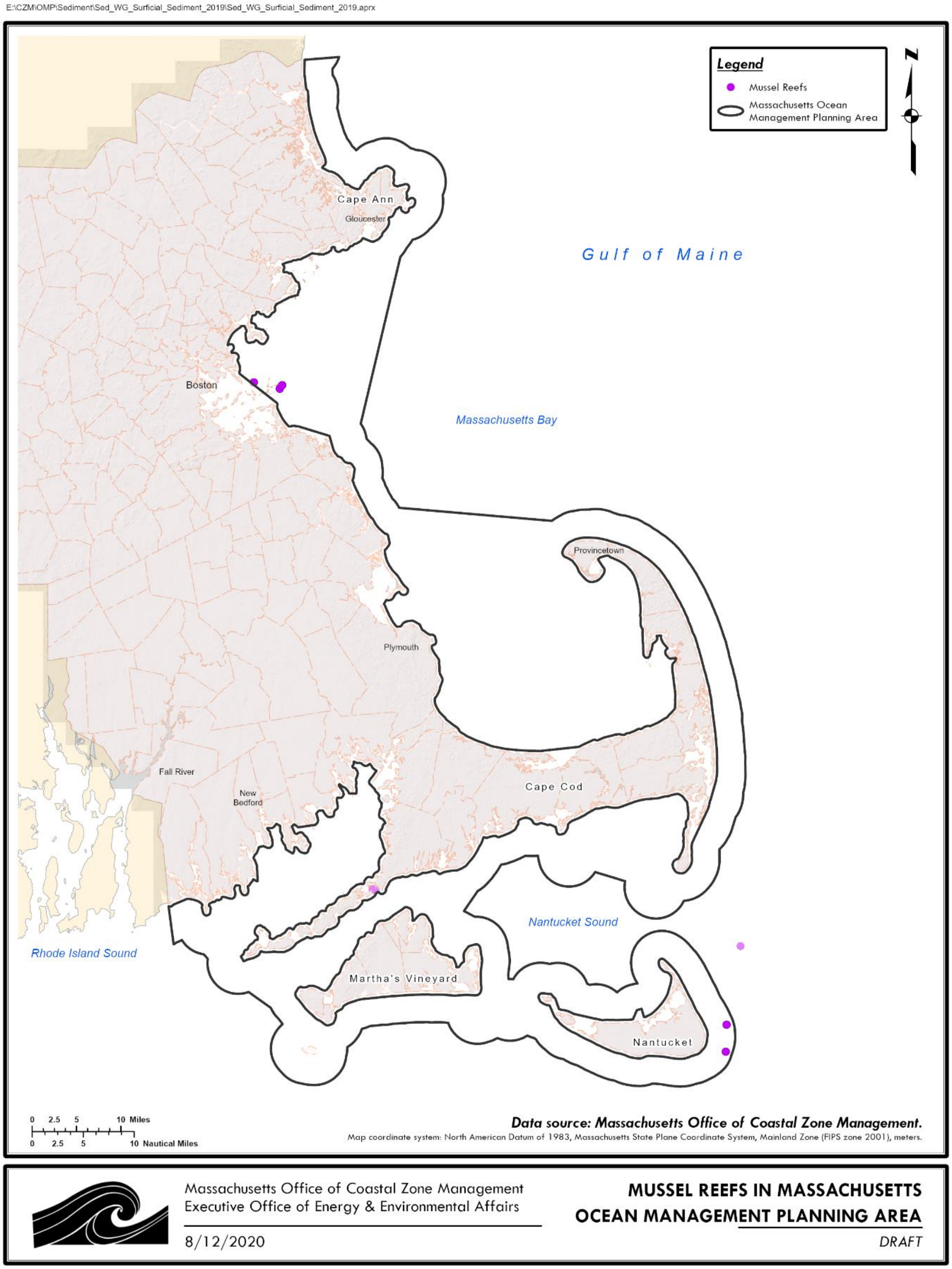


Figure 8. Mussel reefs in the ocean management planning area.

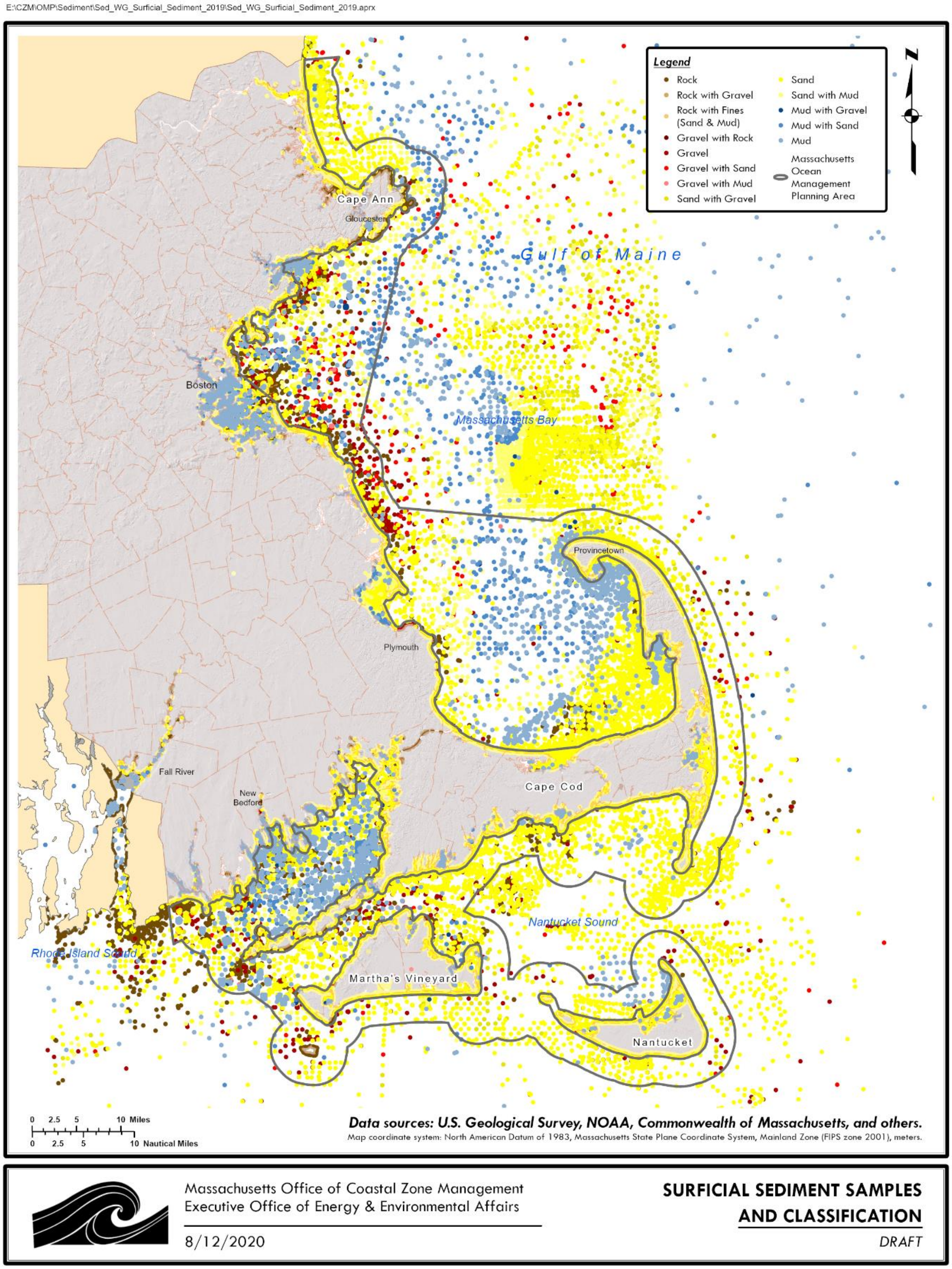


Figure 9. Locations of surficial sediment samples in the CZM/DMF sediment database.

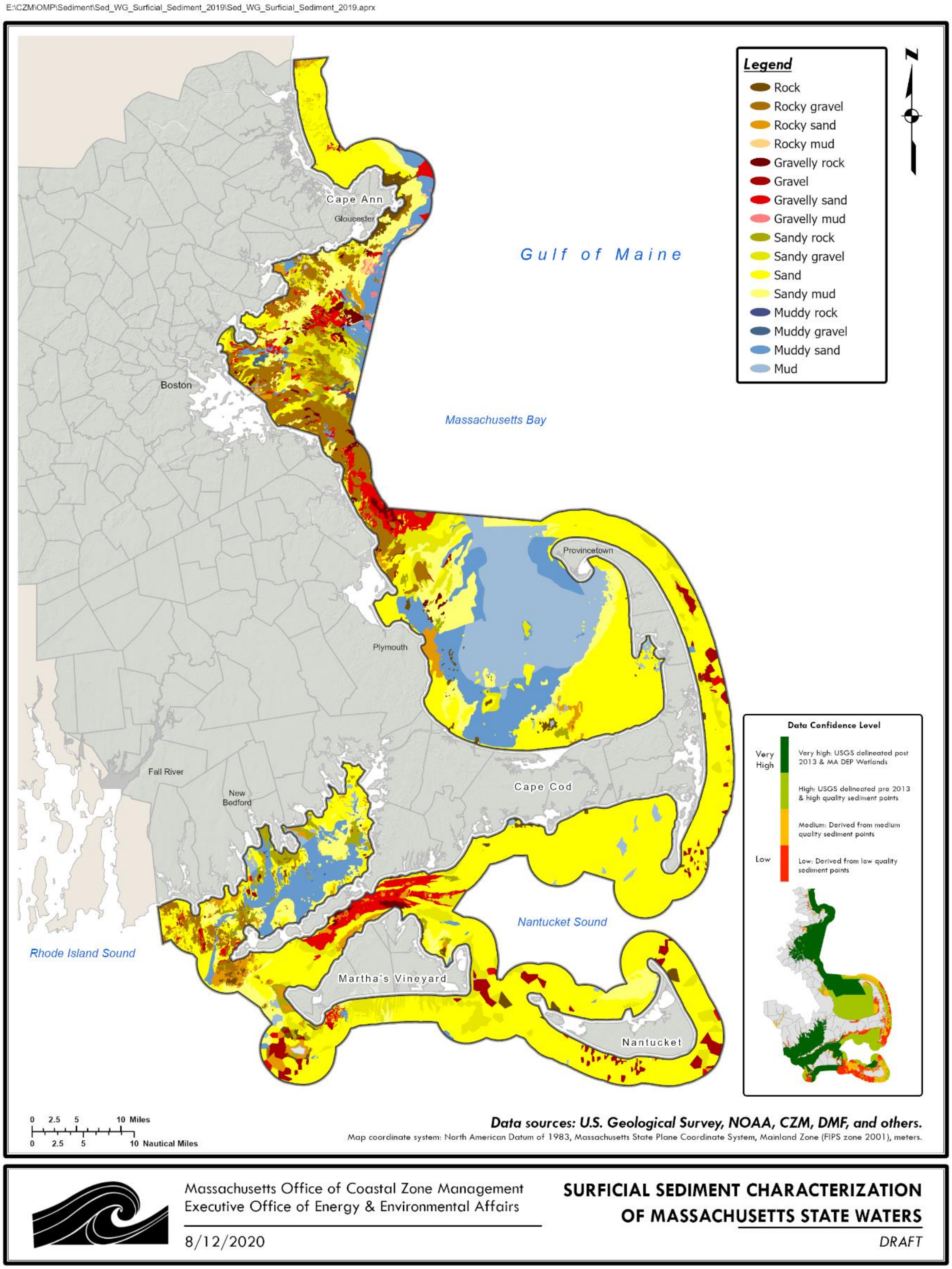


Figure 10. Surficial sediment in state waters.

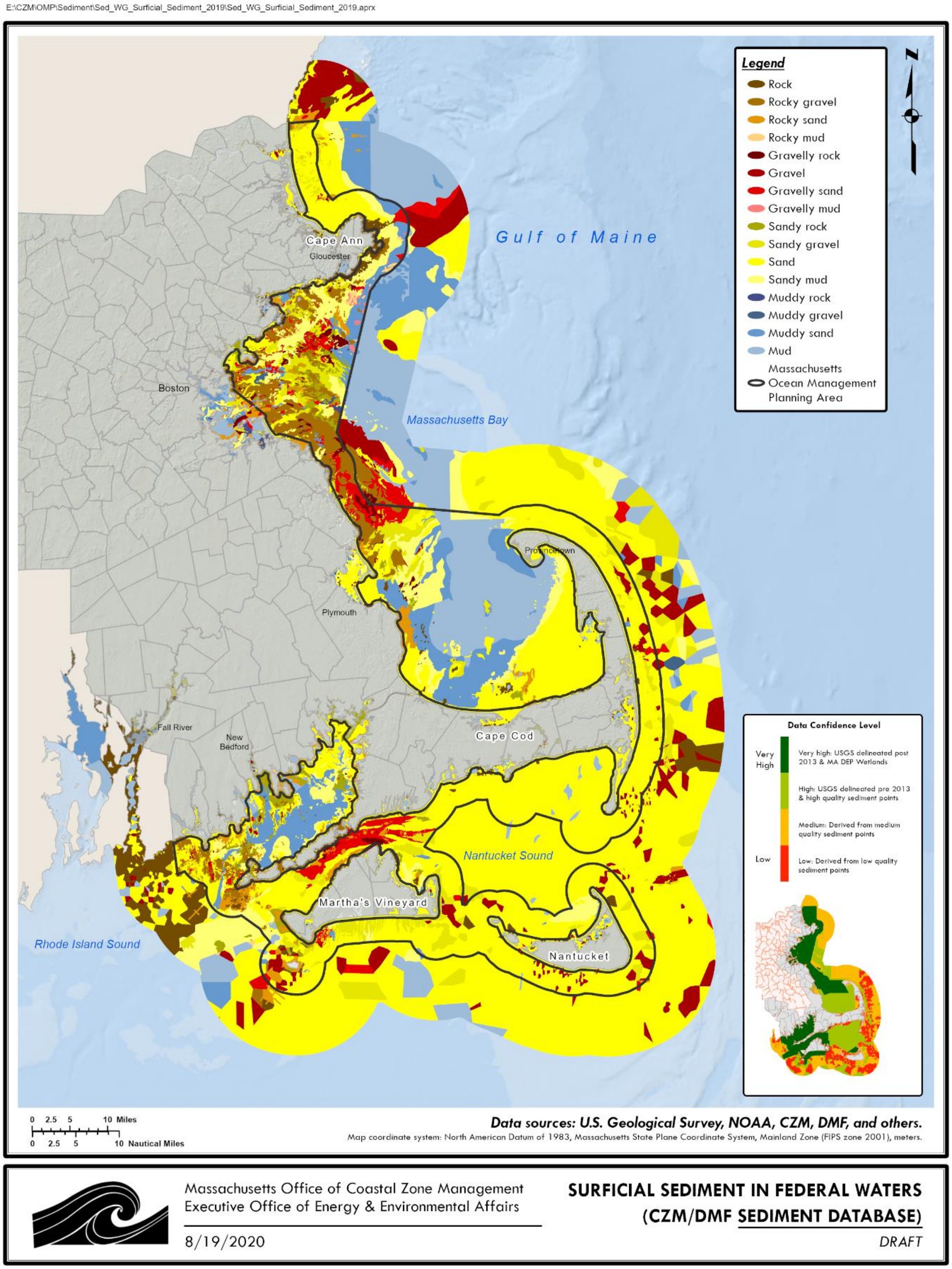


Figure 11. Surficial sediment out to 10 nautical miles using data derived from the CZM/DMF sediment database.

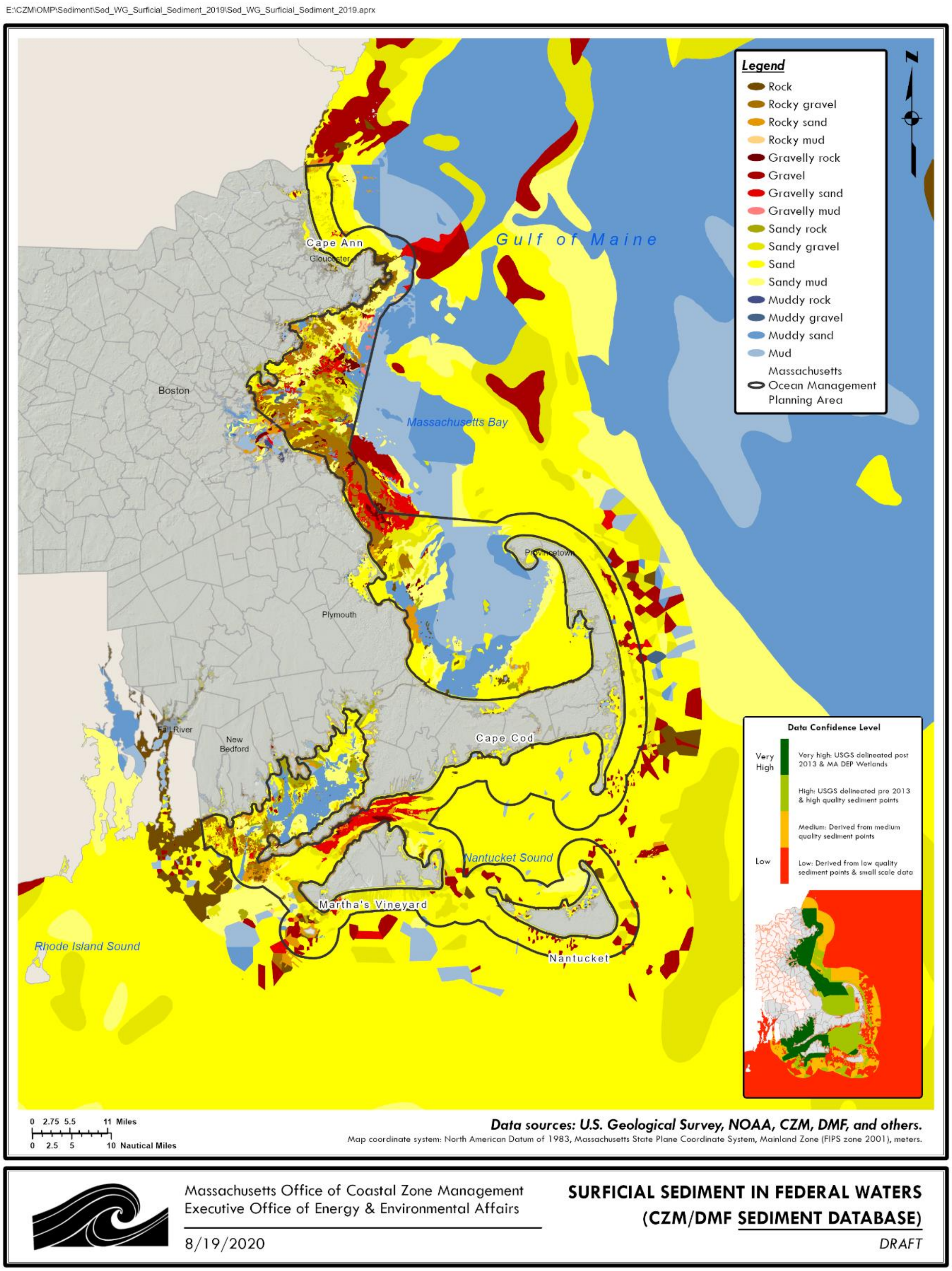


Figure 12. Surficial sediment beyond the ocean management planning area using data derived from the USGS Continental Margin Mapping (CONMAP) Program.

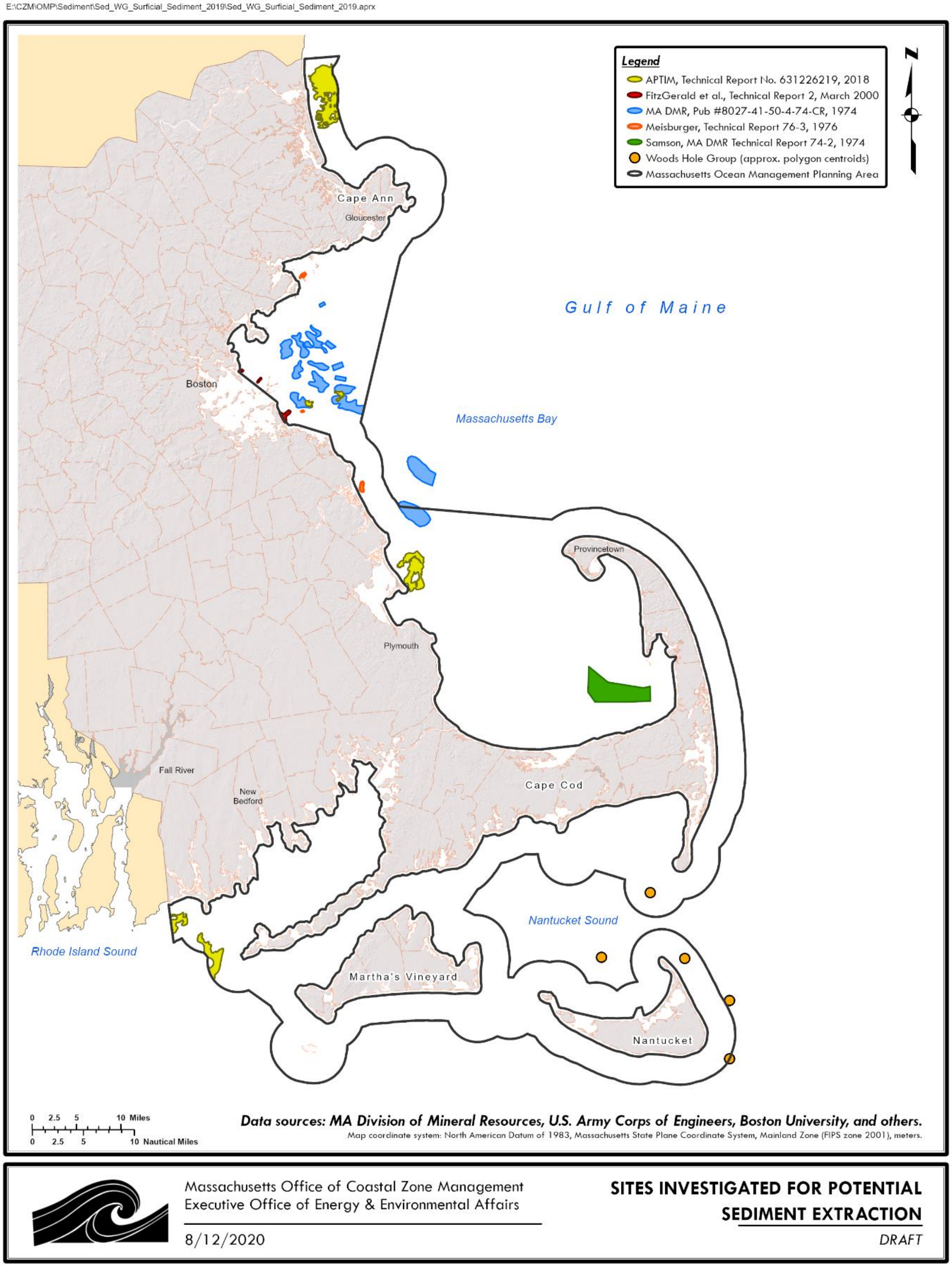


Figure 13. Sites investigated for potential sand extraction.

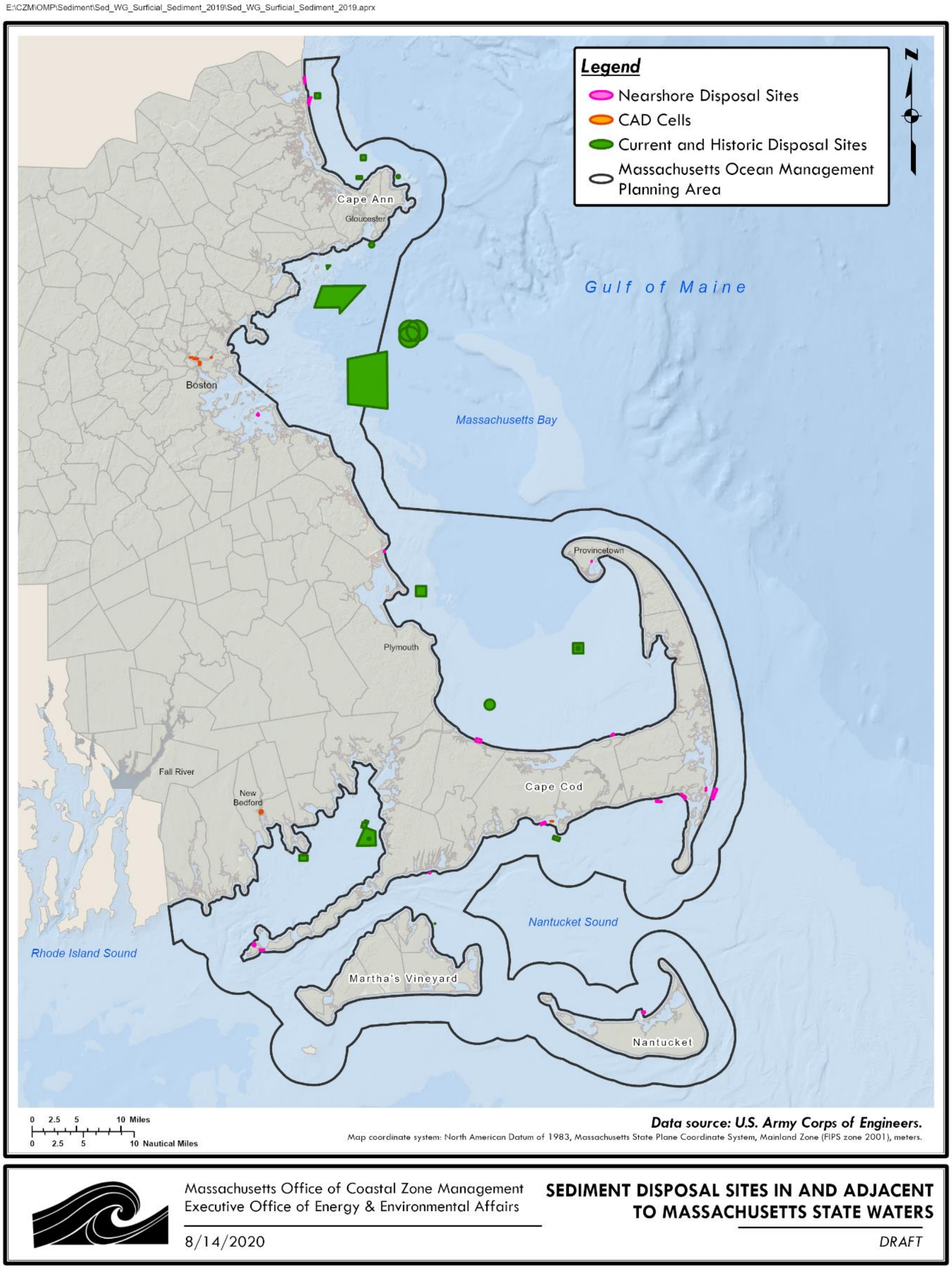


Figure 14. Disposal sites utilized for dredged sediment placement.

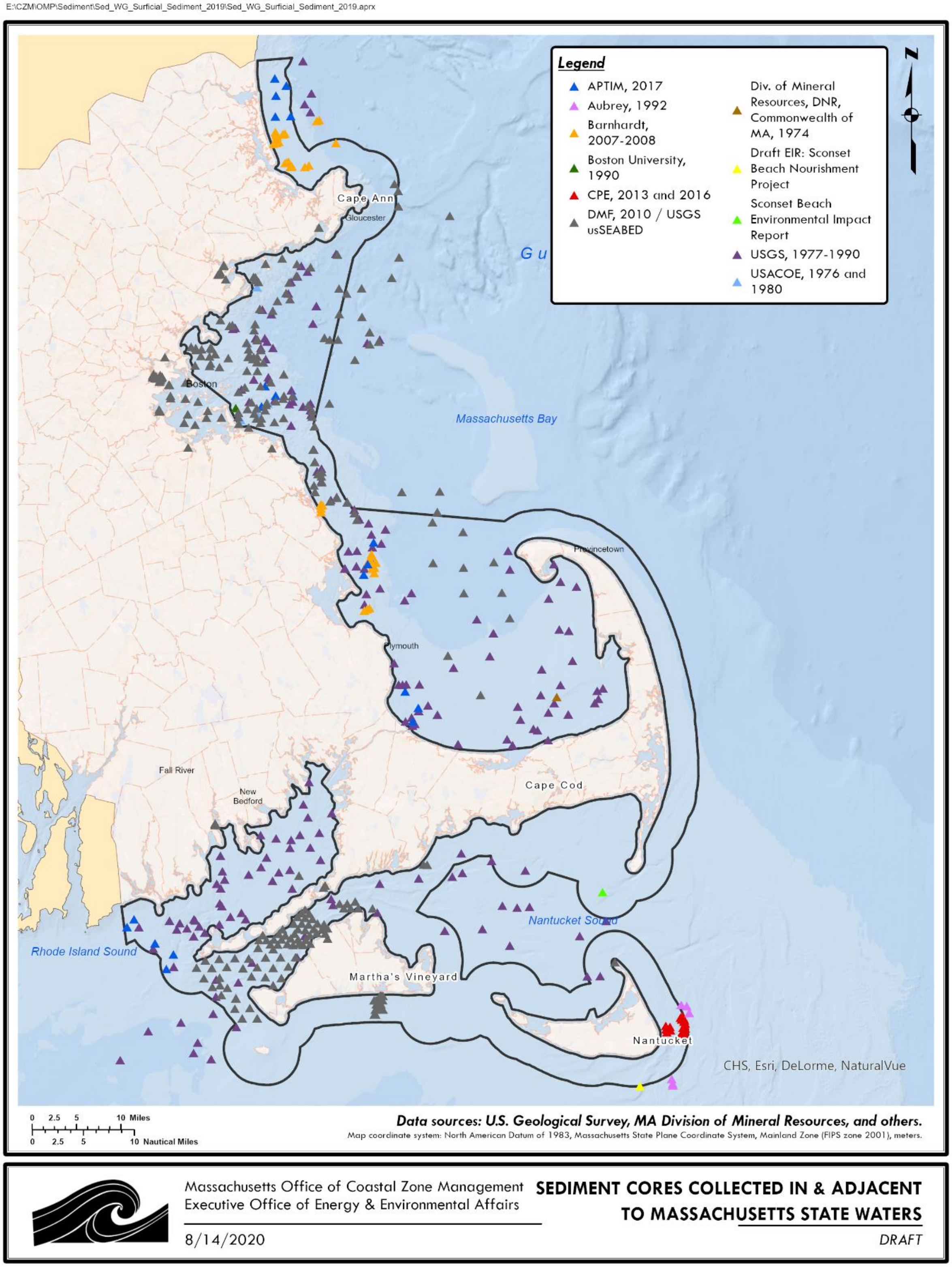


Figure 15. Sediment core locations in and adjacent to state waters.

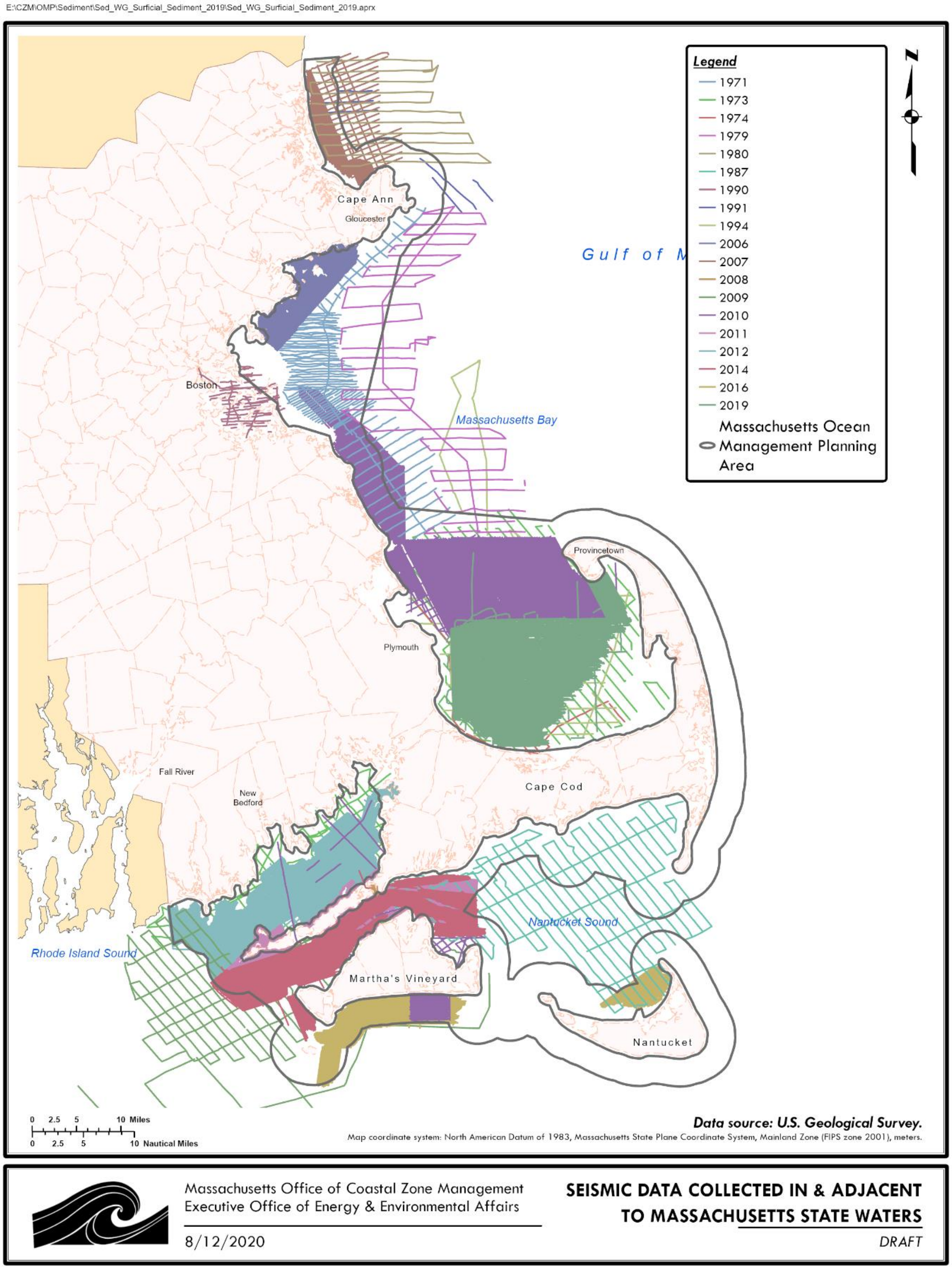


Figure 16. Areas of seismic (sub-bottom) profiling data collected in and adjacent to state waters.

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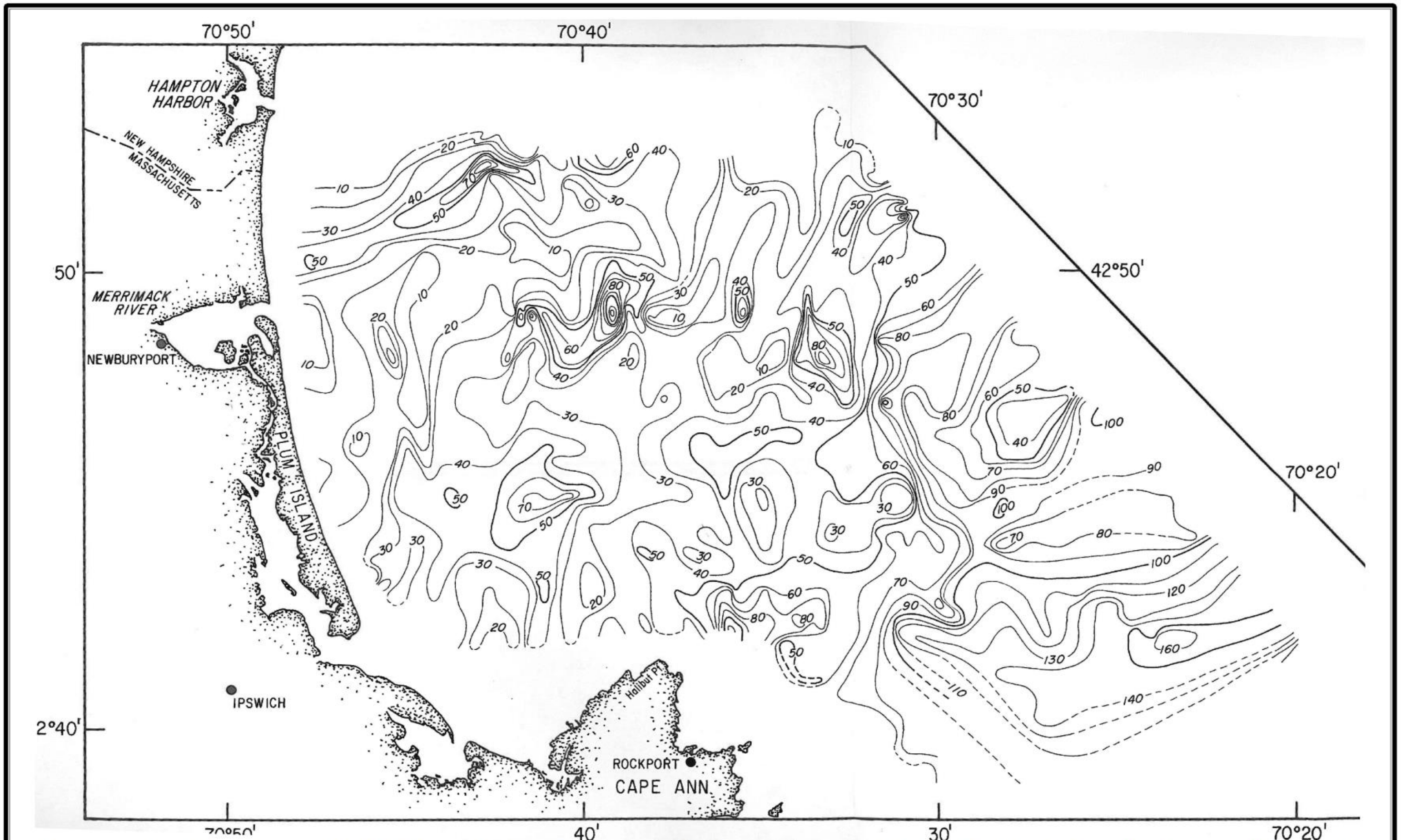

Data source: Oldale, R.N, and Wommack, L.E., 1987, Maps and seismic profiles showing geology of the inner continental shelf, Cape Ann, Massachusetts to New Hampshire: U.S. Geological Survey Miscellaneous Field Studies Map MF–1892, 2 sheets.

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TOTAL SEDIMENT THICKNESS ABOVE BEDROCK IN WATERS NORTH OF CAPE ANN

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Figure 17. Total sediment thickness (in meters above bedrock) in waters north of Cape Ann.

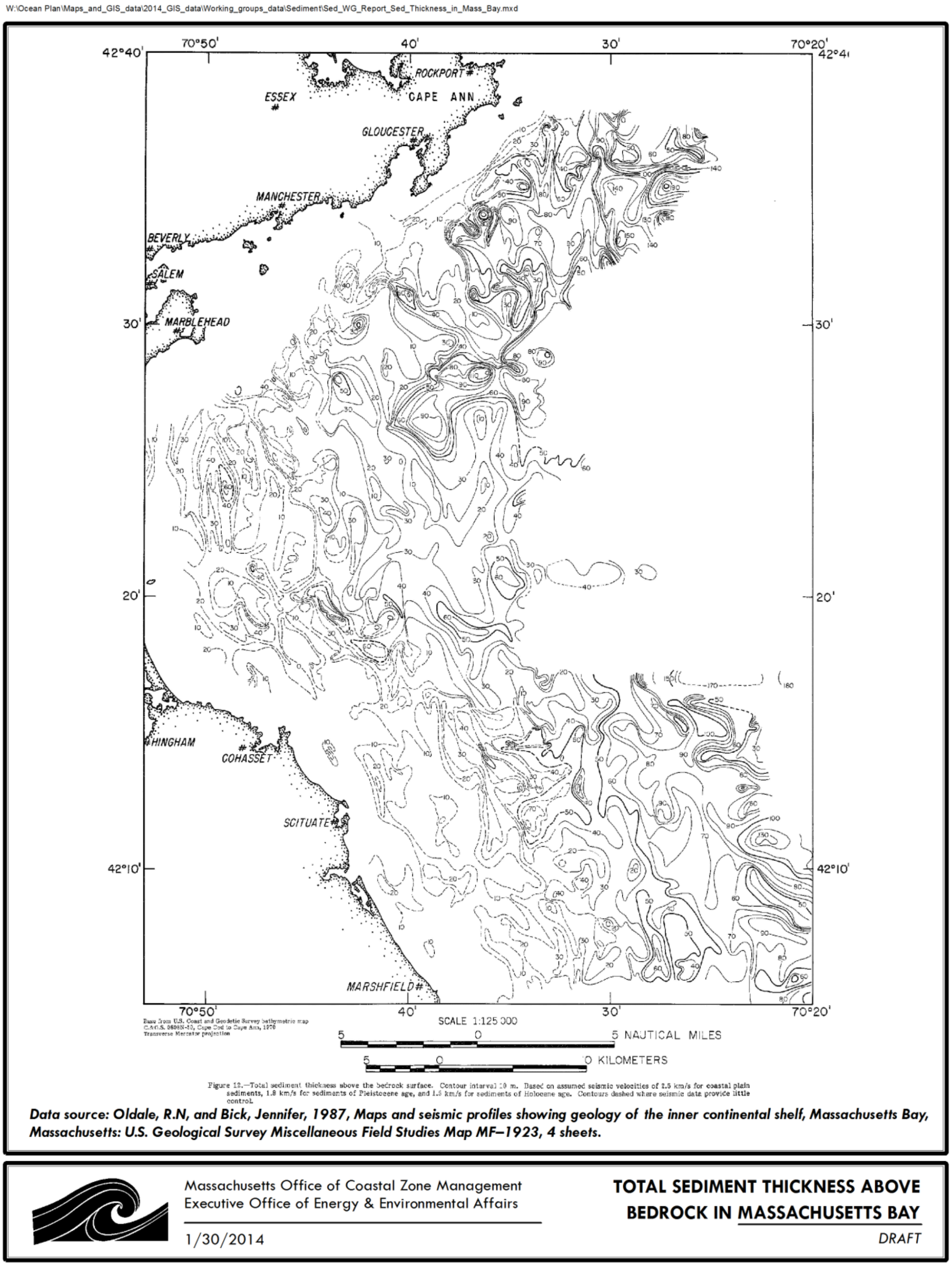

Figure 18. Total sediment thickness (in meters above bedrock) in Massachusetts Bay.

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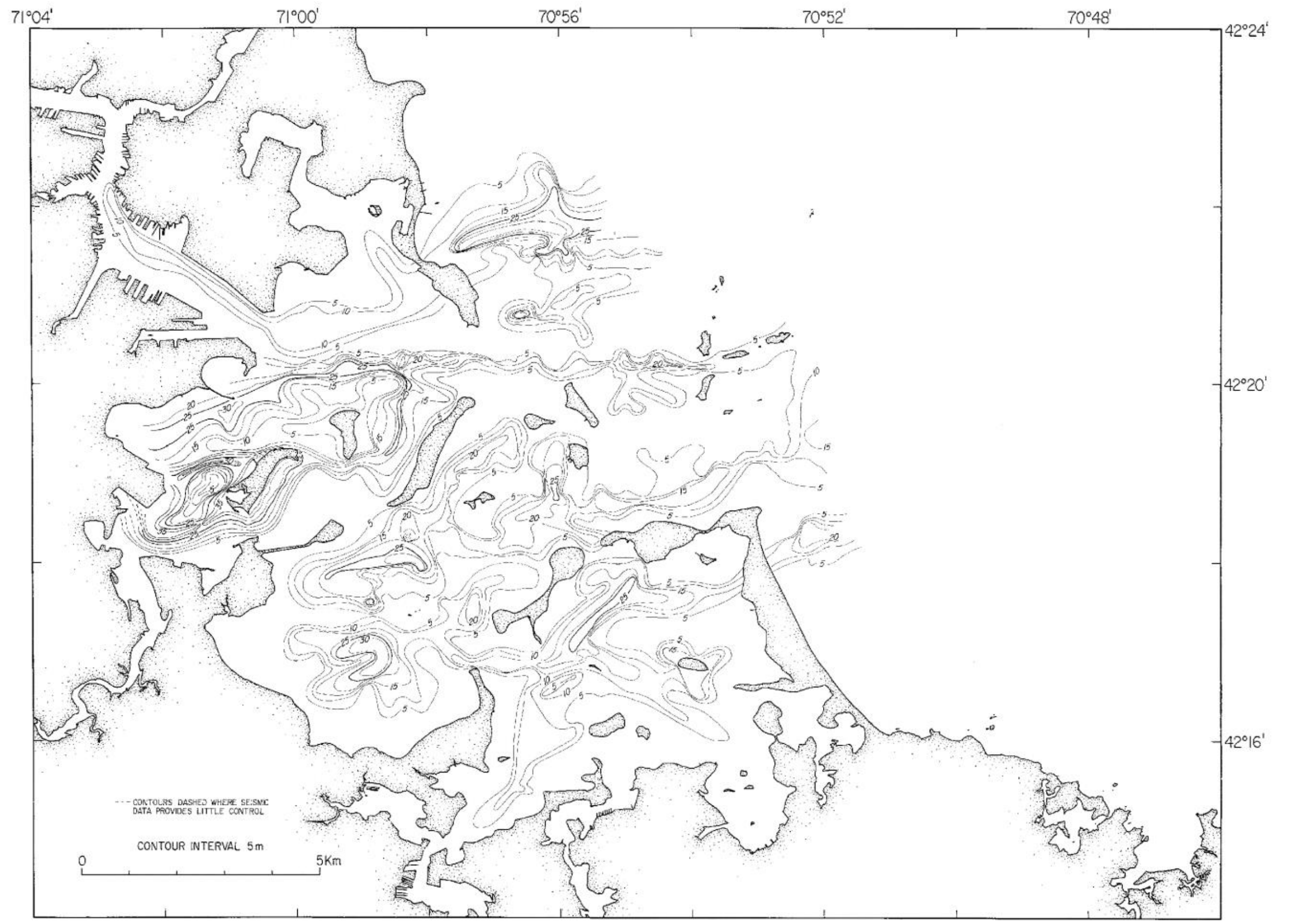

Figure 4.--Isopach map of the total thickness of Quaternary sediments overlying acoustic basement.

Data source: Rendigs, R.R., and Oldale, R.N., 1990. Maps showing the results of a subbottom acoustic survey of Boston Harbor, Massachusetts: U.S. Geological Survey Miscellaneous Field Studies Map MF–2124, 2 sheets.

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TOTAL SEDIMENT THICKNESS ABOVE BEDROCK IN BOSTON HARBOR

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Figure 19. Total sediment thickness (in meters above bedrock) in Boston Harbor.

SECTION FOUR: Data Layer Descriptions for 2021 Ocean Plan

Table 3. Hard/complex seafloor: Proposed 2021 Ocean Plan.

	CZM Proposal for 2021 Ocean Plan
Data Source	***Hard seafloor:*** These data were compiled from four sources: 1) new USGS interpreted seafloor sediment maps (Shallow Geology, Sea-Floor Texture, and Physiographic Zones of the Inner Continental Shelf from Aquinnah to Wasque Point, Martha's Vineyard, and Eel Point to Great Point, Nantucket, Massachusetts, 2019; Continuous Bathymetry and Elevation Models of the Massachusetts Coastal Zone and Continental Shelf, 2018; High-resolution geophysical data from the Inner Continental Shelf: South of Martha's Vineyard and north of Nantucket, Massachusetts, 2016; Geological Sampling Data and Benthic Biota Classification: Buzzards Bay and Vineyard Sound, Massachusetts, 2015; Shallow Geology, Sea-Floor Texture, and Physiographic Zones of Buzzards Bay, Massachusetts, 2015; High-Resolution Swath Interferometric Data Collected Within Muskeget Channel, Massachusetts, 2014; Bathymetry of the Waters Surrounding the Elizabeth Islands, Massachusetts, 2014; Shallow Geology, Seafloor Texture, and Physiographic Zones of the Inner Continental Shelf from Nahant to Northern Cape Cod Bay, Massachusetts, 2013; High-Resolution Geophysical Data from the Inner Continental Shelf: Buzzards Bay, Massachusetts, 2013; Construction of a 3-Arcsecond Digital Elevation Model for the Gulf of Maine, 2013; High-Resolution Geophysical Data From the Inner Continental Shelf at Vineyard Sound, Massachusetts, 2013; High-Resolution Geophysical Data Collected Within Red Brook Harbor, Buzzards Bay, Massachusetts, 2012; High-Resolution Geophysical Data From the Sea Floor Surrounding the Western Elizabeth Islands, Massachusetts, 2012; Sea-Floor Geology and Sedimentary Processes in the Vicinity of Cross Rip Channel, Nantucket Sound, Offshore Southeastern Massachusetts, 2012; Geophysical and Sampling Data from the Inner Continental Shelf: Northern Cape Cod Bay, Massachusetts, 2010; Geophysical and Sampling Data from the Inner Continental Shelf: Duxbury to Hull, Massachusetts, 2010; Geophysical Data Collected off the South Shore of Martha's Vineyard, Massachusetts, 2010; Geological Interpretation of the Sea Floor Offshore of Edgartown, Massachusetts, 2010; High-Resolution Geologic Mapping of the Inner Continental Shelf: Cape Ann to Salisbury Beach, Massachusetts, 2009; Enhanced Sidescan-Sonar Imagery Offshore of Southeastern Massachusetts, 2008; Sea-Floor Character and Sedimentary Processes in the Vicinity of Woods Hole, Massachusetts, 2008; Sea-Floor Character and Sedimentary Processes of Great Round Shoal Channel, Offshore Massachusetts, 2007; Sea-Floor Character and Sedimentary Processes of Quicks Hole, Elizabeth Islands, Massachusetts, 2007; A GIS Library of Multibeam Data for Massachusetts Bay and the Stellwagen Bank National Marine Sanctuary, Offshore of Boston, Massachusetts, 2007; Geological Interpretation of Bathymetric and Backscatter Imagery of the Sea Floor Off Eastern Cape Cod, Massachusetts, 2006; High-Resolution Geologic Mapping of the Inner Continental Shelf: Boston Harbor and Approaches, Massachusetts, 2006; High-Resolution Geologic Mapping of the Inner Continental Shelf: Nahant to Gloucester, Massachusetts, 2006; Shaded Relief, Sea Floor Topography, and Backscatter Intensity of Massachusetts Bay and the Stellwagen Bank Region Offshore of Boston, Massachusetts, 2004; Photographs of the Sea Floor in Western Massachusetts Bay, Offshore of Boston, Massachusetts, 1999; Sea Floor Topographic, Backscatter, and Interpretive Maps and Bottom Photos of the Massachusetts Bay Disposal Site Region off Boston, Massachusetts, 1998), 2) Massachusetts Department of Environmental Protection (DEP) wetlands (1:12,000) rocky intertidal shore delineations, 3) older USGS interpreted sediment maps (Knebel and Circe 1995; Rendigs and Knebel 2002; Poppe et al. 2006; Poppe et al. 2007; and O'Hara and Oldale, 1987), 4) APTIM's *Preliminary Characterization Of Offshore Sand Resources In Selected Study Areas*, 2018, and 5) an the CZM/DMF sediment database used in the 2009 and 2015 Ocean Plans.

Table 3. Continued.

	CZM Proposal for 2021 Ocean Plan
Data Source (Cont.)	***Complex seafloor:*** Andrews, B.D., Baldwin, W.E., Sampson, D.W., and Schwab, W.C., 2018, Continuous bathymetry and elevation models of the Massachusetts coastal zone and continental shelf (ver. 3.0, December 2019): U.S. Geological Survey data release, https://doi.org/10.5066/F72806T7. ***Artificial reefs:*** The Artificial reef data were updated by adding all newly DMF permitted and proposed artificial reefs to the 2014 data set. ***Biogenic reefs:*** *Crepidula* and worm reefs were not used as a component of the Hard and Complex Bottom SSU on account of the age of the data and the ephemeral nature of the living resources. ***Wrecks and obstructions:*** Wreck data were not used as a component of the Hard and Complex Bottom SSU because many wrecks have no super-surface component and the spatial accuracy of the data are often poor.
Data Description	Hard seafloor is seabed characterized by exposed bedrock or concentrations of boulder, cobble, or other similar hard bottom distinguished from surrounding areas of primarily finer-grained material. Complex seafloor is a morphologically rugged seafloor characterized by high variability in bathymetric aspect and gradient. Man-made structures, such as artificial reefs are designed to provide additional suitable substrate for the development of hard bottom biological communities. Hard/complex seafloor is seabed characterized singly or by any combination of hard seafloor, artificial reefs, and complex seafloor.
Data Extent	The Massachusetts ocean management planning area.
Data Adjustment and Pre-processing	***Hard seafloor:*** None. ***Complex seafloor:*** None. ***Artificial reefs:*** None.

Table 3. Continued.

	CZM Proposal for 2021 Ocean Plan
Data Analysis	***Hard seafloor:*** Hard seafloor was mapped by extracting areas characterized as rock, rock with gravel, rock with sand, or rock with mud from the *Surficial sediment in Massachusetts state waters* dataset (see Table 4 below). Surficial sediment was mapped by collating data sources such that high-quality data mask lower quality data in the following order, highest first: 1) new USGS interpreted seabed sediment (Shallow Geology, Sea-Floor Texture, and Physiographic Zones of the Inner Continental Shelf from Aquinnah to Wasque Point, Martha's Vineyard, and Eel Point to Great Point, Nantucket, Massachusetts, 2019; Continuous Bathymetry and Elevation Models of the Massachusetts Coastal Zone and Continental Shelf, 2018; High-resolution geophysical data from the Inner Continental Shelf: South of Martha's Vineyard and north of Nantucket, Massachusetts, 2016; Geological Sampling Data and Benthic Biota Classification: Buzzards Bay and Vineyard Sound, Massachusetts, 2015; Shallow Geology, Sea-Floor Texture, and Physiographic Zones of Buzzards Bay, Massachusetts, 2015; High-Resolution Swath Interferometric Data Collected Within Muskeget Channel, Massachusetts, 2014; Bathymetry of the Waters Surrounding the Elizabeth Islands, Massachusetts, 2014; Shallow Geology, Seafloor Texture, and Physiographic Zones of the Inner Continental Shelf from Nahant to Northern Cape Cod Bay, Massachusetts, 2013; High-Resolution Geophysical Data from the Inner Continental Shelf: Buzzards Bay, Massachusetts, 2013; Construction of a 3-Arcsecond Digital Elevation Model for the Gulf of Maine, 2013; High-Resolution Geophysical Data From the Inner Continental Shelf at Vineyard Sound, Massachusetts, 2013; High-Resolution Geophysical Data Collected Within Red Brook Harbor, Buzzards Bay, Massachusetts, 2012; High-Resolution Geophysical Data From the Sea Floor Surrounding the Western Elizabeth Islands, Massachusetts, 2012; Sea-Floor Geology and Sedimentary Processes in the Vicinity of Cross Rip Channel, Nantucket Sound, Offshore Southeastern Massachusetts, 2012; Geophysical and Sampling Data from the Inner Continental Shelf: Northern Cape Cod Bay, Massachusetts, 2010; Geophysical and Sampling Data from the Inner Continental Shelf: Duxbury to Hull, Massachusetts, 2010; Geophysical Data Collected off the South Shore of Martha's Vineyard, Massachusetts, 2010; Geological Interpretation of the Sea Floor Offshore of Edgartown, Massachusetts, 2010; High-Resolution Geologic Mapping of the Inner Continental Shelf: Cape Ann to Salisbury Beach, Massachusetts, 2009; Enhanced Sidescan-Sonar Imagery Offshore of Southeastern Massachusetts, 2008; Sea-Floor Character and Sedimentary Processes in the Vicinity of Woods Hole, Massachusetts, 2008; Sea-Floor Character and Sedimentary Processes of Great Round Shoal Channel, Offshore Massachusetts, 2007; Sea-Floor Character and Sedimentary Processes of Quicks Hole, Elizabeth Islands, Massachusetts, 2007; A GIS Library of Multibeam Data for Massachusetts Bay and the Stellwagen Bank National Marine Sanctuary, Offshore of Boston, Massachusetts, 2007; Geological Interpretation of Bathymetric and Backscatter Imagery of the Sea Floor Off Eastern Cape Cod, Massachusetts, 2006; High-Resolution Geologic Mapping of the Inner Continental Shelf: Boston Harbor and Approaches, Massachusetts, 2006; High-Resolution Geologic Mapping of the Inner Continental Shelf: Nahant to Gloucester, Massachusetts, 2006; Shaded Relief, Sea Floor Topography, and Backscatter Intensity of Massachusetts Bay and the Stellwagen Bank Region Offshore of Boston, Massachusetts, 2004; Photographs of the Sea Floor in Western Massachusetts Bay, Offshore of Boston, Massachusetts, 1999; Sea Floor Topographic, Backscatter, and Interpretive Maps and Bottom Photos of the Massachusetts Bay Disposal Site Region off Boston, Massachusetts, 1998), 2) Massachusetts Department of Environmental Protection (DEP) wetlands (1:12,000) rocky intertidal shore delineations, 3) older USGS sediment interpretations (Poppe et al. 2007; Poppe et al. 2006; Knebel and Circe 1995; Rendigs and Knebel 2002; and O'Hara and Oldale, 1987), and 4) interpolated Thiessen polygons derived from the CZM/DMF sediment database. (Thiessen polygons proportionally divide and distribute a point coverage into regions known as Thiessen or Voronoi polygons. Each Thiessen polygon defines an area of influence around its sample point, so that any location inside the polygon is closer to that point than any of the other sample points.)

Table 3. Continued.

	CZM Proposal for 2021 Ocean Plan
Data Analysis (Cont.)	***Complex seafloor:*** Areas of high rugosity were mapped as complex seafloor. Rugosity is a measure of terrain roughness and is indicative of the amount of habitat available for colonization by epibenthic organisms and shelter and foraging area for mobile organisms. For this dataset, CZM calculated rugosity using the Vector Ruggedness Measure tool (Sappington et al. 2007) on a 10x10-meter resolution statewide bathymetry dataset provided by USGS (Andrews et al., 2018). Using mapped rocky areas as guidance to select a class break between high and low rugosity, CZM extracted areas greater than 3/8 standard deviations from the mean as high rugosity. ***Artificial reefs:*** None.
Data Classification	***Hard seafloor:*** The 2013-present USGS interpreted surficial sediment data and the CZM/DMF sediment database were classified using the Barnhardt et al. (1998) scheme while all other data were crosswalked from their native sediment classification framework to Barnhardt. Barnhardt is based on four primary sediment units: rock (R), gravel (G), sand (S), and mud (M). Twelve additional two-part units represent combinations of the four primary units, where the majority texture is given an upper-case letter and the next most common texture is given a lower-case letter. Sediment grain sizes follow the Wentworth (1922) scale. Rock is characterized as cobble and larger (>64 mm), so R, Rg, Rs, and Rm are all classified as hard bottom. ***Complex seafloor:*** Complex seafloor was classified as previously. ***Artificial reefs:*** Not applicable. ***Biogenic reefs:*** Not applicable. ***Wrecks and obstructions:*** Not applicable.
Selection of SSU Area	All polygons classified as 1) hard seafloor, 2) complex seafloor, 3) artificial reefs, 4), biogenic reefs or 5) wrecks and obstructions were selected for inclusion in the SSU.

Table 4. Locations of surficial sediment samples in the CZM/DMF sediment database: Proposed 2021 Ocean Plan.

	CZM Proposal for 2021 Ocean Plan
Data Source	An updated version of the CZM/DMF sediment database was used in the 2021 Ocean Plan Update. One additional data set was added to the 2014 sediment database from the following source: APTIM's *Preliminary Characterization of Offshore Sand Resources In Selected Study Areas*, 2018.
Data Description	The updated CZM/DMF sediment database contains the sediment composition of over 50,000 surficial sediment samples within a 10-kilometer buffer of Massachusetts state waters.
Data Extent	The data extent encompasses Massachusetts state waters and extends 10 kilometers seaward of state waters and includes Stellwagen Bank.
Data Adjustment and Pre-processing	Replicate samples were removed whenever they could be clearly identified.
Data Analysis	Not applicable.
Data Classification	Sediment samples were mapped using the Wentworth (1922) grain-size scale and the Barnhardt et al. (1998) sediment classification scheme. Barnhardt is based on four primary sediment units: rock (R), gravel (G), sand (S), and mud (M). Twelve additional two-part units represent combinations of the four primary units, where the majority texture is given an upper-case letter and the next most common texture is given a lower-case letter. Sediment grain sizes follow the Wentworth (1922) scale where mud is <0.62 mm, sand is 0.62–2 mm, gravel is 2–64 mm, and rock is >64 mm (cobble and larger).
Selection of SSU Area	Not applicable. These data are not mapped as SSU areas.

Table 5. Surficial sediment mapping: Proposed 2021 Ocean Plan.

	CZM Proposal for 2021 Ocean Plan
Data Source	***Surficial sediment in Massachusetts state waters:*** These data came from five data sources: 1) new USGS interpreted seabed sediment, (Shallow Geology, Sea-Floor Texture, and Physiographic Zones of the Inner Continental Shelf from Aquinnah to Wasque Point, Martha's Vineyard, and Eel Point to Great Point, Nantucket, Massachusetts, 2019; Continuous Bathymetry and Elevation Models of the Massachusetts Coastal Zone and Continental Shelf, 2018; High-resolution geophysical data from the Inner Continental Shelf: South of Martha's Vineyard and north of Nantucket, Massachusetts, 2016; Geological Sampling Data and Benthic Biota Classification: Buzzards Bay and Vineyard Sound, Massachusetts, 2015; Shallow Geology, Sea-Floor Texture, and Physiographic Zones of Buzzards Bay, Massachusetts, 2015; High-Resolution Swath Interferometric Data Collected Within Muskeget Channel, Massachusetts, 2014; Bathymetry of the Waters Surrounding the Elizabeth Islands, Massachusetts, 2014; Shallow Geology, Seafloor Texture, and Physiographic Zones of the Inner Continental Shelf from Nahant to Northern Cape Cod Bay, Massachusetts, 2013; High-Resolution Geophysical Data from the Inner Continental Shelf: Buzzards Bay, Massachusetts, 2013; Construction of a 3-Arcsecond Digital Elevation Model for the Gulf of Maine, 2013; High-Resolution Geophysical Data From the Inner Continental Shelf at Vineyard Sound, Massachusetts, 2013; High-Resolution Geophysical Data Collected Within Red Brook Harbor, Buzzards Bay, Massachusetts, 2012; High-Resolution Geophysical Data From the Sea Floor Surrounding the Western Elizabeth Islands, Massachusetts, 2012; Sea-Floor Geology and Sedimentary Processes in the Vicinity of Cross Rip Channel, Nantucket Sound, Offshore Southeastern Massachusetts, 2012; Geophysical and Sampling Data from the Inner Continental Shelf: Northern Cape Cod Bay, Massachusetts, 2010; Geophysical and Sampling Data from the Inner Continental Shelf: Duxbury to Hull, Massachusetts, 2010; Geophysical Data Collected off the South Shore of Martha's Vineyard, Massachusetts, 2010; Geological Interpretation of the Sea Floor Offshore of Edgartown, Massachusetts, 2010; High-Resolution Geologic Mapping of the Inner Continental Shelf: Cape Ann to Salisbury Beach, Massachusetts, 2009; Enhanced Sidescan-Sonar Imagery Offshore of Southeastern Massachusetts, 2008; Sea-Floor Character and Sedimentary Processes in the Vicinity of Woods Hole, Massachusetts, 2008; Sea-Floor Character and Sedimentary Processes of Great Round Shoal Channel, Offshore Massachusetts, 2007; Sea-Floor Character and Sedimentary Processes of Quicks Hole, Elizabeth Islands, Massachusetts, 2007; A GIS Library of Multibeam Data for Massachusetts Bay and the Stellwagen Bank National Marine Sanctuary, Offshore of Boston, Massachusetts, 2007; Geological Interpretation of Bathymetric and Backscatter Imagery of the Sea Floor Off Eastern Cape Cod, Massachusetts, 2006; High-Resolution Geologic Mapping of the Inner Continental Shelf: Boston Harbor and Approaches, Massachusetts, 2006; High-Resolution Geologic Mapping of the Inner Continental Shelf: Nahant to Gloucester, Massachusetts, 2006; Shaded Relief, Sea Floor Topography, and Backscatter Intensity of Massachusetts Bay and the Stellwagen Bank Region Offshore of Boston, Massachusetts, 2004; Photographs of the Sea Floor in Western Massachusetts Bay, Offshore of Boston, Massachusetts, 1999; Sea Floor Topographic, Backscatter, and Interpretive Maps and Bottom Photos of the Massachusetts Bay Disposal Site Region off Boston, Massachusetts, 1998), 2 Massachusetts Department of Environmental Protection (DEP) wetlands (1:12,000) rocky intertidal shore delineations, 3) older USGS sediment interpretations (Poppe et al. 2007; Poppe et al. 2006; Knebel and Circe 1995; Rendigs and Knebel 2002; and O'Hara and Oldale, 1987), 4) *The Geophysical and Geological Data Acquisition: Inventory of Potential Beach Nourishment and Coastal Restoration Sand Sources on the Atlantic Outer Continental Shelf (BOEM)*, (Mabee 2019) and 5) an updated version of the CZM/DMF sediment database used in the 20014 Ocean Plan.

Table 5. Continued.

	CZM Proposal for 2021 Ocean Plan
Data Source (Cont.)	***Surficial sediment in federal waters derived from CZM/DMF sediment database:*** These data utilize the same four data sources as *Surficial sediment in Massachusetts state waters* (see above). ***Surficial sediment in federal waters derived from USGS Misc. Investigation Series and CONMAP:*** These data utilize the same four data sources as *Surficial sediment in Massachusetts state waters* (see above) with the addition of: 1) USGS Continental Margin Mapping (CONMAP) sediments grain-size distribution for the U.S. East Coast Continental Margin (Poppe et al. 2005), 2) USGS Misc. Geologic Investigations Map I-746, *Bottom Sediments on the Continental Shelf off the Northeastern United States Cape Cod to Cape Ann, Massachusetts* (Schlee, et al. 1973; and 3) USGS Misc. Investigations Map I-839, *Maps Showing Bottom Sediments on the Continental Shelf off the Northeastern United States-Cape Ann, Massachusetts to Casco Bay, Maine* (Folger et al., 1975).
Data Description	***Surficial sediment in Massachusetts state waters:*** These data characterize the seabed with sixteen sediment types based on four primary sediment units: rock, gravel, sand, and mud. Twelve additional two-part units represent combinations of the four primary units. ***Surficial sediment in federal waters derived from CZM/DMF sediment database:*** These data extend mapping into federal waters using the CZM/DMF sediment database. As with *Surficial sediment in Massachusetts state waters,* the seabed is characterized with sixteen sediment types based on four primary sediment units: rock, gravel, sand, and mud. Twelve additional two-part units represent combinations of the four primary units. ***Surficial sediment in federal waters derived from USGS Misc. Investigation Series and USGS CONMAP:*** These data extend surficial sediment mapping into federal waters using USGS CONMAP data (Poppe et al. 2005), USGS I-746 (Schlee, et al. 1973; and 3) USGS I-839 (Folger et al., 1975). As with *Surficial sediment in Massachusetts state waters,* the seabed is characterized with sixteen sediment types based on four primary sediment units: rock, gravel, sand, and mud. Twelve additional two-part units represent combinations of the four primary units.
Data Extent	***Surficial sediment in Massachusetts state waters*** includes state waters. ***Surficial sediment in federal waters derived from CZM/DMF sediment database*** encompasses state waters and extends seven nautical miles seaward of the ocean management planning area. ***Surficial sediment in federal waters derived from USGS Misc. Investigation Series data* and *USGS CONMAP*** encompasses state waters and extends from the ocean management planning area to approximately 25 nautical miles offshore. (CONMAP data extend past this line seaward to the continental shelf).

Table 5. Continued.

	CZM Proposal for 2021 Ocean Plan
Data Adjustment and Pre-processing	None.
Data Analysis	***Surficial sediment in Massachusetts state waters*** and ***Surficial sediment in federal waters derived from CZM/DMF sediment database:*** These maps were created by collating data sources such that high-quality data mask lower quality data in the following order, highest first: 1) 2013-present USGS interpreted surficial sediment data, 2) Massachusetts Department of Environmental Protection (DEP) wetlands (1:12,000) rocky intertidal shore delineations, 3) BOEM (Mabee, 2019), 4) older USGS sediment interpretations (Poppe et al. 2007; Poppe et al. 2006; Knebel and Circe 1995; Rendigs and Knebel 2002; and O'Hara and Oldale, 1987), and 5) interpolated Thiessen polygons derived from the CZM/DMF sediment database. ***Surficial sediment in federal waters derived from USGS Misc. Investigation Series*** **and** ***CONMAP data:*** This map was created in the same manner as above, however, all areas outside of Massachusetts state waters were mapped using USGS I-746 (Schlee, et al. 1973), USGS I-839 (Folger et al., 1975), and USGS CONMAP data (Poppe et al. 2005).

Table 5. Continued.

	CZM Proposal for 2021 Ocean Plan
Data Classification	The 2013-present USGS interpreted surficial sediment data and the CZM/DMF sediment database were classified using the Barnhardt et al. (1998) scheme while all other data were crosswalked from their native classification framework to Barnhardt. Barnhardt is based on four primary sediment units: rock (R), gravel (G), sand (S), and mud (M). Twelve additional two-part units represent combinations of the four primary units, where the majority texture is given an upper-case letter and the next most common texture is given a lower-case letter. Sediment grain sizes follow the Wentworth (1922) scale where mud is <0.62 mm, sand is 0.62–2 mm, gravel is 2–64 mm, and rock is >64 mm (cobble and larger). CZM used the following crosswalks for converting the DEP wetlands and older interpretive data from their native classification schemes to Barnhardt: • DEP wetlands: Rocky intertidal shores were extracted and classified as rock (R). Barrier beaches, barrier beaches-coastal beaches, barrier beaches-coastal dunes, barrier beach systems, coastal beaches, and coastal dunes were extracted and classified as sand (S). • Interpretive map of the surficial geology of Great Round Shoal Channel (Poppe et al. 2007): Barchanoid and transverse sand waves were extracted and classified as sand (S), exposed glacial drift = gravel (G*), and reworked Holocene sand = sand (S).* This category was changed from n/a in 2014 to G* per USGS with the asterisk denoting that the crosswalk is weak without corroborating laboratory analyzed sediment samples. When G* was assigned, the polygons were further analyzed to assign a "clean" Barnhardt code using best professional judgment based upon sediment points and adjacent polygon classifications. • Interpretive map of the surficial sediment distributions off Eastern Cape Cod (Poppe et al. 2006) (Shepard [1954] name followed by Barnhardt name and code): gravel = Rock (R) or gravel (G)*, gravelly sediment = sand with gravel (Sg), sand = sand (S), silty sand = sand with mud (Sm), clayey silt = mud (M), silty clay = mud (M). * When Sg or Gs was assigned, the polygons were further analyzed to assign a "clean" Barnhardt code using best professional judgment based upon sediment points, adjacent polygon classifications, and location (coastal, deep ocean, or erosional surface). • Interpretive map of sedimentary environments in Boston Harbor-Massachusetts Bay (Knebel and Circe 1995) crosswalked by USGS at CZM's request: Each polygon was assigned a sediment type by interpreting the intersecting CZM/DMF sediment database points. For those polygons with no intersecting points, the following crosswalk was used (sedimentary environment/backscatter patterns followed by Barnhardt name and code): erosion or nondeposition/isolated reflection = rock (R), erosion or nondeposition/strong backscatter = gravel with sand (Gs), sediment reworking/strong to weak backscatter patches = sand (S), and deposition/weak backscatter = mud (M). • Interpretive map of surficial sediment in Cape Cod Bay (Rendigs and Knebel 2002) crosswalked by USGS using the CZM/DMF sediment database to assign sediment classes: sandy to clayey silt = mud (M), fine to very fine sand = mud with sand (Ms), very coarse to very fine sand = sand (S), sand with mud (Sm), or mud with sand (Ms). • Misc. Geologic Investigations Maps (Schlee, et al. 1973 and Folger et al., 1975) data were crosswalked by USGS at CZM's request: Gravel = G; Sandy gravel = see Note 1, Muddy; sandy gravel = Gs* with the note "*Muddy, sandy gravel is tricky to translate because the Schlee pyramids put more emphasis on mud (silt and clay) than the Barnhardt does"; Sand = S; Gravelly sand = see Note 1; Pebbly sand = see Note 1; Silty, clayey sand = Sm; Clayey silt = M; Clay = M; Silty clay = M; Sand-silt-clay = Ms; Bedrock and (or) coarse glacial debris = R** with the note "**Bedrock = R; coarse glacial is likely Rg, but could be R, Rs, or Rm or Gr, Gs, G or Gm depending on its current environment (coastal (probably Rs, G, Gs), deep ocean (usually Rm or Gm), or erosional surface Gr, Rg, R)."

Table 5. Continued.

	CZM Proposal for 2021 Ocean Plan
Data Classification (Cont.)	Note 1: "Due to problems with the scan of the paper map and/or poor original cartography, these three categories were indistinguishable on the USGS map. To salvage these categories, the data were overlaid on the CZM/DMF sediment database to redefine the sediment classes within the Schell et al. polygons. The majority sediment type from the sediment database was used to determine a final Barnhardt code. When the number of sediment samples falling within a given polygon was equally split between two or more Barnhardt classes, the class with the highest data confidence was assigned. When no sediment samples fell within a given polygon, "Sg or Gs" was assigned." All Gs* or R** polygons were further analyzed to assign a "clean" Barnhardt code using best professional judgment based upon sediment points, adjacent polygon classifications, and location (coastal, deep ocean, or erosional surface). • BOEM data (Mabee, 2019) was crosswalked by CZM: Bedrock outcrop = R, channel fill = Sm, lake bottom = Ms, mobile sand sheet = S, mobile sand/gravel sheet = Gs, moraine = Rs, sand bar complex = S, sand sheet/fan = Gs, and till = Gs or Rs depending on description. All Gs or Rs polygons were further analyzed to assign a "clean" Barnhardt code using best professional judgment based upon sediment points, adjacent polygon classifications, and location (coastal, deep ocean, or erosional surface). • CONMAP data (Poppe et al. 2005) was crosswalked by USGS at CZM's request (Shepard [1954] name and code followed by Barnhardt name and code): bedrock (br) = rock (R), gravel (gr) = gravel (G), gravelly sand (gr-sd) = sand with gravel (Sg), sand (sd) = sand (S), clayey sand or silty sand (cl-st/sd) = sand with mud (Sm), sandy silt or clayey silt (sd-cl/st) = mud with sand (Ms), clay (cl) = mud (M), sandy clay or silty clay (sd-st/cl) = mud with sand (Ms), and sand, silt, clay (sd/st/cl) = mud with sand (Ms).
Selection of SSU Area	Not applicable. These data are not mapped as SSU areas.

Table 6. High-resolution seafloor mapping data: Proposed 2021 Ocean Plan.

	CZM Proposal for 2021 Ocean Plan
Data Source	High-resolution seafloor mapping data are from the following two sources: 1) CZM and U.S. Geological Survey (USGS) Seafloor Mapping Cooperative; 2) USGS
Data Description	In 2003, CZM and the USGS Woods Hole Science Center initiated a Seafloor Mapping Cooperative to jointly address the need for data and information characterizing seafloor resources. The goal of the cooperative is to comprehensively map the bathymetry and geology of the seafloor inside the three-nautical-mile limit of Massachusetts waters and in adjacent federal waters. As of 2012, the cooperative has mapped 2,200 square kilometers of Massachusetts marine waters and has published or is preparing to release these data as USGS Open-File Reports. Completed areas and dates of publication of USGS Open-File Reports are the following: 1) Nahant to Gloucester (2006), 2) Boston Harbor and Approaches (2006), 3) Cape Ann to Salisbury Beach (2009), 4) Duxbury to Hull (2010), 5) Northern Cape Cod Bay (2010), 6) Buzzards Bay (2013), 7) Vineyard Sound (2013), and 8) South of Martha's Vineyard and north of Nantucket (2016). Reports are in progress for southern Cape Cod Bay. Additional mapping completed by USGS only in Massachusetts state waters include the following areas and dates of publication of USGS Open-File Reports: 1) Eastern Cape Cod (2006), 2) Quicks Hole (2007), 3) Great Round Shoal (2007), 4) Massachusetts Bay and Stellwagen Bank National Marine Sanctuary (2007), 5) Woods Hole (2008), 6) Edgartown (2009), 7) South Shore of Martha's Vineyard (2009), and 8) Eastern Rhode Island Sound (2011, and 9) Town Neck Beach, Sandwich (2016). NOAA's National Ocean Service (NOS) has conducted many bathymetric surveys in Massachusetts and adjacent waters: NOS Hydrographic Surveys D00149, F00508, F00545, F00550, F00619, F00660, H11076, H11636, H11695, H11736, H11737, H11920, H11921, H11922, H12083, H12642, H12643, H12696, H12707, H12801, H12802, H12811, W00037, W00038, W00039, W00044, W00045, W00047, W000194, W00313, and W00318. Coastal topobathy LIDAR data collected by NOAA and the U.S. Army Corps of Engineers (USACE) were collated for the 2020 Ocean Plan: 1) 2005-2006 Plum Island LIDAR, 2) 2010 USACE NCMP Topobathy Lidar: Northeast Atlantic Coast, 3) 2007 USACE NCMP Topobathy Lidar: New England, 4) 2010 USACE NCMP Topobathy Lidar: Northeast Atlantic Coast, 5) 2011 USACE Topographic LiDAR: MA and NH, 6) 2013 USACE NAE Topobathy Lidar: MA, 7) 2013 USACE NAE Topobathy Lidar: Cuttyhunk, Marshfield, Menemsha, and Nantucket (MA), 8) 2014 USACE NAE Topobathy Lidar: Newbury (MA), 9) 2015 USACE NAE Topobathy Lidar: MA, 10) 2015 NOAA NGS Topobathy Lidar: Buzzards Bay Blocks 1-3 (MA), 11) 2015 USACE NAE Topobathy Lidar: MA, and 12) W00313: NOS Hydrographic Survey, 2016-05-27.
Data Extent	In and adjacent to Massachusetts state waters.
Data Adjustment and Pre-processing	None.

Table 6. Continued.

	CZM Proposal for 2021 Ocean Plan
Data Analysis	The coverage footprints of these surveys were merged by CZM to create a map depicting high-resolution acoustic mapping in and adjacent to Massachusetts state waters.
Data Classification	Not applicable.
Selection of SSU Area	Not applicable. These data are not mapped as SSU areas.

Table 7. Mussel reefs: Proposed 2020 Ocean Plan.

	CZM Proposal for 2021 Ocean Plan
Data Source	No change, refer to 2014 Plan for details
Data Description	This dataset represents the locations of photos where the dominant biotic group was classified as a mussel reef.
Data Extent	In and adjacent to Massachusetts state waters.
Data Adjustment and Pre-processing	None.
Data Analysis	None.
Data Classification	Not applicable.
Selection of SSU Area	Not applicable. These data are not mapped as SSU areas.

Table 8. Sites investigated for potential sand and gravel extraction: Proposed 2021 Ocean Plan.

	CZM Proposal for 2021 Ocean Plan
Data Source	Sites investigated for potential sand and gravel extraction were compiled from reports by the U.S. Army Corps of Engineers, Boston University, Massachusetts Division of Mineral Resources, APTIM Corp., and others.
Data Description	This dataset shows the locations of sites with potentially high-quality sand and gravel resources that were identified through general exploration as well as targeted projects. CZM mapped these sites using originator-supplied GIS data or digitizing older georeferenced paper maps.
Data Extent	In and adjacent to Massachusetts state waters.
Data Adjustment and Pre-processing	None.
Data Analysis	None.
Data Classification	Not applicable.
Selection of SSU Area	Not applicable. These data are not mapped as SSU areas.

Table 9. Nearshore disposal sites: Proposed 2021 Ocean Plan.

	CZM Proposal for 2021 Ocean Plan
Data Source	The U.S. Army Corps of Engineers (USACE) provided a dataset of all the confined aquatic disposal (CAD) cells and nearshore disposal sites (current and historic) in Massachusetts state waters in their database.
Data Description	This dataset shows the locations of nearshore CAD cells and disposal sites in Massachusetts state waters used by USACE.
Data Extent	Massachusetts state waters.
Data Adjustment and Pre-processing	None.
Data Analysis	None.
Data Classification	Not applicable.
Selection of SSU Area	Not applicable. These data are not mapped as SSU areas.

Table 10. Sediment core locations: Proposed 2021 Ocean Plan.

	CZM Proposal for 2021 Ocean Plan
Data Source	***Sediment cores in and adjacent to Massachusetts state waters:*** These data came from several data sources: 1) APTIM, 2017, 2) Aubrey, 1992, 3) Barnhardt, 2007 and 2008, 4) Boston University, 1990, 5) Coastal Planning and Engineering, 2013 and 2016, 6) Div. of Mineral Resources, DNR, Commonwealth of MA, 1974, 7) MA Div. of Marine Fisheries, 2010, 8) Sconset Beach Nourishment Project Final Environmental Impact Report, 9) USACOE, 1976 and 1980, and 10) Oldale, 1983, 11) Oldale and Bick, 1978, 12) Oldale and O'Hara, 1990, 13) O'Hara and Oldale, 1980, 14) O'Hara and Oldale, 1987, and 15) Robb and Oldale, 1977.
Data Description	CZM mapped these data using published and unpublished data created by the originator. Older paper maps were georeferenced by CZM and pertinent data were digitized and attributed.
Data Extent	In and adjacent to Massachusetts state waters.
Data Adjustment and Pre-processing	None.
Data Analysis	None.
Data Classification	Not applicable.
Selection of SSU Area	Not applicable. These data are not mapped as SSU areas.

Table 11. Areas of seismic (sub-bottom) profiling data: Proposed 2021 Ocean Plan.

	CZM Proposal for 2021 Ocean Plan
Data Source	Seismic (sub-bottom) profiling data are from the following two sources: 1) CZM and U.S. Geological Survey (USGS) Seafloor Mapping Cooperative; 2) USGS
Data Description	In 2003, CZM and the USGS Woods Hole Science Center initiated a Seafloor Mapping Cooperative to jointly address the need for data and information characterizing seafloor resources. The goal of the cooperative is to comprehensively map the bathymetry and geology of the seafloor inside the three-nautical-mile limit of Massachusetts waters and in adjacent federal waters. Seismic-reflection profiles (pictures of sub-surface sediment layers) have been collected and published as USGS Open-File Reports: 2005-1293, 2007-1373, 2008-1004, 2008-1288, 2009-1001, 2009-1001, 2009-1003, 2009-1072, 2010-1006, 2010-1091, 2011-1184, 2012-1002, 2012-1006, and 2016-1168. Additional USGS seismic data within state waters not collected as part of the Cooperative includes: Field Activities 1972-001-FA, 1973-005-FA, 1974-011-FA, 1979-024-FA, 1980-010-FA, 1994-026-FA, 2010-003-FA, 2010-047-FA, 2010-100-FA, and 2011-013-FA as well as Miscellaneous Field Studies Maps, 1911, 2124, and 2147.
Data Extent	In and adjacent to Massachusetts state waters.
Data Adjustment and Pre-processing	None.
Data Analysis	None.
Data Classification	Not applicable.
Selection of SSU Area	Not applicable. These data are not mapped as SSU areas.

Table 12. Total sediment thickness: Proposed 2021 Ocean Plan.

	CZM Proposal for 2021 Ocean Plan
Data Source	No change, refer to 2014 Plan for details
Data Description	These figures were published by USGS and show total sediment thickness in meters above bedrock.
Data Extent	Boston Harbor, Massachusetts Bay, and in waters north of Cape Ann.
Data Adjustment and Pre-processing	None.
Data Analysis	None.
Data Classification	Not applicable.
Selection of SSU Area	Not applicable. These data are not mapped as SSU areas.

SECTION FIVE: References

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APPENDIX A

2009/2014 Data Layer Descriptions

Table A.1. Hard/complex seafloor: Comparison of 2009 Ocean Plan to Proposed 2014 Ocean Plan.

	2009 Ocean Plan	CZM Proposal for 2014 Ocean Plan
Data Source	***Hard seafloor:*** These data came from two data sources: 1) U.S. Geological Survey (USGS) interpreted physiographic zone and bottom type maps as published in Open-File Reports (OFR), and 2) a CZM/Massachusetts Division of Marine Fisheries (DMF) sediment database comprised of data from USGS usSEABED, CZM-USGS Seafloor Mapping Cooperative, DMF surveys, U.S. Environmental Protection Agency's National Coastal Assessment, and Massachusetts Water Resources Authority's monitoring program. ***Complex seafloor:*** These data were mapped using 30x30-meter resolution bathymetry data provided by USGS.	***Hard seafloor:*** These data were compiled from four sources: 1) new USGS interpreted seafloor sediment maps (Pendleton et al. 2013 and unpublished data in review), 2) Massachusetts Department of Environmental Protection (DEP) wetlands (1:12,000) rocky intertidal shore delineations, 3) older USGS interpreted sediment maps (Knebel and Circe 1995; Rendigs and Knebel 2002; Poppe et al. 2006; Poppe et al. 2007), and 4) an updated version of the CZM/DMF sediment database used in the 2009 Ocean Plan. ***Complex seafloor:*** The 2009 USGS bathymetry data have not been supplanted and were subsequently reused. ***Artificial reefs:*** Footprints of permitted and proposed artificial reefs were mapped by CZM using coordinates provided by DMF. ***Biogenic reefs:*** *Crepidula* reefs and worm reefs were mapped as biogenic reefs using information from analyzed seafloor photographs. Over 10,000 images of the seafloor have been obtained from the CZM-USGS Seafloor Mapping Cooperative and from surveys conducted by CZM and partners on the Ocean Survey Vessel *Bold*. CZM has classified the biological information in these photos according to a modified version of the Coastal and Marine Ecological Classification Standard, specifically the benthic biotic component (Federal Geographic Data Committee 2012). This dataset represents the locations of photos where the dominant biotic group was classified as a gastropod reef or a worm reef. ***Wrecks and obstructions:*** These data were mapped using the Board of Underwater Archaeological Resources' (BUAR) recreational shipwreck sites designated as "exempted sites" (member sites of the National Oceanic and Atmospheric Administration [NOAA]/U.S. Department of the Interior [DOI] National System of Marine Protected Areas) and NOAA's Automated Wreck and Obstruction Information System (AWOIS). AWOIS is a catalog of reported wrecks and obstructions that are considered navigational hazards in coastal U.S. waters. These data are not a comprehensive inventory of wrecks.

Table A.1. Continued.

	2009 Ocean Plan	CZM Proposal for 2014 Ocean Plan
Data Description	Hard seafloor is seabed characterized by exposed bedrock or concentrations of boulder, cobble, or other similar hard bottom distinguished from surrounding unconsolidated sediments. Complex seafloor is a morphologically rugged seafloor characterized by high variability in bathymetric aspect and gradient. Hard/complex seafloor is the seabed characterized singly by hard seafloor or complex seafloor, or the overlap thereof.	Hard seafloor is seabed characterized by exposed bedrock or concentrations of boulder, cobble, or other similar hard bottom distinguished from surrounding unconsolidated sediments. Complex seafloor is a morphologically rugged seafloor characterized by high variability in bathymetric aspect and gradient. Biogenic reefs and man-made structures, such as artificial reefs, wrecks, or other functionally equivalent structures, may provide additional suitable substrate for the development of hard bottom biological communities. Hard/complex seafloor is seabed characterized singly or by any combination of hard seafloor, complex seafloor, artificial reefs, biogenic reefs, or wrecks and obstructions.
Data Extent	The Massachusetts ocean management planning area.	The Massachusetts ocean management planning area.
Data Adjustment and Pre-processing	***Hard seafloor:*** Hard seafloor data derived from the USGS usSEABED sediment point database were analyzed for consistency and replicate samples were removed whenever they could be clearly identified. ***Complex seafloor:*** None.	***Hard seafloor:*** None. ***Complex seafloor:*** None. ***Artificial reefs:*** None. ***Biogenic reefs:*** None. ***Wrecks and obstructions:*** Duplicate wrecks identified in both the BUAR and AWOIS datasets were removed from AWOIS.

Table A.1. Continued.

	2009 Ocean Plan	CZM Proposal for 2014 Ocean Plan
Data Analysis	***Hard seafloor:*** Rocky zones were extracted from USGS interpreted maps published in the Cape Ann to Salisbury Beach OFR (Barnhardt et al. 2009), Nahant to Gloucester OFR (Barnhardt et al. 2006), and Boston Harbor and Approaches OFR (Ackerman et al. 2006). Hard bottom sediment data points were culled from the CZM/DMF database and buffered with a 125-meter radius. The rocky zones and buffered hard bottom points were merged and gridded to a 250x250-meter grid (i.e., where hard bottom intersected a grid cell, the grid cell was denoted as hard seafloor). ***Complex seafloor:*** Complex seafloor was calculated on bathymetry data using an algorithm developed by Sappington et al. (2007) that directly measures seafloor complexity. The unitless value can range from 0 (no seabed complexity) to 1 (complete seabed complexity). Complexity values were overlaid on a 250x250-meter grid.	***Hard seafloor:*** Hard seafloor was mapped by extracting areas characterized as rock, rock with gravel, rock with sand, or rock with mud from the *Surficial sediment in Massachusetts state waters* dataset (see Table 4 below). Surficial sediment was mapped by collating data sources such that high-quality data mask lower quality data in the following order, highest first: 1) new USGS interpreted seabed sediment (Pendleton et al. 2013 and unpublished data in review), 2) DEP wetlands, 3) older USGS sediment interpretations (Poppe et al. 2007; Poppe et al. 2006; Knebel and Circe 1995; Rendigs and Knebel 2002), and 4) interpolated Thiessen polygons derived from the CZM/DMF sediment database. (Thiessen polygons proportionally divide and distribute a point coverage into regions known as Thiessen or Voronoi polygons. Each Thiessen polygon defines an area of influence around its sample point, so that any location inside the polygon is closer to that point than any of the other sample points.) ***Complex seafloor:*** Complex seafloor was calculated as previously. ***Artificial reefs:*** None. ***Biogenic reefs:*** The locations of *Crepidula* reefs and worm reefs were buffered with a 100-meter radius to convert the point data to polygons. This radius was based on best professional judgment. ***Wrecks and obstructions:*** Wrecks and obstructions were buffered with a 100-meter radius to convert the point data to polygons. This radius was based on best professional judgment.

Table A.1. Continued.

	2009 Ocean Plan	CZM Proposal for 2014 Ocean Plan
Data Classification	***Hard seafloor:*** Hard bottom data were classified using the Wentworth (1922) grain-size scale that defines hard bottom ("bedrock or concentrations of boulder, cobble, or other similar hard bottom") as sediment with a grain size of 64 mm or larger. ***Complex seafloor:*** Complex seafloor was classified from descriptive statistics calculated on the dataset as a whole. Seafloor complexity values greater than 3/8 standard deviation from the mean were classified as complex. This class break was based on a comparison between areas of known hard bottom (USGS delineated) and the complex dataset; complexity values coincident with hard bottom were noted at greater than or equal to 3/8 standard deviation.	***Hard seafloor:*** The 2013-present USGS interpreted surficial sediment data and the CZM/DMF sediment database were classified using the Barnhardt et al. (1998) scheme while all other data were crosswalked from their native sediment classification framework to Barnhardt. Barnhardt is based on four primary sediment units: rock (R), gravel (G), sand (S), and mud (M). Twelve additional two-part units represent combinations of the four primary units, where the majority texture is given an upper case letter and the next most common texture is given a lower case letter. Sediment grain sizes follow the Wentworth (1922) scale. Rock is characterized as cobble and larger (>64 mm), so R, Rg, Rs, and Rm are all classified as hard bottom. ***Complex seafloor:*** Complex seafloor was classified as previously. ***Artificial reefs:*** Not applicable. ***Biogenic reefs:*** Not applicable. ***Wrecks and obstructions:*** Not applicable.
Selection of SSU Area	All 250x250-meter grid cells classified as 1) hard seafloor, or 2) complex seafloor were selected for inclusion in the SSU.	All polygons classified as 1) hard seafloor, 2) complex seafloor, 3) artificial reefs, 4), biogenic reefs or 5) wrecks and obstructions were selected for inclusion in the SSU.

Table A.2. Locations of surficial sediment samples in the CZM/DMF sediment database: Comparison of 2009 Ocean Plan to Proposed 2014 Ocean Plan.

	2009 Ocean Plan	CZM Proposal for 2014 Ocean Plan
Data Source	The CZM/Massachusetts Division of Marine Fisheries (DMF) sediment database used in the 2009 Plan was comprised of data from the following sources: 1) U.S. Geological Survey (USGS) usSEABED, 2) CZM-USGS Seafloor Mapping Cooperative, 3) DMF surveys, 4) U.S. Environmental Protection Agency's National Coastal Assessment, and 5) Massachusetts Water Resources Authority's (MWRA) monitoring program.	An updated version of the CZM/DMF sediment database was used in the 2014 Plan Update. Additional data were added to the 2009 sediment database from the following sources: 1) CZM/DMF/USGS Ocean Survey Vessel (OSV) *Bold* surveys, 2) USGS sediment lab, 3) National Oceanic and Atmospheric Administration (NOAA) National Ocean Survey nautical charts, 4) Massachusetts Department of Environmental Protection (DEP) wetlands data, 5) seafloor photos from the CZM-USGS Seafloor Mapping Cooperative and OSV *Bold* surveys, 6) CZM's Dredged Material Management Plan survey in Buzzards Bay, 7) DMF's 2006 Northeast Consortium study in Massachusetts Bay, 8) U.S. Army Corps of Engineers sediment data, and 9) new MWRA monitoring program data.
Data Description	The CZM/DMF sediment database contained the sediment composition of nearly 20,000 surficial sediment samples within a 10-kilometer buffer of Massachusetts state waters.	The updated CZM/DMF sediment database contains the sediment composition of over 50,000 surficial sediment samples within a 10-kilometer buffer of Massachusetts state waters.
Data Extent	The data extent encompassed Massachusetts state waters and extended 10 kilometers seaward of state waters.	The data extent encompasses Massachusetts state waters and extends 10 kilometers seaward of state waters and includes Stellwagen Bank.
Data Adjustment and Pre-processing	Sediment data derived from the USGS usSEABED database were analyzed for consistency and replicate samples were removed whenever they could be clearly identified.	Replicate samples were removed whenever they could be clearly identified.
Data Analysis	Not applicable.	Not applicable.

Table A.2. Continued.

	2009 Ocean Plan	CZM Proposal for 2014 Ocean Plan
Data Classification	Sediment samples were described using the Wentworth (1922) grain-size scale and the Folk (1954, 1974) sediment classification scheme. The Wentworth scale was used to define the grain-size ranges for mud (<0.62 mm), sand (0.62–2 mm), gravel (2–64 mm), and hard bottom (>64 mm). The samples were then classified using the Folk scheme. The Folk sediment classes were combined to create maps of the following four generic sediment classes: 1) generally mud (Folk classes mud [M], sandy mud [sM], slightly gravelly mud [(g)M], slightly gravelly sandy mud [(g)sM], and gravelly mud [gM]), 2) generally sand (Folk classes muddy sand [mS], sand [S], slightly gravelly muddy sand [(g)mS], and slightly gravelly sand [(g)S]), 3) generally gravel (Folk classes gravelly muddy sand [gmS], gravelly sand [gS], muddy gravel [mG], muddy sandy gravel [msG], sandy gravel [sG], and gravel [G]), and 4) generally hard bottom.	Sediment samples were mapped using the Wentworth (1922) grain-size scale and the Barnhardt et al. (1998) sediment classification scheme. Barnhardt is based on four primary sediment units: rock (R), gravel (G), sand (S), and mud (M). Twelve additional two-part units represent combinations of the four primary units, where the majority texture is given an upper case letter and the next most common texture is given a lower case letter. Sediment grain sizes follow the Wentworth (1922) scale where mud is <0.62 mm, sand is 0.62–2 mm, gravel is 2–64 mm, and rock is >64 mm (cobble and larger).
Selection of SSU Area	Not applicable. These data are not mapped as SSU areas.	Not applicable. These data are not mapped as SSU areas.

Table A.3. Surficial sediment mapping: Comparison of 2009 Ocean Plan to Proposed 2014 Ocean Plan.

	2009 Ocean Plan	CZM Proposal for 2014 Ocean Plan
Data Source	Surficial sediment data came from two data sources: 1) U.S. Geological Survey (USGS) interpreted physiographic zone maps as published in Open-File Reports, and 2) a CZM/Massachusetts Division of Marine Fisheries (DMF) sediment database comprised of data from USGS usSEABED, CZM-USGS Seafloor Mapping Cooperative, DMF surveys, U.S. Environmental Protection Agency's (EPA) National Coastal Assessment, and Massachusetts Water Resources Authority's (MWRA) monitoring program.	***Surficial sediment in Massachusetts state waters:*** These data came from four data sources: 1) new USGS interpreted seafloor sediment maps (Pendleton et al. 2013 and unpublished data in review), 2) Massachusetts Department of Environmental Protection (DEP) wetlands (1:12,000) sandy beach and rocky shore delineations, 3) older USGS interpreted sediment maps (Knebel and Circe 1995; Rendigs and Knebel 2002; Poppe et al. 2006; Poppe et al. 2007), and 4) an updated version of the CZM/DMF sediment database used in the 2009 Ocean Plan. ***Surficial sediment in federal waters derived from CZM/DMF sediment database:*** These data utilize the same four data sources as *Surficial sediment in Massachusetts state waters* (see above). ***Surficial sediment in federal waters derived from CONMAP:*** These data utilize the same four data sources as *Surficial sediment in Massachusetts state waters* (see above) with the addition of the USGS Continental Margin Mapping (CONMAP) sediments grain-size distribution for the U.S. East Coast Continental Margin (Poppe et al. 2005).
Data Description	The Massachusetts surficial sediment map characterized the seabed sediment as muddy, sandy, gravelly, or rocky.	***Surficial sediment in Massachusetts state waters:*** These data characterize the seabed with sixteen sediment types based on four primary sediment units: rock, gravel, sand, and mud. Twelve additional two-part units represent combinations of the four primary units. ***Surficial sediment in federal waters derived from CZM/DMF sediment database:*** These data extend mapping into federal waters using the CZM/DMF sediment database. As with *Surficial sediment in Massachusetts state waters,* the seabed is characterized with sixteen sediment types based on four primary sediment units: rock, gravel, sand, and mud. Twelve additional two-part units represent combinations of the four primary units. ***Surficial sediment in federal waters derived from CONMAP:*** These data extend surficial sediment mapping into federal waters using USGS CONMAP data (Poppe et al. 2005). As with *Surficial sediment in Massachusetts state waters,* the seabed is characterized with sixteen sediment types based on four primary sediment units: rock, gravel, sand, and mud. Twelve additional two-part units represent combinations of the four primary units.

Table A.3. Continued.

	2009 Ocean Plan	CZM Proposal for 2014 Ocean Plan
Data Extent	The Massachusetts ocean management planning area.	***Surficial sediment in Massachusetts state waters*** includes state waters. ***Surficial sediment in federal waters derived from CZM/DMF sediment database*** encompasses state waters and extends seven nautical miles seaward of the ocean management planning area. ***Surficial sediment in federal waters derived from CONMAP data*** encompasses state waters and extends from the ocean management planning area to approximately 25 nautical miles offshore. (CONMAP data extend past this line seaward to the continental shelf).
Data Adjustment and Pre-processing	Sediment data derived from the USGS usSEABED sediment point database were analyzed for consistency and replicate samples were removed whenever they could be clearly identified.	None.
Data Analysis	Sediment data from the USGS publication, *usSEABED: Atlantic Coast Offshore Surficial Sediment Data Release* (Reid et al. 2005) were augmented by seafloor sediment data from DMF lobster surveys, DMF trawl surveys, EPA grab samples, MWRA grab samples and sediment-profile imaging (SPI) data, and USGS Open-File Reports (OFR). The data points were converted to Thiessen polygons to create a surficial sediment map.	***Surficial sediment in Massachusetts state waters*** and ***Surficial sediment in federal waters derived from CZM/DMF sediment database:*** These maps were created by collating data sources such that high-quality data mask lower quality data in the following order, highest first: 1) 2013-present USGS interpreted surficial sediment data (Pendleton et al. 2013 and unpublished data in review), 2) DEP wetlands, 3) older USGS sediment interpretations (Poppe et al. 2007; Poppe et al. 2006; Knebel and Circe 1995; Rendigs and Knebel 2002), and 4) interpolated Thiessen polygons derived from the CZM/DMF sediment database. ***Surficial sediment in federal waters derived from CONMAP data:*** This map was created in the same manner as above, however, all areas outside of Massachusetts state waters were mapped using USGS CONMAP data (Poppe et al. 2005).

Table A.3. Continued.

	2009 Ocean Plan	CZM Proposal for 2014 Ocean Plan
Data Classification	Sediment was mapped using the Wentworth (1922) grain-size scale and the Folk (1954, 1974) sediment classification scheme. The resulting maps consisted of four generic sediment classes: generally mud (<0.62 mm), generally sand (0.62–2 mm), generally gravel (2–64 mm), and generally hard bottom (>64 mm).	The 2013-present USGS interpreted surficial sediment data and the CZM/DMF sediment database were classified using the Barnhardt et al. (1998) scheme while all other data were crosswalked from their native classification framework to Barnhardt. Barnhardt is based on four primary sediment units: rock (R), gravel (G), sand (S), and mud (M). Twelve additional two-part units represent combinations of the four primary units, where the majority texture is given an upper case letter and the next most common texture is given a lower case letter. Sediment grain sizes follow the Wentworth (1922) scale where mud is <0.62 mm, sand is 0.62–2 mm, gravel is 2–64 mm, and rock is >64 mm (cobble and larger). CZM used the following crosswalks for converting the DEP wetlands and older interpretive data from their native classification schemes to Barnhardt: • DEP wetlands: Rocky intertidal shores were extracted and classified as rock (R). Barrier beaches, barrier beaches-coastal beaches, barrier beaches-coastal dunes, barrier beach systems, coastal beaches, and coastal dunes were extracted and classified as sand (S). • Interpretive map of the surficial geology of Great Round Shoal Channel (Poppe et al. 2007): Barchanoid and transverse sand waves were extracted and classified as sand (S). • Interpretive map of the surficial sediment distributions off Eastern Cape Cod (Poppe et al. 2006) (Shepard [1954] name followed by Barnhardt name and code): gravelly sediment = sand with gravel (Sg), sand = sand (S), silty sand = sand with mud (Sm), clayey silt = mud (M), silty clay = mud (M). Areas classified as gravel under the Shepard scheme could be either gravel or rock under Barnhardt, so gravel areas were removed from the dataset. • Interpretive map of sedimentary environments in Boston Harbor-Massachusetts Bay (Knebel and Circe 1995) crosswalked by USGS at CZM's request: Each polygon was assigned a sediment type by interpreting the intersecting CZM/DMF sediment database points. For those polygons with no intersecting points, the following crosswalk was used (sedimentary environment/backscatter patterns followed by Barnhardt name and code): erosion or nondeposition/isolated reflection = rock (R), erosion or nondeposition/strong backscatter = gravel with sand (Gs), sediment reworking/strong to weak backscatter patches = sand (S), and deposition/weak backscatter = mud (M). • Interpretive map of surficial sediment in Cape Cod Bay (Rendigs and Knebel 2002) crosswalked by USGS using the CZM/DMF sediment database to assign sediment classes: sandy to clayey silt = mud (M), fine to very fine sand = mud with sand (Ms), very coarse to very fine sand = sand (S), sand with mud (Sm), or mud with sand (Ms). • CONMAP data (Poppe et al. 2005) crosswalked by USGS at CZM's request (Shepard [1954] name and code followed by Barnhardt name and code): bedrock (br) = rock (R), gravel (gr) = gravel (G), gravelly sand (gr-sd) = sand with gravel (Sg), sand (sd) = sand (S), clayey sand or silty sand (cl-st/sd) = sand with mud (Sm), sandy silt or clayey silt (sd-cl/st) = mud with sand (Ms), clay (cl) = mud (M), sandy clay or silty clay (sd-st/cl) = mud with sand (Ms), and sand, silt, clay (sd/st/cl) = mud with sand (Ms).

Table A.3. Continued.

	2009 Ocean Plan	CZM Proposal for 2014 Ocean Plan
Selection of SSU Area	Not applicable. These data are not mapped as SSU areas.	Not applicable. These data are not mapped as SSU areas.

Table A.4. High-resolution seafloor mapping data: Comparison of 2009 Ocean Plan to Proposed 2014 Ocean Plan.

	2009 Ocean Plan	CZM Proposal for 2014 Ocean Plan
Data Source	Not applicable.	High-resolution seafloor mapping data are from the following two sources: 1) CZM and U.S. Geological Survey (USGS) Seafloor Mapping Cooperative 2) USGS
Data Description	Not applicable.	In 2003, CZM and the USGS Woods Hole Science Center initiated a Seafloor Mapping Cooperative to jointly address the need for data and information characterizing seafloor resources. The goal of the cooperative is to comprehensively map the bathymetry and geology of the seafloor inside the three-nautical-mile limit of Massachusetts waters and in adjacent federal waters. As of 2012, the cooperative has mapped 2,200 square kilometers of Massachusetts marine waters and has published or is preparing to release these data as USGS Open-File Reports. Completed areas and dates of publication of USGS Open-File Reports are the following: 1) Nahant to Gloucester (2006), 2) Boston Harbor and Approaches (2006), 3) Cape Ann to Salisbury Beach (2009), 4) Duxbury to Hull (2010), 5) Northern Cape Cod Bay (2010), 6) Buzzards Bay (2013), and 7) Vineyard Sound (2013). Reports are in progress for the areas south of Martha's Vineyard and north of Nantucket. Additional mapping completed by USGS only in Massachusetts state waters include the following areas and dates of publication of USGS Open-File Reports: 1) Eastern Cape Cod (2006), 2) Quicks Hole (2007), 3) Great Round Shoal (2007), 4) Massachusetts Bay and Stellwagen Bank National Marine Sanctuary (2007), 5) Woods Hole (2008), 6) Edgartown (2009), 7) South Shore of Martha's Vineyard (2009), and 8) Eastern Rhode Island Sound (2011).
Data Extent	Not applicable.	In and adjacent to Massachusetts state waters.
Data Adjustment and Pre-processing	Not applicable.	None.
Data Analysis	Not applicable.	The coverage footprints of these surveys were merged by CZM to create a map depicting high-resolution acoustic mapping in and adjacent to Massachusetts state waters.
Data Classification	Not applicable.	Not applicable.
Selection of SSU Area	Not applicable.	Not applicable. These data are not mapped as SSU areas.

Table A.5. Mussel reefs: Comparison of 2009 Ocean Plan to Proposed 2014 Ocean Plan.

	2009 Ocean Plan	CZM Proposal for 2014 Ocean Plan
Data Source	Not applicable.	The mussel reefs were mapped using information from analyzed seafloor photographs. Over 10,000 images of the seafloor have been obtained from the CZM and U.S. Geological Survey Seafloor Mapping Cooperative and from surveys conducted by CZM and partners on the Ocean Survey Vessel *Bold*. CZM has classified the biological information in these photos according to a modified version of the Coastal and Marine Ecological Classification Standard, specifically the benthic biotic component (Federal Geographic Data Committee 2012).
Data Description	Not applicable.	This dataset represents the locations of photos where the dominant biotic group was classified as a mussel reef.
Data Extent	Not applicable.	In and adjacent to Massachusetts state waters.
Data Adjustment and Pre-processing	Not applicable.	None.
Data Analysis	Not applicable.	None.
Data Classification	Not applicable.	Not applicable.
Selection of SSU Area	Not applicable.	Not applicable. These data are not mapped as SSU areas.

Table A.6. Sites investigated for potential sand and gravel extraction: Comparison of 2009 Ocean Plan to Proposed 2014 Ocean Plan.

	2009 Ocean Plan	CZM Proposal for 2014 Ocean Plan
Data Source	Not applicable.	Sites investigated for potential sand and gravel extraction were compiled from reports by the U.S. Army Corps of Engineers, Boston University, Massachusetts Division of Mineral Resources, and others.
Data Description	Not applicable.	This dataset shows the locations of sites with potentially high-quality sand and gravel resources that were identified through general exploration as well as targeted projects. CZM mapped these sites using originator-supplied GIS data or digitizing older georeferenced paper maps.
Data Extent	Not applicable.	In and adjacent to Massachusetts state waters.
Data Adjustment and Pre-processing	Not applicable.	None.
Data Analysis	Not applicable.	None.
Data Classification	Not applicable.	Not applicable.
Selection of SSU Area	Not applicable.	Not applicable. These data are not mapped as SSU areas.

Table A.7. Nearshore disposal sites utilized by the U.S. Army Corps of Engineers: Comparison of 2009 Ocean Plan to Proposed 2014 Ocean Plan.

	2009 Ocean Plan	CZM Proposal for 2014 Ocean Plan
Data Source	Not applicable.	The U.S. Army Corps of Engineers (USACE) provided a dataset of all of the nearshore disposal sites in Massachusetts state waters in their database.
Data Description	Not applicable.	This dataset shows the locations of nearshore disposal sites in Massachusetts state waters used by USACE.
Data Extent	Not applicable.	Massachusetts state waters.
Data Adjustment and Pre-processing	Not applicable.	None.
Data Analysis	Not applicable.	None.
Data Classification	Not applicable.	Not applicable.
Selection of SSU Area	Not applicable.	Not applicable. These data are not mapped as SSU areas.

Table A.8. Sediment core locations: Comparison of 2009 Ocean Plan to Proposed 2014 Ocean Plan.

	2009 Ocean Plan	CZM Proposal for 2014 Ocean Plan
Data Source	Not applicable.	Sediment core locations were mapped by compiling data from the Massachusetts Division of Mineral Resources (now defunct), U.S. Geological Survey (published and unpublished), and various private sector consultants.
Data Description	Not applicable.	CZM mapped these data using published and unpublished data created by the originator. Older paper maps were georeferenced by CZM and pertinent data were digitized and attributed.
Data Extent	Not applicable.	In and adjacent to Massachusetts state waters.
Data Adjustment and Pre-processing	Not applicable.	None.
Data Analysis	Not applicable.	None.
Data Classification	Not applicable.	Not applicable.
Selection of SSU Area	Not applicable.	Not applicable. These data are not mapped as SSU areas.

Table A.9. Areas of seismic (sub-bottom) profiling data: Comparison of 2009 Ocean Plan to Proposed 2014 Ocean Plan.

	2009 Ocean Plan	CZM Proposal for 2014 Ocean Plan
Data Source	Not applicable.	Seismic (sub-bottom) profiling data are from the following two sources: 1) CZM and U.S. Geological Survey (USGS) Seafloor Mapping Cooperative 2) USGS
Data Description	Not applicable.	In 2003, CZM and the USGS Woods Hole Science Center initiated a Seafloor Mapping Cooperative to jointly address the need for data and information characterizing seafloor resources. The goal of the cooperative is to comprehensively map the bathymetry and geology of the seafloor inside the three-nautical-mile limit of Massachusetts waters and in adjacent federal waters. As of 2012, the cooperative has mapped 2,200 square kilometers of Massachusetts marine waters and has published or is preparing to release these data as USGS Open-File Reports. Seismic-reflection profiles (pictures of sub-surface sediment layers) have been collected and published as USGS Open-File Reports in the following areas: 1) Nahant to Gloucester (2006), 2) Cape Ann to Salisbury Beach (2009), 3) Duxbury to Hull (2010), 4) Northern Cape Cod Bay (2010), 5) Buzzards Bay (2013), and 6) Vineyard Sound (2013). Reports are in progress for the areas south of Martha's Vineyard and north of Nantucket. Additional seismic-reflection profiles collected by USGS only in Massachusetts state waters include the following areas and dates of publication of USGS Open-File Reports: 1) Woods Hole (2008), 2) Edgartown (2009), and 3) South Shore of Martha's Vineyard (2009).
Data Extent	Not applicable.	In and adjacent to Massachusetts state waters.
Data Adjustment and Pre-processing	Not applicable.	None.
Data Analysis	Not applicable.	None.
Data Classification	Not applicable.	Not applicable.
Selection of SSU Area	Not applicable.	Not applicable. These data are not mapped as SSU areas.

Table A.10. Total sediment thickness: Comparison of 2009 Ocean Plan to Proposed 2014 Ocean Plan.

	2009 Ocean Plan	CZM Proposal for 2014 Ocean Plan
Data Source	Not applicable.	The total sediment thickness maps were scanned and georeferenced by the U.S. Geological Survey (USGS). The sediment thickness in Boston Harbor was originally published in 1990 by USGS (Rendigs and Oldale). The sediment thickness on the inner continental shelf of Massachusetts Bay was originally published in 1987 by USGS (Oldale and Bick). The sediment thickness in waters north of Cape Ann was originally published in 1987 by USGS (Oldale and Wommack).
Data Description	Not applicable.	These figures were published by USGS and show total sediment thickness in meters above bedrock.
Data Extent	Not applicable.	Boston Harbor, Massachusetts Bay, and in waters north of Cape Ann.
Data Adjustment and Pre-processing	Not applicable.	None.
Data Analysis	Not applicable.	None.
Data Classification	Not applicable.	Not applicable.
Selection of SSU Area	Not applicable.	Not applicable. These data are not mapped as SSU areas.

APPENDIX B

PRELIMINARY CHARACTERIZATION OF OFFSHORE SAND RESOURCES IN SELECTED STUDY AREAS

FINAL REPORT OF FINDINGS
Project No. 631226219

March 28, 2018

PRELIMINARY CHARACTERIZATION OF OFFSHORE SAND RESOURCES IN SELECTED STUDY AREAS

FINAL REPORT OF FINDINGS

Project No. 631226219

March 28, 2018
(*Final,* Revision 2)

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APTIM

Executive Summary

Aptim Environmental & Infrastructure, Inc. (APTIM) together with CR Environmental, Inc. (CR) were contracted by the Massachusetts Office of Coastal Zone Management on June 13, 2017, to conduct a preliminary characterization of offshore sand resources in five (5) Study Areas located offshore of Massachusetts. The project consisted of an historic data review, collection of 20, up to 4-meter long vibracores, collection of 25 surface grab samples, collection of towed video footage, and sediment analysis.

The first phase of the project consisted of a desktop study, where APTIM performed an extensive search for previous geophysical and geotechnical investigations conducted within the five (5) Study Areas. After reviewing the available data, APTIM, CR, and the Massachusetts Office of Coastal Zone Management conducted a kick off meeting on May 26, 2017 to discuss the proper allocation of vibracore samples, surface grab samples and video collection efforts. It was decided that the field investigation would consist of the collection of five (5) vibracores in Study Area 1 offshore of the Merrimack River, four (4) vibracores in Study Area 2 offshore of Nantasket Beach, three (3) vibracores in Study Area 3 offshore of Duxbury Bay, three (3) vibracores in Study Area 4 offshore of Sandwich, five (5) vibracores in Study Area 5 offshore of Cuttyhunk along with five (5) surface grab samples in each of the Study Areas and enough towed video transects to accurately determine the bottom type and habitat. APTIM and CR submitted a final Data Acquisition Plan on July 14, 2017. APTIM collected the vibracores offshore of Massachusetts between September 15, and October 5, 2017, while CR conducted separate offshore operations to collect the surface grab samples and towed video data between August 2 and November 9, 2017.

Upon the completion of field investigations, vibracores and surface grabs samples were sent to APTIM's geotechnical laboratory in Boca Raton, Florida for description and analysis. Vibracores were processed to determine sedimentary properties by strata in terms of thickness, color, texture (grain size), composition and presence of clay, silt, sand, gravel, or any other identifying features. Samples from individual layers were extracted for grain size distribution analysis. Much like samples taken from the vibracores, surface grab samples were also described and processed for grain size. Results from the vibracore analysis were correlated to the available seismic sub-bottom data (where available) in order to create isopach surfaces of the potential sand resources in each of the Study Areas to determine an estimated sand volume available. Video transects were analyzed in real time for habitat type, sediment composition, observed fauna (epibenthic/nekton), and their relative abundance. Table 2 provides a breakdown of the investigation results per Study Area (also described below). These results include either the range of the average thickness of these isopach, ± one standard deviation, or the average thickness not shown as a range (for areas without historic seismic sub-bottom data), shown as a discrete value representing the average thickness of that sand deposit as logged in the newly collected vibracores within that specific Study Area. The volumes shown are the actual calculated estimated volumes in m^3 rounded to the nearest 10,000 m^3. The rounded m^3 volume value was then converted to cubic yards and rounded to the nearest 100 cubic yards.

For Study Area 1, the dominant substrate type was low relief sand waves with some coarse grain sands and pebbles in the troughs. Dominant fauna included juvenile sea scallops, lobster, mysid shrimp, and amphipods. A total of 37 lobsters were observed on 85% of the collected transects. Dominant fish included winter flounder (16) and sculpin (18). APTIM was able to determine an estimated preliminary volume of 99,730,000 m^3 (130,442,000 cy) of potential sand resources throughout Study Area 1.

For Study Area 2, the bottom substrates were highly variable, ranging from flat sand, mud to sand waves, pebble-cobble, and partially buried or dispersed boulders. Dominant invertebrates included sea scallops, rock crabs, and sand dollars. The dominant fish observed was cunner with 62 observations. The Massachusetts OMP Study Area 2 was broken down into three (3) Study Areas (2A, 2B and 2C). Interpretation of historic seismic sub-bottom data correlated to the vibracore results from this project indicated preliminary estimates of potential sand resource volumes of 3,600,000 m^3 (4,708,600 cy) in the Study Area 2A. Recent backscatter and high resolution bathymetric data within Study Area 2B indicate the presence of surficial gravels as well as high-relief ledges, likely rocky in nature, crossing portions of the Study Area. As a result, little or no potential sand resource volume is expected in Study Area 2B. Based on historical surficial backscatter data indicating limited surficial sands, Study Area 2C was narrowed down to a smaller area with an estimated preliminary volume of 3,600,000 m^3 (4,708,600 cy) of potential sand resources.

Offshore of Duxbury Bay, the bottom substrate at Study Area 3 was primarily flat sand, mud with limited observations of pebble-cobble bottom, and occasional shell aggregate bottom. Dominant invertebrates were mysid shrimp and sand dollars. Commercial species observed included 17 observations of rock crabs and nine (9) lobsters. The dominant fish species at Study Area 3 off of Duxbury Bay included red hake (33), winter flounder (15) and sculpin (12). The Massachusetts OMP Study Area 3 was broken down into two (2) Study Areas (3A and 3B). Interpretations of the historic sidescan sonar data in Study Area 3A indicate that the surface is likely mostly sand, therefore, in order to determine the potential volume of sand, an average thickness value was calculated from the isopach and used as a general representation of the entire Study Area 3A, yielding an estimated preliminary volume of 46,940,000 m^3 (61,395,200 cy) of potential sand resources. The isopach in Study Area 3B was clipped to the Interpreted Sandy Area polygon in order to avoid areas that appear to have a hard bottom/rock outcrop. The total estimated preliminary volume of Study Area 3B is 46,000,000 m^3 (60,165,700 cy) of potential sand resources.

Offshore of Sandwich, the habitat type at Study Area 4 was primarily flat sand and mud with the exception of sand waves with coarser sand east of the Cape Cod Canal. Occasional biogenically-structured bottom (burrows and mounds) was also observed. A limited amount of pebble-cobble bottom was observed and some rock disposal material was observed in the Cape Cod Canal Offshore Dredged Material Disposal Site. Dominant fauna included sand dollars that were abundant at all of nine (9) sandy bottom transects. The dominant fauna on the silty/sand sediment at the Disposal Site were mysid shrimp. Counts of the commercial species included 40 rock crabs, 20 winter flounder, and 10 lobsters. Study Area 4 was divided into two (2) Study Areas, 4A and 4B. Study Area 4B was considered, but not included for additional geotechnical data collection as it is designated as a USACE/EPA Offshore Dredge Material Disposal Site and can likely be initially characterized via historic dredging records. The estimated preliminary volume in Study Area 4A is estimated to be 51,670,000 m^3 (67,581,800 cy) of potential sand resources. Given the fact that no seismic sub-bottom data were available for this area, it is impossible to know the exact nature and full extent of the deposit without additional design-level data.

For Study Area 5, offshore of Cuttyhunk, the bottom substrate was primarily flat sand/mud, with occasional exceptions of observed sand waves and partially buried and dispersed boulders. The dominant invertebrate at eight (8) of the 10 transects were two (2) species of hermit crabs. Fish species observed at Study Area 5 included 21 red hake and one (1) winter flounder. The Massachusetts OMP Study Area 5 was broken down into two (2) Study Areas (5A and 5B). Sand deposits in Study Area 5A are associated with a shoaling feature with an estimated preliminary volume of 54,470,000 m^3 (71,244,100 cy) of potential sand resources. Study Area 5B contains a thin (approximately 1.4 m (4.27 ft) thick) sand layer overlaying a paleochannel complex likely filled with clays and silts yielding an estimated preliminary volume of approximately 7,460,000 m^3 (9,757,300 cy) of potential sand resources.

In total, APTIM was able to identify potential sand resources totaling a preliminary, reconnaissance-level estimate of approximately 313,470,000 m^3 (410,003,400 cy) across all five (5) Study Areas. These are preliminary volumes of potential sand resources based on widely-spaced reconnaissance-level geotechnical data and varying levels of geophysical data coverage. Actual borrow area design would require additional, design-level geotechnical and geophysical data collection in order to accurately and fully characterize these sand deposits, account for environmental and cultural resources, determine compatibility of the potential sand resource with the recipient beach, evaluate dredgeability of the sand resource, and design permit plans and specifications (including dredge cuts) for a final borrow area.

Table 1: Project results summary

Region	Study Area	Vibracores	Surface Grabs	Towed Video Transects	Dominant Bottom Habitat/Substrate (Auster, 1998)	Dominant Fauna	Average Grain Size (mm)	Average Silt %	Average Sand Thickness (m)	Area of Isopach (m^2)	Estimated Volume of Isopach (m^3)	Estimated Volume of Isopach (cy)
Merrimack River	1	5	5	10 at 750 m long 1 at 250 m[1] long	Low relief sand waves with coarse grains and pebbles in troughs.	Juvenile sea scallops, lobsters, mysid shrimp, amphipods. Lobsters in 85% of transects (37 total), winter flounder and sculpin.	0.30	2.50	1.76 to 3.84	35,665,334	99,730,000	130,442,000
Nantasket Beach	2A	1	2	2 at 750 m long	Variable. Flat sand and mud, sand waves, pebble-cobble, partially buried and dispersed boulders.	Sea scallops, rock crabs, lobsters. Cunner, sculpin, red hake and winter flounder.	0.11	11.75	2.54 to 4.18	1,070,310	3,600,000	4,708,600
	2B	0	0	1 at 750 m long			N/A; There were no cores or grabs in this sub-area					
	2C	3	3	7 at 750 m long			0.11	12.28	2.67	1,348,929	3,600,000	4,708,600
Duxbury Beach	3A	1	2	4 at 500 m long	Primarily flat sand and mud; also limited pebble-cobble, shell aggregates.	Mysid shrimp, sand dollars, rock crabs, lobsters. Red hake, winter flounder, sculpin.	0.17	1.69	0.84 to 5.68	14,398,272	46,940,000	61,395,200
	3B	2	3	6 at 500 m long			0.16	10.59	0.71 to 4.55	17,497,037	46,000,000	60,165,700
Sandwich	4A	3	5	9 at 1000 m long	Primarily flat sand and mud; also sand waves, biogenic structures (burrows and mounds).	Sand dollars, mysid shrimp, rock crabs, lobster. Winter flounder and skate.	0.23	2.68	3.38	15,286,265	51,670,000	67,581,800
	4B	0	0	1 at 1000 m long			N/A; There were no cores or grabs in this sub-area					
Cuttyhunk	5A	3	2	5 at 500 m long	Primarily flat sand and mud; also sand waves, partially buried or dispersed boulders.	Hermit crabs, slipper limpets, bread crumb sponges, lobster, channeled whelk. Red hake, winter flounder	0.19	4.66	1.61 to 7.33	12,180,335	54,470,000	71,244,100
	5B	2	3	5 at 500 m long			0.17	6.49	0.76 to 2.04	5,338,989	7,460,000	9,757,300

[1] Transect ended at 250 meters because the video sled was at the edge of the shape file (defined boundary of the sand resources area) drifting in the wrong direction. A new transect was started 1000 m to the east and 750 meters completed

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Abbreviations

AGC	Automatic Gain Control
APTIM	Aptim Environmental & Infrastructure, Inc.
ASTM	American Society for Testing and Materials
Avg	Average
cm	centimeters
CMEC	Construction Materials Engineering Council, Inc.
Comp	Composite
CR	CR Environmental, Inc.
cy	cubic yards
CZM	Massachusetts Office of Coastal Zone Management
DBE	Disadvantages Business Enterprise
DGPS	Differential Global Positioning System
EPA	Environmental Protection Agency
ft	feet
GPS	Global Positioning System
HD	High Definition
in	inch
kHz	kilohertz
km	kilometer
m	meter
m^2	square meters
m^3	cubic meters
mp	megapixel
NAVD88	North American Vertical Datum, 1988
ODMDS	Offshore Dredge Material Disposal Site
OMP	Ocean Management Plan
OTI	Outland Technologies'
SBA	Small Business Administration
Thk	Thickness
USACE	United States Army Corps of Engineers
USCG	U.S. Coast Guard
USGS	U.S. Geological Survey
Vac	volts, alternating current
WBE	Women Business Enterprise
WOSB	Women Owned Small Business

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Introduction

APTIM Environmental & Infrastructure, Inc. (APTIM) was contracted by the Massachusetts Office of Coastal Zone Management (CZM) on June 13, 2017, to conduct a preliminary characterization of offshore sand resources in five (5) study areas located offshore of Massachusetts. The project consisted of conducting an historic data review of the investigation areas, collection of 20 vibracores up to four-meters long, and 25 surface grab samples along with towed video footage of the seafloor. Additionally, APTIM was tasked with conducting detailed logging and analysis of the collected geotechnical samples and estimating volumes of potential sand resources for future coastal restoration efforts.

APTIM teamed with CR Environmental, Inc. (CR), located in Falmouth, Massachusetts to conduct this investigation. CR is a Massachusetts certified Women Business Enterprise (WBE) and certified Disadvantaged Business Enterprise (DBE); and a Small Business Administration (SBA) self-certified Women Owned Small Business (WOSB). APTIM and CR have a relationship extending back to 2006, working jointly to collect and provide the highest quality data in geophysical, geotechnical and oceanographic surveys in support of shore-protection projects.

Together, APTIM and CR coordinated the desktop study, site selection, data collection, processing and reporting. The field collection phase consisted of two separate operations. APTIM conducted the desktop historical data analysis study and, with the assistance of a CR research vessel, the vibracore collection components of the project. CR conducted the surface grab samples and underwater towed video collection from a separate, smaller local vessel owned and operated by CR. The vibracores, along with the surface grab samples collected by CR, were transported to APTIM's accredited geotechnical laboratory in Boca Raton, Florida and analyzed in accordance with American Society for Testing and Materials (ASTM) standard procedure D 2488-09a (Standard Practice for Description and Identification of Soils). APTIM then reviewed the results of the vibracore analysis, and together with the data from the desktop study, identified potential sand resource characteristics and volumes in all five (5) investigation areas.

Scope of Work

The purpose of this project was to conduct a preliminary characterization of sand resources off the coast of Massachusetts in five (5) areas identified in the Massachusetts Ocean Management Plan (OMP) as having the potential for use in future shore-protection projects. APTIM and CR conducted a project kickoff meeting with CZM in Boston, Massachusetts on May 26, 2017, to discuss the project schedule, historic data and operational plans. At the meeting, the overall Scope of Work, proposed equipment, schedule, and project planning activities were discussed. In an effort to complete the most amount of work as possible within the available CZM budget, it was decided that a total of 20 vibracores, 25 surface grab samples, and underwater towed video would be collected within the five (5) Study Areas.

APTIM conducted a thorough review of existing geophysical and geotechnical data and information to gain an understanding of the geologic background and existing geologic conditions of the proposed Study Areas, outlined in Section 9.0 Desktop Study. For the desktop study APTIM utilized historic geophysical (sidescan sonar, bathymetric and seismic sub-bottom) data along with historic geotechnical data (surface grab samples and vibracores) and photographs of the seafloor provided by the United States Geological Survey (USGS) and CZM to narrow down areas of potential sand for this investigation. In areas with limited raw geophysical and geotechnical data, APTIM relied on historic reports prepared for The Division of Mineral Resources State of Massachusetts, The Commonwealth of Massachusetts Department of Natural Resources Division of Mineral Resources, the USGS, and other references provided by CZM.

Upon the completion of the desktop study and the review of the chosen geotechnical sample sites and towed video transects, APTIM submitted a final Data Acquisition Plan to CZM on July 14, 2017. APTIM and CR commenced field operations on August 2, 2017. APTIM collected 20, up to 4-meter long vibracores within the proposed Study Areas, consisting of five (5) vibracores in Study Area 1 offshore of the Merrimack River, four (4) vibracores in Study Area 2 offshore of Nantasket Beach, three (3) vibracores in Study Area 3 offshore of Duxbury Bay, three (3) vibracores in Study Area 4 offshore of Sandwich, and five (5) vibracores in Study Area 5 offshore of Cuttyhunk in Buzzards Bay. Vibracore sample locations were determined based on the previous geophysical data review, targeting deposits with a generally higher potential for thicker and/or larger sand resources.

CR conducted the towed video and surface grab sample operations separately from APTIM's vibracore operations. At each of the five (5) Study Areas, 10 up to 1,000-meter primary transects were selected for underwater video sled survey coverage. Additional secondary underwater video coverage was collected at each site if time and weather permitted. At each of the Study Areas, five (5) surface grab samples were collected for sediment grain size. Final locations of the sediment samples were based on the video observations.

Upon completion of field operations, APTIM and CR analyzed all of the collected data to develop interpretations in support of producing a comprehensive summary of the surficial and subsurface geology of the Study Areas. Geotechnical data (vibracores and surface samples) were analyzed for sedimentary properties in terms of layer thickness, color, texture (grain size), composition and presence of clay, silt, sand, gravel, or any other identifying features, and grain size distribution. Towed video footage was used to determine a qualitative summary of incidental macrofauna and nekton.

Desktop Study Results

In order to obtain an understanding of the geologic background and existing geologic conditions of the proposed Study Areas, APTIM conducted a thorough review of existing geophysical and geotechnical data and information. APTIM maintains a comprehensive internal database that is an excellent starting point for conducting preliminary evaluations of the potential for offshore sand resources. In addition to APTIM's extensive internal database, APTIM reviewed geologic data and information from the USGS and The Massachusetts Department of Natural Resources Division of Mineral Resources, provided by CZM. Based on the review of historic bathymetry data, acoustic backscatter data, seismic-reflection profiles, sediment samples, and photography from the five (5) proposed Massachusetts OMP Sand Resource Areas, APTIM was able to determine areas of potential sand resources for future shore protection projects in Massachusetts.

Study Area 1: Merrimack River

Five (5) vibracore samples were proposed within Study Area 1 offshore of the Merrimack River. APTIM used historic backscatter, bathymetry, surface grab samples, and photography to further delineate the sandy bottom within Study Area 1 (Figures 1 and 2).

While this area did not need to be divided into Study Areas, the historic data all confirmed the presence of rock outcrops in several areas throughout the study area. These areas were clipped out of the Study Area and not considered for further data collection. For Study Area 1, the historic backscatter data are presented in a reverse pattern, with the lighter colors representing low backscatter areas indicative of finer/sandy materials (Barnhardt et al., 2009). The dark colors represent high backscatter indicative of areas of rock, gravel, or other coarse materials. In addition to the extensive seismic sub-bottom data, there are extensive historic surface grab samples confirming the sidescan sonar imagery, allowing for easy delineation of the sandy seafloor (Buczkowski and Kelsey, 2006; Barnhardt et al., 2009).

This area has full coverage of historic USGS seismic sub-bottom data, providing APTIM geologists with ample data to review and propose vibracore locations (Barnhardt et al., 2009). Prior to the collection of the vibracores, APTIM utilized the exported imagery of the seismic sub-bottom data for review and site selection together with shapefiles with shot-point information and as-run tracklines.

Historic seismic sub-bottom data indicate the presence of buried rock, sands, and potentially finer materials, likely associated with paleofluvial activities (Figures 3, 4, 5, 6, and 7). APTIM targeted the thickest and potentially sandiest deposits as interpreted from the seismic sub-bottom data, while avoiding areas of rock outcrops or finer materials. In the northwest portion of the Study Area, APTIM attempted to target the thickest portion of the sand feature in an attempt to characterize the maximum sand deposit possible. In the northeast, APTIM collected a vibracore on the lateral extents of the potential sand deposit to assist with the identification of the edges of the deposit, including the potential to sample the material beneath the sandy deposit. The centrally-located proposed vibracore was intended to target the central portion of the deposit, allowing for regional coverage and general characterization of the overall sand feature. The southeast location targeted the edge of the deposit before it drops off to a deeper, rocky seafloor, while the southwest location targeted the thickest deposit on the southern end of the Study Area. All five (5) cores allowed for general coverage and characterization of this potential sand deposit.

All vibracores were collocated along existing seismic sub-bottom lines at or near seismic sub-bottom line crossings, enabling for the easy seismic sub-bottom tie-in of any resulting interpretation from the collected vibracore data.

Study Area 2: Nantasket Beach

Four (4) vibracores were proposed to be collected within Study Area 2, offshore of Nantasket Beach. Based on APTIM's desktop study, two (2) Study Areas (2A and 2C) were classified as having a higher potential for beach compatible resources within areas of sandy seafloor (Figures 8 and 9). Historic data from the Massachusetts Coastal Mineral Inventory Survey report (Willet, 1972), the United States Army Corps of Engineers (Meisburger, 1976) historic data from the USGS, including Maps and Seismic Profiles Showing Geology of the Inner Continental Shelf, Massachusetts Bay, Massachusetts (Oldale and Bick, 1987), and other historic USGS geophysical and bathymetric data (Ackerman et al., 2006) were used to classify the bottom types within Study Area 2 and to further delineate sandy seafloor in Study Areas 2A, 2B and 2C (Figures 8 and 9) (Barnhardt et al., 2010; Pendleton et al., 2013). APTIM compared historic USGS backscatter and bathymetric data and USGS photographs to confirm seafloor types within the Study Area in an effort to avoid high relief bathymetric data and high (light colored) backscatter data associated with hard bottom/rock outcrops and areas of gravel or cobble seafloor and target areas with the highest potential for beach compatible resources.

Study Area 2A was selected based on historic sidescan sonar data and USGS bottom photographs. A review of these data, along with limited early analog seismic data images, supported the interpretation of a surficial sand deposit within this Massachusetts OMP Sand Resource Area. One vibracore sample was proposed within Study Area 2A on an existing seismic sub-bottom line to further characterize the deposit for beach compatibility.

For Study Area 2B, early analog seismic sub-bottom data images from The Massachusetts Coastal Mineral Inventory Survey report (Willet, 1972) were reviewed to delineate Study Area 2B within a historic sand mineral resource area (BA II). The historic data classifies the area as sand with occasional silt and clay. Unfortunately, more recent backscatter and high resolution bathymetric data indicate the presence of surficial gravels as well as high-relief ledges, likely rocky in nature, crossing portions of Study Area 2B. As a result, and with limited portions of sandy seafloor remaining in Study Area 2B, no vibracore samples were proposed in Study Area 2B.

Study Area 2C was delineated using early analog seismic sub-bottom data images from The Massachusetts Coastal Mineral Inventory Survey report within a historic sand mineral resource area (BA I) (Willet, 1972). The historic data classifies the area as sand with occasional silt and clay. More recent bathymetric and backscatter data, however, indicate some areas of gravel seafloor (high, light-colored, backscatter) and areas of mixed sand/gravel seafloor (central Study Areas 2C). Due to the increased amount of surficial gravel, APTIM proposed only two (2) vibracore samples within Study Area 2C at locations where the Massachusetts OMP Sand Resource Area overlaps low (darker-colored) backscatter sandy areas, while avoiding high relief areas and high (light-colored) backscatter areas interpreted to be gravel, hard bottom, and/or rock outcrops.

Upon reviewing all of the data, APTIM was able to identify an area of low (dark-colored) backscatter, indicating a sandy and/or silty seafloor, just outside of the Massachusetts OMP Sand Resource Area shape that correlated to a potential sand source in the Massachusetts Coastal Mineral Inventory Survey report (Willet, 1972). While the same sand source in the Oldale and Bick, 1987, publication did not occur that far west, it is likely that was due to the lack of data coverage, not necessarily data indicating that the deposit had thinned considerably. As such, and based on the extensive gravel area present within Study Areas 2B and 2C, APTIM proposed one (1) vibracore in this area just west of Study Area 2C.

A total of four (4) vibracore sites were proposed within Study Area 2: one (1) in Study Area 2A, two (2) within Study Area 2C, and one (1) immediately west of Study Area 2C in a low (dark-colored) backscatter area interpreted to have a sand deposit in the Massachusetts Coastal Mineral Inventory Survey report.

Study Area 3: Duxbury Beach

Three (3) vibracore samples were proposed within Study Area 3, offshore of Duxbury Bay. Study Area 3 was evaluated using historic sidescan sonar data, historic bottom photographs, bathymetry data, and some historic USGS seismic sub-bottom data available for a portion of the Study Area (Figures 10 and 11) (Andrews et al., 2010; Buczkowski and Kelsey, 2006; Normandeau Associates, 2010; Pendleton et al., 2013). Bathymetry data were digitized, and compared to sidescan sonar data and USGS photographs to classify surficial sand areas for vibracore placement. Areas shown as low (dark-colored) backscatter corresponded to sandy areas, as verified by historic surface grab samples and seafloor photography. Areas of high (lighter-colored) backscatter indicated the presence of gravel, cobble or rocks, and were therefore excluded from the Study Area.

The Study Area was divided into two (2) main Study Areas: 3A being the northern Study Area, and 3B the southern Study Area. A total of three (3) vibracores were proposed within Study Area 3: one (1) in Study Area 3A and two (2) in Study Area 3B. For Study Area 3A, there were no historic seismic sub-bottom data available to confirm the presence of subsurface sand deposits across the entire area. That said, there were high resolution sidescan sonar backscatter, bathymetry, and photographic data indicating the presence of surficial fine-grained sands and some sand with shell material. Based on this information, and the desire to further characterize the subsurface geology of Study Area 3A, APTIM placed one (1) proposed vibracore location within the fine-grained sand area.

For Study Area 3B, there were some seismic sub-bottom data available (Barnhardt et al., 2010; Pendleton et al., 2013). APTIM reviewed and utilized the exported imagery of the seismic sub-bottom data for review and site selection. The seismic sub-bottom data, together with the historic surficial backscatter, grab samples, and photographic data, confirmed the presence of a sand feature. This feature is visible on multiple sub-bottom lines, and can be tied using the sub-bottom lines across Study Area 3B (Figures 12, 13, and 14). APTIM selected two (2) areas within this subsurface sand feature, traceable on multiple seismic sub-bottom lines, for vibracore collection.

Study Area 4: Sandwich

Three (3) vibracores were collected within Study Area 4, offshore of Sandwich. Based on APTIM's desktop study, one (1) Study Area (4A) is classified as having a higher potential for beach compatible resources. A second Study Area (4B) was considered but avoided as it is designated as a USACE/EPA Offshore Dredge Material Disposal Site and can likely be initially characterized via historic dredging records (Figures 15 and 16). The Coastal Engineering Research Centers Seismic and Coring Investigation of Cape Cod Bay (Samson, 1974), together with historic NOAA bathymetric and backscatter data (U.S. Department of Commerce National Oceanic and Atmospheric Administration National Ocean Survey, 2007) and USGS surface grab samples (Buczkowski and Kelsey, 2006; Doner, 2012), were used to classify the bottom type within Study Area 4 and further delineate the sandy seafloor areas within Study Area 4A. APTIM reviewed the historic data to target the areas with the highest volume of potential resources.

Study Area 4A lies partly within a historic sand mineral resource identified in the early 1970's (Samson, 1974). Historic data were plotted in ArcGIS then used to select the proposed vibracore samples. For the most part, where historic data exist, the vast majority of Study Area 4A appears to have a sandy seafloor. While recent seismic sub-bottom data do not exist, the Samson, 1974, report indicates the presence of subsurface sands. APTIM proposed vibracore samples within the thickest apparent deposits shown in the Samson, 1974, isopach map in the north, central-north, and southwest portions of the Massachusetts OMP Sand Resource Area.

Study Area 5: Cuttyhunk

Five (5) vibracores were collected within Study Area 5, offshore of Cuttyhunk. Study Area 5 is divided into two (2) Study Areas: 5A to the south and 5B to the north. APTIM used historic backscatter, bathymetry, surface grab samples, and photography to further delineate the sandy bottom within both Study Areas (Figures 17 and 18) (Ackerman et al., 2012; Ackerman et al., 2015; Buczkowski and Kelsey, 2006; Doner, 2012; Foster et al., 2016). This area had full coverage of historic USGS seismic sub-bottom data, providing APTIM geologists with ample data to review and propose vibracore locations (Foster et al., 2016). APTIM reviewed and utilized the exported imagery of the seismic sub-bottom data for review and site selection.

Based on the acoustic representation of the seismic sub-bottom data, it appears that each Study Area has a discreet, subsurface sand deposit (Figures 19, 20, 21, 22, and 23). For Study Area 5A in the south, APTIM selected three (3) proposed vibracore locations to characterize the southern sand deposit. The northern 5A vibracore was located to target the thinner, lateral extents of the sand deposit, providing regional coverage of the deposit allowing for characterization of the lateral extents of the deposit. The southeast and southwest locations in Study Area 5A were meant to target the sand deposit at its thickest and prior to the end of the deposit when it drops off significantly to a deeper, rocky seafloor.

For Study Area 5B, APTIM selected two (2) vibracore locations to characterize the northern sand deposit. The northwest location targeted the thickest portion of the sand feature, while the northeast location targeted the lateral extent of the feature in an effort to characterize both the sand deposit and some of the material below the sand deposit, allowing for characterization of the bottom of the sand deposit and the underlying stratigraphy.

All vibracores were collocated with existing seismic sub-bottom lines at or near seismic sub-bottom line crossings, enabling for the easy tie-in of any resulting interpretation from the collected vibracore data.

Vibracore Survey Systems and Equipment

Vibracore Sampling Vessel

The *R/V Jamie Hanna*, a USCG inspected and certified vessel, based out of Hull, Massachusetts, was used for vibracore operations. The *R/V Jamie Hanna* is a 55 ft. (16.7 m) Wesmac hulled vessel, acquired with the sole purpose of geophysical, geotechnical and biological surveys. It comes equipped with two low emission diesel engines, two Pullmaster H8 5,000 lb. capacity winches, two 1000 lb. capacity oceanographic winches, a 1,000 lb. capacity stainless davit, and a 5,000 lb. capacity 15 ft. hydraulic a-frame. The *R/V Jamie Hanna* is also equipped with a full head and full galley for offshore operations.

A hydraulically operated a-frame, located on the vessel’s stern, offered sufficient height to raise, lower, and retrieve the vibracore system. Furthermore, the hydraulic a-frame added a level of safety for crewmembers in the retrieval and deployment stages of the vibracore, preventing any unnecessary overhang. The ample deck space allowed the vibracore to be laid on the back deck, permitting the safe and secure retrieval of vibracore samples for stowing on the vessel during operations.

Navigation and Positioning

Hypack

Hypack 2017 is a state-of-the-art navigation and hydrographic surveying software system. The navigation system was interfaced with a differential global positioning system (DGPS) and an onboard navigation computer. The location of the DGPS antennae, the over-the-side mounted fathometer, and the A-frame sheave point were entered into the system to account for offsets, and all data were integrated in real time using the Hypack 2017 software. Online screen graphic displays included the pre-plotted vibracore locations, the updated boat track across the Study Area, adjustable left/right indicator, as well as other positioning information such as boat speed and bearing.

Trimble DGPS

The navigation and positioning system deployed for the vibracore survey consisted of a Trimble DGPS interfaced to Hypack, Inc.'s Hypack 2017. A Pro Beacon receiver provided the DGPS with corrections from the nearest USCG navigational beacon. The DGPS initially receives the civilian signal from the GPS NAVSTAR satellites. The locator automatically acquires and simultaneously tracks the NAVSTAR satellites, while receiving precisely measured code phase and Doppler phase shifts, which enables the receiver to compute the position and velocity of the vessel. The receiver then determines the time, latitude, longitude, height, and velocity once per second. GPS accuracy with differential correction provides for a position accuracy of 30 to 122 cm (1 to 4 ft).

Single Beam Fathometer

APTIM collected single-beam bathymetry data over each vibracore site. The Odom Hydrographic Systems, Inc.'s Hydrotrac, is a single frequency portable hydrographic echo sounder that was used to determine the top of core depth. The Hydrotrac operates at frequencies of 24, 33, 40, 200, 210, or 340 kilohertz (kHz) and is a digital, survey-grade sounder. A 210 kHz transducer was used for the bathymetric survey.

Upon completion of the fieldwork, data were edited and reduced with Hypack 2017. Tidal data from local predictions and regional tide gauges were reviewed and used to correct the raw water depths to vertical elevations. The offshore bathymetry data were finalized and reported as the top of vibracore elevation for each vibracore site on each vibracore log.

Vibracore System

APTIM utilized the SEAS VC-700 Vibracoring System, configured to collect undisturbed sediment vibracores up to 4 m (13.12 ft) in length. The VC-700 is a single vibracore electric vibracoring system operational to depths of 200 m (656 ft). This electric vibracore system allows for the successful collection of vibracores in relatively deep-water depths, in the case of this project approaching 35 m (114.83 ft).

The self-contained, free-standing electrically operated vibracore unit contains a VC-700 vibrator head (4.4 kilowatt) configured to 415 Vac or 220 Vac 3-phase power, allowing for a user to operate the vibracorer at fluctuating vibration frequencies to penetrate through otherwise unyielding strata. A 210 m long 4-core Hydrofirm sea cable provided power to the drive unit of the vibracore from the surface control system, located on vessel.

The vessel was anchored at all geologic sample locations to further the vessel's stability for vibracore operations.

Vibracore Operations

Vibracore Sampling Protocol

APTIM collected 20 vibracores within the Study Areas between September 17, 2017 and October 3, 2017. Vibracore sample locations were determined based on APTIM's desktop study targeting deposits with a generally thicker and higher potential for increased sand resources. Figures 24 to 28 provide as-built locations for the vibracores and surface grab samples collected in each of the Study Areas.

Vibracore operations were based out of Hull, Massachusetts, at the home dock of the *R/V Jamie Hanna*. The dock had facilities for secure equipment and vibracore storage, supporting equipment for vessel mobilization and demobilization, and was centrally located for Study Areas 2 (Nantasket Beach), 3 (Duxbury Bay), and 4 (Sandwich). For Study Area 1 (Merrimack River), APTIM transited to the site from Hull and conducted operations on site, returning at the end of the day. For Study Area 5 (Cuttyhunk), CR and Goodwin Marine Services had prepositioned the *R/V Jamie Hanna* in Sandwich, allowing APTIM to transit to the site from Sandwich, conduct operations on site, and return to Sandwich at the end of the day.

During vibracore operations, the vibracore recovered a minimum of 80% of the expected penetration through the unconsolidated strata through which it penetrated, except for two cores in Study Area 5 where only 59% and 68% recovery was achieved after three attempts at each site. To calculate the percent recovery, the total recovery length was divided by the measured depth of penetration (by use of markings and a slide ring on the vibracore barrel exterior).

The desired depth of penetration was four (4) meters (13.12 ft). However, that maximum penetration was not necessarily achieved at all sample locations. When located over a boring site, APTIM made every reasonable effort to reach the required depth or to reach penetration refusal. Penetration refusal was completed when less than 0.30 m (1 ft) of advance was accomplished after five (5) minutes of vibration (as measured by winch cable payout through the A-frame sheave). When refusal was met at less than 80% of the desired depth of penetration, APTIM removed the sampled portion and a new vibracore pipe was set up for a second attempt. Retries were accomplished until the desired penetration and recovery was accomplished, or until two (2) retries were attempted (for a total of three (3) attempts), whichever occurred first.

Vibracore Sampling Field Operations Timeline

Vibracore operations began on September 15, 2017 when APTIM staff arrived in Hull, Massachusetts and began to mobilize the R/V Jaime Hanna at Goodwin Marine Services.

Mobilization was completed on September 16, 2017. Vibracore data collection began on September 17, 2017 at Study Area 2 Nantasket Beach where vibracores MA-CZM-2017-VC01 to MA-CZM-2017-VC04 were collected. Vibracores MA-CZM-2017-VC05 to MA-CZM-2017-VC09 were collected at Study Area 1 Merrimack River on September 18, 2017. Hurricane Jose made its way offshore of the Study Area and survey operations were put on hold waiting for weather conditions to stabilize from September 19, 2017 to September 22, 2017. Survey operations did not begin again until September 25, 2017 when vibracores MA-CZM-2017-VC10 and MA-CZM-2017-VC11 were collected at Study Area 5 Cuttyhunk. Mechanical issues (weldment failure) caused the SEAS VC-700 Vibracoring System to be out of service until repairs could be made, during this time near-future regularly scheduled maintenance on the *R/V Jamie Hanna* was pushed up to take place during the same time the SEAS VC-700 Vibracoring System was down for repairs. Vibracoring operations were shut down from September 26, 2017 to October 1, 2017 allowing for the SEAS VC-700 Vibracoring System and *R/V Jamie Hanna* maintenance. Vibracores MA-CZM-2017-VC15 to MA-CZM-2017-VC17 were collected at Study Area 3 Duxbury Beach on October 2, 2017. Vibracores MA-CZM-2017-VC18 to MA-CZM-2017-VC20 were collected at Study Area 4 Sandwich on October 2, 2017. Vibracores MA-CZM-2017-VC12 to MA-CZM-2017-VC14 were collected at Study Area 5 Cuttyhunk on October 3, 2017. Demobilization of the *R/V Jamie Hanna* occurred from October 4th to October 5th, at which time all field personnel returned to their respective home offices and the vibracores were transported to APTIM's geotechnical lab in Boca Raton, Florida.

Data Processing and Interpretation Methods

In order to more accurately estimate potential volumes of sand within the Study Areas, APTIM processed the available historic seismic sub-bottom data and calculated composite geotechnical statistics (where able) and estimated sand resource volumes based by correlating the results of the geotechnical data analysis performed on the vibracores with historic seismic sub-bottom data. The following subsection describes in more detail the methods used by APTIM to process and interpret the geotechnical and historic seismic sub-bottom data.

Vibracore Sample Processing

Upon collection of the vibracores and removal of the vibracore tube, APTIM geologists sealed, measured, and marked each vibracore to prepare the vibracores for transport. The vibracores, along with the surface grab samples collected by CR, were transported to APTIM's accredited geotechnical laboratory in Boca Raton, Florida. Vibracores were split lengthwise and logged in detail by APTIM geologists, describing sedimentary properties by layer in terms of layer thickness, color, texture (grain size), composition and presence of clay, silt, gravel, or any other identifying features in accordance with ASTM standard procedure D 2488-09a. A flow chart of vibracore logging and sample analysis steps is included as Figure 29.

The vibracores were photographed in 2 ft (0.6 m) intervals using an Olympus Stylus TG-3 16 megapixel camera with a 4.5 mm to 18.0 mm, f2.0 to f4.9 lens (Equivalent to 25 mm to 100 mm on a 35 mm film) that was mounted on a frame directly above the vibracores. The photographs were taken using full spectrum overhead lighting and an 18% gray background, which provided a known reference color and is the standard reference value against which all camera light meters are calibrated.

Sediment samples were extracted from the vibracores at irregular intervals based on distinct stratigraphic layers and sediment quality (strata with apparent high silt/clay content were typically avoided) in the sediment sequence. For stratigraphic layers within each vibracore that occurred at different depths, but that were significantly similar, a sample was not collected or analyzed for the deeper unit(s). Instead, APTIM reported the results of the first sample for the first unit as the virtual results of the similar deeper unit(s). The vibracores were wrapped and boxed for proper storage within APTIM's temporary storage facility.

The vibracores will be stored by APTIM for one (1) year after the completion of the contract, after which time the vibracores will be discarded. If CZM would like to retain the vibracores, the vibracores will be made available to CZM for pickup, or APTIM will transport the vibracores to CZM for additional cost.

Sedimentary properties of the surface grab samples were also described. Each grab sample was split into two (2) representative sub-samples: one (1) sub-sample to conduct the laboratory analysis and the other sub-sample for archiving within APTIM's storage facility with the vibracore samples.

Much like with the vibracore sediment samples, for surface grab samples from the same Study Area that are significantly similar, a sample was not analyzed for all multiple similar samples. Instead, APTIM reported the grain size analysis results of one of the similar samples as a virtual sample for the other similar samples. This was only done in the case of specific samples being significantly similar to others within the same Study Area. If significant similarity is in doubt, the surface grab sample was analyzed in full to determine its own specific geotechnical qualities. This was done for surface grab sample MER7-G3B, which was noted as a virtual sample of surface grab sample MER10-G. It should also be noted that surface grab samples CANAL6-G5 and DUX6-G5 were not analyzed for grain size as they were predominantly clay.

The sediment samples extracted from the vibracores and the surface grab samples were prepared for processing in APTIM's geotechnical laboratory. This laboratory is accredited by the Construction Materials Engineering Council, Inc. (CMEC) for ASTM D422/T88 Sieve Analysis, D1140, D4648, and CPE-HAT-09 and is validated by USACE's Materials Testing Center for ASTM D422/T88, D1140, D3740, D4648, CPE-HAT-09, and E329. Geologic samples were analyzed to determine texture (grain size and sorting) and color. The testing methods are summarized below.

The sediment samples were analyzed to determine color and grain size distribution. During sieve analysis, the wet, dry, and washed Munsell colors were noted. Grain size was determined through sieve analysis in accordance with ASTM Standard Materials Designation D422-63 for particle size analysis of soils. This method covers the quantitative determination of the distribution of sand particles. Sediment finer than the No. 230 sieve (4.0 phi) was analyzed following ASTM Standard Test Method, Designation D1140-00. Mechanical sieving was accomplished using calibrated sieves with a gradation of half phi intervals. Additional sieves representing key ASTM sediment classification boundaries were included to meet appropriate beach-compatible mineral characterization. Weights retained on each sieve were then recorded cumulatively. The sieve stack, together with its Wentworth equivalence, used for mechanical analysis is provided in Table 2. Grain size results were entered into the gINT® software program, which computes the mean and median grain size, sorting, and silt/clay percentages for each sample using the moment method.

Table 2: Granularmetric Analysis Mesh Sizes with associated Wentworth Size Class

Sieve Number	Size (phi)	Size (mm)	Wentworth Scale	
3/4	-4.25	19.00	Pebble	Gravel
5/8	-4.00	16.00		
7/16	-3.50	11.20		
5/16	-3.00	8.00		
3 ½	-2.50	5.60		
4	-2.25	4.75		
5	-2.00	4.00		
7	-1.50	2.80	Granule	
10	-1.00	2.00		
14	-0.50	1.40	Very Coarse Sand	Sand
18	0.00	1.00		
25	0.50	0.71	Coarse Sand	
35	1.00	0.50		
45	1.50	0.36	Medium Sand	
60	2.00	0.25		
80	2.50	0.18	Fine Sand	
120	3.00	0.13		
170	3.50	0.09	Very Fine Sand	
200	3.75	0.08		
230	4.00	0.06		

Based on the grain size results of the surface grab samples and vibracores, and the results of the initial data review, APTIM conducted an evaluation of potential sand resources. This includes the identification of potential sand resource thickness, aerial extents, and estimated volumes.

Seismic Sub-Bottom Processing

Processing of the historic USGS seismic sub-bottom data was completed using Chesapeake Technology, Inc.'s SonarWiz 7 software. This software allows the user to apply specific gains and settings in order to produce enhanced seismic sub-bottom imagery that can then be interpreted and digitized for specific stratigraphic facies relevant to project goals. Figures 30 through 33 depict the location of all historic seismic sub-bottom data coverage, as well as the historic seismic sub-bottom data coverage used for the development of the sediment thickness calculations. As can be seen in some instances, not all available historic data were utilized due to the fact that some *.segy* files were corrupted and APTIM was unable to properly import them into SonarWiz, the data was not available, or the quality of the data did not permit a feature to be digitized.

Raw and/or processed *.segy* files were imported into SonarWiz 7 and the data bottom tracked and gained. The process of bottom tracking uses the high-amplitude signal associated with the seafloor to map it as the starting point for gains and swell corrections. Automatic gain control (AGC) was applied and manipulated when necessary to produce a better image (contrasts between low and high return signals). In addition Time-Varying Gain (TVG) was used to adjust the imagery below the seafloor to increase the contrast within the stratigraphy, and increase the amplitude of the stratigraphy with depth, accounting for some of the signal attenuation normally associated with sound penetration over time.

Geotechnical Data Interpretation

For proper integration into the seismic sub-bottom project in SonarWiz 7, individual layers in each vibracore were color-coded based on the amount (percent) of fine material (percent passing the #230 sieve). Samples with a fine-grain content less than or equal to 5% were color coded as green/good potential for sand while samples that were between 5% and 10% were classified as yellow/moderate potential for sand. Layers described as being clay were classified as red/poor potential for sand. Descriptive vibracore logs (Appendix A), granularmetric reports (Appendices B and C), granularmetric curves (Appendix D) and photographs of vibracores (Appendix E) were used to compile sediment characteristics and vibracore composite statistics in all of the Study Areas.

Composite mean grain size and percent silt content were computed for each vibracore within the Study Areas by calculating the weighted average (sample weighted by effective lengths of the sampled layer above the base of sand elevation). The final product of this calculation was a composite vibracore sample with weights for each phi interval. This composite vibracore sample was then input into gINT with any other composite vibracores (if available) where a final mean grain size and silt content was calculated for each study area (where able) based on the weighted average. Generally, the maximum base of sand elevation was determined to be the base of the last layer classified as potentially beach-compatible (green), however, sometimes discrete yellow or red layers containing increased silt contents were also included in the composite statistics as long as the overall resulting deposit would still be classified as sandy and not silt or clay.

Seismic Sub-bottom Interpretation

After data processing, subsurface data interpretation was performed using SonarWiz 7 software. Bottom tracked seismic sub-bottom lines were opened to digitally display the recorded subsurface stratigraphy. Using the software's Sonar File Manager, color-coded vibracore descriptions were added directly to the seismic sub-bottom profiles. As described earlier, a project specific color scheme, based on a stoplight (red, yellow, green) color scale, was developed for the CZM vibracores based on the amount of fine grain content and general layer description.

Using the color-coded vibracore descriptions as a guide, the seismic sub-bottom stratigraphy was interpreted and the depth of the top of marginal to poor quality material (also known as the base of beach-compatible "good" sand) was determined. The stratigraphic reflector that best correlated with this layer was digitized by clicking on the reflector within SonarWiz to create a digital color-coded boundary. This boundary appears on the subsequent seismic sub-bottom imagery to allow for an easy, visual reference for the boundary between potentially beach-compatible material and marginal to poor quality material.

At this point, the thickness of each potential sand resource was calculated and exported from SonarWiz to serve as the basis for the initial isopach (sediment thickness) maps for each of the four (4) Study Areas that had historic seismic sub-bottom data (note, Study Area 4 did not have any historic seismic sub-bottom data, and as a result, an isopach could not be created for Study Area 4). This was accomplished by using the "Thickness" tool within SonarWiz, which subtracts the elevation below the towfish of the digitized reflector representing the non-beach-compatible material (i.e., high silt, clay, or bedrock/hard bottom content) boundary (as interpreted from the historic seismic sub-bottom data) from the elevation below the towfish of the digitized seafloor reflector. This then creates a visual, digital feature of the thickness of the deposit (between the seafloor and the boundary of non-compatible material) on each individual seismic sub-bottom line. From here, a file is exported from SonarWiz for all lines containing the thickness file, creating one single X/Y/Thickness ASCII file for the geologic deposit. This X/Y/Thickness ASCII file is then gridded into a surface to develop the isopach map (see section 12.5 below for more information on isopach creation).

Isopach Creation

The ASCII X/Y/Thickness file from SonarWiz was imported into Golden Software Inc.'s Surfer software program (software version 13), gridded, and reviewed for quality and accuracy (i.e., obvious visual inconsistencies, inaccuracies, and/or anomalies in the resulting gridded surface, like isolated holes, valleys, or obvious interpretation mismatches between survey lines). Output cell sizes (X, Y) ranged from 9.75 m to 39.96 m (Table 3) and were auto calculated by the software program depending on the size of the study area, seismic sub-bottom coverage of the study areas, and the resulting interpreted-data density of the available seismic sub-bottom data points in each study area. Upon review, if the resulting gridded thickness surface displayed discrepancies or clear artifacts (such as mismatched interpreted thicknesses at line crossings due to interpreting and digitizing different features on adjacent lines), the historic seismic sub-bottom data was reviewed and adjustments to the interpreted boundary location were made to the seismic sub-bottom digitization to fix these inconsistencies, ensuring that all interpreted and digitized features tied together in each study area. Once adjusted in SonarWiz, the

X/Y/Thickness file was re-exported (as detailed in section 12.4) and re-gridded in Surfer to review the resulting isopach surface. This process was repeated until all visual inconsistencies and tie issues in the seismic sub-bottom data were corrected. After this quality assurance/quality control step, a final ASCII X/Y/Thickness file was exported for each area and gridded into a raster isopach surface within ArcGIS.

Table 3: Topo to Raster Grid Information

Field	Value
Feature Layer	Point file
Field	Thickness field
Type	Point Elevation
Cell Output Size (Auto-populates)	SA1: 34.45 X, 34.47 Y SA2: 9.75 X, 9.75 Y SA3: 32.74 X, 32.74 Y SA5: 39.85 X, 39.96 Y
Output extent	Default
Margin in cells	20 (default)
Smallest Z value to be used in interpolation	Blank
Largest Z value to be used in interpolation	Blank
Drainage enforcement	Enforce
Primary type of input data	Spot
Maximum number of iterations	20 (default)
Roughness penalty	Blank
Profile curvature roughness penalty	Blank
Discretization error factor	1 (default)
Vertical standard error	0 (default)
Tolerance 1	0 (default)
Tolerance 2	200 (default)

To accomplish this, the X/Y/Thickness file was imported into ArcGIS and a topographic surface was created using the Spatial Analyst Topo to Raster tool. APTIM chose to use this tool due to the widely spaced, limited nature of the data coverage, together with the relative straightforwardness and limited input and processing variables of this tool. In addition, as described in ArcGIS, this tool has the ability to follow abrupt changes in terrain likely due to stream channels, ridges, and other geomorphic features, which are likely the most prevalent geomorphologic controls related to the interpretation of the boundaries/features digitized in these datasets. This Topo to Raster tool uses an iterative finite difference interpolation technique. As described by ArcGIS, this grid development tool is "optimized to have the computational efficiency of local interpolation methods, such as inverse distance weighted (IDW) interpolation, without losing the surface continuity of global interpolation methods, such as Kriging and Spline. It is essentially a discretized thin plate spline technique (Wahba, 1990) for which the roughness penalty has been modified to allow the fitted DEM [Digital Elevation Model] to follow abrupt changes in terrain, such as streams, ridges and cliffs" (ArcGIS, 2012). Surfaces were generated by selecting the parameters outlined in Table 3.

The generated surface provided a visual and digital representation of the thickness (in meters) of the potential sand resource. The isopach surface was then clipped to the digitized Interpreted Sandy Seafloor delineation in order to avoid areas of exposed hard bottom and focus on the sandy seafloor areas evident as part of the historic data review described in Section 9.0. A volume of the resulting clipped isopach surface was then calculated by using the Surface Volume tool in ArcGIS. This tool utilizes the difference between two (2) surfaces to determine a potential volume in cubic meters (m^3) of the sand deposit. For this particular project, the volume was determined by comparing the clipped, computed isopach surface to a zero thickness plane, generating a total potential volume of the sandy seafloor area.

It is important to note that the accuracy of the isopach and volume results is a function of the overall data density in each study area. While none of the study areas had data coverage consistent with borrow area design-level densities, all had sufficient coverage to make reconnaissance-level calculations on rough magnitude of potential volumes and locations of sand resources. In some cases, some areas (Study Areas 1 and 5, for instance) had more data coverage and data density than others (Study Area 2), and as a result have a higher accuracy of reconnaissance-level results. That said, all isopach and volume data are based on reconnaissance-level coverage and would require additional, design-level information to confirm and refine specific sand resource statistics.

Vibracore Results

The following sections describe the vibracore results, geotechnical composite statistics (where able), and resulting Study Area volumetric estimates.

Where historic seismic sub-bottom data existed (Study Areas 1, 2A, 3A, 3B, 5A, and 5B), the newly-collected vibracore data were correlated to the historic seismic sub-bottom data to develop an isopach as described earlier. The results below show the range of the average thickness of these isopach, ± one standard deviation. The volumes shown are the actual calculated estimated volumes of the isopach in m^3 rounded to the nearest 10,000 m^3. The rounded m^3 volume value was then converted to cy and rounded to the nearest 100 cy.

Where historic seismic sub-bottom data did not exist (Study Areas 2C and 4A), the average thickness of the sandy deposit (as logged from the newly collected vibracores) was multiplied by the area of the Interpreted Sandy Seafloor area to develop the potential volume of the sand deposit. In this case, the average thickness is not shown as a range, but shown as a discrete value representing the average thickness of that sand deposit as logged in the newly collected vibracores within that specific Study Area. The volumes shown are the actual calculated estimated volumes in m^3 rounded to the nearest 10,000 m^3. The rounded m^3 volume value was then converted to cy and rounded to the nearest 100 cy.

In areas where historic seismic sub-bottom data did not exist, where there was insufficient sandy seafloor to develop a potential borrow area, and/or there was a sediment disposal area with dredge records available to support additional characterization (Study Areas 2B and 4B), no new data was collected for this investigation, and as a result, no Interpreted Sandy Seafloor area or estimated volumes were calculated. The following Table 4 summarizes the as collected information of the vibracore field operations.

Table 4: Results of vibracore field operations

Vibracore	Number of Attempts	Penetration (ft)	Recovery (ft)	Recovery %	Study Area
MA-CZM-2017-VC01	1	12.0	12.0	100	2
MA-CZM-2017-VC02	1	12.0	9.8	82	2
MA-CZM-2017-VC03	1	12.3	12.3	100	2
MA-CZM-2017-VC04	2	12.3	11.8	96	2
MA-CZM-2017-VC05	3	8.7	8.7	100	1
MA-CZM-2017-VC06	3	12.3	12.2	99	1
MA-CZM-2017-VC07	3	11.5	10.8	94	1
MA-CZM-2017-VC08	1	12.3	12.3	100	1
MA-CZM-2017-VC09	1	12.3	12.0	98	1
MA-CZM-2017-VC10	3	11.5	6.8	59	5
MA-CZM-2017-VC11	2	9.9	9.9	100	5
MA-CZM-2017-VC12	3	12.3	8.4	68	5
MA-CZM-2017-VC13	1	12.3	11.5	93	5
MA-CZM-2017-VC14	2	10.5	10.5	100	5
MA-CZM-2017-VC15	3	11.0	10.7	97	3
MA-CZM-2017-VC16	1	12.2	11.2	92	3
MA-CZM-2017-VC17	1	11.0	11.0	100	3
MA-CZM-2017-VC18	1	11.0	10.0	91	4
MA-CZM-2017-VC19	1	12.3	11.5	93	4
MA-CZM-2017-VC20	1	12.3	10.8	88	4

Additionally, the description and geotechnical information for the top layer of each vibracore was analyzed and described according to CZM's modified Barnhardt sediment classification scheme (Table 5).

Table 5: Top of vibracore Barnhardt sediment classification

Vibracore	Study Area	Easting	Northing	CZM Barnhardt sediment classification
MA-CZM-2017-VC01	2A	257169.10	895589.73	Fine with Gravel
MA-CZM-2017-VC02	2C	257831.68	899232.26	Fine
MA-CZM-2017-VC03	2C	259735.01	897546.71	Fine
MA-CZM-2017-VC04	2C	262857.57	897529.60	Fine with Gravel
MA-CZM-2017-VC05	1	262481.69	948256.51	Fine with Rock
MA-CZM-2017-VC06	1	259678.20	948189.85	Fine with Rock
MA-CZM-2017-VC07	1	259788.11	951977.41	Fine with Rock
MA-CZM-2017-VC08	1	261676.60	953809.18	Fine with Rock

MA-CZM-2017-VC09	1	259585.07	955109.78	Fine with Rock
MA-CZM-2017-VC10	5A	239899.46	793490.73	Fine with Rock
MA-CZM-2017-VC11	5A	241178.01	796123.47	Fine with Rock
MA-CZM-2017-VC12	5A	237838.67	798152.26	Fine with Rock
MA-CZM-2017-VC13	5B	234032.12	802507.65	Fine with Rock
MA-CZM-2017-VC14	5B	232757.46	801103.10	Fine with Gravel
MA-CZM-2017-VC15	3A	277516.22	870903.09	Fine with Rock
MA-CZM-2017-VC16	3B	276445.66	866962.22	Fine with Rock
MA-CZM-2017-VC17	3B	275720.97	865047.61	Fine with Rock
MA-CZM-2017-VC18	4A	283241.53	843846.94	Fine with Rock
MA-CZM-2017-VC19	4A	285623.80	840878.07	Fine with Rock
MA-CZM-2017-VC20	4A	284592.15	838399.08	Fine with Rock

Table 6 below provides sand thicknesses and resulting vibracore composite statistics. It should be noted that the identified final composite values are only an estimate based on a few, widely-spaced geologic samples, and that additional vibracores and design-level geophysical data should be collected during an offshore design-level investigation in order to more confidently determine the beach-compatibility, volumes, hazards, protected resources, and dredgeability of potential preliminary borrow areas.

Study Area 1 Merrimack River

Seismic sub-bottom interpretation of Study Area 1 offshore of Merrimack River yielded one of the largest potential sand volumes (Figure 34). The area was covered by 570 line kilometers (km) of historic seismic sub-bottom data and five (5) vibracores. MA-CZM-2017-VC05 and MA-CZM-2017-VC06 characterized the subsurface as sand, with a silt content not exceeding 3%. MA-CZM-2017-VC07 characterized the topmost 2.3 m (7.5 ft) of the subsurface as sand, with a thin layer of sand with a high silt/clay content (almost 30%) which was excluded from the composite statistics for the vibracore and the Study Area and represents the base of the sand resource. MA-CZM-2017-VC08 indicated that the topmost 3.2 m (10.5 ft) of the vibracore were sands, with the lower 0.5 m (1.7 ft) of the vibracore as clay with silty sands. This lower layer was excluded from the composite statistics. MA-CZM-2017-VC-09 characterized the upper part of the subsurface stratigraphy as sand, with the lower 1.0 m (3.2 ft) of the vibracore as sand with a silt content of 7.41%. Even though this deeper layer contained slightly increased silt content, it was included in the composite statistics of the vibracore and of the Study Area as the overall composite (including this increased silt layer) still resulted in general geotechnical statistics considered to be beach-compatible. Table 7 below provides a breakdown of the composite statistics for the Merrimack River Study Area.

Table 6: Vibracore sand thicknesses and composite statistics

Vibracore	Study Area	Top of Core (ft)	Bottom of Sand (ft)	Sand Thickness (ft)	Composite Grain Size (mm)	Composite Sorting (mm)	Composite Silt %
MA-CZM-2017-VC01	2A	-76.1	-86.0	9.9	0.1	0.62	11.8
MA-CZM-2017-VC02	2C	-122.0	n/a	n/a	n/a	n/a	n/a
MA-CZM-2017-VC03	2C	-120.4	n/a	n/a	n/a	n/a	n/a

MA-CZM-2017-VC04	2C	-123.7	-132.4	8.7	0.1	0.66	12.3
MA-CZM-2017-VC05	1	-104	-112.7	8.7	0.4	0.41	1.3
MA-CZM-2017-VC06	1	-79.7	-91.9	12.2	0.1	0.55	3.3
MA-CZM-2017-VC07	1	-86	-93.6	7.6	0.3	0.54	1.9
MA-CZM-2017-VC08	1	-107.6	-118.2	10.6	0.5	0.47	1.0
MA-CZM-2017-VC09	1	-92.5	-104.5	12.0	0.3	0.34	4.3
MA-CZM-2017-VC10	5A	-71.9	-78.7	6.8	0.2	0.65	2.1
MA-CZM-2017-VC11	5A	-66.6	-76.5	9.9	0.3	0.50	7.0
MA-CZM-2017-VC12	5A	-58.4	-66.8	8.4	0.1	0.66	3.9
MA-CZM-2017-VC13	5B	-56.8	-62.6	5.8	0.2	0.46	6.8
MA-CZM-2017-VC14	5B	-62.3	-65.6	3.3	0.17	0.53	6.0
MA-CZM-2017-VC15	3A	-80.1	-90.8	10.7	0.2	0.60	1.7
MA-CZM-2017-VC16	3B	-78.4	-89.6	11.2	0.2	0.49	10.6
MA-CZM-2017-VC17	3B	-71.5	-82.5	11.0	0.1	0.46	16.4
MA-CZM-2017-VC18	4A	-43.3	-53.3	10.0	0.3	0.61	1.1
MA-CZM-2017-VC19	4A	-56.8	-67.3	10.5	0.2	0.58	4.6
MA-CZM-2017-VC20	4A	-55.1	-65.9	10.8	0.2	0.46	2.3

The area appears to have a generally thick sand deposit to the north and south of the area, with some rock outcrops and/or thin sand layers in the central and western areas. The hard bottom outcrops can be seen both on the interpreted seismic sub-bottom data (Figure 35 shown in brown) as well as the historic sidescan sonar and seafloor photographs. Due to the drastic change in bottom type in the area, the isopach surface was clipped to the interpreted sandy area shapefile to isolate the portions of the Study Area that have hard bottom/rock outcrops (Figure 34). The final potential volume of 99,730,000 m^3 (130,442,000 cy) is estimated based off the interpreted seismic sub-bottom data with the plotted vibracores (Table 8).

As can be seen by comparing the Massachusetts OMP Sand Resource Area and the Interpreted Sandy Area derived from the sidescan sonar and seafloor photographs, only approximately 68% of the area could potentially be developed into a future borrow area. Additional geophysical and geotechnical data will be necessary to fully characterize and further delineate the sand resource offshore of the Merrimack River, however, from the available data it does appear to be a significant sand source with likely beach-compatible sand resources in substantial project quantities.

Table 7: Composite statistics for Study Area 1

Vibracore	Study Area	Mean Grain Size (mm)	Sorting (mm)	Silt %	Composite Grain Size (mm)	Composite Sorting (mm)	Composite Silt %
MA-CZM-2017-VC05	1	0.36	0.41	1.3			
MA-CZM-2017-VC06	1	0.15	0.55	3.3			
MA-CZM-2017-VC07	1	0.33	0.54	1.9	0.30	0.40	2.5
MA-CZM-2017-VC08	1	0.52	0.47	1.0			
MA-CZM-2017-VC09	1	0.31	0.34	4.3			

Table 8: Estimated volumes for Study Area 1

Study Area	Vibracores	MA OMP Sand Res. Area (m^2)	Interp. Sandy Area (m^2)	Approximate Sand Thickness Range (m)	Volume (m^3)	Volume (cy)
1	MA-CZM-2017-VC05 MA-CZM-2017-VC06 MA-CZM-2017-VC07 MA-CZM-2017-VC08 MA-CZM-2017-VC09	52,282,963	35,665,334	1.76 to 3.84	99,730,000	130,442,000

Study Area 2 Nantasket Beach

Study Area 2 offshore of Nantasket Beach yielded the smallest potential sand volumes. The area was sub-divided into Study Area 2A to the west, Study Area 2C as the largest centralized portion, and Study Area 2B to the south (Figure 36). Only Study Area 2A had any historic seismic sub-bottom data (a total of 61 line km of data). Study Area 2 was sampled by four (4) cores, of which only two (2) characterized the subsurface as having potential sand. Based on vibracore MA-CZM-2017-VC01, the subsurface is best characterized as sand with higher silt content (9%), with an increase in the silt content at an elevation of -86.0 ft below the seafloor. This layer, with almost 20% sand was not included as part of the vibracore composite. Upon review of the available seismic sub-bottom data, this sand layer is associated with a buried channel complex. MA-CZM-2017-VC02 and MA-CZM-2017-VC03 indicate that the subsurface geology is generally clay, with some sand around MA-CZM-VC03. Since the visual inspections of MA-CZM-2017-VC02 and MA-CZM-2017-VC03 indicate that they are predominantly clay, and therefore not beach-compatible, no sediment samples were analyzed for grain size content, therefore there are no composite statistics for these two (2) cores. MA-CZM-2017-VC04 characterizes the subsurface as mostly sand with up to 14% silt content, with the lower 0.9 m (3.0 ft) of the vibracore consisting of mostly sandy clays. Table 9 below provides the composite information for the collected vibracores.

As previously mentioned, interpretation of the seismic sub-bottom data in Study Area 2A indicated that the estimated 3,600,000 m^3 (4,708,600 cy) of potential sand is associated with the infill of a channel (Figure 37). This sand infill is present across the entire 2A area (Figure 37) and could be a potential source of sand for future shore protection projects, however, sediment deposits are normally not well organized within channels, complicating the development of a borrow area. Study Area 2C was narrowed down to a small 1,348,929 m^2 area around MA-CZM-2007-VC04 (approximately 12% of the central portion of Study Area 2) based off the historical sidescan sonar data. This area could have a potential sand volume of 3,600,000 m^3 (4,708,600 cy) based on the sand thickness (Table 6) and the Interpreted Sandy Area (Table 10). Since no seismic sub-bottom data were available to corroborate the information provided by the vibracores, fence diagrams were made correlating vibracores MA-CZM-2017-VC02, MA-CZM-2017-VC03 and MA-CZM-2017-VC04 (Figure 38). The fence diagrams indicate that the majority of Study Area 2C is clay, with some mixed fine sands and clayey sands being introduced toward the southwest within Study Area 2C. While there is some indication of mixed sands in MA-CZM-2017-VC04, these sands contain high percentages of fine material (between

7% and 14% of material passing through the 230 sieve) and would need to be evaluated in the context of a potential recipient beach to fully determine beach compatibility and environmental impacts.

Table 9: Composite statistics for Study Area 2

Vibracore	Study Area	Mean Grain Size (mm)	Sorting (mm)	Silt %	Composite Grain Size (mm)	Composite Sorting (mm)	Composite Silt %
MA-CZM-2017-VC01	2A	0.11	0.62	11.75	n/a	n/a	n/a
MA-CZM-2017-VC02	2C	n/a	n/a	n/a	n/a	n/a	n/a
MA-CZM-2017-VC03	2C	n/a	n/a	n/a	n/a	n/a	n/a
MA-CZM-2017-VC04	2C	0.11	0.66	12.28	n/a	n/a	n/a

Table 10: Estimated volumes for Study Area 2

Study Area	Vibracores	MA OMP Sand Res. Area (m^2)	Interp. Sandy Area (m^2)	Approximate Sand Thickness Range (m)	Volume (m^3)	Volume (cy)
2A	MA-CZM-2017-VC01	1,739,373	1,070,310	2.54 to 4.18	3,600,000	4,708,600
2B	n/a	1,039,425	n/a	n/a	n/a	n/a
2C	MA-CZM-2017-VC04	11,056,961	1,348,929	2.67	3,600,000	4,708,600

Additional data are required for the entire Study Area 2, more specifically within Study Area 2C in order to properly determine the nature of the sand deposit around MA-CZM-2017-VC04. Moreover, due to the lack of available vibracores, and a poor indication of potential sand resources, no samples were taken in Study Area 2B, limiting the potential borrow area to a small portion of areas 2C and 2A. While data coverage, and actual sand resources, appear to be limited, there is sufficient likely beach-compatible sand resources present in shore protection project quantities for small to moderate sized shore protection projects within Study Area 2. Additional seismic sub-bottom and vibracore data coverage, however, could potentially identify larger quantities within the Study Area.

Study Area 3 Duxbury Beach

Study Area 3 offshore of Duxbury Beach was sampled by three (3) vibracores and approximately 560 line km of historic seismic sub-bottom data covering mostly Study Area 3B and the small southern portion of Study Area 3A. MA-CZM-2017-VC15, located in Study Area 3A, characterizes the subsurface geology as sand, likely associated with a shoal feature with less than 2% of silt content. MA-CZM-2017-VC16 and MA-CZM-2017-VC17 are located in Study Area 3B. MA-CZM-2017-VC16 characterizes the subsurface geology as a 1.3 m (4.3 ft) thick sand layer with little silt content, followed by a 2.1 m (6.1 ft) layer of sand with 15% silt content. This siltier layer was included in the composite statistics for the vibracore and the 3B area. MA-CZM-2017-VC17, much like MA-CZM-2017-VC16, indicates that the subsurface geology consists of a 1 m (3.3 ft) layer of sand followed by a thicker layer of sand with higher silt content, which was also included as part of the composite statistics for the area (Table 11). Including these marginal units allowed for the maximum understanding of the potential sand resource deposit pending additional geophysical and geotechnical data collection and further characterization of the potential resource.

Table 11: Composite statistics for Study Area 3

Vibracore	Study Area	Mean Grain Size (mm)	Sorting (mm)	Silt %	Composite Grain Size (mm)	Composite Sorting (mm)	Composite Silt %
MA-CZM-2017-VC15	3A	0.17	0.60	1.69	n/a	n/a	n/a
MA-CZM-2017-VC16	3B	0.16	0.49	10.59	0.15	0.47	13.46
MA-CZM-2017-VC17	3B	0.14	0.46	16.43			

Interpretation of the available historic seismic sub-bottom data indicated that the sand available in both areas 3A and 3B is likely associated with a shoal deposit that crosses the entire Study Area 3 (Figure 39). The isopach in Study Area 3B was clipped to the Interpreted Sandy Area polygon in order to avoid areas that appear to have a hard bottom/rock outcrop (Figure 40). The total volume within Study Area 3B of 46,000,000 m^3 (60,165,700 cy) of sand is generally located in the central portion of the Study Area, where the shoal feature appears to be more prominent (Table 12). Interpretations of the historic sidescan sonar data in Study Area 3A indicate that the surface is likely mostly sand, therefore, in order to determine the potential volume of sand, the sand thickness (Table 6) was used as a general representation of the entire Massachusetts OMP Sand Resource Area 3A, yielding a potential volume of 46,940,000 m^3 (61,395,200 cy) of sand. It is important to note however, that this is an estimated volume, assuming the subsurface stratigraphy of Study Area 3A is mostly uniform in nature (i.e. assuming that the three shoal futures visible in Figure 40 are consistent throughout the area to the north where geophysical data is lacking).

From the available historic data and collected vibracores, Study Area 3 appears to be a viable source of likely beach compatible sand, with some silt content, in shore protection project quantities. However, additional geotechnical and geophysical data are necessary to further delineate the potential sand resource and better understand the subsurface geology in both areas, especially in Study Area 3A.

Table 12: Estimated volumes for Study Area 3

Study Area	Vibracores	MA OMP Sand Res. Area (m^2)	Interp. Sandy Area (m^2)	Approximate Sand Thickness Range (m)	Volume (m^3)	Volume (cy)
3A	MA-CZM-2017-VC15	14,398,272	n/a	0.84 to 5.68	46,940,000	61,395,200
3B	MA-CZM-2017-VC16 MA-CZM-2017-VC17	25,371,615	17,497,037	0.71 to 4.55	46,000,000	60,165,700

Study Area 4 Sandwich

Study Area 4 offshore of Sandwich was divided into 2 sub-areas: Study Area 4A being the larger nearshore area and 4B being the delineation of the Offshore Dredge Material Disposal Site (ODMDS). Study Area 4A was sampled by three (3) vibracores and did not have any historic seismic sub-bottom data. The three (3) collected vibracores (MA-CZM-2017-VC18, MA-CZM-2017-VC19 and MA-CZM-2017-VC20) characterize the subsurface as a thick (up to 3.2 m (10.5 ft)) layer of sand, with MA-CZM-2017-VC19 indicating that the sand layer is overlaying a clayey sand unit. Due to the lack of historic data in Study Area 4, all collected vibracores were used to estimate the potential sand composite (Table 13).

Table 13: Composite statistics for Study Area 4

Vibracore	Study Area	Mean Grain Size (mm)	Sorting (mm)	Silt %	Composite Grain Size (mm)	Composite Sorting (mm)	Composite Silt %
MA-CZM-2017-VC18	4A	0.31	0.61	1.10	0.23	0.52	2.68
MA-CZM-2017-VC19	4A	0.21	0.58	4.57			
MA-CZM-2017-VC20	4A	0.18	0.46	2.31			

Since Study Area 4A was lacking historic seismic sub-bottom data, preventing the development of a detailed isopach map, the volume estimates for Study Area 4A were calculated by determining the average sand thickness of the deposit from the base of sand elevation between the three (3) vibracores and multiplying it by the area of the entire Massachusetts OMP Sand Resource Area for Study Area 4A. The potential volume in Study Area 4A is estimated to be 51,670,000 m^3 (67,581,800 cy) of sand (Table 14). Given the fact that no seismic sub-bottom data were available for this area, it is impossible to know the exact nature and full extent of the deposit, and impossible to develop a detailed isopach for this area. As such, there is no isopach figure for Study Area 4 presented in this report. Since no seismic sub-bottom data were available to corroborate the information provided by the vibracores, fence diagrams were made correlating vibracores MA-CZM-2017-VC18, MA-CZM-2017-VC19 and MA-CZM-2017-VC20 (Figure 41). The fence diagram illustrates the general uniform nature of the surficial sand deposit across all of Study Area 4A, with the sand averaging approximately 3.38 m (11.09 ft) thick. In addition, based on MA-CZM-2017-VC19, the diagram shows the potential for clay deposits at deeper elevations immediately beneath the surficial sand deposit.

Table 14: Estimated volumes for Study Area 4

Study Area	Vibracores	MA OMP Sand Res. Area (m^2)	Interp. Sandy Area (m^2)	Approx. Average Sand Thickness (m)	Volume (m^3)	Volume (cy)
4A	MA-CZM-2017-VC18 MA-CZM-2017-VC19 MA-CZM-2017-VC20	15,286,265	n/a	3.38	51,670,000	67,581,800
4B	n/a	2,026,170	n/a	n/a	n/a	n/a

Additional information is needed in Study Area 4 in order to better delineate and understand the nature of the sand deposit, however based on the collected vibracores it is likely that Study Area 4 could be a potential sand source with beach compatible sand in project quantities.

Study Area 5 Cuttyhunk

Study Area 5, located offshore of Cuttyhunk in Buzzards Bay, was divided into two (2) sub-areas, with area Study Area 5A located further offshore and Study Area 5B located nearshore. There were five (5) vibracores collected in Study Area 5 and approximately 350 line km of historic seismic sub-bottom data. Vibracore MA-CZM-2017-VC10, MA-CZM-2017-VC11 and MA-CZM-2017-VC12 were collected in Study Area 5A (further from shore). MA-CZM-2017-VC10 had a short recovery (6.8 ft), however, it characterizes the top 2 m (6.6 ft) as sand deposits. MA-CZM-2017-VC11 and MA-CZM-2017-VC12 penetrated approximately 3 m (9.8 ft) and also characterizes the subsurface geology as sand. MA-CZM-2017-VC13 and MA-CZM-

2017-VC14 located in Study Area 5B (closer to shore) had deeper penetration, however, they indicate that only the topmost layers are thin sand. According to MA-CZM-2017-VC13, the layers below 1.7 m (5.6 ft) are predominantly clay, while MA-CZM-2017-VC14 is mostly clay below 1 m (3.3 ft) from the surface (Table 15). In both areas, the composite statistics only utilized the layers which were describes as being mostly sand, which yielded a thicker sand layer in Study Area 5A and a thin sand deposit in Study Area 5B (Table 16).

Analysis of the available historic seismic sub-bottom data indicate that the sand in Study Area 5 is likely associated with a seven (7) to 10 m thick shoal deposit that thins out closer to shore (Figure 42). The isopach in Study Areas 5A and 5B was clipped to the Interpreted Sandy Area polygon in order to avoid areas that appear to have a hard bottom/rock outcrop. A total of 61,930,000 m^3 (81,001,400 cy) of potential sand are located across Study Area 5, with 54,470,000 m^3 (71,244,100 cy) in Study Area 5A and 7,460,000 m^3 (9,757,300 cy) in Study Area 5B (Table 16, Figure 43).

Table 15: Composite statistics for Study Area 5

Vibracore	Study Area	Mean Grain Size (mm)	Sorting (mm)	Silt %	Composite Grain Size (mm)	Composite Sorting (mm)	Composite Silt %
MA-CZM-2017-VC10	5A	0.15	0.65	2.14	0.19	0.52	4.66
MA-CZM-2017-VC11		0.29	0.50	7.04			
MA-CZM-2017-VC12		0.14	0.66	3.91			
MA-CZM-2017-VC13	5B	0.18	0.46	6.78	0.17	0.49	6.49
MA-CZM-2017-VC14		0.17	0.53	6.00			

Table 16: Estimated volumes for Study Area 5

Study Area	Vibracores	MA OMP Sand Res. Area (m^2)	Interp. Sandy Area (m^2)	Approximate Sand Thickness Range (m)	Volume (m^3)	Volume (cy)
5A	MA-CZM-2017-VC10 MA-CZM-2017-VC11 MA-CZM-2017-VC12	18,201,875	12,180,335	1.61 to 7.33	54,470,000	71,244,100
5B	MA-CZM-2017-VC13 MA-CZM-2017-VC14	12,462,666	5,338,989	0.76 to 2.04	7,460,000	9,757,300

From the available historic data and newly collected vibracores, Study Area 5 appears to be a viable source of potential sand, with significant volumes of likely beach-compatible sand, however, additional information is needed in order to better delineate the shoal feature and characterize the sediment.

Surface Grab and Towed Video Systems and Equipment

Vessels

Vessel support for the underwater video operations and sediment grab sampling was provided by CR's 26-foot *R/V Lophius,* and the 25-foot *R/V Charlotte Anne* based in Falmouth, MA, and the 40-foot lobster boat, *Cynthia Lee* based in New Bedford. These vessels were all equipped with lifting davits and lobster pot haulers to deploy the underwater video sled and Ted Young modified Van Veen grab sampler. They also have 12 volt and 110 power supplies, benches for sample logging, and precision navigation and depth sounding equipment. For these sediment grab sampling efforts, CR provided a three man crew: a USCG licensed boat captain, a field biologist, and an oceanographic technician.

Navigation

Navigation for the survey and sampling events was accomplished using a Hemisphere sub-meter GPS and digital compass system capable of receiving the USCG Beacon corrections and providing vessel heading. A shipboard computer running HYPACK® hydrographic surveying software was used to provide a steering display for the vessel's captain. The use of georeferenced imagery (e.g., orthophotos) as background files ensured that the correct sampling stations and video transects were occupied. The GPS antenna was mounted at the stern of the vessel, and cable out was carefully monitored during survey operations to apply an accurate layback or offset to the video sled position.

Underwater Video Sled

At the Study Areas, 10 500 to 1,000 meter long video transects were selected for underwater video sled survey coverage.

Underwater video data were collected with CR's portable towed video sled consisting of a lightweight aluminum frame, Outland Technologies' (OTI) high-resolution low light color camera, and two UWL-401 LED lights with variable output control. The video camera was cabled to the surface to an OTI-960 DVR recorder and topside monitor. The video sled is also equipped with a High Definition GoPro Hero 4+ Black video camera in a Nimar deep water housing mounted below the OTI camera and programmed to record HD video at 1080P (resolution), 30 frames per second, and take 12 megapixel still frames every 5-10 seconds. The GoPro camera was time synced to the OTI camera and the navigation computer at regular intervals during battery changes. Prior to launching the video sled, both cameras were set in record mode and the time, date, and video transect ID was recorded from a labelled board. When the video sled came in contact with bottom, the HYPACK navigation file was started.

Surface Grab Sampler

At each of the Study Areas, five (5) surface grab samples were collected for sediment grain size. The surface grab samples were collected at five (5) of the 10 video transects and located away from the planned APTIM vibracore locations. Sediment grain size samples were collected with a Ted Young modified Van Veen sediment sampler. Samples were inspected through the upper doors of the grab sampler, and samples with good recovery collected in buckets, transferred to one gallon zip lock bags, labeled, and stored on ice. Grain size samples were temporarily stored at CR's Falmouth, MA headquarters and then transported for analysis to APTIM's geotechnical laboratory in Boca Raton, Florida.

Surface Grab and Towed Video Operations

The video sled surveys and grab sampling operations at the Study Areas along the Massachusetts coast were performed from August-November 2017 (Table 17).

Table 17: Dates of CR's survey operations per Study Area

Study Area	Survey Dates
4	August 2 to 3, 2017
2	August 16 to 17, 2017
1	September 12 to 13, 2017
3	November 3 and 6, 2017
5	November 8 to 9, 2017

At the completion of each survey, navigation and underwater video data were backed up on a portable hard drive. The navigation data were edited for outlying positions and adjusted for the amount of cable out to provide underwater video sled positions at five (5) second intervals.

The 10 video transect tracklines at each of the five (5) Study Areas are shown on Figures 44 to 48. The start of each color-coded trackline is labeled (e.g., S2). In a few cases, the tracklines were broken into two (2) segments if the sled became entangled in lobster gear or if the vessel was near the edge of the shapefile boundary. These second segments were identified with an "A".

The first site to be surveyed was Study Area 4, offshore of Sandwich, in early August. The proposed survey plan was to run ten (10) 1,000 meter transects at each of the Study Areas. After snagging multiple lobster pots, and having to tow the sled at 1.5-2 knots to obtain the required survey coverage, CR made the decision that the video transect lengths would have to be shortened on future surveys to obtain high quality underwater video footage. CR discussed this situation with CZM (Todd Callaghan), and he concurred that the video transects should be shortened to improve the quality, especially in areas of homogeneous bottoms. Therefore, on subsequent surveys, CR performed video drifts at 0.5 -1 knot and data quality was greatly improved. Transect lengths were shortened to 750 meters at Study Areas 1 and 2 and 500 meters at Study Areas 3 and 5. Although video data at Study Area 4 was adequate to identify major substrate types and biota, it was of average quality for screen captures and video analysis. CR is willing to return to Study Area 4 during the fixed gear closure (February-April) to obtain better quality video data in slow drift mode.

Towed Video Survey Operations

During field operations the video sled was raised and lowered with the ship's pot hauler and the height of the system off the bottom was continually adjusted to achieve the best bottom coverage and video quality. The video system operated in "drift and tow mode" and the vessel speed varied between 0.5 and 2 knots based on sea conditions and bottom currents. Mounted lasers set at 25 cm (9.8 in) apart on the video sled frame were used for scaling purposes. Occasionally, due to impacts with the side of the vessel or the bottom, the lasers would be knocked out of alignment, but this was corrected when the sled returned to surface. Batteries were changed if lasers went out or were intermittent.

The onboard field biologist performed real-time visual observations of the video at all times. Codes were used when recording substrate type based on CZM's modified Barnhardt et al. (1998) classification (Table 1 in Appendix L), and habitat/substrate classifications following Auster (1998) (Table 2 in Appendix L). The CZM modified Barnhardt et al. (1998) bottom sediment classes were: Fine, Fine with Gravel, Fine with Rock, Gravel with Fine, Gravel, Gravel with Rock, Rock with Fine, Rock with Gravel and Rock. Auster et al. (1998) developed a hierarchical approach for classifying marine bottom habitats in the outer continental shelf of the northwest Atlantic. Sediments were classified along a gradient of grain sizes from mud to boulders. The various forms these take and the associations of the infauna and epifauna with sediments produce a wide diversity of habitat types for fish and associated fauna. Eight general habitat categories increase from simple (Category 1) to highly complex (Category 8) (Table 2 in Appendix L).

Observations of algae and the dominant fauna (epibenthic/nekton) and the relative abundance (rare, occasional, common, or abundant) of the dominant invertebrate or fish species observed were recorded using species codes (Table 3 in Appendix L) approximately every 250 meters on formatted Excel spreadsheets. Data were checked for accuracy during the surface interval between transects. These data provide rough counts or numbers of times assemblages of a species were observed while the survey was underway.

Underwater Video Sled Viewing Area

When the video sled system was operated in a drift mode, the average vessel speed was 0.5 to 1 knot. In drift mode the video sled undulates in the water column and is either suspended a few inches above the bottom or comes to rest flat on the bottom. The viewing area of the video sled when it is off the bottom is approximately one square meter. When the video sled is on the bottom, the viewing area of the camera is approximately 50 cm x 50 cm and the video quality is optimal for substrate and biota identifications and video screen captures. The lasers are set 25 cm (9.8 in) apart and are useful for scaling bottom features and biota.

GoPro HD Camera Still Photographs and Video Review

The GoPro HD camera on the video sled was programmed to automatically record a photograph every 10 seconds at Study Area 4 offshore of the canal. This was changed to 5 second intervals for the remainder of the sites to collect more useable sharp photographs. There were up to 500 still images taken per transect. The photograph quality is best when the video sled comes to a complete stop when used in a drifting mode. Each of the still photos are time stamped, the GoPro still photographs can be used as a guide to navigate to segments of GoPro HD video. In addition, one can scroll through all the still photos to examine changes in bottom type or biota over the entire transect at a rapid pace.

The GoPro camera provided detailed 1080P HD video footage detecting bottom features and biota that were not observed on the analog real time OTI camera. Thus, the GoPro data should be used to perform future video analyses. CR post-processed the GoPro camera video files using Adobe Media Encoder CC software. The resulting video files have embedded time stamps (local time) and file names on each frame enabling identification of video frame coordinates by comparing time on the video to time in the navigation files using tables or ESRI ArcGIS software. In cases where transects included more than one raw video file, the multiple files were "stitched" together to generate a single high-resolution file for each transect.

An efficient semi-automated method for review of the post-processed GoPro video files and extraction of full-resolution frame captures could include use of free open-license software packages. Playback could be conducted using Media Player Classic, available at https://mpc-hc.org/. Media Player Classic is a simple program that allows the tracks to be replayed in slow motion or you can step through the video frame by frame to select the appropriate video segments for screen captures.

A video de-coding software program, ffdshow, can be configured to automatically extract frame capture images at a specified frame interval (e.g., 1 capture per 30 frames = 1 capture per second) while simultaneously applying user-specified color, contrast or saturation levels during playback with Media Player Classic. This software is available at http://ffdshow-tryout.sourceforge.net/. Finally review of extracted image files (.jpg, .tif or other specified ffdshow output formats) may be expedited using free Irfanview software, available at http://www.irfanview.com/.

Towed Video and Surface Grab Data Interpretation and Results

A preliminary inspection of the underwater video data was performed to determine data quality and completeness, confirm identifications, and create representative high quality screen captures of substrate types and biota (Plates 1-17 in Appendix K).

At two (2) transects (hull-8 at Study Area 2 off Nantasket Beach, and canal-10 at Study Area 4 off Sandwich), the GoPro camera turned off, possibly due to an impact with the side of the vessel during deployment. There is OTI video data to use for analysis but no GoPro video or still picture data for these two (2) transects.

In a few transects at Study Area 4 off Sandwich, the video light brightness was adjusted too low and the color balance is off, giving the footage a green tint. At these transects, the low light OTI camera footage is well illuminated and can be used instead of the GoPro data.

At the completion of survey operations, the Field Data Spreadsheets for each of the Study Areas, listing both the Auster and CZM codes for habitat-substrate types and the CR biota abbreviations, were edited (Tables 4 to 8 in Appendix L). The information on the Field Data Spreadsheets is ordered by time. Information on the dominant species and substrate type for each study area's transects is summarized in Tables 9 to 13 in Appendix L. Species observed at each study area are provided in Table 14 in Appendix L. A total of 37 invertebrates, 11 fish, one (1) tunicate, and four (4) algal species were observed over the course of the study.

In terms of overall habitat complexity, Study Area 2 off Nantasket Beach, with areas of pebble-cobble bottom and partially buried and dispersed boulders, was the most complex in structure followed by Study Area 5 of Cuttyhunk which also had areas of pebble-cobble and boulders. Study Area 1 of the Merrimack was characterized by sand waves. Study Area 3 off of Duxbury Bay and Study Area 4 off the canal at Sandwich were the least complex, with primarily flat sand/mud bottom substrates.

Geotechincal sediment analysis of the surface grab samples in each of the Study Areas characterize the seafloor as generally sand and some areas with some clay. Table 18 below shows the CZM Modified Barnhardt classification of each of the collected surface samples.

More detail can be teased from the notes on species presence and habitat-substrate on the field data spreadsheets (Tables 4 to 8 in Appendix L) for individual transects within each Study Area. The observed species numbers provide a relative idea of the abundance of a species within a study area during the month the work was conducted. Numbers have not been normalized for length of transect or time. Rock crabs and Jonah crabs could not be differentiated in the field and are reported as rock crabs. Likewise the flat claw hermit crab and long-wrist hermit crabs were recorded as hermit crabs and were not differentiated in the field observations but can be identified in the video footage.

Deliverables for the video survey effort are contained in a portable hard drive accompanying this report. The hard drive includes:

- The OTI camera video files (Appendix M, digital only),
- GoPro HD video files and still photographs (Appendix N, digital only),
- 150 to 200 selected HD towed video screen captures from each of the five main study areas (Appendix O, digital only) and
- A navigation table with times and corrected positions of the video sled every five seconds (Appendix P digital only).
- Post-processed GoPro HD video with time stamps, enabling identification of frame coordinates by comparing the navigation file time with the video time using the navigation tables or ESRI ArcGIS software (Appendix Q, digital only).

Table 18: Surface grab sediment classification

Surface Grab Sample ID	Study Area	Easing	Northing	CZM Barnhardt Sediment Classification
BUZ10-G5	5A	240287.74	792641.10	Sand with Rock
BUZ1-G1	5B	232760.94	802636.98	Sand with Rock
BUZ2-G2	5B	233048.41	801884.71	Sand with Gravel

BUZ6-G3	5A	237499.26	798970.14	Sand with Gravel
BUZ9-G4	5A	240206.44	795415.04	Sand with Rock
CANAL2-G3	4A	283003.85	844583.68	Sand with Rock
CANAL4-G4A	4A	283105.07	842254.59	Sand with Rock
CANAL6-G5	4A	283539.40	839631.30	Fine
CANAL7-G2	4A	285205.95	840521.27	Sand with Rock
CANAL9-G1	4A	285715.54	837977.32	Sand with Rock
DUX3-G1	3A	278991.95	871887.63	Sand with Rock
DUX4-G2	3A	276756.33	871867.76	Sand with Rock
DUX6-G5	3B	277206.28	863108.03	Fine
DUX7-G3A	3B	274737.64	867514.37	Sand with Rock
DUX9-G4	3B	276696.64	865531.22	Sand with Gravel
HULL1-G5A	2A	257134.88	895877.88	Fine
HULL2-G4	2A	257862.30	896014.30	Sand with Rock
HULL4-G1	2C	263323.98	897006.43	Sand with Gravel
HULL5-G2	2C	262608.54	898060.89	Sand with Gravel
HULL7-G3A	2C	261231.15	898099.88	Sand with Rock
MER10-G1	1	261287.16	946846.97	Sand with Rock
MER2-G5	1	261020.50	955438.23	Sand with Rock
MER4-G4	1	260341.34	953193.41	Sand with Rock
MER7-G3B	1	261486.81	949990.06	Sand with Rock
MER8-G2	1	260292.42	948669.34	Sand with Rock

Study Area 1: Merrimack River

Study Area 1 results are presented in Tables 4, 9, and 14 in Appendix L and Plates 1 to 3 in Appendix K. The Study Area was sampled by a total of 10, 750 m long video transects.

- The dominant substrate type was low relief sand waves with some coarse grain sands and pebbles in the troughs.
- A total of 14 invertebrates and eight (8) fish species were observed.
- Dominant fauna included juvenile sea scallops, lobster, mysid shrimp, and amphipods.
- Lobsters were observed on 85% of the collected transects.
- A total of 200 scallops, mostly juvenile, 37 lobsters, and 29 rock crabs were observed during the video survey.
- Dominant fish included winter flounder (16) and sculpin (18).

Study Area 2: Nantasket Beach

Study Area 2 results are presented in Tables 5, 10, and 14 in Appendix L and Plates 4 to 7 in Appendix K. The Study Area was sampled by a total of 10, 750 m long video transects.

- Bottom substrates at Study Area 2 were highly variable, ranging from flat sand and mud, mud to sand waves, pebble-cobble, and partially buried or dispersed boulders.
- A total of 21 invertebrates, eight (8) fish, and four (4) algal species were observed.
- Dominant invertebrates included sea scallops, rock crabs, and sand dollars.
- A total of 407 sea scallops were observed, 186 rock crabs, and only nine (9) lobsters
- The dominant fish observed was cunner with 62 observations. Cunner were always associated with pebble-cobble and partially buried or dispersed boulder habitat. A total of 41 sculpin, 31 red hake, and 18 winter flounder were also observed in Massachusetts Bay offshore of Nantasket Beach, Hull.

Study Area 3 Duxbury Beach

Study Area 3 results are presented in Tables 6, 11, and 14 in Appendix L and Plates 8 to 10 in Appendix K. The Study Area was sampled by a total of 10, 500 m long video transects.

- The bottom substrate at Study Area 3 was primarily flat sand and mud with limited observations of pebble-cobble bottom at Transects dux-5A, 6, and 10 and shell aggregate bottom at Transect dux 8.
- A total of 11 invertebrates, eight (8) fish, and one (1) algal species were observed at Study Area 3.
- Dominant invertebrates were mysid shrimp and sand dollars.
- Commercial invertebrate species observed included 17 rock crabs and nine (9) lobsters. No sea scallops were observed.
- The dominant fish species at Study Area 3 of Duxbury Bay included red hake (33), winter flounder (15), and sculpin (12).

Study Area 4: Sandwich

Study Area 4 results are presented in Tables 7, 12, and 14 in Appendix L and Plates 11 to 13 in Appendix K. The Study Area was sampled by a total of 10, 1,000 m long video transects.

- The habitat type at Study Area 4 was primarily flat sand and mud with the exception of sand waves with coarser sand at Transect canal-9 east of the Cape Cod Canal and some biogenic structure bottom with burrows and mounds at Transects canal-1, 5, 6, and 10. A limited amount of pebble-cobble bottom was observed at transect canal-2 and some rock disposal material was observed at transect canal-1 in the Canal Disposal Site.
- A total of 13 invertebrate, six (6) fish, and two (2) algal species were observed at Study Area 4.
- Dominant fauna included sand dollars that were abundant at all of nine (9) sandy bottom transects. Dominant fauna at the silty/sand sediment at the Disposal Site was mysid shrimp.

- Counts of the commercial species included 40 rock crabs, 20 winter flounder, and 10 lobsters. A total of 13 skates were also observed.

Study Area 5: Cuttyhunk

Study Area 5 results are presented in Tables 8, 13, and 14 in Appendix L and Plates 14 to 17 in Appendix K. The Study Area was sampled by a total of 10, 500 m long video transects.

- Bottom substrate at Study Area 5 was primarily flat sand and mud. The exceptions were observations of sand waves at Transects buz-4 and buz-7 and partially buried or dispersed boulder bottom at Transects buz-5 and 7.
- A total of 22 invertebrate and four (4) fish species were observed.
- The dominant invertebrate at eight (8) of the 10 transects were the two species of hermit crabs. Slipper limpet was the dominant species on one 250 meter segment of Transect buz-5 and bread crumb sponge was the dominant species in areas of partially buried or dispersed boulders at Transect buz-7
- No rock crabs, or sea scallops were observed at Study Area 5, the commercial invertebrate species observed were one (1) lobster and nine (9) channeled whelks.
- Fish species observed at Study Area 5 included 21 red hake and one (1) winter flounder.

Fishing Activity at the Potential Sand Resources Sites

During survey operations, lobster pots were numerous at all Study Areas excluding Study Area 5 in Buzzards Bay off of Cuttyhunk. The vessel track was often altered to avoid pots, and there were multiple entanglements with lobster gear. In all of the Study Areas in Cape Cod Bay and Massachusetts Bay, lobsters were observed living in the sand bottom during the summer and fall months of the underwater video survey. In Buzzards Bay, the lobsters appeared to target the rocky and muddy bottom substrate.

CR identified local lobstermen that fish in the Massachusetts OMP Sand Resource Areas. They have information concerning the fixed and mobile gear fisheries in their locale and can provide information regarding bottom habitat and biota upon request.

Summary

APTIM and CR were contracted by CZM on June 13, 2017, to conduct a preliminary characterization of potential offshore sand resources in five (5) study areas located offshore of Massachusetts. The project consisted of conducting an historic data review of the investigation areas, collection of 20, up to four-meter long vibracores, and 25 surface grab samples along with towed video footage of the seafloor. Additionally, APTIM was tasked with conducting detailed logging and analysis of the collected geotechnical samples and estimating volumes of potential sand resources for future coastal restoration efforts.

APTIM and CR held a kickoff meeting for the project with CZM at CZM's offices in Boston on May 26, 2017, and submitted a final Data Acquisition Plan on July 14, 2017. APTIM collected the vibracores offshore of Massachusetts between September 15 and October 5, 2017, while CR conducted separate offshore operations to collect the surface grab samples and towed video data between August 2 and November 9, 2017.

For Study Area 1, offshore of the Merrimack River, APTIM and CR collected five (5) vibracores, five (5) surface grab samples, and 10 towed video transects across the entire potential sand resource area. The dominant substrate type of Study Area 1 was low relief sand waves with some coarse grain sands and pebbles in the troughs. Dominant fauna included juvenile sea scallops, lobster, mysid shrimp, and amphipods. Lobsters were observed on 85% of the collected transects. Dominant fish included winter flounder (16) and sculpin (18).

After adjusting the potential sand resource area by removing areas of rock or other incompatible seafloor, and processing and interpreting the available USGS seismic sub-bottom data, APTIM was able to determine an estimated preliminary volume of 99,730,000 m^3 (130,442,000 cy) of potential sand resources throughout Study Area 1. This is a preliminary volume of potential sand resources based on widely-spaced reconnaissance level geotechnical data and some geophysical data coverage.

For Study Area 2, offshore of Nantasket Beach, APTIM and CR collected four (4) vibracores, five (5) surface grab samples, and 10 towed video transects across the entire potential sand resource area. The bottom substrates at Study Area 2 were highly variable, ranging from flat sand, mud to sand waves, pebble-cobble, and partially buried or dispersed boulders. A total of 21 invertebrates, eight (8) fish, and four (4) algal species were observed. Dominant invertebrates included sea scallops, rock crabs, and sand dollars. The dominant fish observed was cunner with 62 observations. Cunner were always associated with pebble-cobble and partially buried or dispersed boulder habitat. A total of 41 sculpin, 31 red hake, and 18 winter flounder were also observed in Massachusetts Bay offshore of Nantasket Beach in Hull.

Study Area 2 was divided into three (3) Study Areas when evaluating for sand resources: 2A, 2B and 2C. Interpretation of Study Area 2A historic seismic sub-bottom data based on the vibracore results from this project, indicated preliminary estimates of potential sand resource volumes of 3,600,000 m^3 (4,708,600 cy). That said, the sand is predominantly associated with the infill of a paleochannel, and deposits are not normally well organized within channels, complicating the development of a potential borrow area. Additional, design-level data would be required to fully characterize the nature and full extents of this sand deposit.

Recent backscatter and high resolution bathymetric data within Study Area 2B indicate the presence of surficial gravels as well as high-relief ledges, likely rocky in nature, crossing portions of the Study Area. As a result, little no potential sand resource volume is expected in Study Area 2B, so no vibracore samples were collected in Study Area 2B.

Based on historical surficial backscatter data indicating limited surficial sands, Study Area 2C was narrowed down to a small 1,348,929 m^2 area around MA-CZM-2007-VC04 (approximately 12% of the central portion of Study Area 2). When this smaller area is evaluated with the vibracore results, this Study Area has an estimated preliminary volume of 3,600,000 m^3 (4,708,600 cy) of potential sand resources.

Offshore of Duxbury Bay, APTIM and CR collected three (3) vibracores, five (5) surface grab samples, and 10 towed video transects across the entire potential sand resource area designated Study Area 3. The bottom substrate at Study Area 3 was primarily flat sand, mud with limited observations of pebble-cobble bottom and occasional shell aggregate bottom. A total of 11 invertebrates, eight (8) fish, and one (1) algal species were observed at Study Area 3. Dominant invertebrates were mysid shrimp and sand dollars. Commercial species observed included 17 observations of rock crabs and nine (9) lobsters. No sea scallops were observed. The dominant fish species at Study Area 3 of Duxbury Bay included red hake (33), winter flounder (15) and sculpin (12).

In terms of potential sand resources, Study Area 3 was subdivided into two (2) Study Areas: 3A and 3B. Interpretations of the historic sidescan sonar data in Study Area 3A indicate that the surface is likely mostly sand, therefore, in order to determine the potential volume of sand, an average thickness value was calculated from the isopach and used as a general representation of the entire Study Area 3A, yielding an estimated preliminary volume of 46,940,000 m^3 (61,395,200 cy) of potential sand resources. It is important to note however, that this is an estimated volume, assuming the subsurface stratigraphy of Study Area 3A is mostly uniform in nature (i.e. assuming that the three shoal futures visible in the southern portion of Study Area 3A are consistent throughout the Study Area to the north where geophysical data is lacking).

The isopach in Study Area 3B was clipped to the Interpreted Sandy Area polygon in order to avoid areas that appear to have a hard bottom/rock outcrop. The total estimated preliminary volume of Study Area 3B is 46,000,000 m^3 (60,165,700 cy) of potential sand resources in a shoal complex generally located in the central portion of the study area, where the shoal feature appears to be more prominent.

Offshore of Sandwich, APTIM and CR collected three (3) vibracores, five (5) surface grab samples, and 10 towed video transects across the entire potential sand resource area designated Study Area 4. The habitat type at Study Area 4 was primarily flat sand, mud with the exception of sand waves with coarser sand east of the Cape Cod Canal and occasional biogenic structure bottom with burrows and mounds. A limited amount of pebble-cobble bottom was observed and some rock disposal material was observed in the Cape Cod Canal Offshore Dredged Material Disposal Site. A total of 13 invertebrate, six (6) fish, and two (2) algal species were observed at Study Area 4. Dominant fauna included sand dollars that were abundant at all of nine (9) sandy bottom transects. Dominant fauna at the silty/sand sediment at the Disposal Site was mysid shrimp. Counts of the commercial species included 40 rock crabs, 20 winter flounder, and 10 lobsters.

Study Area 4 was divided into two (2) Study Areas, 4A and 4B. Study Area 4B was considered, but not included for additional geotechnical data collection as it is designated as a USACE/EPA Offshore Dredge Material Disposal Site and can likely be initially characterized via historic dredging records.

Volume estimates for Study Area 4A were calculated by determining the average base of sand elevation between the three (3) vibracores and utilizing the area of the entire Massachusetts OMP Sand Resource Area for Study Area 4A. The estimated preliminary volume in Study Area 4A is estimated to be 51,670,000 m^3 (67,581,800 cy) of potential sand resources. Given the fact that no seismic sub-bottom data were available for this area, it is impossible to know the exact nature and full extent of the deposit without additional design-level data.

For Study Area 5, offshore of Cuttyhunk, APTIM and CR collected five (5) vibracores, five (5) surface grab samples, and 10 towed video transects across the entire potential sand resource area. The bottom substrate at Study Area 5 was primarily flat sand/mud, with occasional exceptions of observed sand waves and partially buried and dispersed boulders. A total of 22 invertebrate and four (4) fish species were observed. The dominant invertebrate at eight (8) of the 10 transects were the two species of hermit crabs. No rock crabs, or sea scallops were observed at Study Area 5 and the only commercial invertebrate species observed was one (1) lobster and nine (9) channeled whelks. Fish species observed at Study Area 5 included 21 red hake and one (1) winter flounder.

In terms of sand resources, Study Area 5 was divided into two (2) Study Areas: 5A and 5B. Sand deposits in Study Area 5A are associated with a shoaling feature which is predominant in the southern portion of the study area, where a majority of the estimated preliminary 54,470,000 m^3 (71,244,100 cy) of potential sand resources within 5A are located.

Study Area 5B contains a thin (approximately 1.4 m (4.27 ft) thick) sand layer overlaying a paleo-channel complex likely filled with clays and silts. This thin sand deposit in Study Area 5B yielded an estimated preliminary volume of approximately 7,460,000 m^3 (9,757,300 cy) of potential sand resources. These are preliminary volumes of potential sand resources based on widely-spaced reconnaissance level geotechnical data and some geophysical data coverage.

In total, APTIM was able to identify potential sand resources totaling a preliminary, reconnaissance-level estimate of approximately 313,470,000 m^3 (410,003,400 cy) across all Massachusetts OMP Sand Resource Areas. These are preliminary volumes of potential sand resources based on widely-spaced reconnaissance-level geotechnical data and varying levels of geophysical data coverage. Actual borrow area design would require additional, design-level geotechnical and geophysical data collection in order to accurately and fully characterize these sand deposits, account for environmental and cultural resources, determine compatibility of the potential sand resource with the recipient beach, evaluate dredgeability of the sand resource, and design permit plans and specifications (including dredge cuts) for a final borrow area.

Figures

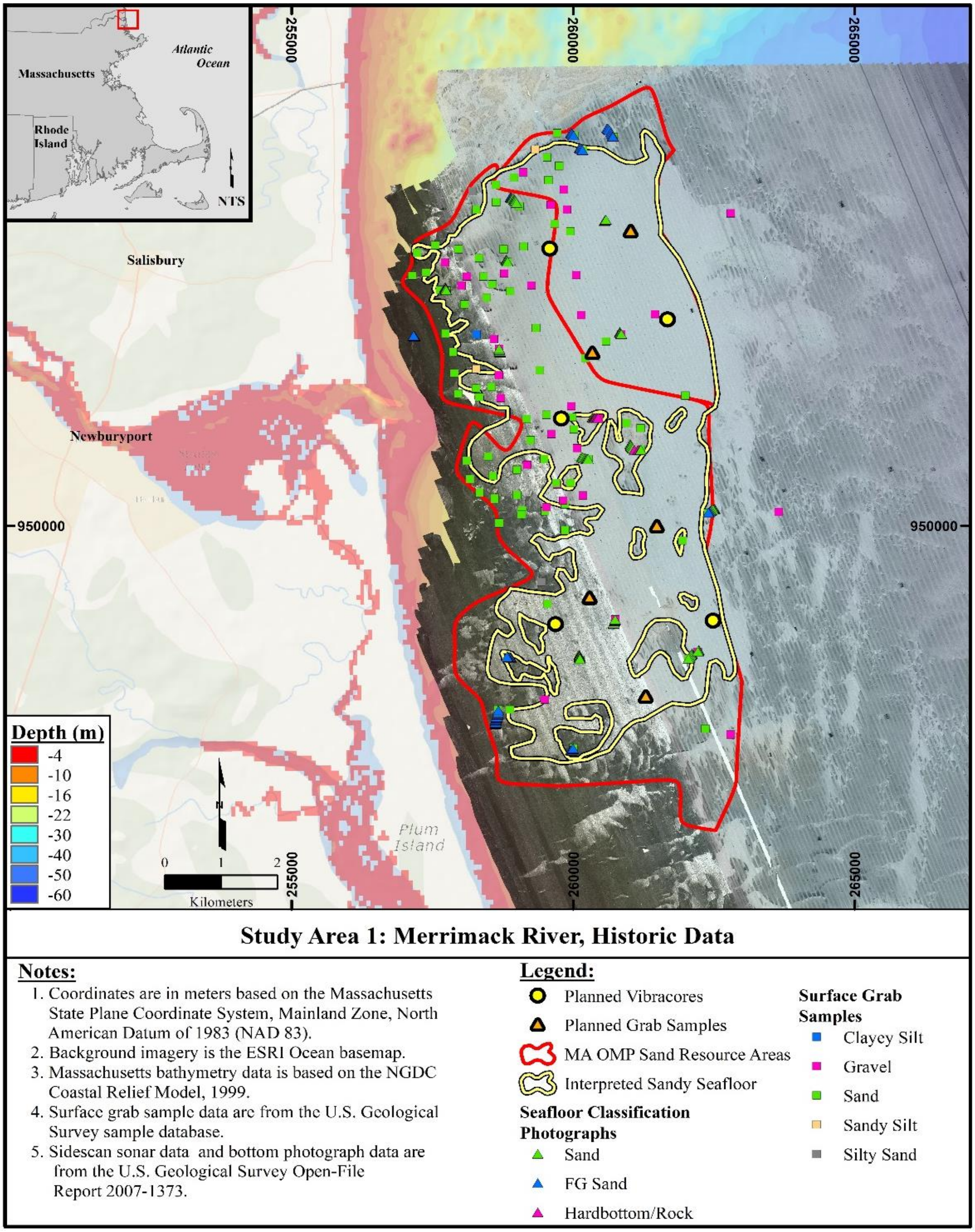


Figure 1: Study Area 1 showing the Massachusetts OMP Sand Resource Areas, APTIM's revised "sandy seafloor" sand resource areas, and APTIM's planned vibracore locations. Figure also depicts historic data including sidescan sonar (darker imagery representing higher backscatter, indicating harder materials), surface grab samples, and seafloor classification information

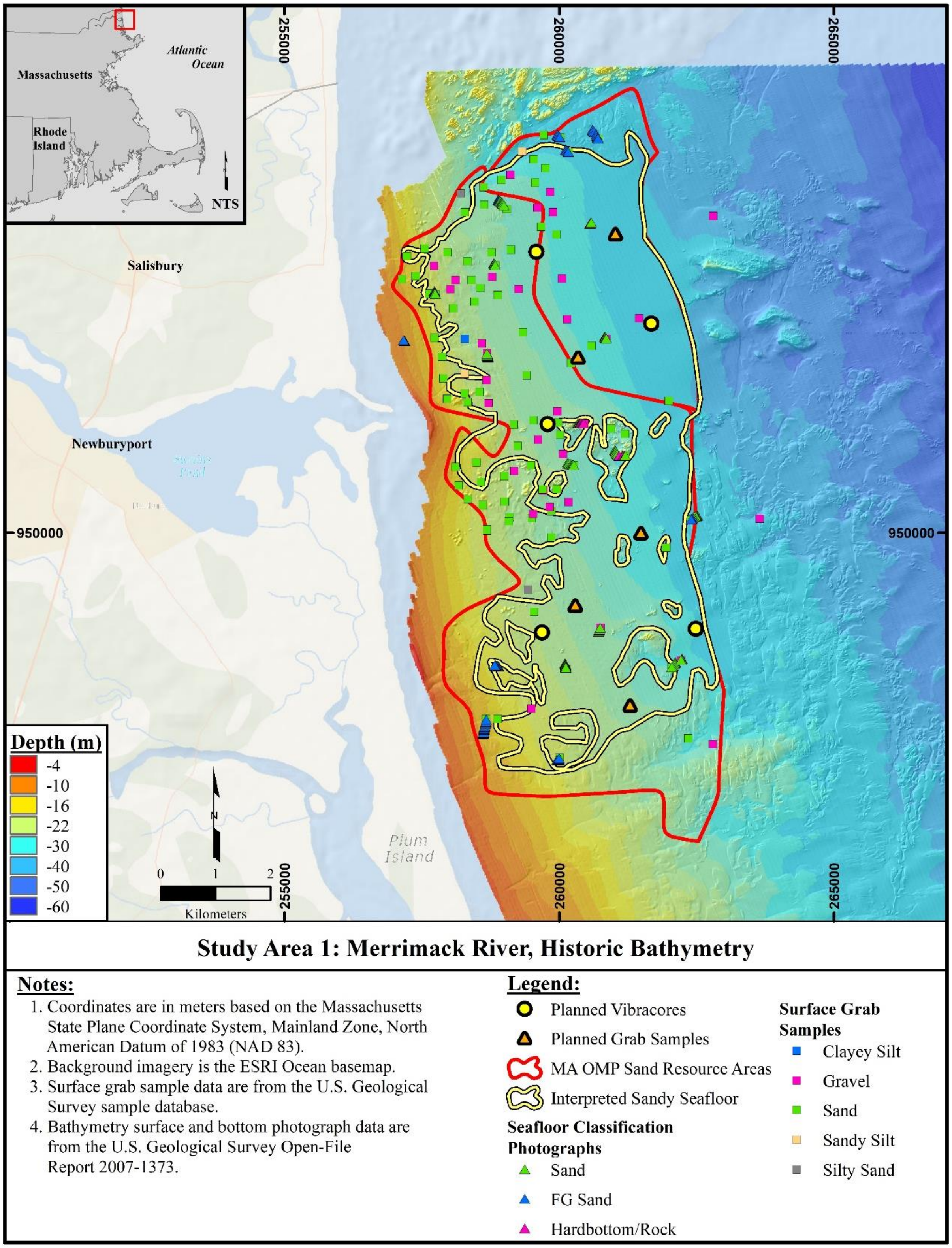


Figure 2: Study Area 1 showing the Massachusetts OMP Sand Resource Areas, APTIM's revised "sandy seafloor" sand resource areas, and APTIM's planned vibracore locations. Figure also depicts historic data including bathymetry, surface grab samples, and seafloor classification information

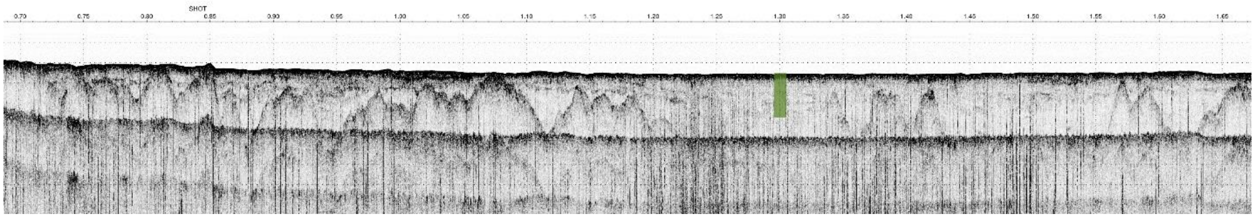


Figure 3 Historic USGS seismic sub-bottom line l12f1 depicting proposed vibracore location (green line) in Study Area 1. Proposed vibracore is targeting unconsolidated sediments away from clear bedrock peaks (dark reflectors)

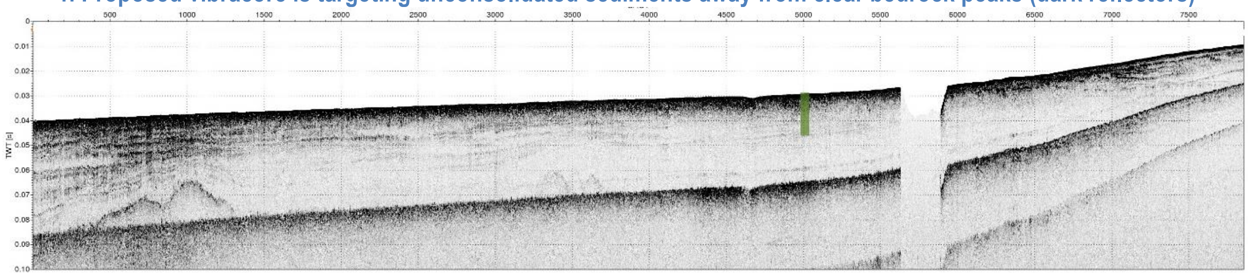


Figure 4: Historic USGS seismic sub-bottom line l40f1 depicting proposed vibracore location (green line) in Study Area 1. Proposed vibracore is targeting a thick, unconsolidated surficial sediment deposit showing flat-lying stratigraphy

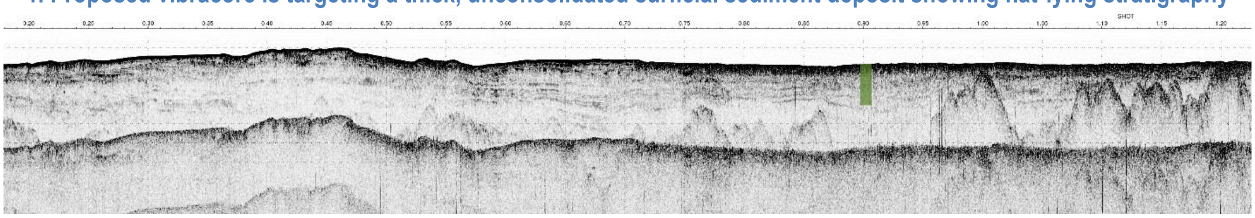


Figure 5: Historic USGS seismic sub-bottom line l53f1 depicting proposed core location (green line) in Study Area 1. Proposed vibracore is targeting a thick, unconsolidated surficial sediment deposit showing flat-lying stratigraphy away from clear bedrock peaks (dark reflectors)

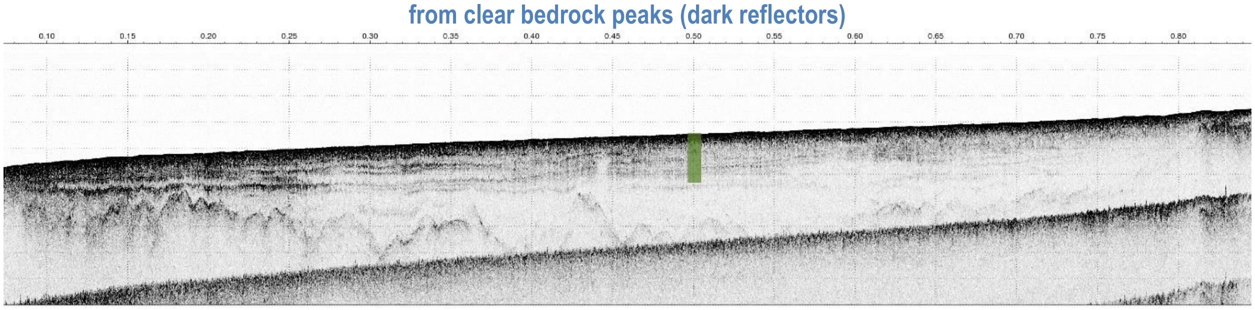


Figure 6: Historic USGS seismic sub-bottom line l117f1 depicting proposed vibracore location (green line) in Study Area 1. Proposed vibracore is targeting a thick, unconsolidated surficial sediment wedge showing flat-lying stratigraphy

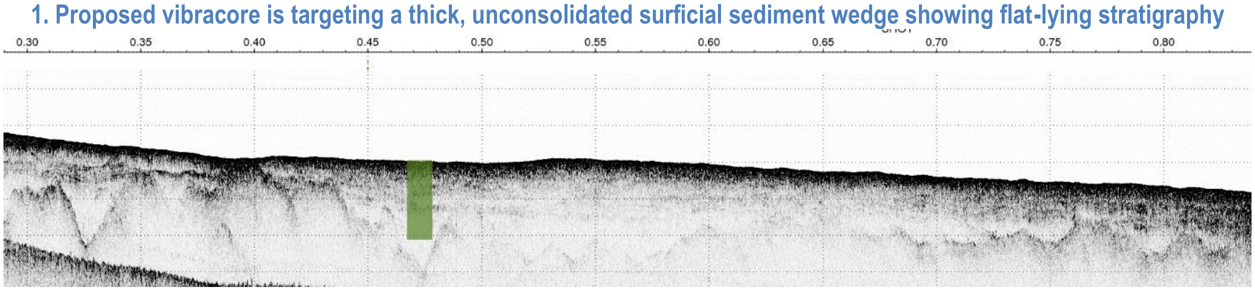
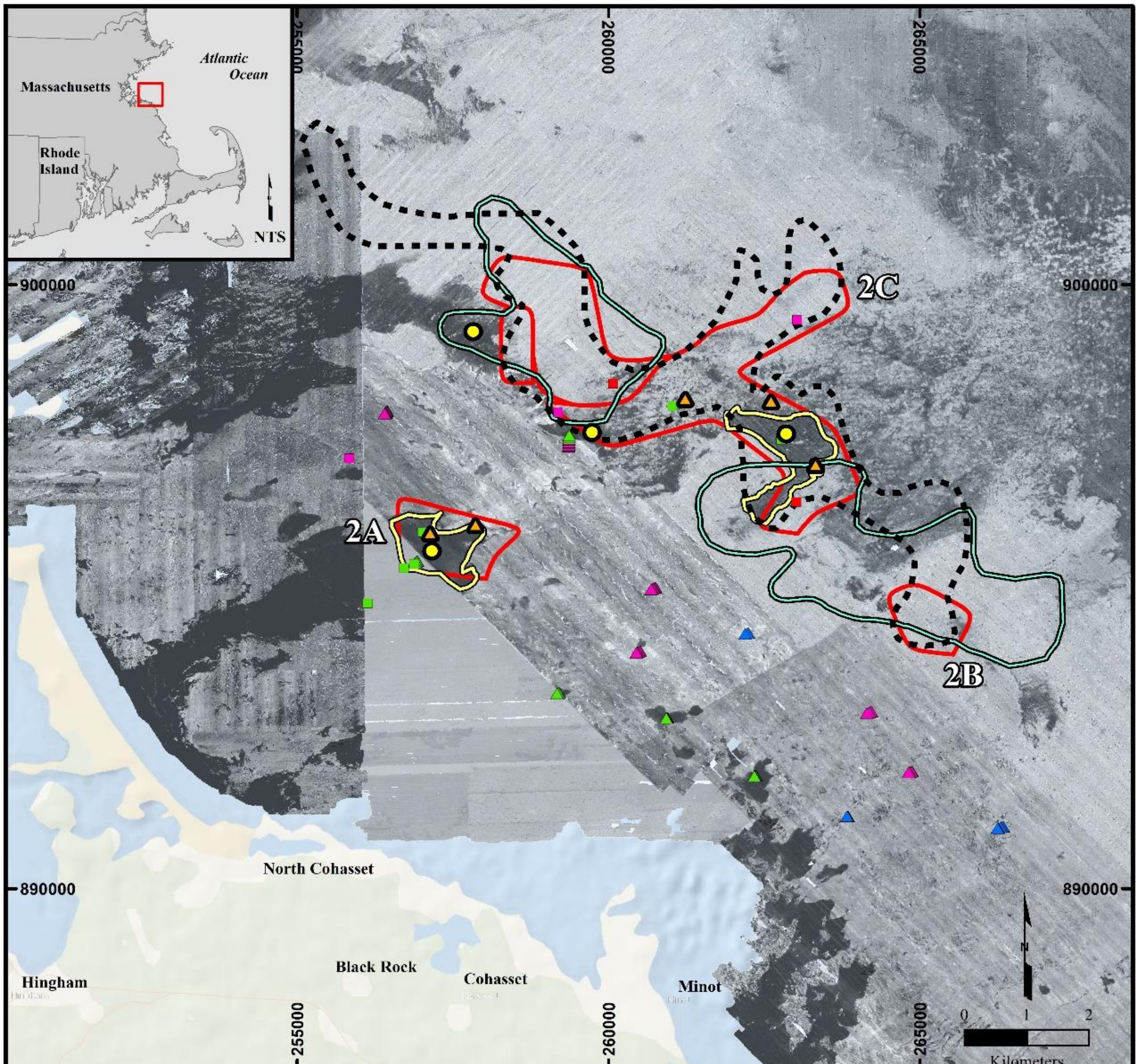


Figure 7: Historic USGS seismic sub-bottom line l116f1 depicting proposed vibracore location (green line) in Study Area 1. Proposed vibracore is targeting a thick, unconsolidated surficial sediment deposit showing flat-lying stratigraphy away from clear bedrock peaks (dark reflectors)



Study Area 2: Nantasket Beach, Historic Data

Notes:

1. Coordinates are in meters based on the Massachusetts State Plane Coordinate System, Mainland Zone, North American Datum of 1983 (NAD 83).
2. Background imagery is the ESRI Ocean basemap.
3. Surface grab samples data are from the U.S. Geological Survey sample database.
4. Historic data is from the MA Dept. of Natural Resources (1972), Oldale and Bick, (1923, 1987) and Normandeau Associates, Inc. (2010), full citation available in the references section.
5. Sidescan sonar surface and bottom photographs are from the U.S. Geological Survey Open File Report 2012-1157 and 2009-1072.

Legend:

- Planned Vibracores
- Planned Grab Samples
- MA OMP Sand Resource Areas
- Historic Sand Mineral Resource Areas (1972)
- Historic Sand Mineral Resource Area (1987)
- Interpreted Sandy Seafloor

Seafloor classification Photographs

- FG Sand
- FG Sand/Gravel
- Rock/Hardbottom

Surface Grab Samples

- Boulders
- Clayey Silt
- Gravel
- Sand

Figure 8: Study Area 2 showing the Massachusetts OMP Sand Resource Areas, APTIM's revised "sandy seafloor" sand resource areas, and APTIM's planned vibracore locations. Figure also depicts historic data including sidescan sonar (darker imagery representing lower backscatter, indicating softer materials), surface grab samples, and seafloor classification information

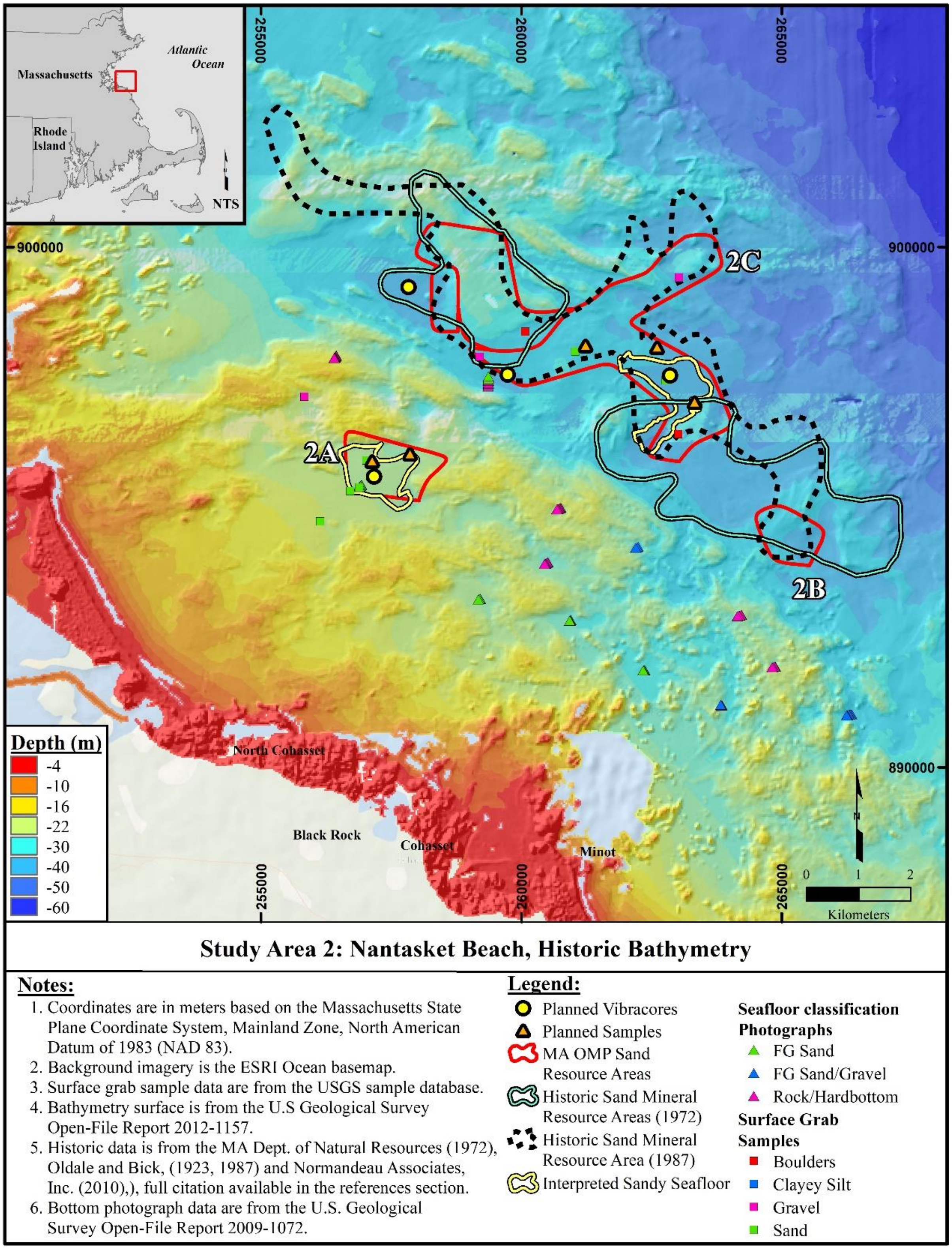


Figure 9: Study Area 2 showing the Massachusetts OMP Sand Resource Areas, APTIM's revised "sandy seafloor" sand resource areas, and APTIM's planned vibracore locations. Figure also depicts historic data including bathymetry, surface grab samples, and seafloor classification information

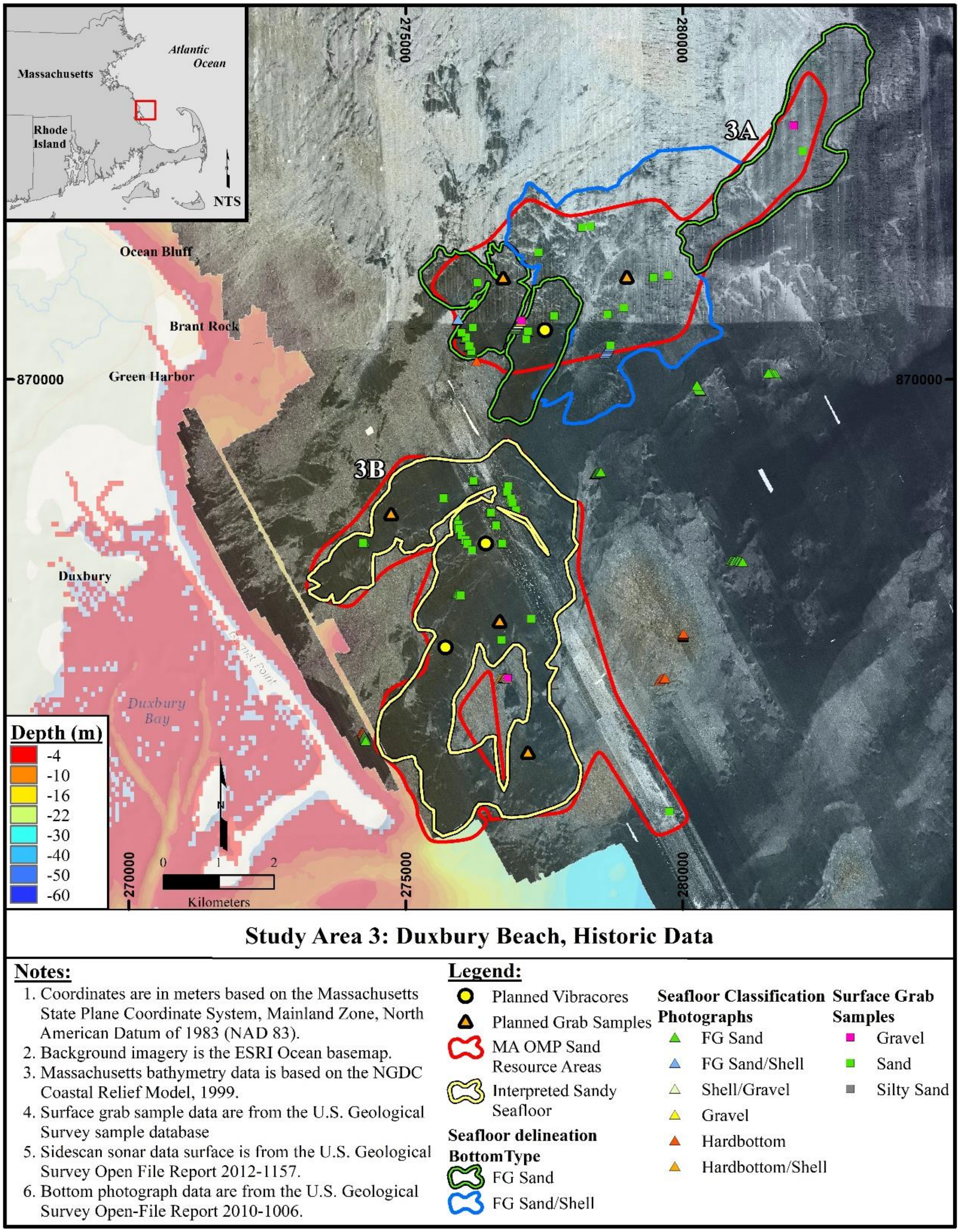


Figure 10: Study Area 3 showing the Massachusetts OMP Sand Resource Areas, APTIM's revised "sandy seafloor" sand resource areas, and APTIM's planned vibracore locations. Figure also depicts historic data including sidescan sonar (darker imagery representing lower backscatter, indicating softer materials), surface grab samples, and seafloor classification information

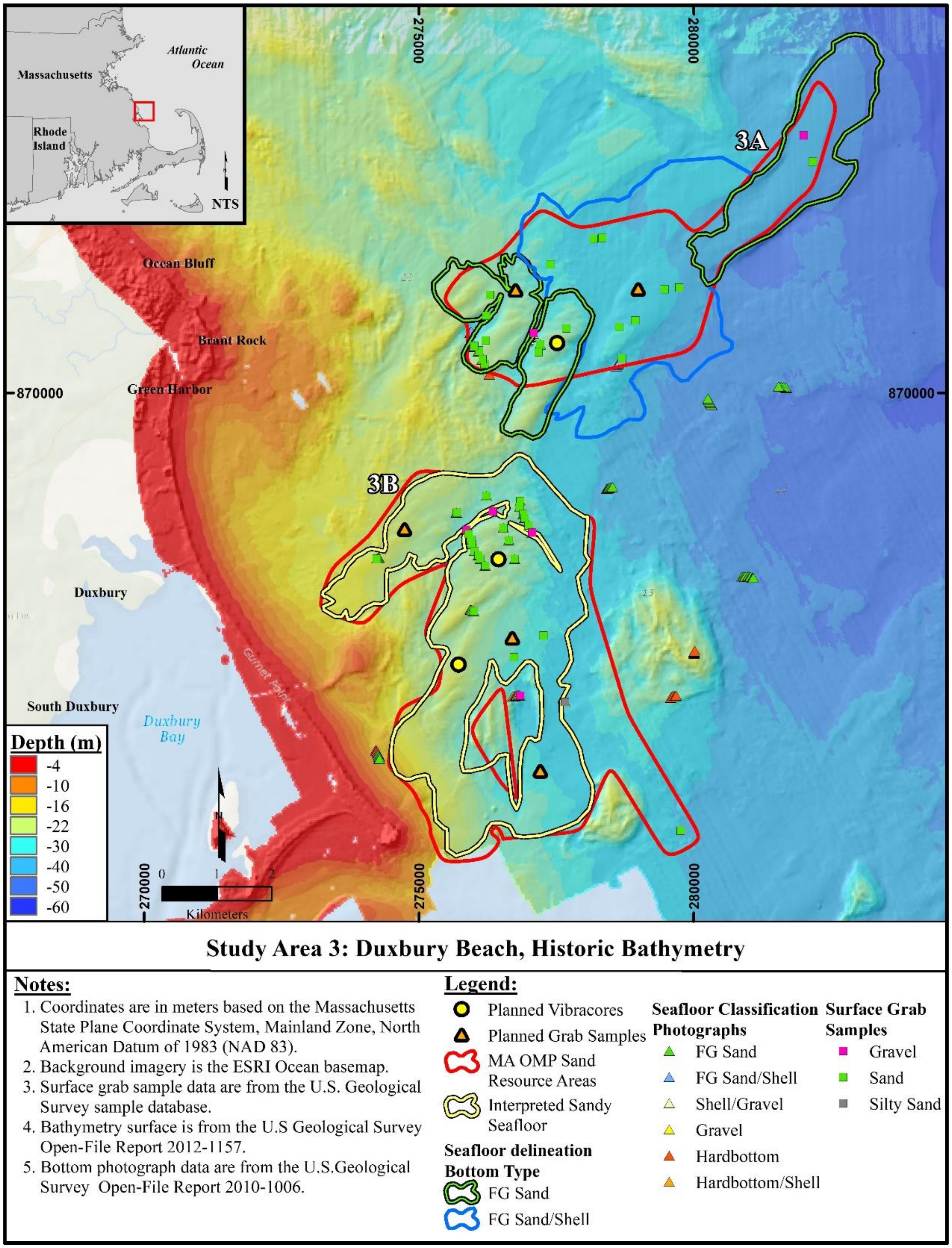


Figure 11: Study Area 3 showing the Massachusetts OMP Sand Resource Areas, APTIM's revised "sandy seafloor" sand resource areas, and APTIM's planned vibracore locations. Figure also depicts historic data including bathymetry, surface grab samples, and seafloor classification information

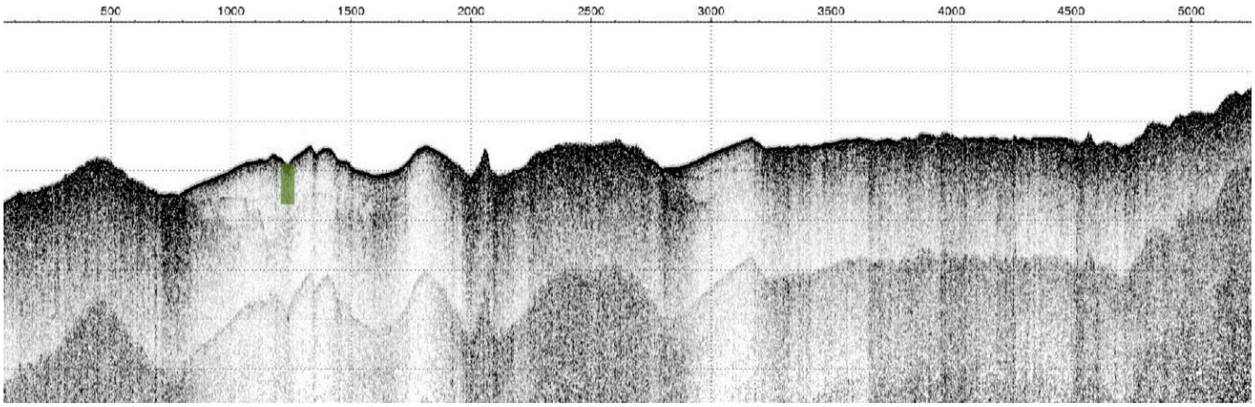


Figure 12: Historic USGS seismic sub-bottom line l13f2 depicting proposed vibracore location (green line) in Study Area 3. Proposed vibracore is targeting a thick, unconsolidated surficial sediment shoal, while avoiding nearby exposed bedrock and clear bedrock peaks (dark reflectors)

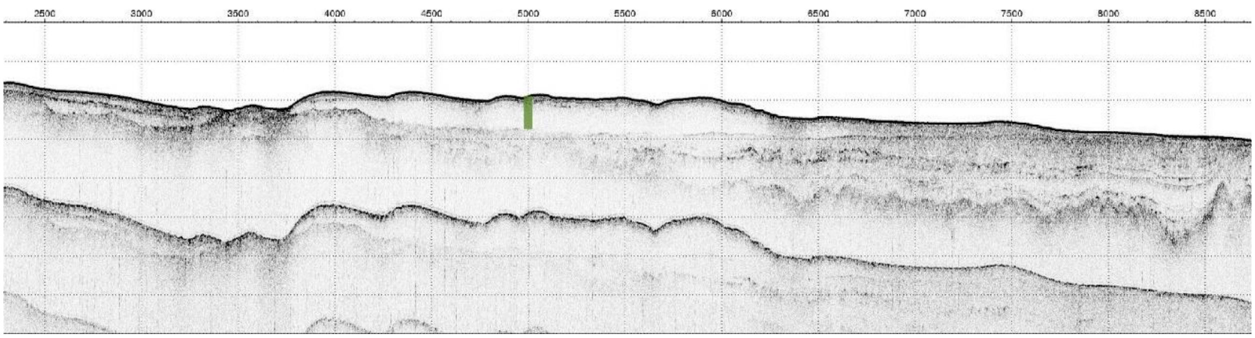


Figure 13: Historic USGS seismic sub-bottom line l74f1 depicting proposed vibracore location (green line) in Study Area 3. Proposed vibracore is targeting a thick, unconsolidated surficial sediment shoal

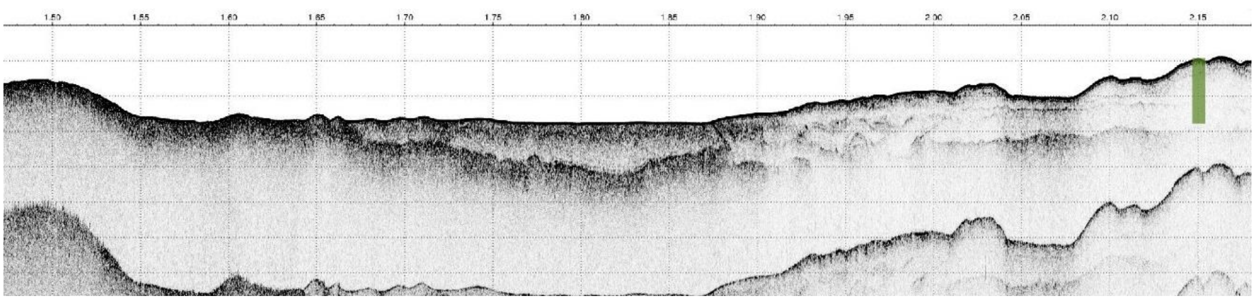


Figure 14: Historic USGS seismic sub-bottom line l108f1 depicting proposed vibracore location (green line) in Study Area 3. Proposed vibracore is targeting a thick, unconsolidated surficial sediment shoal, while avoiding nearby exposed bedrock and clear bedrock peaks (dark reflectors)

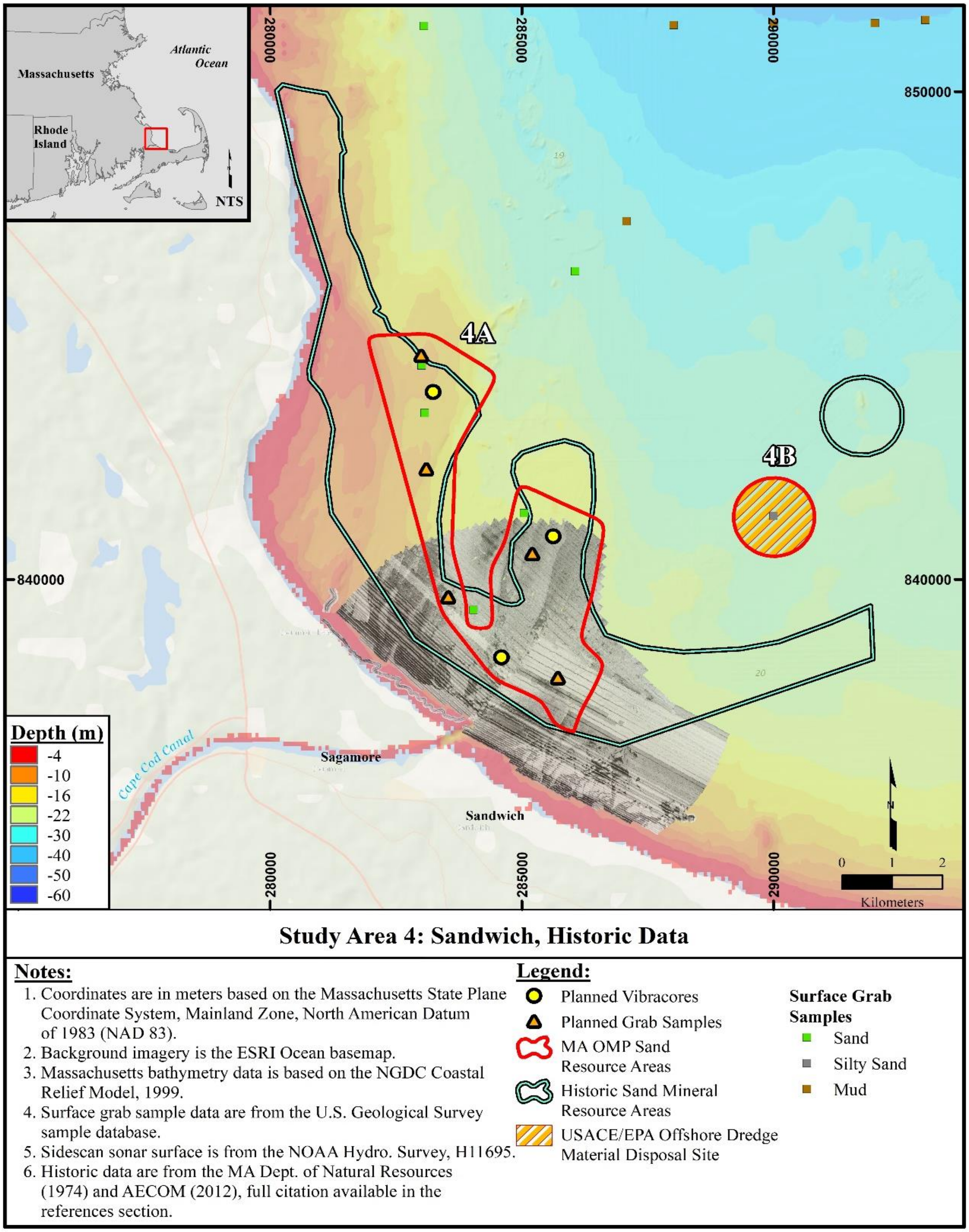


Figure 15: Study Area 4 showing the Massachusetts OMP Sand Resource Areas, APTIM's revised "sandy seafloor" sand resource areas, and APTIM's planned vibracore locations. Figure also depicts historic data including sidescan sonar (darker imagery representing higher backscatter, indicating harder materials), surface grab samples, and seafloor classification information

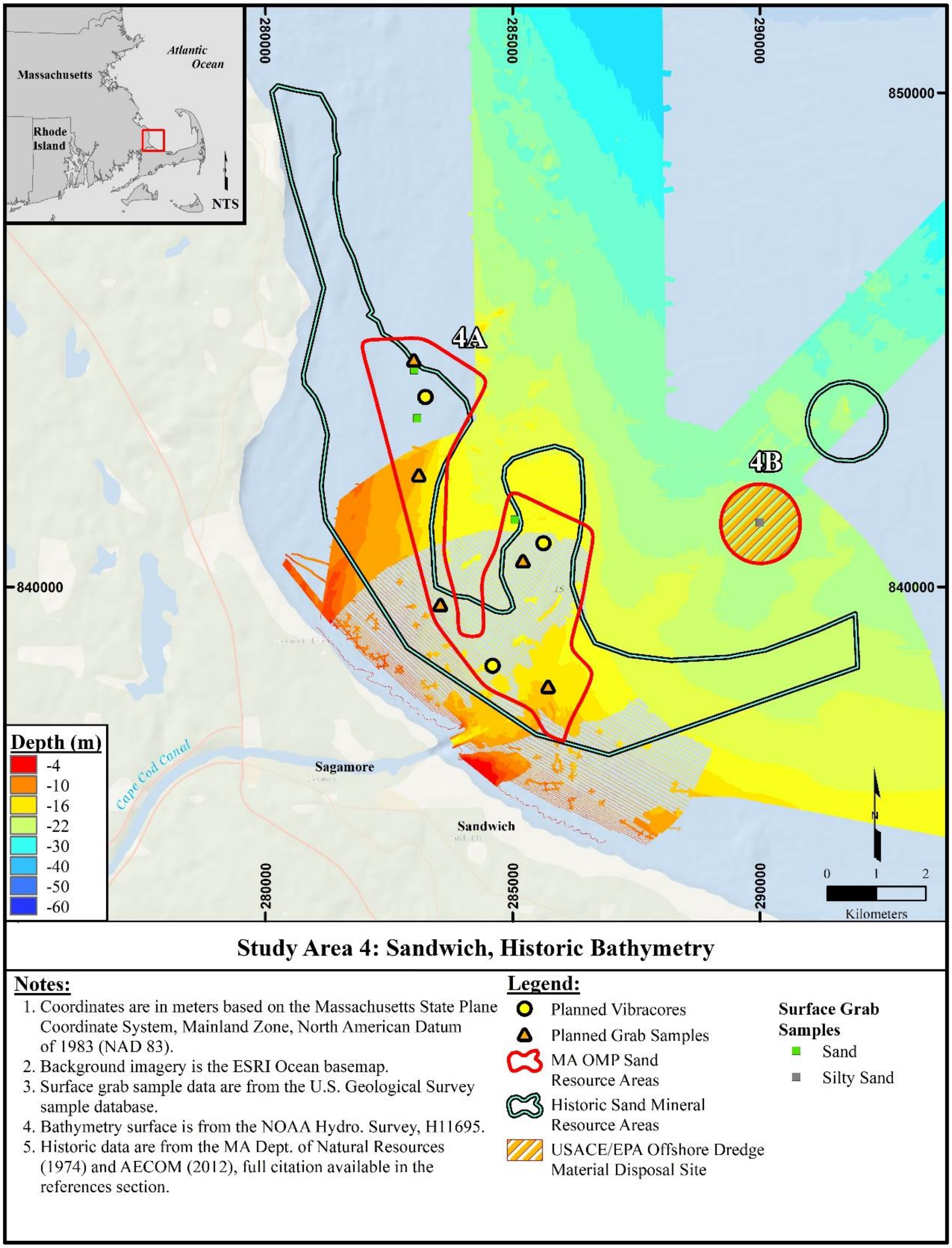


Figure 16: Study Area 4 showing the Massachusetts OMP Sand Resource Areas, APTIM's revised "sandy seafloor" sand resource areas, and APTIM's planned vibracore locations. Figure also depicts historic data including bathymetry, surface grab samples, and seafloor classification information

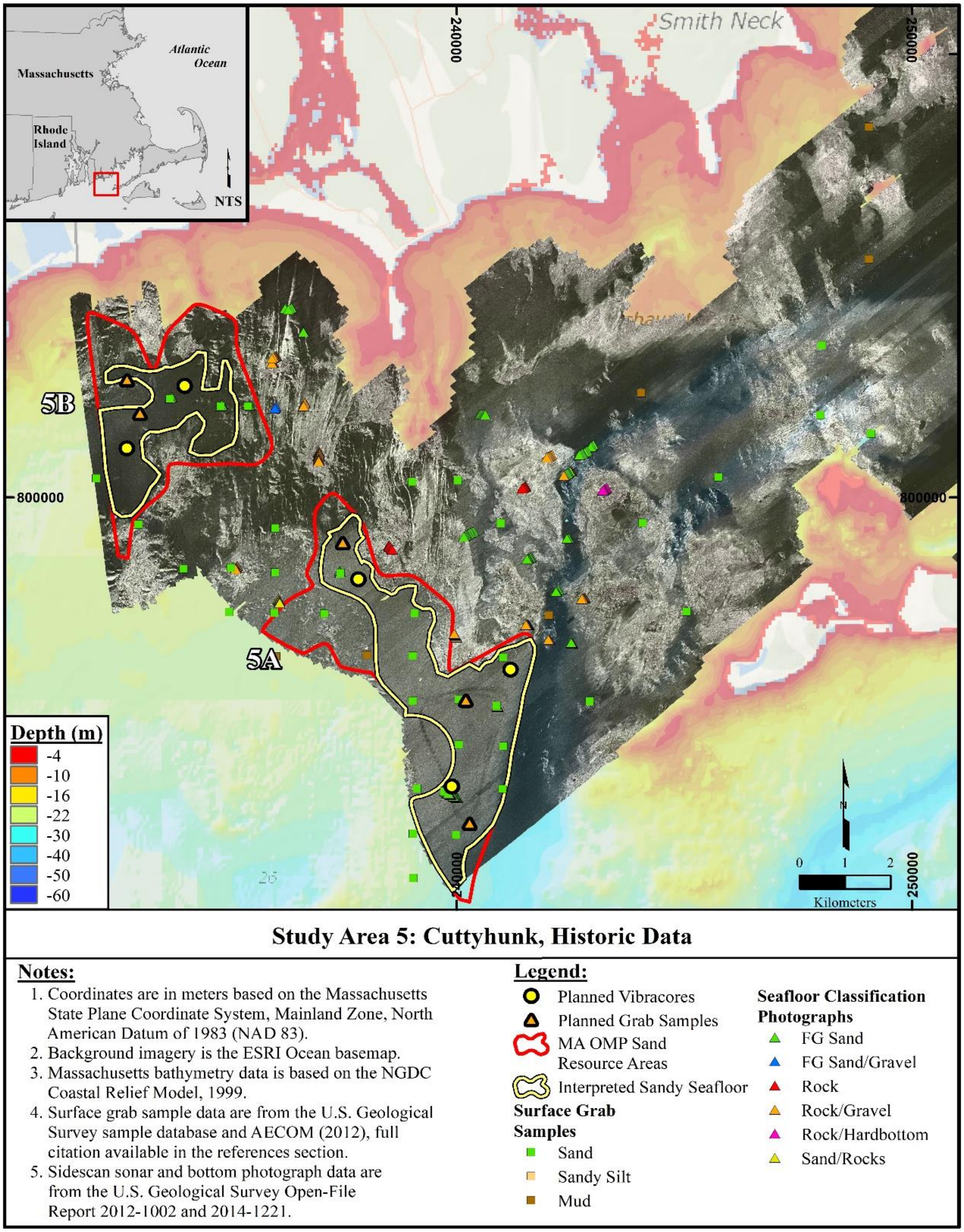


Figure 17: Study Area 5 showing the Massachusetts OMP Sand Resource Areas, APTIM's revised "sandy seafloor" sand resource areas, and APTIM's planned vibracore locations. Figure also depicts historic data including sidescan sonar (darker imagery representing lower backscatter, indicating softer materials), surface grab samples, and seafloor classification information

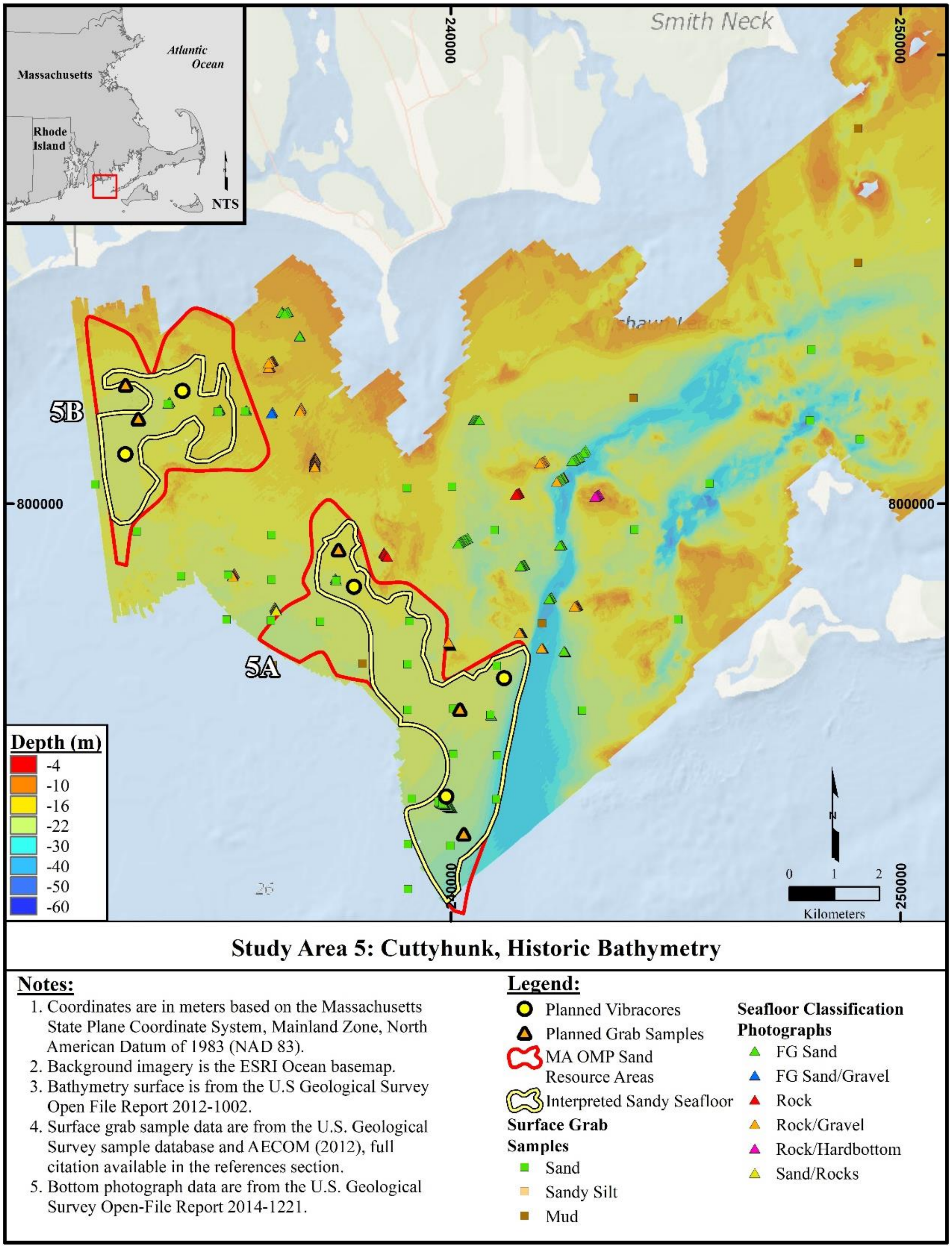


Figure 18: Study Area 5 showing the Massachusetts OMP Sand Resource Areas, APTIM's revised "sandy seafloor" sand resource areas, and APTIM's planned vibracore locations. Figure also depicts historic data including bathymetry, surface grab samples, and seafloor classification information

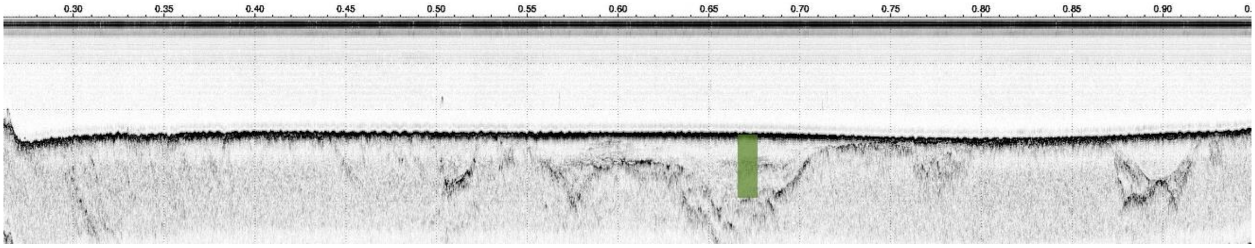


Figure 19: Historic USGS seismic sub-bottom line l70f1 depicting proposed vibracore location (green line) in Study Area 5. Proposed vibracore is targeting a subsurface, channel-like deposit containing flat-lying stratigraphy. The location is away from nearby clear bedrock peaks and exposed bedrock (dark reflectors)

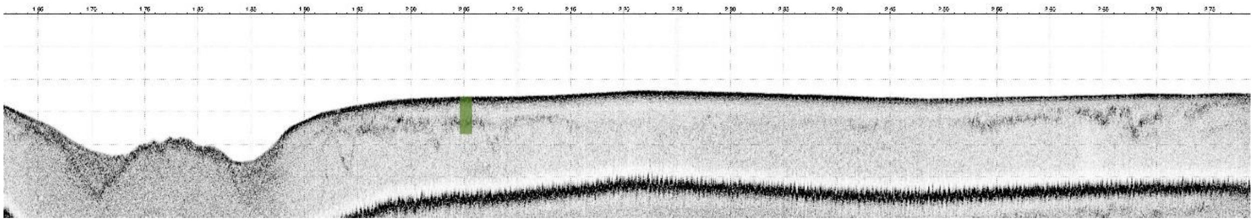


Figure 20: Historic USGS seismic sub-bottom line l175f1 depicting proposed vibracore location (green line) in Study Area 5. Proposed vibracore is targeting a surficial sand deposit, inside of the sand resource area which is bound by a deep, bathymetric low likely controlled by antecedent bedrock topography (dark reflectors)

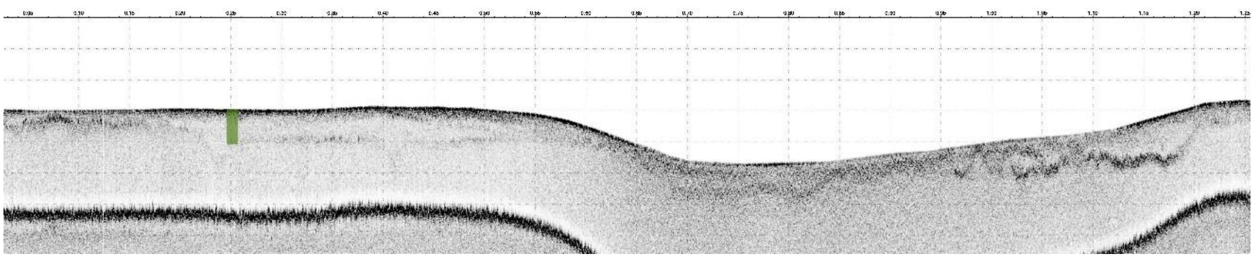


Figure 21: Historic USGS seismic sub-bottom line l188f1 depicting proposed vibracore location (green line) in Study Area 5. Proposed vibracore is targeting a surficial sand deposit, inside of the sand resource area which is bound by a deeper, bathymetric low likely controlled by antecedent bedrock topography (dark reflectors)

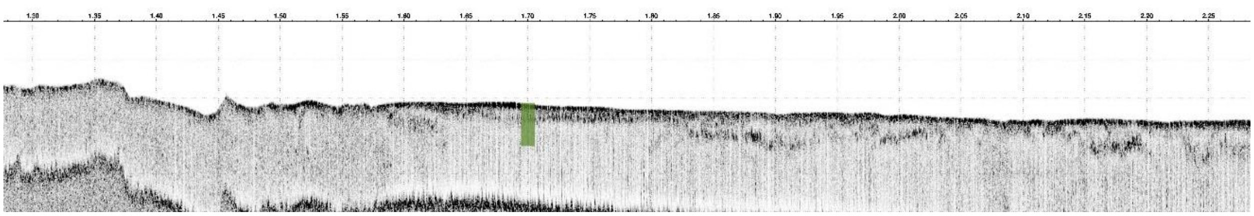


Figure 22: Historic USGS seismic sub-bottom line l259f2 depicting proposed vibracore location (green line) in Study Area 5. Proposed vibracore is targeting a subsurface, channel-like deposit. The location is away from nearby exposed bedrock (dark reflectors), but does target a darker reflector for characterization

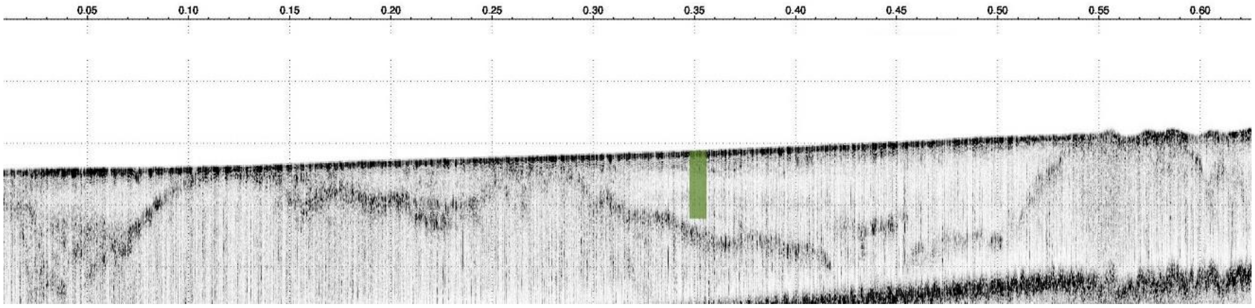


Figure 23: Historic USGS seismic sub-bottom line l307f1 depicting proposed vibracore location (green line) in Study Area 5. Proposed vibracore is targeting a subsurface, channel-like deposit. The location is away from nearby clear bedrock peaks and exposed bedrock (dark reflectors)

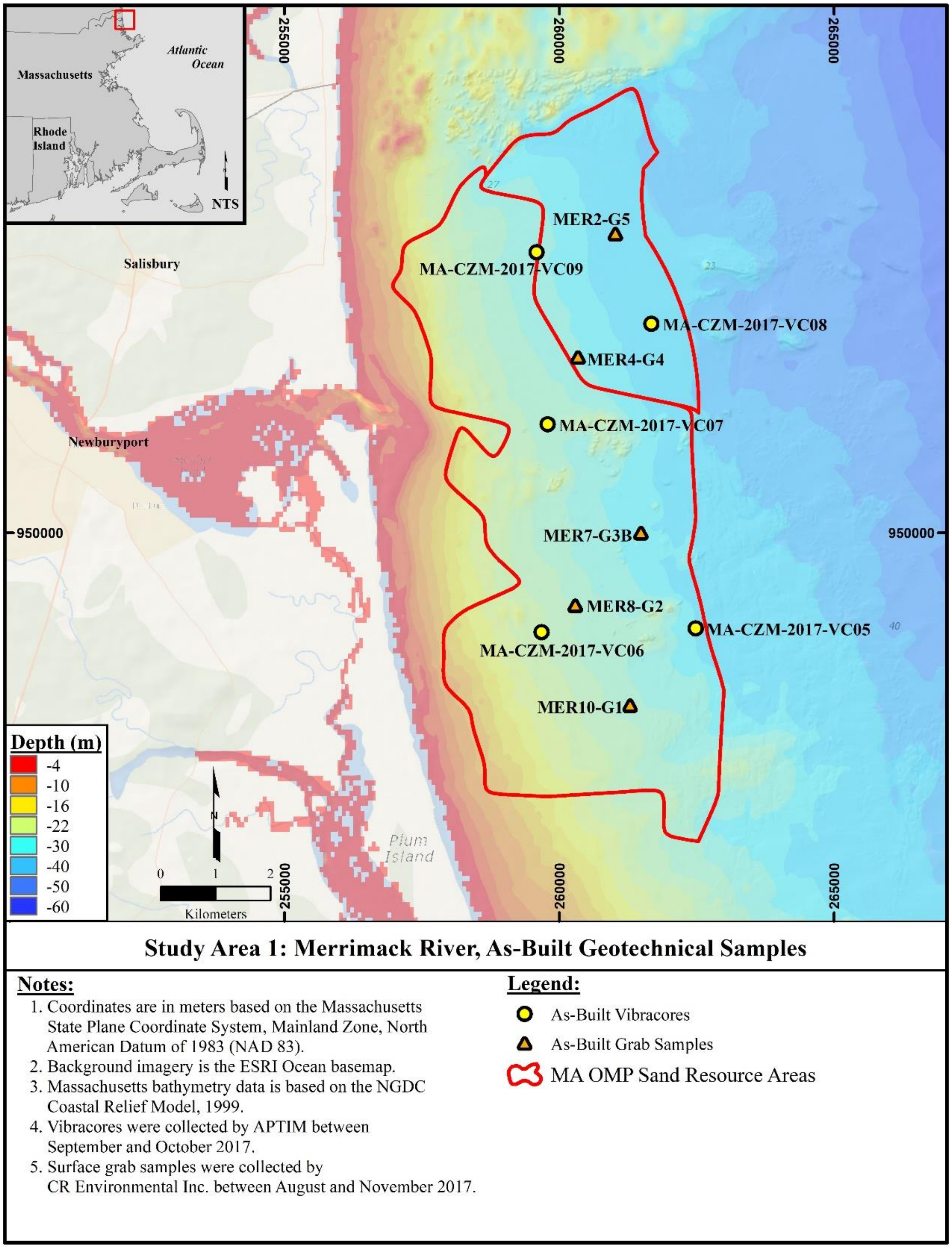


Figure 24: Study Area 1 showing the Massachusetts OMP sand resource area and as-collected vibracores and surface grab sample locations collected by APTIM and CR

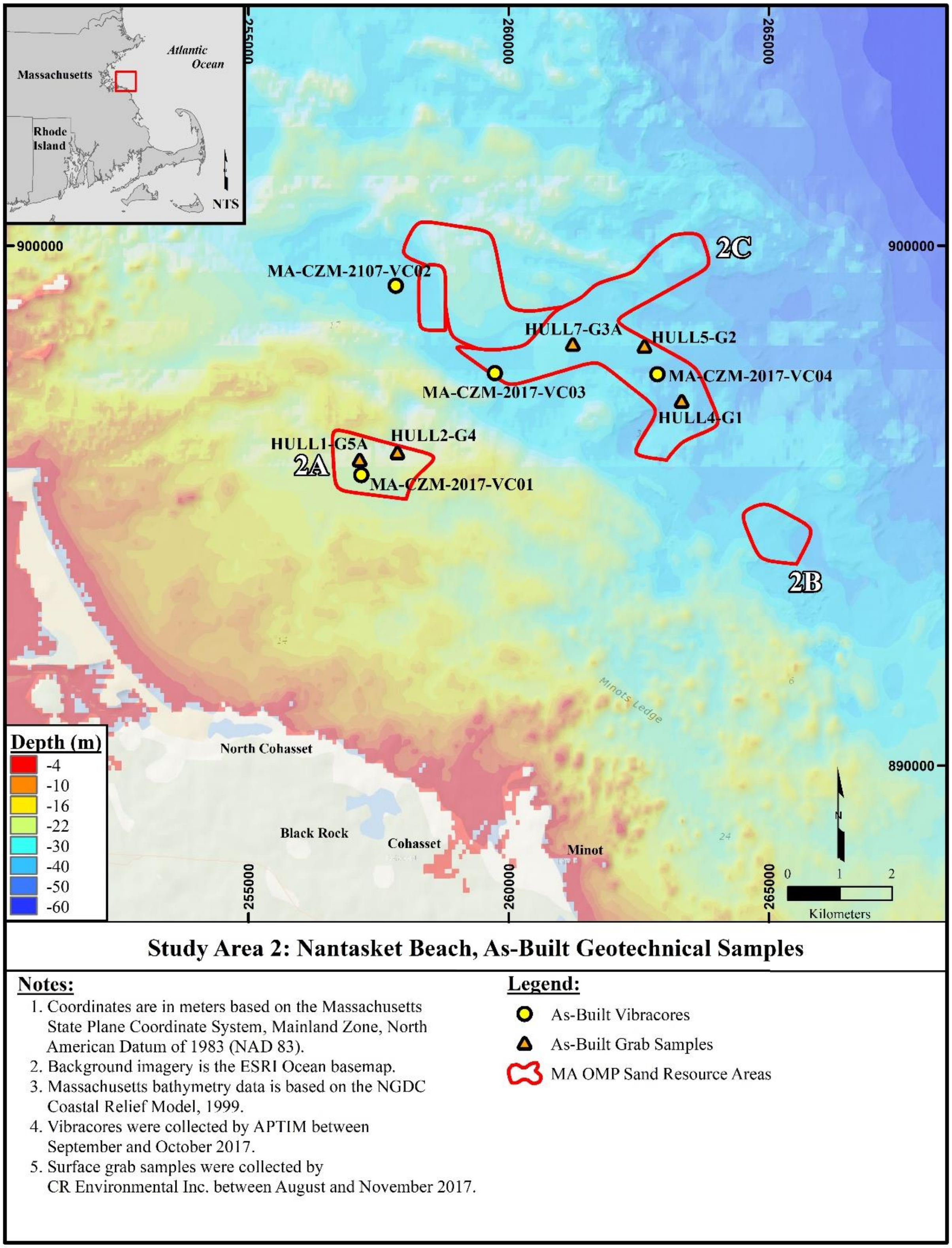


Figure 25: Study Area 2 showing the Massachusetts OMP sand resource area and as-collected vibracores and surface grab sample locations collected by APTIM and CR

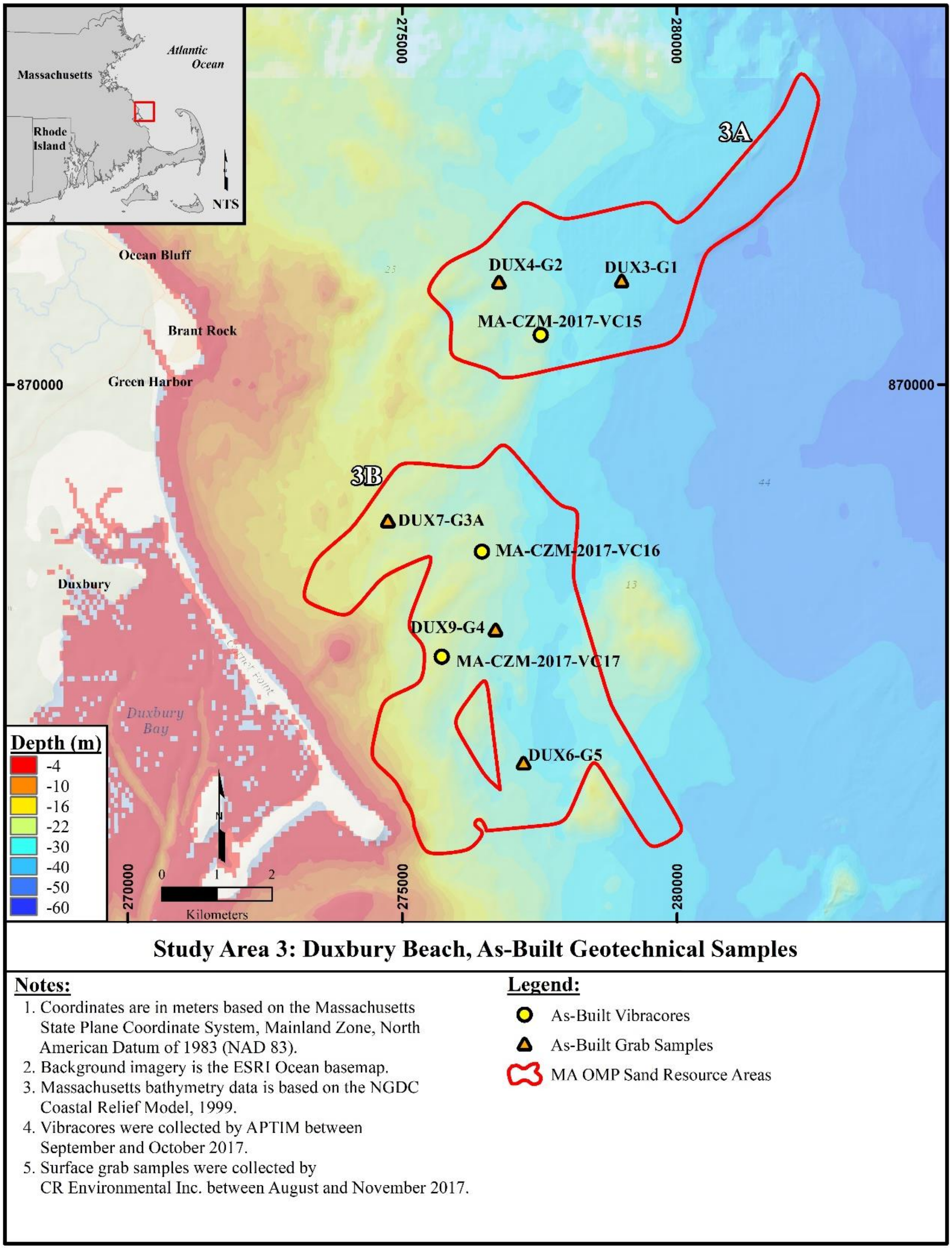


Figure 26: Study Area 3 showing the Massachusetts OMP sand resource area and as-collected vibracores and surface grab sample locations collected by APTIM and CR

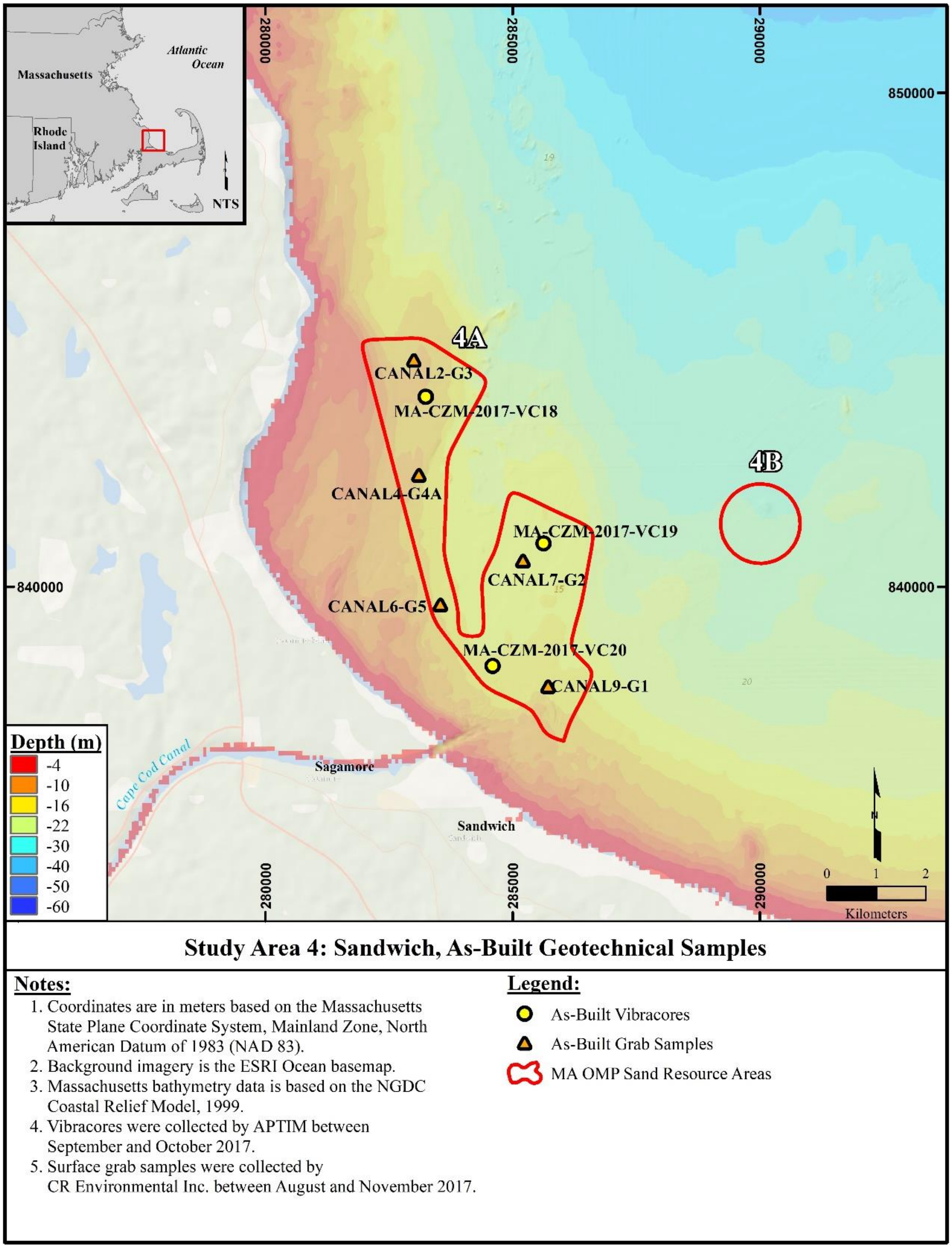
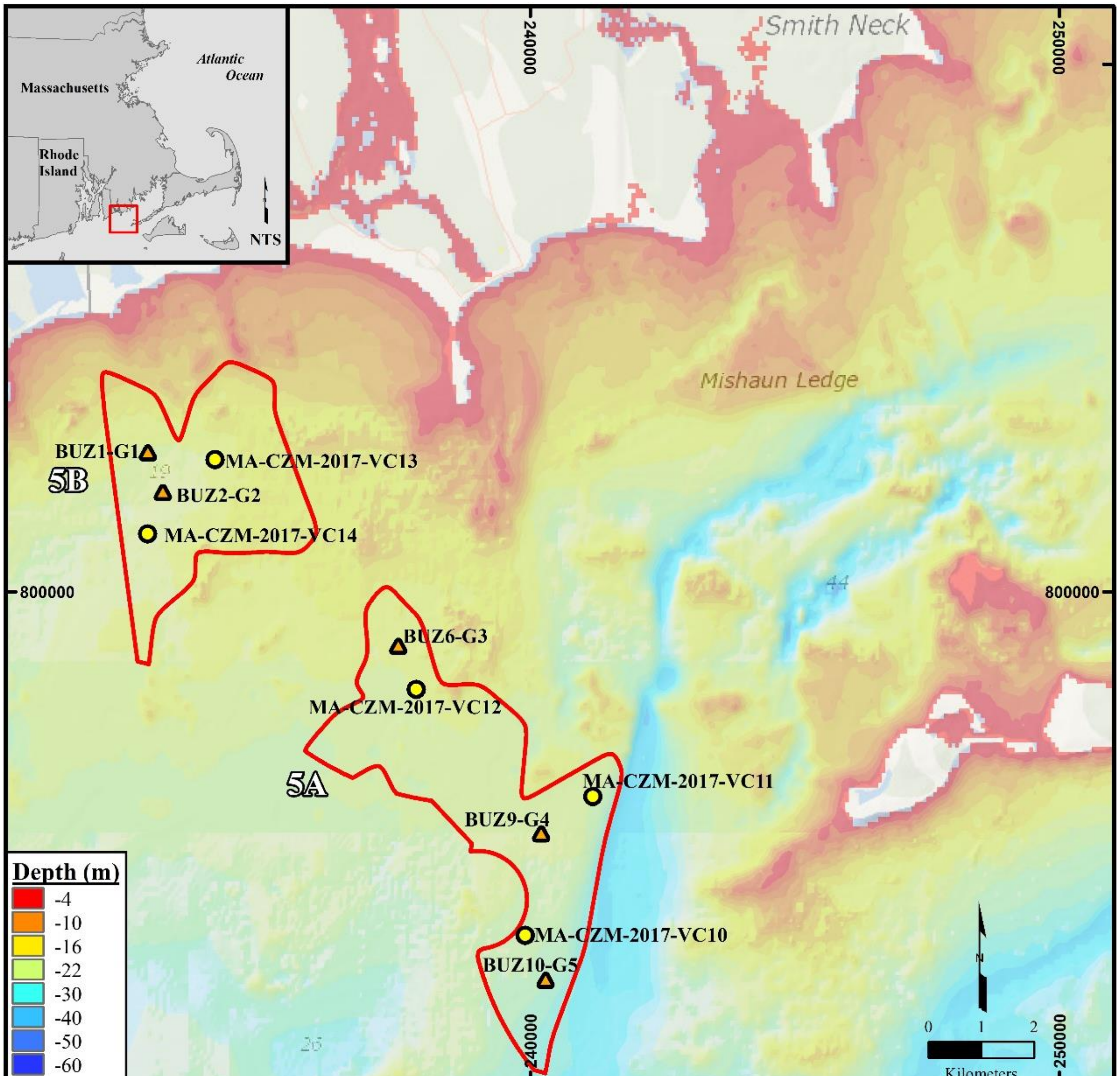


Figure 27: Study Area 4 showing the Massachusetts OMP sand resource area and as-collected vibracores and surface grab sample locations collected by APTIM and CR



Study Area 5: Cuttyhunk, As-Built Geotechnical Samples

Notes:

1. Coordinates are in meters based on the Massachusetts State Plane Coordinate System, Mainland Zone, North American Datum of 1983 (NAD 83).
2. Background imagery is the ESRI Ocean basemap.
3. Massachusetts bathymetry data is based on the NGDC Coastal Relief Model, 1999.
4. Vibracores were collected by APTIM between September and October 2017.
5. Surface grab samples were collected by CR Environmental Inc. between August and November 2017.

Legend:

- As-Built Vibracores
- As-Built Grab Samples
- MA OMP Sand Resource Areas

Figure 28: Study Area 5 showing the Massachusetts OMP sand resource area and as-collected vibracores and surface grab sample locations collected by APTIM and CR

Figure 29: Flow chart depicting the steps for vibracore logging, sampling, and sample analysis.

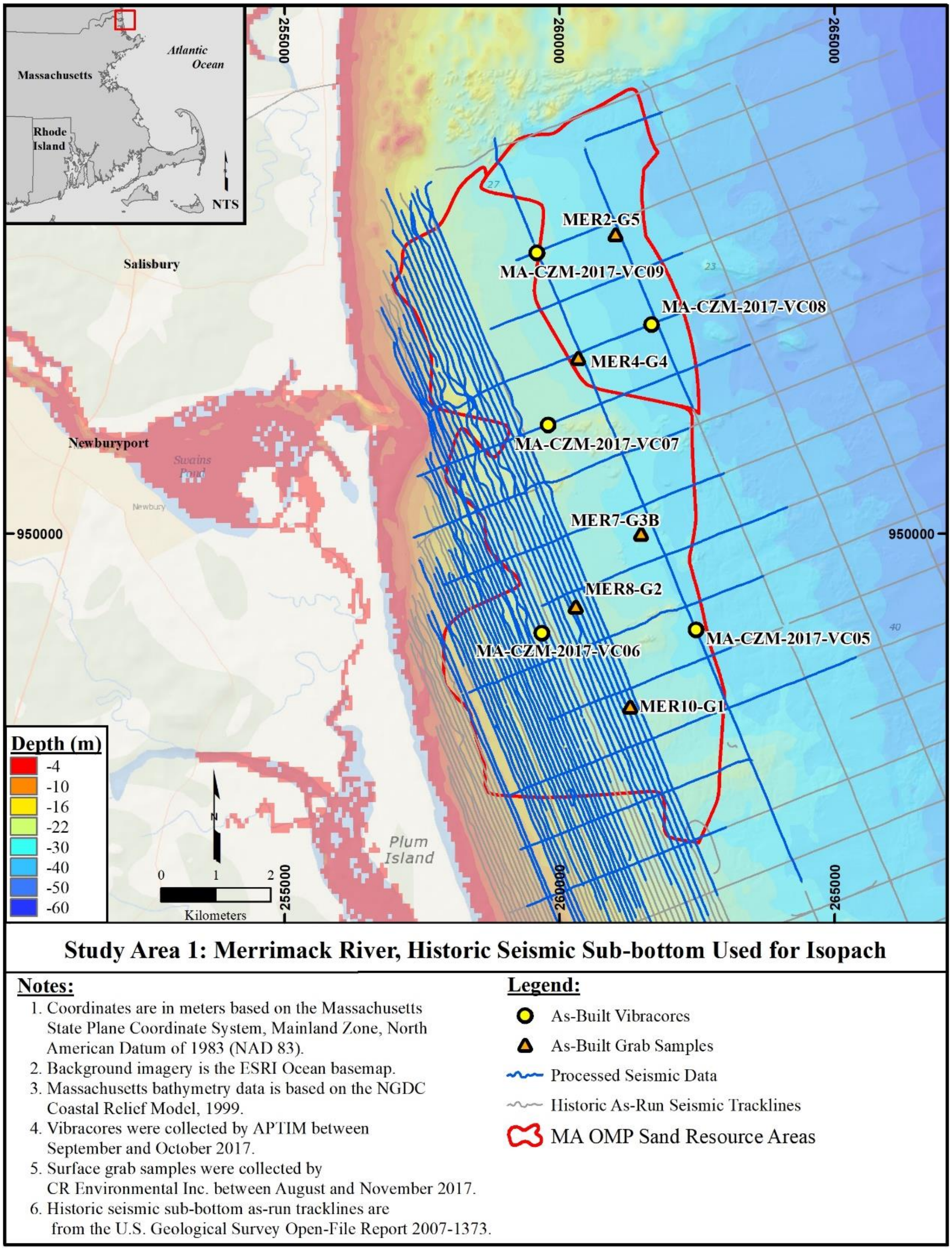


Figure 30: Study Area 1 showing the Massachusetts OMP sand resource area and historic seismic tracklines from the USGS Open File Report 2007-1373 (gray lines) and the historic seismic data coverage used for the development of the isopach maps (blue lines)

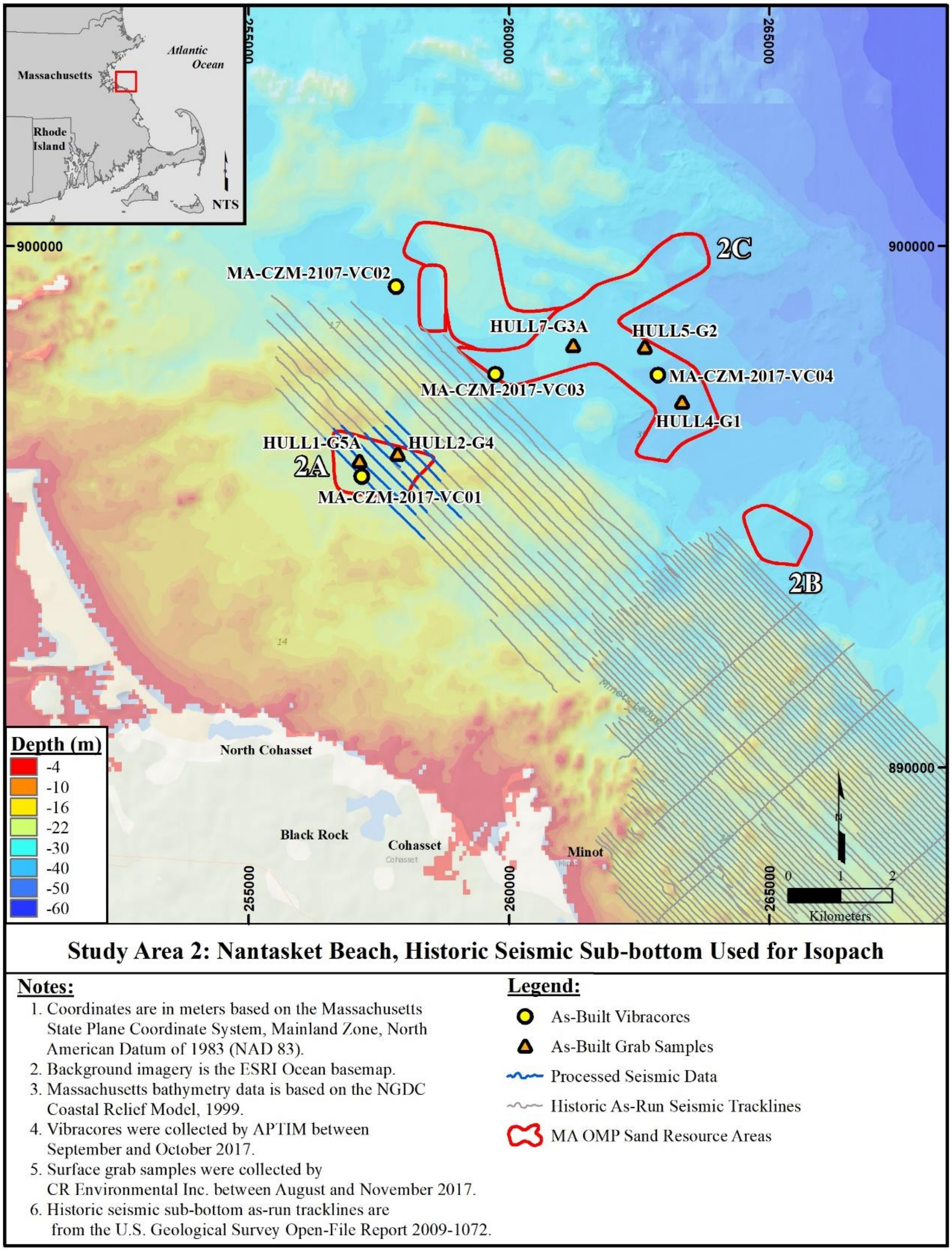
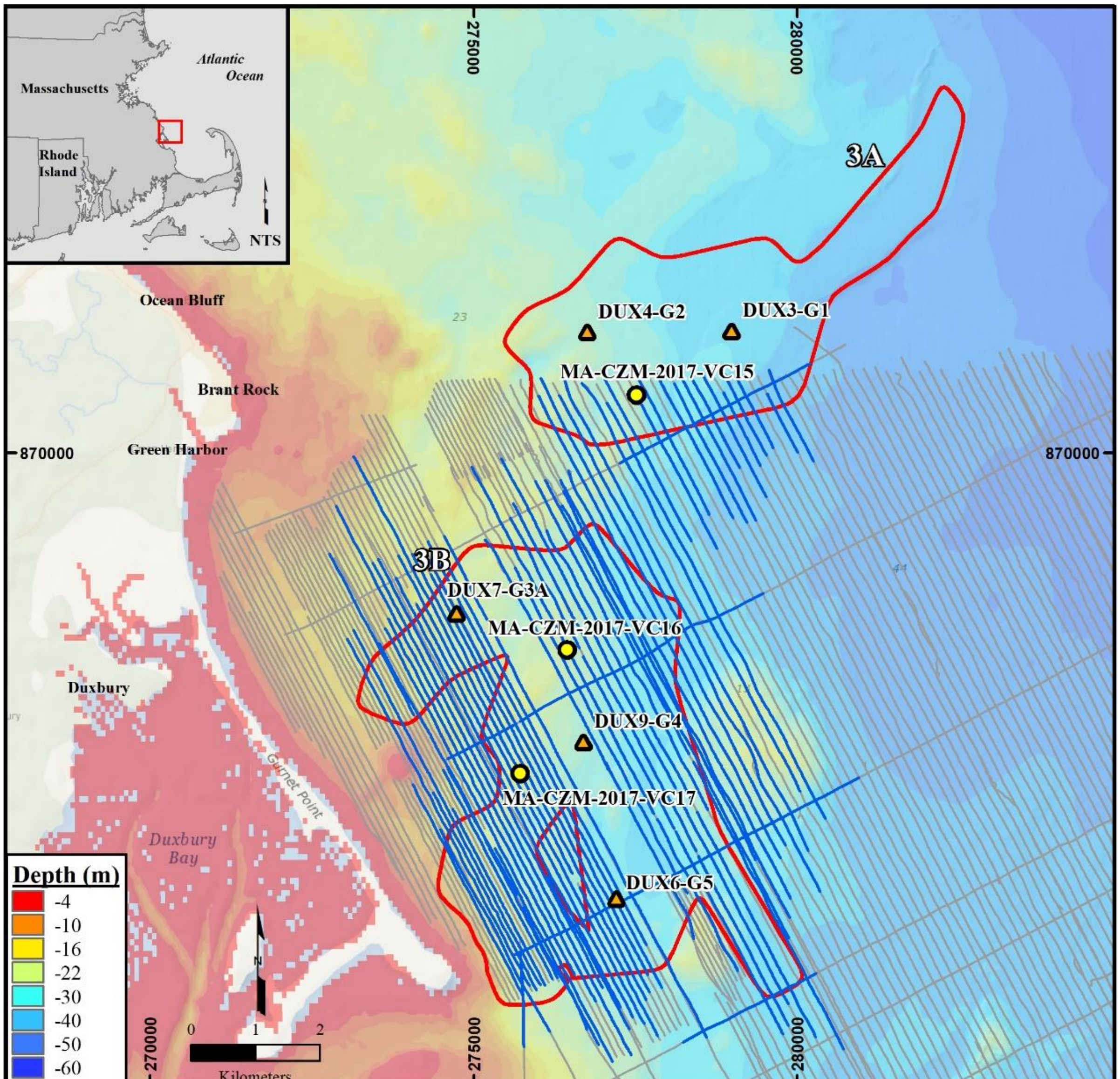


Figure 31: Study Area 2 showing the Massachusetts OMP sand resource area and historic seismic tracklines from the USGS Open File Report 2009-1072 (gray lines) and the historic seismic data coverage used for the development of the isopach maps (blue lines)



Study Area 3: Duxbury Beach, Historic Seismic Sub-bottom Used for Isopach

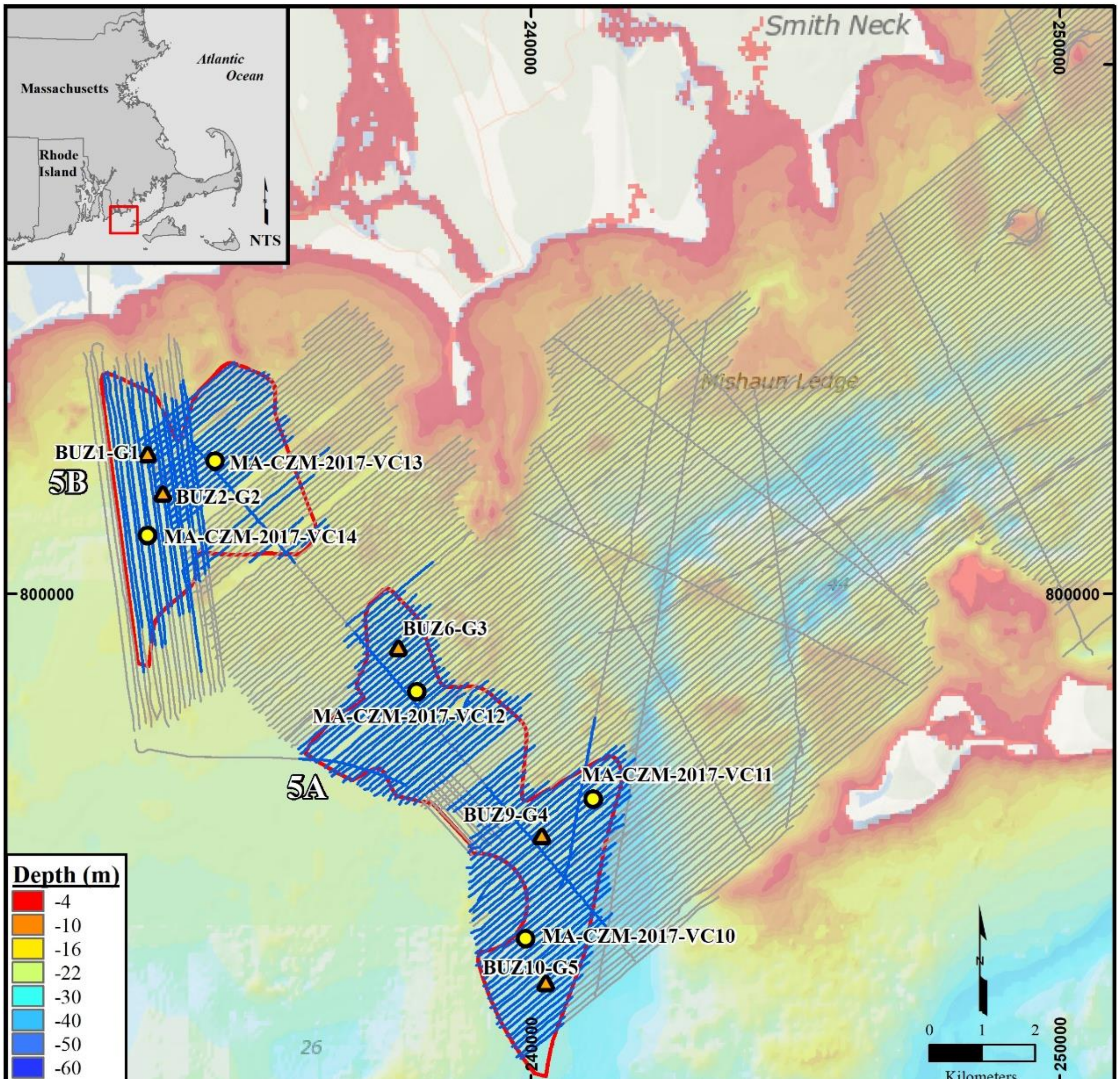
Notes:

1. Coordinates are in meters based on the Massachusetts State Plane Coordinate System, Mainland Zone, North American Datum of 1983 (NAD 83).
2. Background imagery is the ESRI Ocean basemap.
3. Massachusetts bathymetry data is based on the NGDC Coastal Relief Model, 1999.
4. Vibracores were collected by APTIM between September and October 2017.
5. Surface grab samples were collected by CR Environmental Inc. between August and November 2017.
6. Historic seismic sub-bottom as-run tracklines are from the U.S. Geological Survey Open-File Report 2010–1006.

Legend:

- As-Built Vibracores
- As-Built Grab Samples
- Processed Seismic Data
- Historic As-Run Seismic Tracklines
- MA OMP Sand Resource Areas

Figure 32: Study Area 3 showing the Massachusetts OMP sand resource area and historic seismic tracklines from the USGS Open File Report 2010-1006 (gray lines) and the historic seismic data coverage used for the development of the isopach maps (blue lines)



Study Area 5: Cuttyhunk, Historic Seismic Sub-bottom used for Isopach

Notes:

1. Coordinates are in meters based on the Massachusetts State Plane Coordinate System, Mainland Zone, North American Datum of 1983 (NAD 83).
2. Background imagery is the ESRI Ocean basemap.
3. Massachusetts bathymetry data is based on the NGDC Coastal Relief Model, 1999.
4. Vibracores were collected by APTIM between September and October 2017.
5. Surface grab samples were collected by CR Environmental Inc. between August and November 2017.
6. Historic seismic sub-bottom as-run tracklines are from the U.S. Geological Survey Open-File Report 2012-1002.

Legend:

- As-Built Vibracores
- As-Built Grab Samples
- Processed Seismic Data
- Historic As-Run Seismic Tracklines
- MA OMP Sand Resource Areas

Figure 33: Study Area 5 showing the Massachusetts OMP sand resource area and historic seismic tracklines from the USGS Open File Report 2012-1002 gray lines) and the historic seismic data coverage used for the development of the isopach maps (blue lines)

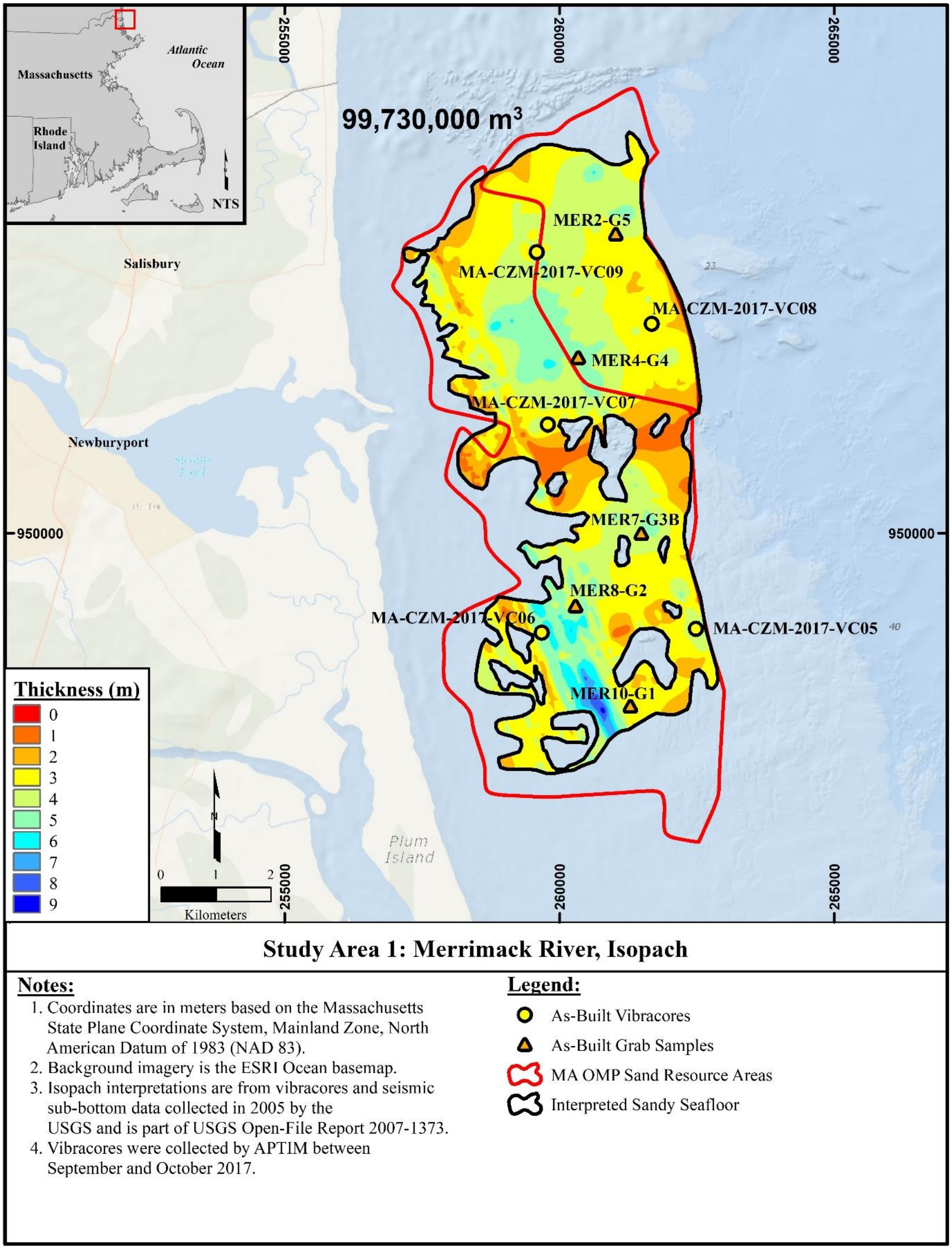


Figure 34: Study Area 1 showing Massachusetts OMP area, interpreted sandy seafloor area and as-built vibracores. Isopach surface was created from the interpretations and digitization of the seismic data collected and used by the USGS as part of the Open-File Report 2007-1373

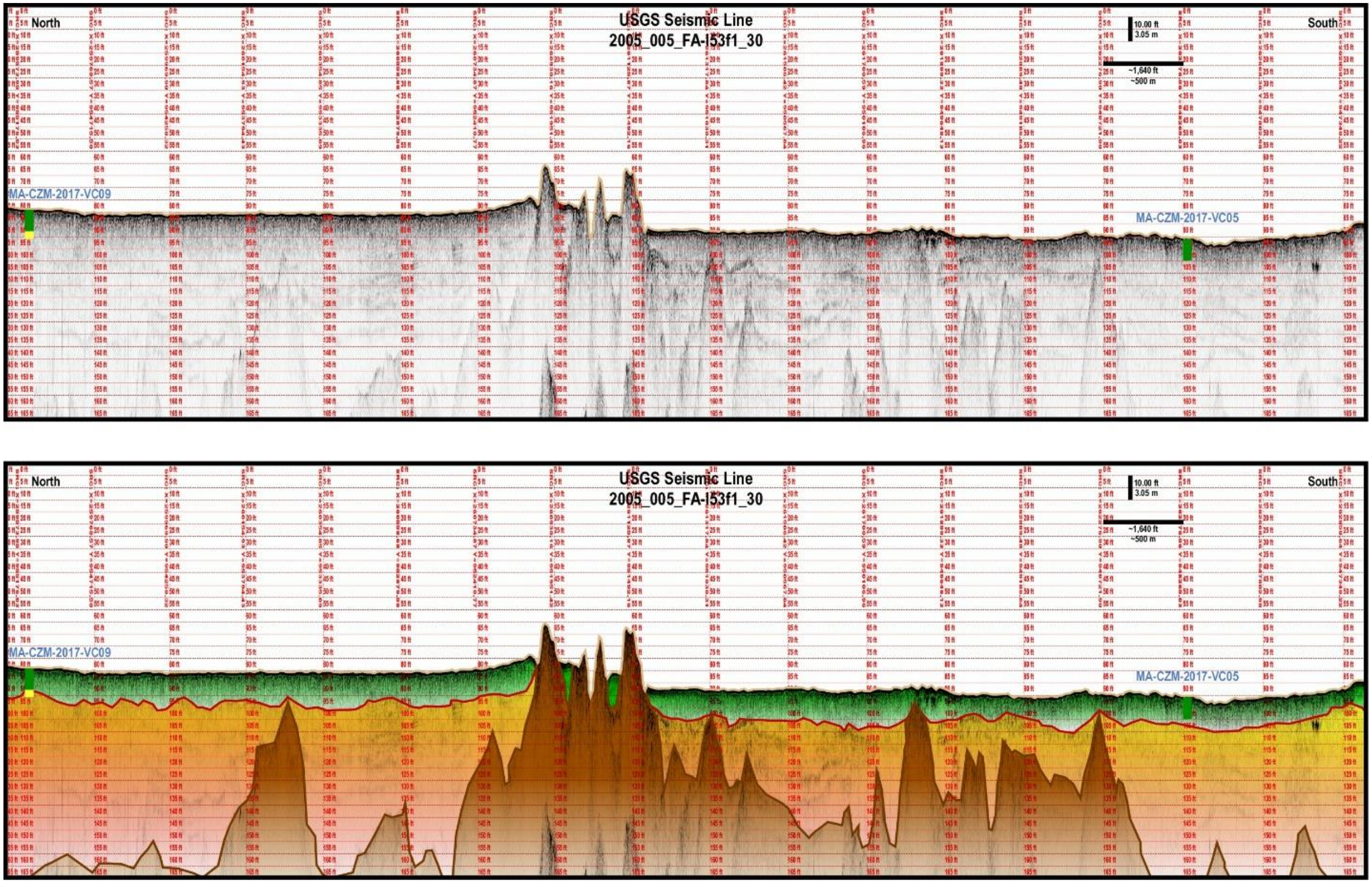


Figure 35: Historic USGS seismic sub-bottom line 2005_005_FA_I53f1_30 (Open-File Report 2007-1373) depicting the location of as-built vibracore MA-CZM-2017-VC05 and MA-CZM-2017-VC09 in Study Area 1. The vibracore is targeting unconsolidated sediments away from clear bedrock peaks (top image). On the lower image the subsurface shaded as green represents the sand portion of the seismic line, while the subsurface geology shaded as red/yellow highlights the sand portion with higher clay content. Areas shaded as brown represent bedrock and outcrop

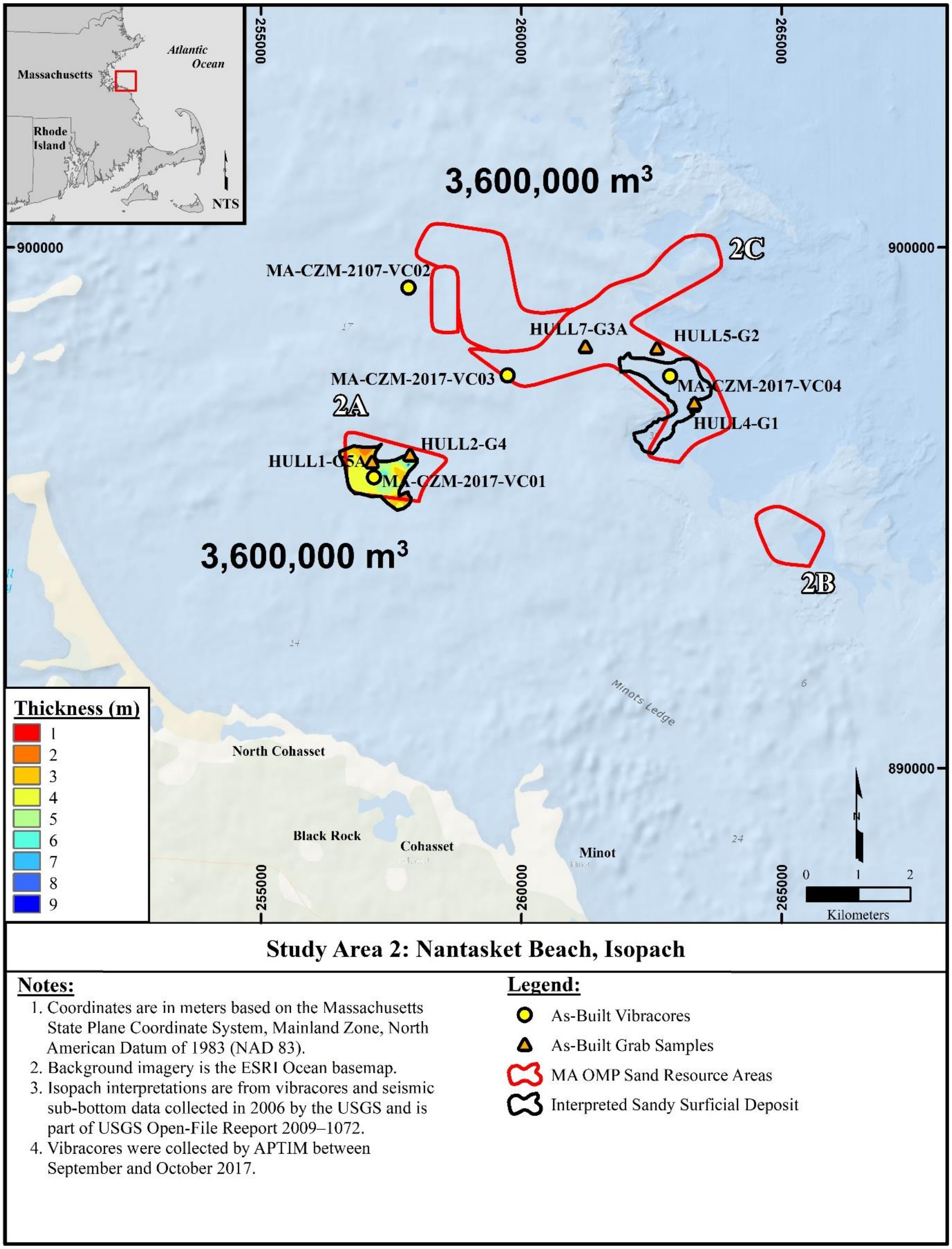


Figure 36: Study Area 2 showing Massachusetts OMP area, interpreted sandy seafloor area and as-built vibracores. Isopach surface was created from the interpretations and digitization of the seismic data collected and used by the USGS as part of the Open-File Report 2009-1072

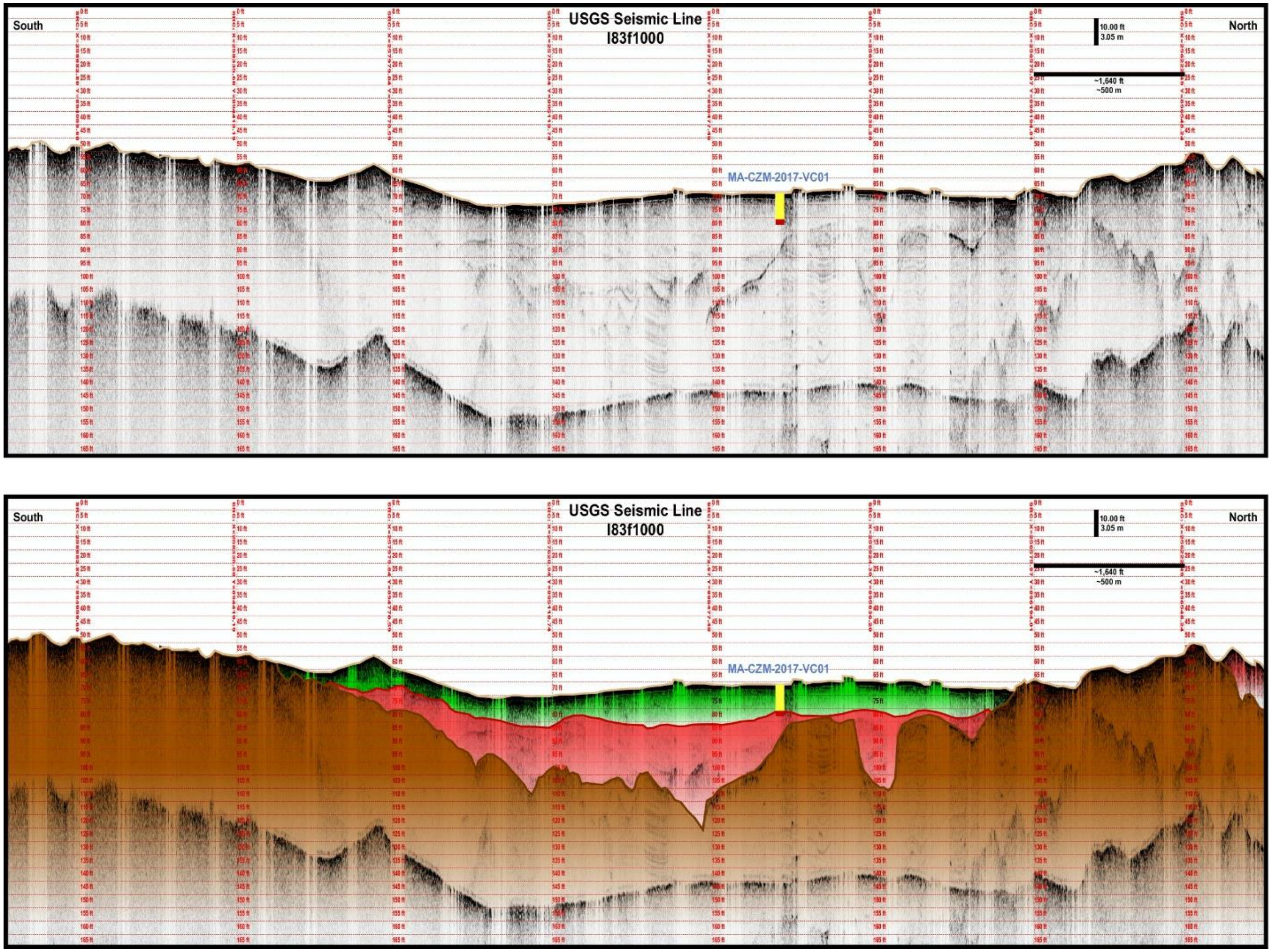


Figure 37: Historic USGS seismic sub-bottom line I83f1000 (Open-File Report 2009-1072) depicting the as-built vibracore MA-CZM-2017-VC01 location in Study Area 2. The vibracore is targeting the subsurface, channel-like deposit (top image). On the lower image the subsurface shaded as green represents the sand portion of the seismic line, while the subsurface geology shaded as red highlights the clay portion of the vibracore. Areas shaded as brown highlight the bedrock (i.e. hard bottom)

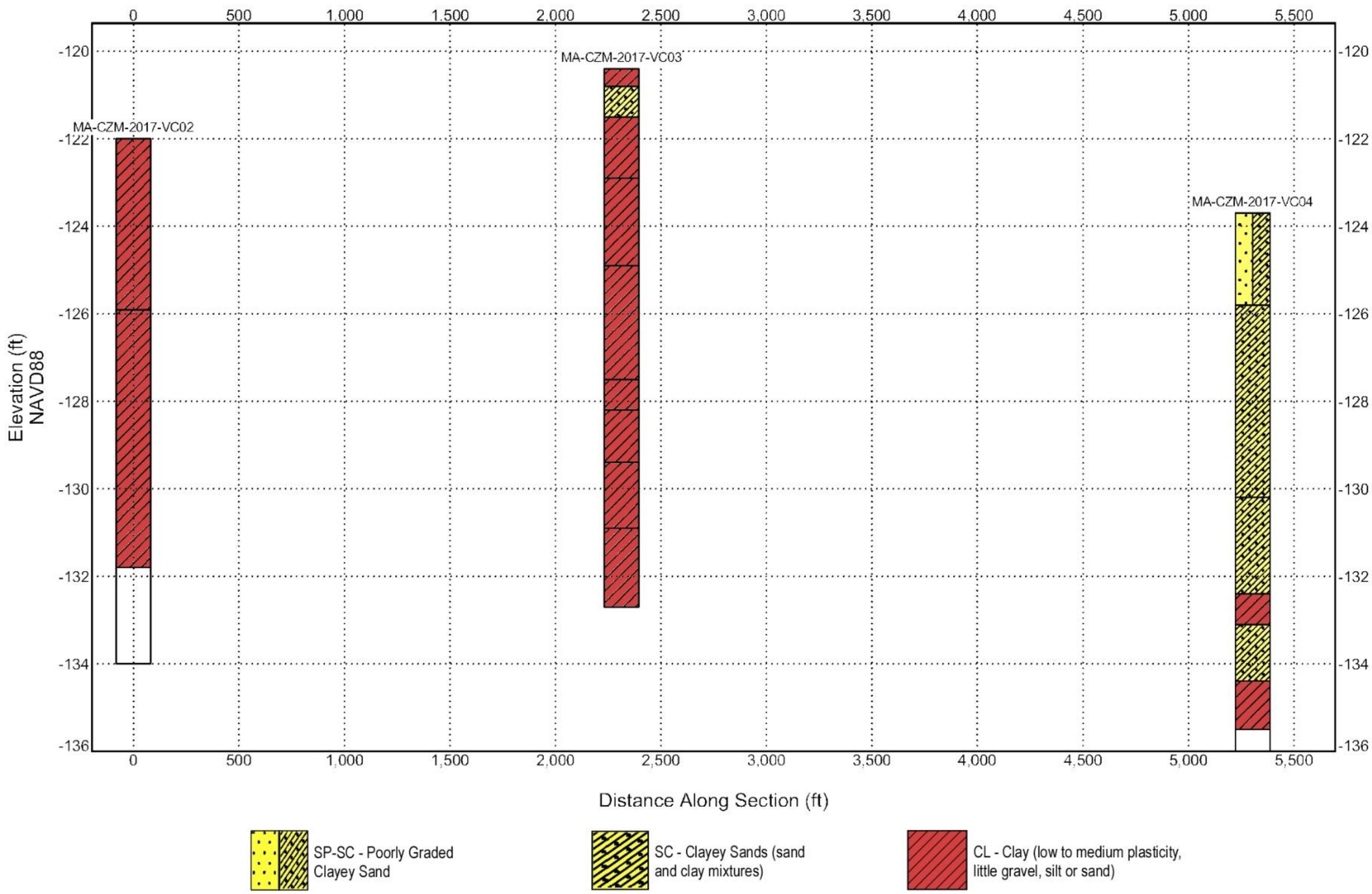


Figure 38: Fence diagram for Study Area 2C showing the correlation between the sand and clay deposits across the collected vibracores in the Study Area. Layers color coded as red indicate portions with high clay content, while layers in yellow indicate sands with less than 10% clay content

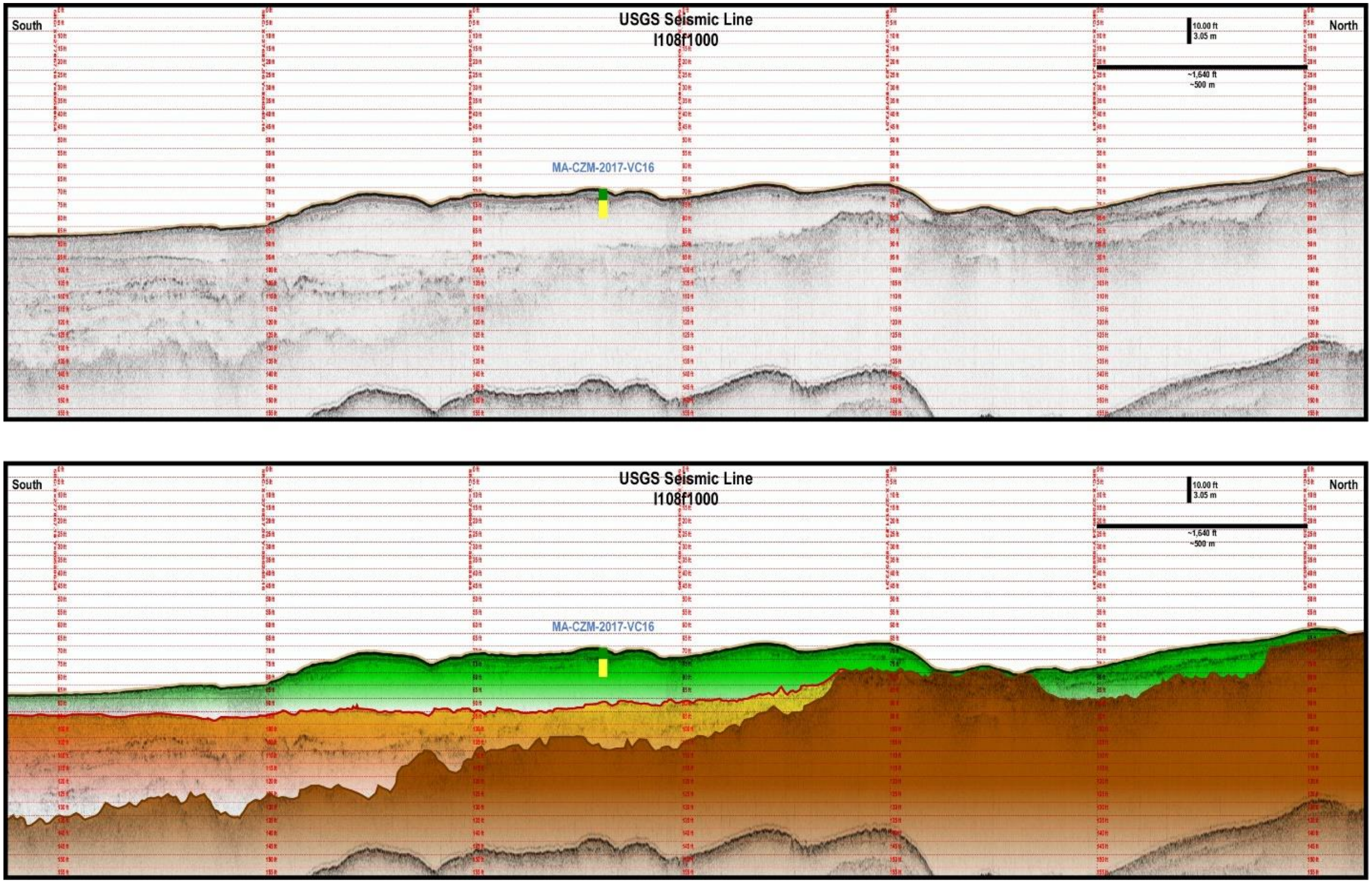
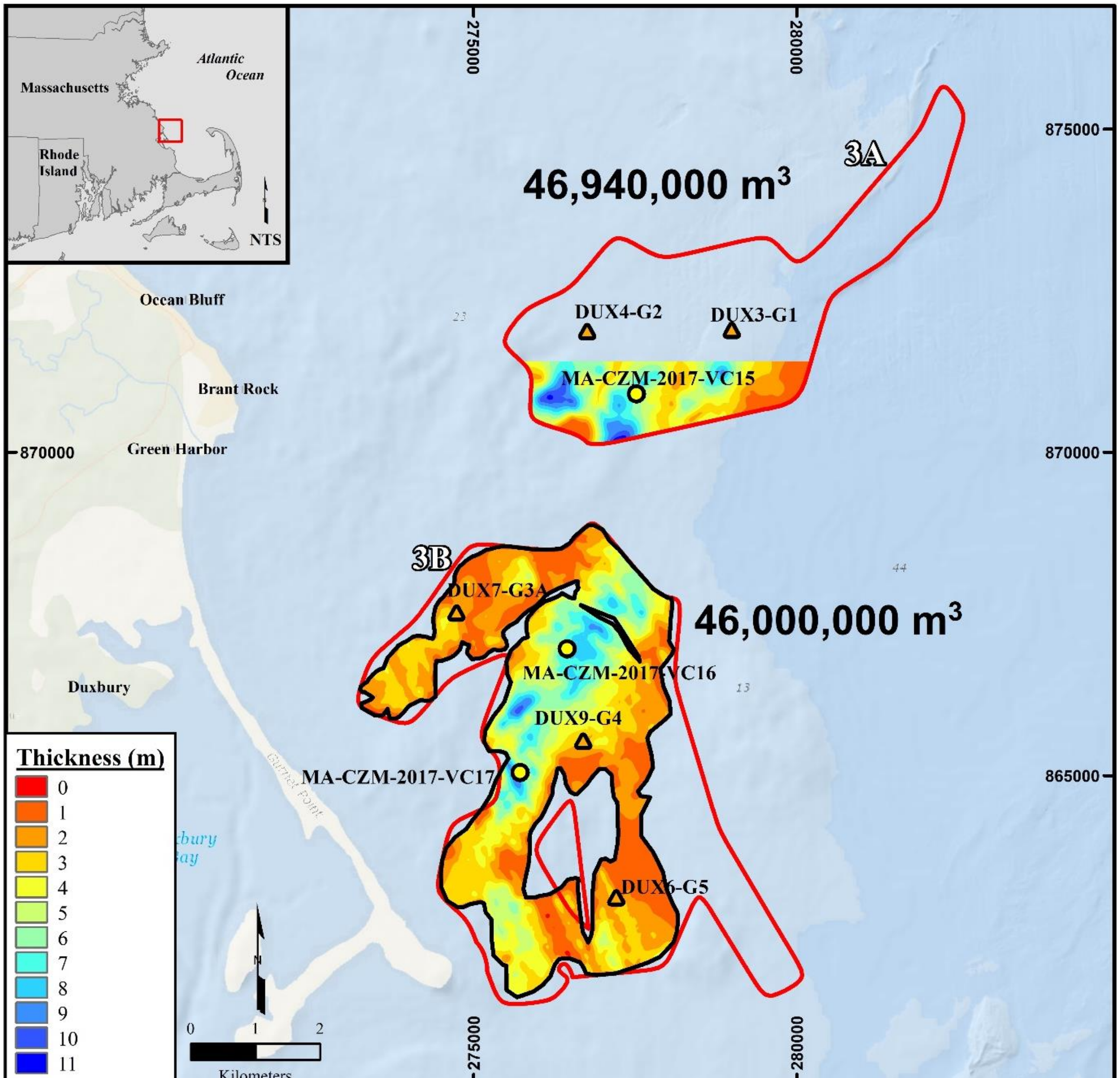


Figure 39: Historic USGS seismic sub-bottom line I108f1000 (Open-File Report 2010-1006) depicting the as-built vibracore MA-CZM-2017-VC16 location in Study Area 3. The vibracore is targeting the sand hill (top image). On the lower image the subsurface shaded as green represents the sand portion of the seismic line, while the subsurface geology shaded as yellow/red highlights the potentially non-beach-compatible deposit. Areas shaded as brown highlight the bedrock (i.e. hard bottom)



Study Area 3: Duxbury Beach, Isopach

Notes:

1. Coordinates are in meters based on the Massachusetts State Plane Coordinate System, Mainland Zone, North American Datum of 1983 (NAD 83).
2. Background imagery is the ESRI Ocean basemap.
3. Isopach interpretations are from vibracores and seismic sub-bottom data collected in 2007, 2008 and 2009 by the USGS and is part of USGS Open-File Report 2010–1006.
4. Vibracores were collected by APTIM between September and October 2017.

Legend:

- As-Built Vibracores
- As-Built Grab Samples
- MA OMP Sand Resource Areas
- Interpreted Sandy Seafloor

Figure 40: Study Area 3 showing Massachusetts OMP area, interpreted sandy seafloor area and as-built vibracores. Isopach surface was created from the interpretations and digitization of the seismic data collected and used by the USGS as part of the Open-File Report 2010-1006

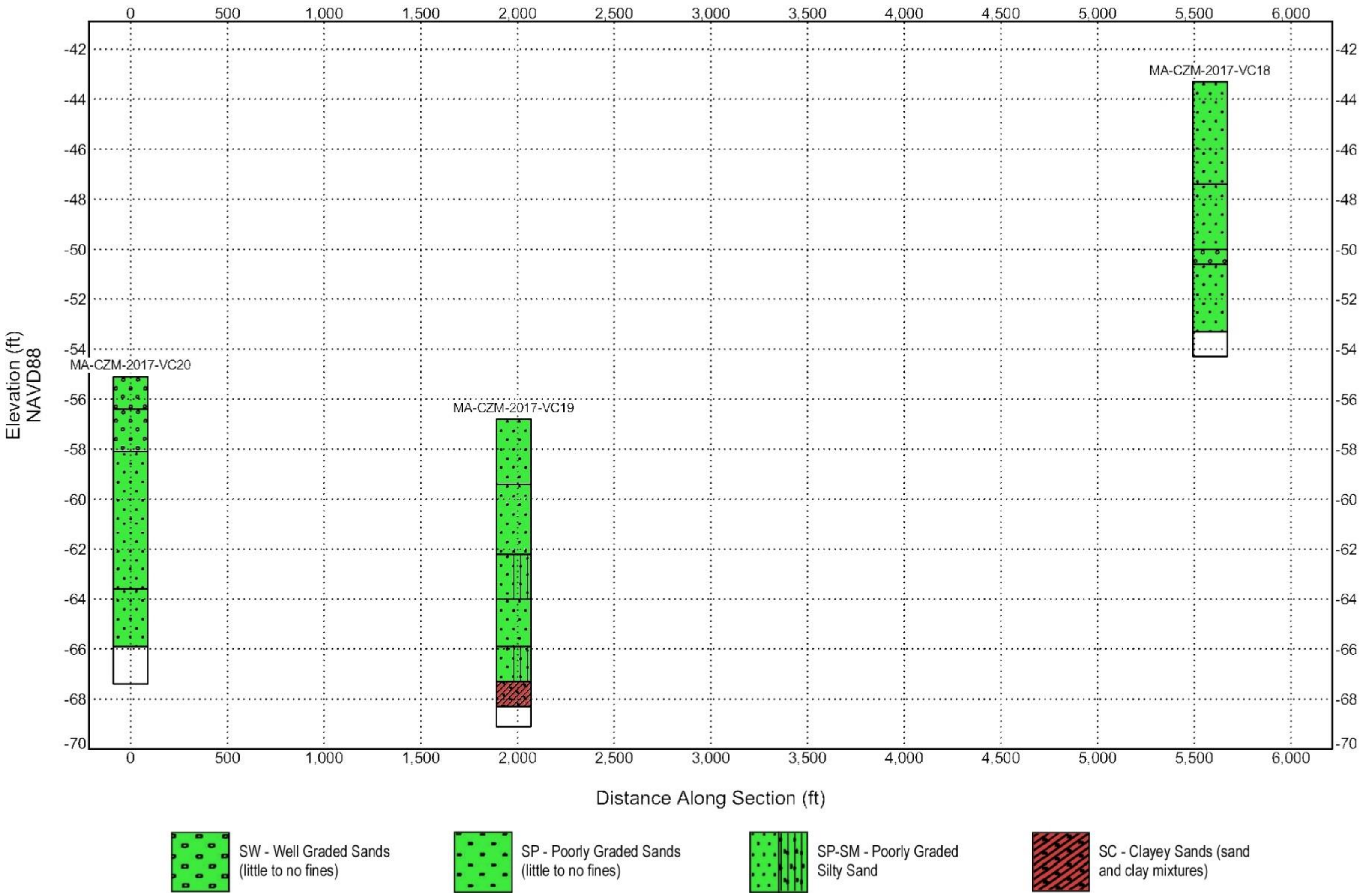


Figure 41: Fence diagram for Study Area 4A showing the correlation between the sand and clayey sand deposits across the collected vibracores in the Study Area. Layers color coded as green indicate portions with less than 5% fine grain content, while layers in red indicate sands with more than 10% clay content

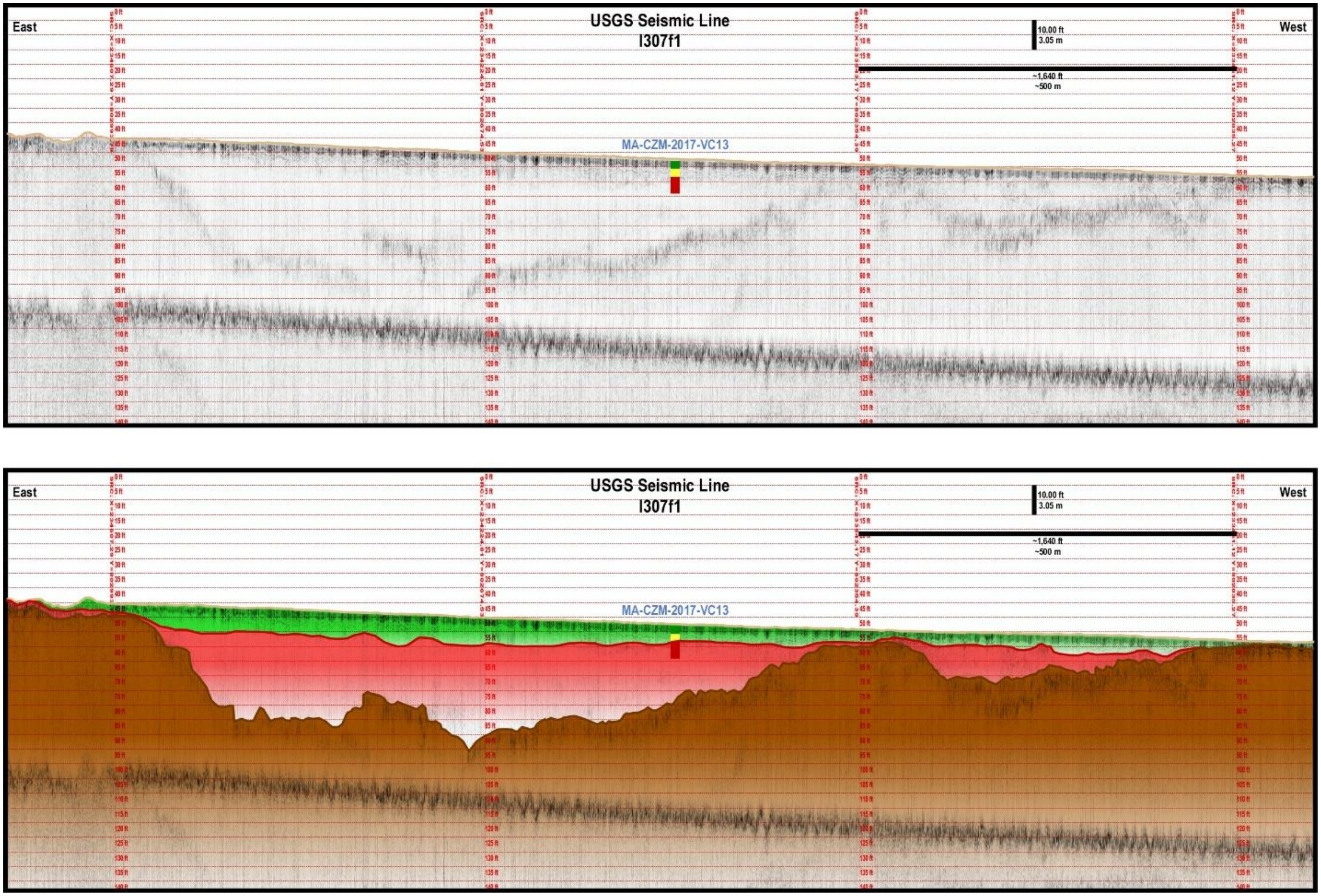
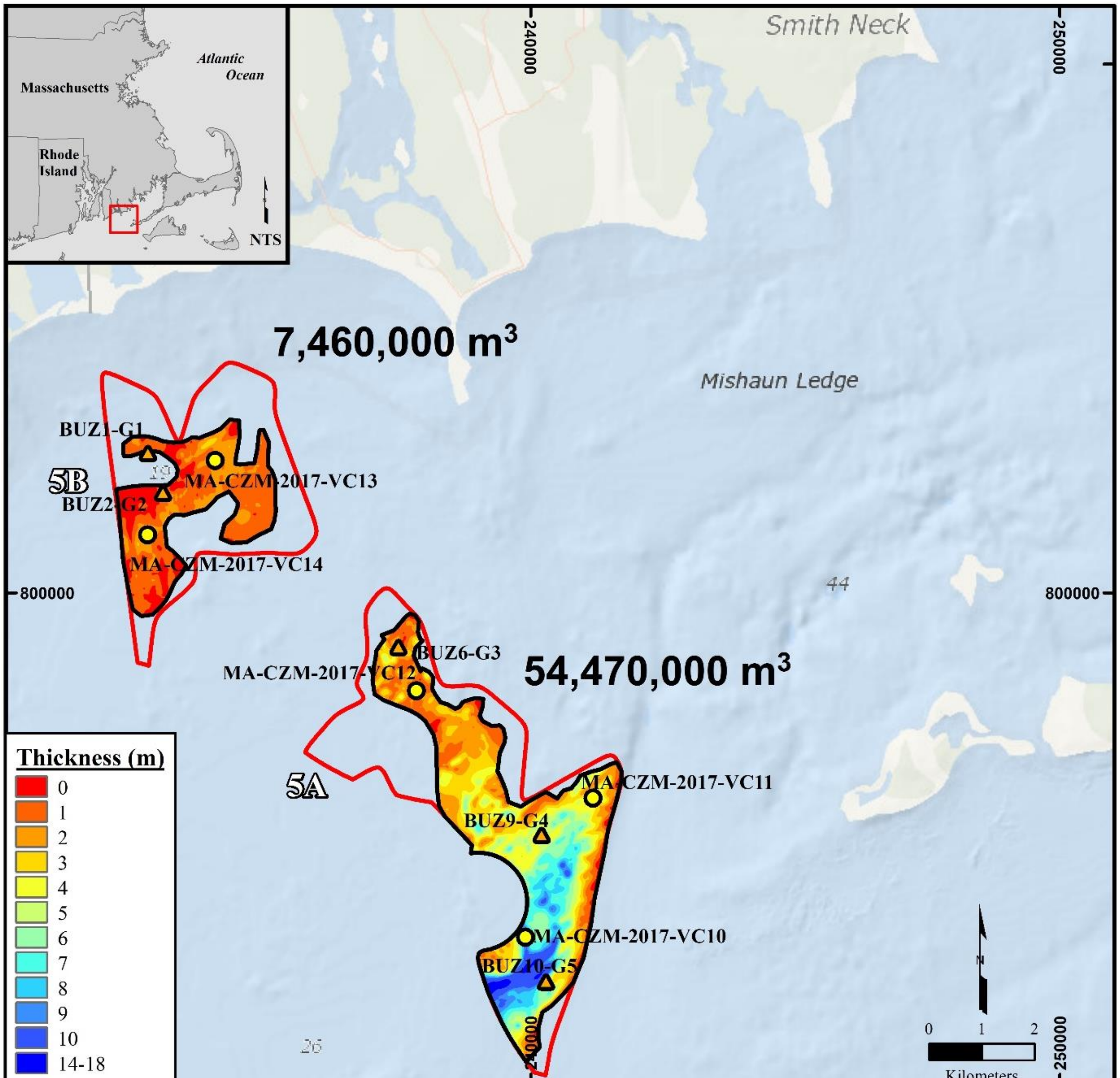


Figure 42: Historic USGS seismic sub-bottom line I307f1 (Open-File Report 2012-1002) depicting the as-built vibracore MA-CZM-2017-VC13 location in Study Area 5B. The vibracore is targeting the subsurface, channel-like deposit (top image). On the lower image the subsurface shaded as green represents the sand portion of the seismic line, while the subsurface geology shaded as red highlights the potentially non-beach-compatible deposit (high clay content). Areas shaded as brown highlight the bedrock (i.e. hard bottom)



Study Area 5: Cuttyhunk, Isopach

Notes:

1. Coordinates are in meters based on the Massachusetts State Plane Coordinate System, Mainland Zone, North American Datum of 1983 (NAD 83).
2. Background imagery is the ESRI Ocean basemap.
3. Isopach interpretations are from vibracores and seismic sub-bottom data collected in 2009 and 2011 by the USGS and is part of USGS Open-File Report 2012-1002.
4. Vibracores were collected by APTIM between September and October 2017.

Legend:

- As-Built Vibracores
- As-Built Grab Samples
- MA OMP Sand Resource Areas
- Interpreted Sandy Seafloor

Figure 43: Study Area 5 showing Massachusetts OMP area, interpreted sandy seafloor area and as-built vibracores. Isopach surface was created from the interpretations and digitization of the seismic data collected and used by the USGS as part of the Open-File Report 2012-1002

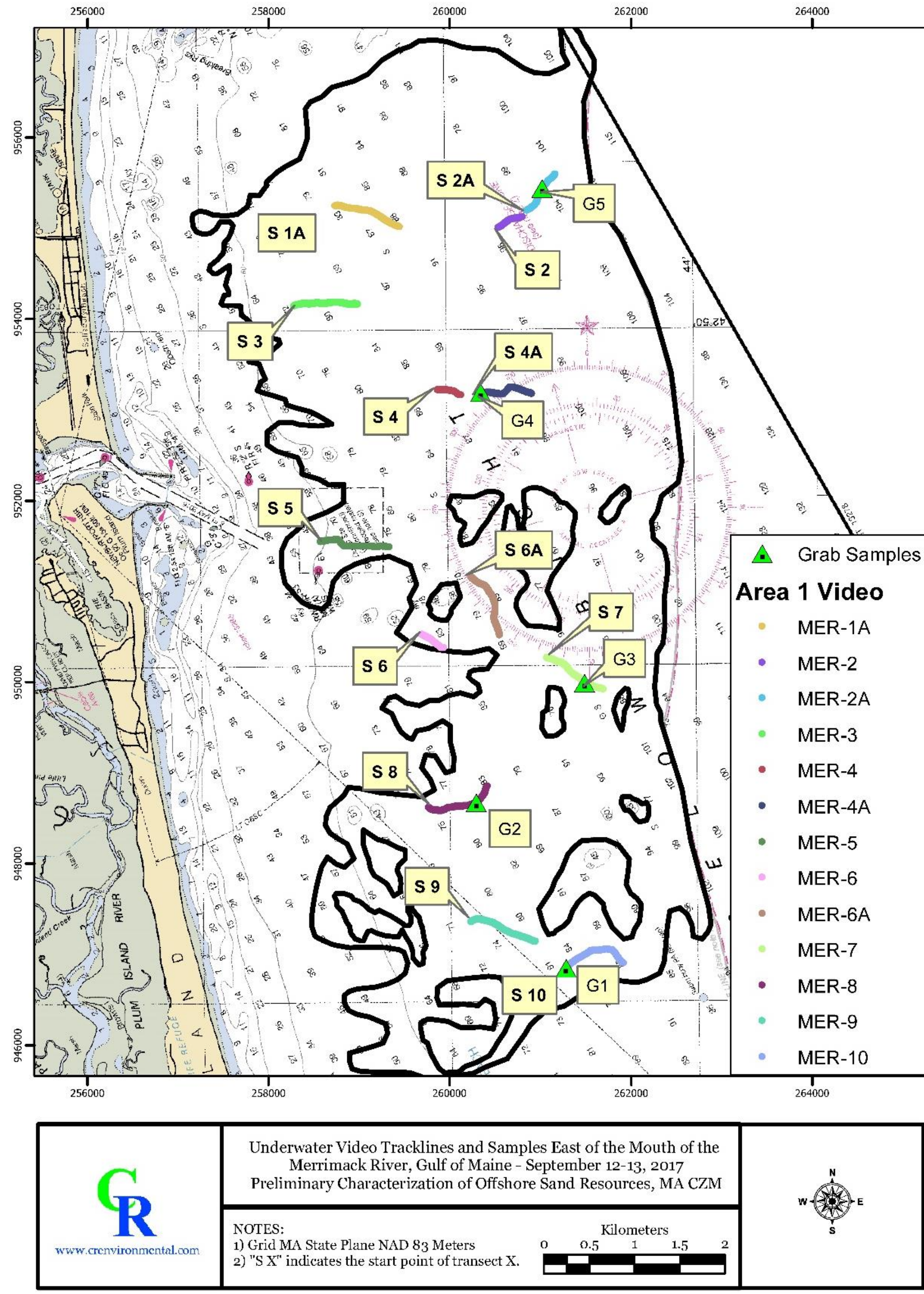


Figure 44: Study Area 1 showing the interpreted sandy seafloor area along with as-run video transects and grab samples collected by CR

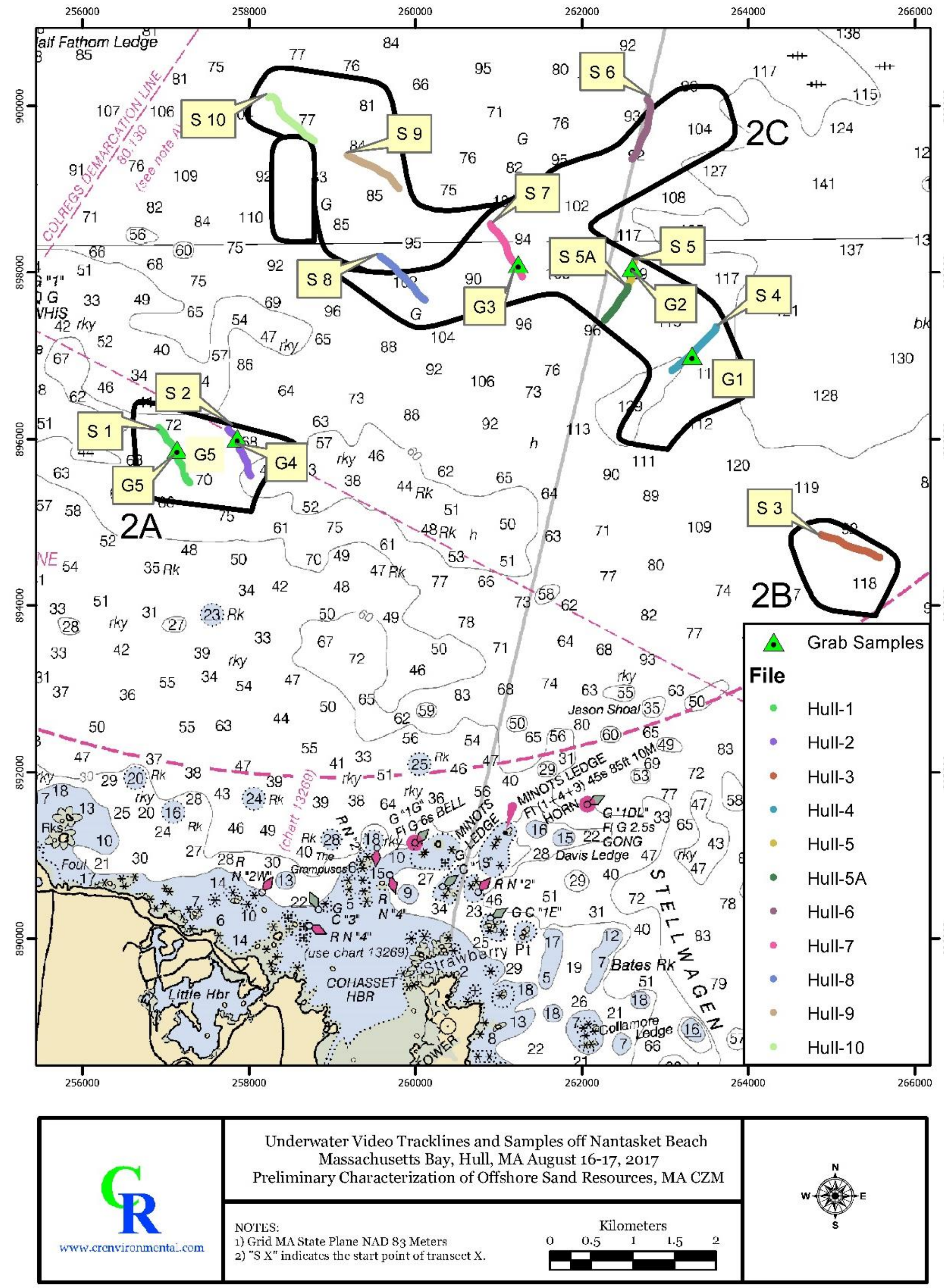


Figure 45: Study Area 2 showing the interpreted sandy seafloor area along with as-run video transects and grab samples collected by CR

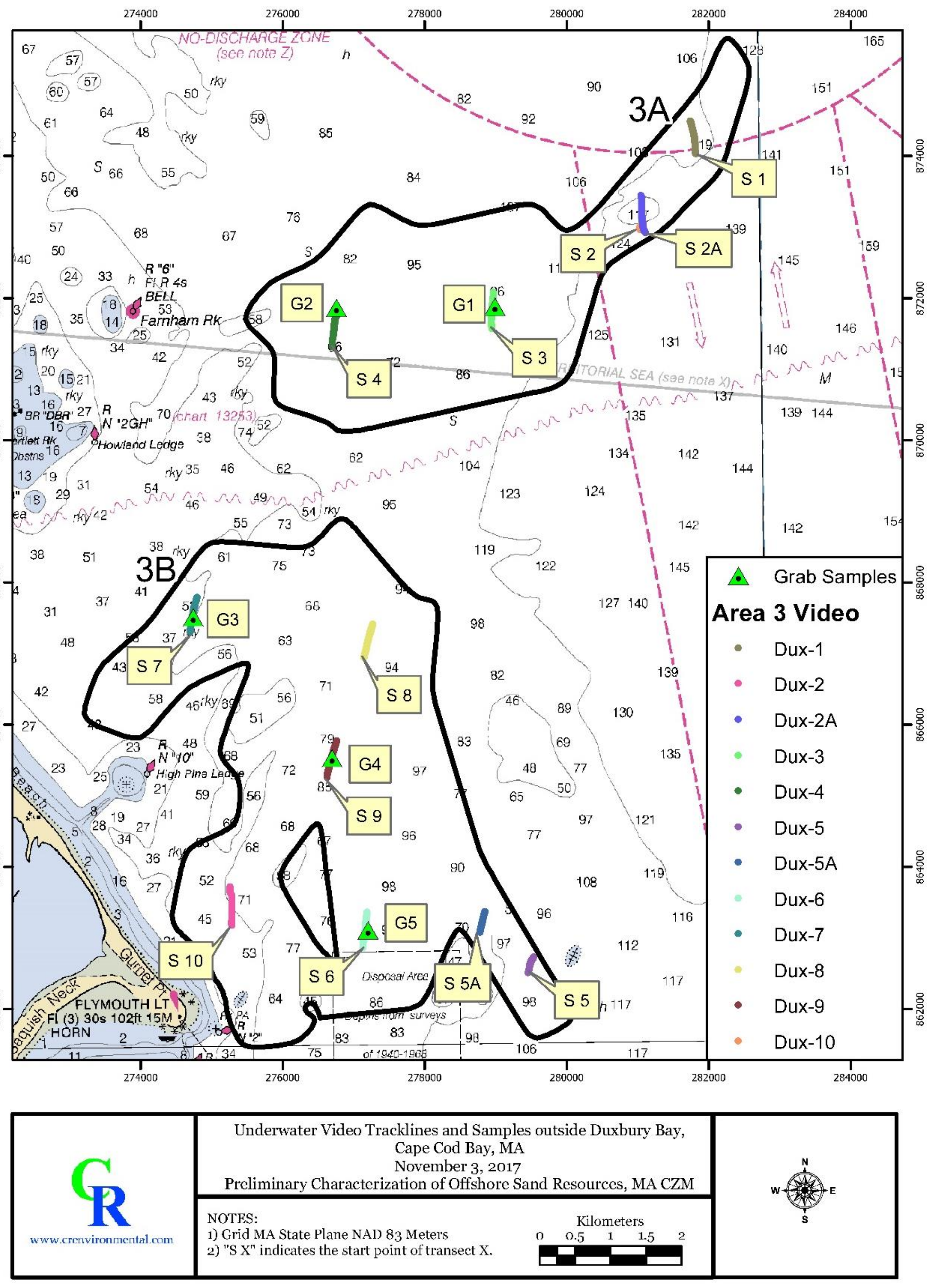


Figure 46: Study Area 3 showing the Massachusetts OMP Sand Resource Areas along with as-run video and grab samples transects collected by CR

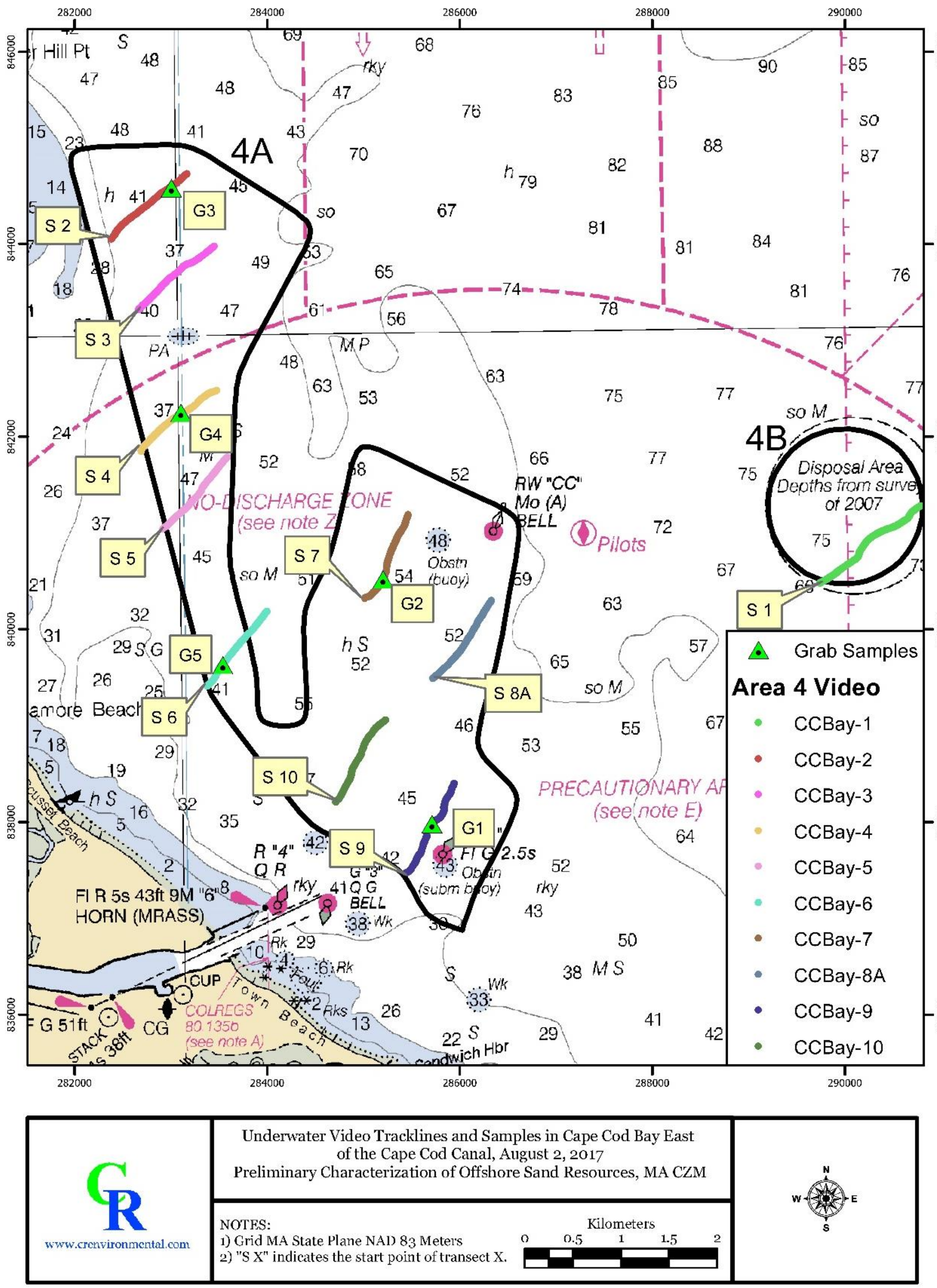


Figure 47: Study Area 4 showing the Massachusetts OMP Sand Resource Areas along with as-run video transects and grab samples collected by CR

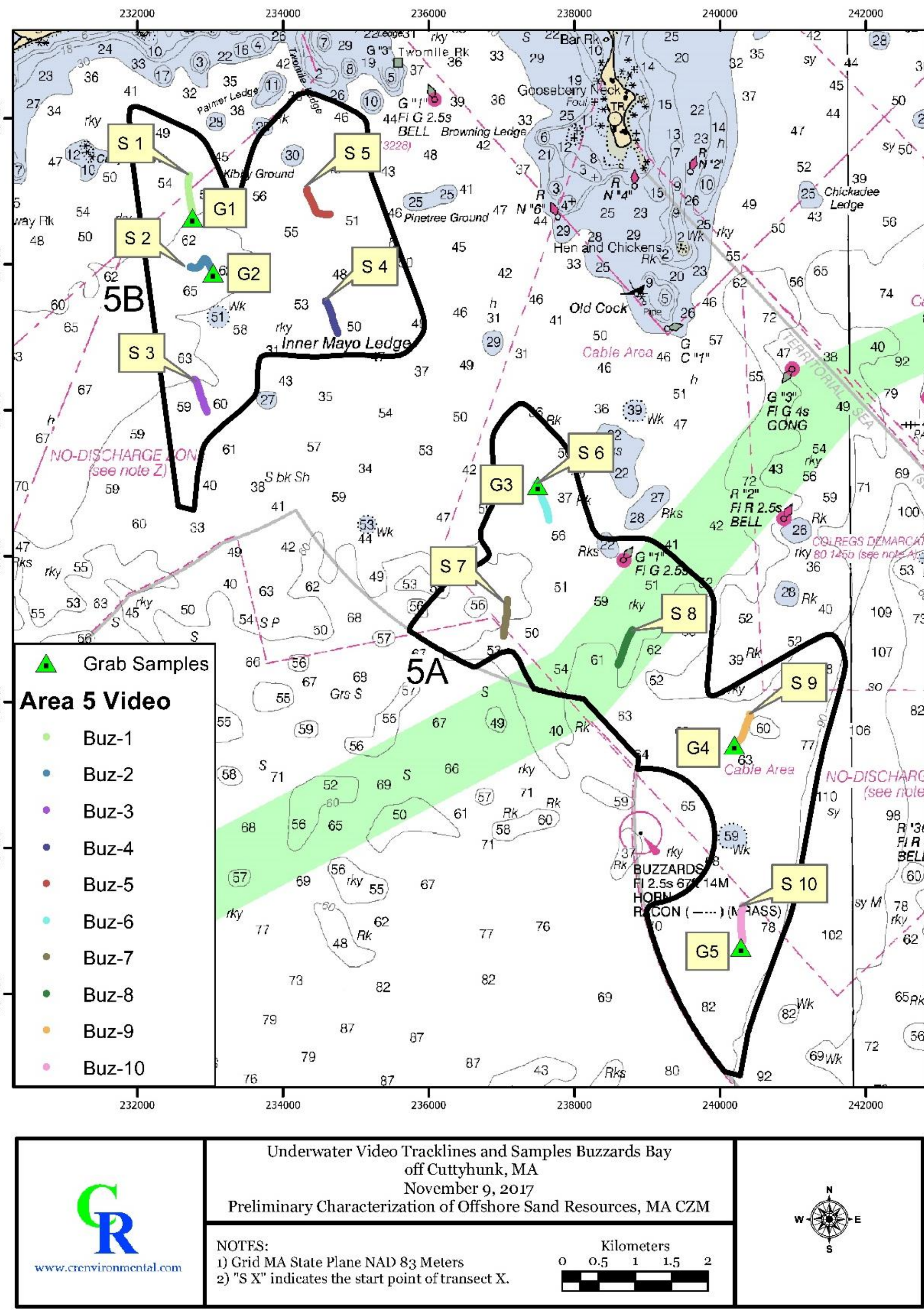


Figure 48: Study Area 5 showing Massachusetts OMP Sand Resource Areas along with as-run video transects and grab samples collected by CR

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Appendices

Appendix A(digital only)

Vibracore Logs

Appendix B(digital only)

Vibracore Granularmetric Reports

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APPENDIX C

SAND RESOURCES ASSESSMENT AT CRITICAL BEACHES ON THE MASSACHUSETTS COAST

TECHNICAL REPORT
Agreement: M14AC00006

July 24, 2016

Announcement M13AS00014: Hurricane Sandy Coastal Recovery and Resiliency - Resource Identification, Delineation and Management Practices

Agreement: M14AC00006 Massachusetts Geological Survey/University of Massachusetts; Sand Resource Assessment at Critical Beaches on the Massachusetts Coast

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Technical Report

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Abstract

Topographic profiles and grain size analyses were completed for 18 public beaches along the Massachusetts coast that are threatened by erosion, have important infrastructure that is at risk or are in communities with no active coastal management plan. The purpose of this work was to fully characterize the beaches so that beach-compatible material can be identified in off-shore borrow areas. A total of 234 topographic profiles (winter and summer combined) surveyed normal to the beaches plus 889 sediment samples and 86 pebble counts (winter and summer combined) were collected and analyzed for the following beaches: 1) Barges Beach, Gosnold, East and Horseneck Beaches, Westport, Low and Miacomet Beaches, Nantucket, Surf Beach, Falmouth, Town Beach, Oak Bluffs (also referred to as Pay and Inkwell beaches) and Sylvia State Beach, Oak Bluffs and Edgartown during August/September 2014 and March, 2015; and, 2) Humarock Beach, Scituate, Nahant Beach, Nahant, Nantasket Beach, Hull, Peggotty Beach, Scituate, Plum Island, Newbury and Newburyport, Long Beach, Plymouth (referred to as Plymouth), Revere Beach, Revere, Long Beach, Rockport (referred to as Rockport), Fieldston/Brant Rock Beach, Marshfield (collectively referred to as Marshfield hereafter) and Salisbury Beach, Salisbury during August/September, 2015 and March, 2016. Sediment samples/pebble counts were collected at low tide, mid tide, and high tide positions, the berm crest and dune, if present. Between 2 and 10 profiles were surveyed at each beach, depending on the length of the beach, using a Topcon GTS 210 total station and/or a real time kinematic Trimble R8 Global Navigation Satellite System (GNSS) connected to the cellular network. Spacing between profiles ranged from 80 to 600 meters.

Results indicate that increased wave activity during winter strips sand from the intertidal zone. At cobble (till- and moraine-dominated) beaches (Horseneck, East, Barges, Town, Humarock, as well as parts of Nantasket, Peggotty, Marshfield and Plymouth) removal of a summer veneer of sand reveals larger grains below but little appreciable change in profile, whereas at finer-grained sandy beaches (outwash-dominated or extensive barrier beaches) significant loss of berm was observed (Low, Miacomet, Salisbury, and Plum Island). Less berm loss is noted as the deposits become progressively coarser (e.g., Sylvia, Oak Bluffs-Edgartown; Surf, Falmouth). Results of this work will be used to help determine which beaches can or will be nourished with sand from an offsite source.

A second objective of this work was to core backbarrier ponds at selected sites to obtain a record of overwash deposits corresponding to intense past storms and provide an estimate of the frequency of major events. Coring was completed at Miacomet Pond, Nantucket, East Beach, Westport, Bartlett Pond, Plymouth, Cambourne Pond, Rockport and a marsh behind Short Beach in Winthrop. However, only Bartlett Pond yielded a usable record suitable for analysis. Work on the core from Bartlett Pond reveals continuous long-term overwash deposits going back as far as 1000 years ago. Analysis of the Bartlett Pond cores show several major storm events that can be linked directly to historic storm events back to 1723. Furthermore, these large events appear to be associated with extra-tropical cyclones (sometimes called nor'easters), not tropical cyclones (hurricanes). This is in contrast to the south-facing shores of Massachusetts (and NYC) where large storm tides are dominated by tropical cyclones. These results point to the importance of considering all the differences in coastal conditions (tidal ranges, different storm populations, etc.) in assessing the return period of flood events. Furthermore, information gained from these

historic and sedimentary records also seem to suggest an underassessment of the recurrence interval of large flood events in the Boston area. Results emphasize the value in combining sedimentological, modeled and historical records of early historical floods for improving these assessments.

Introduction

The following is the technical report for Agreement M14AC00006: Massachusetts Geological Survey/University of Massachusetts – Sand Resource Assessment at Critical Beaches on the Massachusetts Coast. This project has two objectives:

1. Objective 1 is to fully characterize 18 public beaches in Massachusetts that are threatened by erosion or have important infrastructure that is at risk (Figure 1). This characterization includes surveying winter and summer beach profiles and collecting samples for grain size analysis so that beach-compatible material can be identified in off-shore borrow areas. This objective complies with the “sand resources needs assessment” goal of the Marine Minerals Program (MMP). Beach nourishment cannot proceed without an understanding of the existing beach profile and sediment characteristics.

2. Objective 2 provides a better understanding of the frequency of major erosion and overwash events at selected beaches by coring and dating the individual storm event layers within overwash fans. If a substantial investment is planned to nourish a beach it seems prudent to have some understanding of the frequency of overwash events before the investment is made. This objective addresses directly MMP’s goal concerning coastal restoration and resiliency.

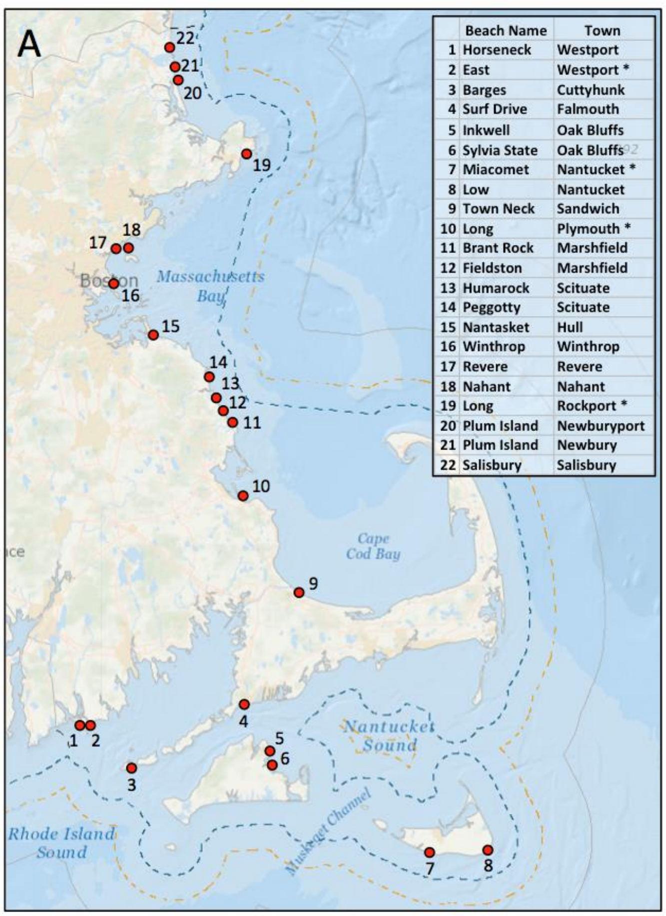

Figure 1. Location of beaches examined in this study. Note: Winthrop (16) and Town Neck (9) in Sandwich are not part of this study. In addition, for the purposes of this study, Brant Rock (11) and Fieldston (12) beaches are lumped as one beach called Marshfield and beaches 20 and 21 are also lumped as one beach (Plum Island) for the purposes of this study giving a total of 18 beaches. Inkwell Beach is synonymous with Town Beach, Oak Bluffs (5); Long Beach, Rockport is referred to as Rockport and Long Beach, Plymouth is referred to as Plymouth to avoid confusion.

Background and Relevance of This Project

Coastal communities in Massachusetts are vulnerable to erosion and relative sea level rise. Extensive development and armoring of shorelines, largely prior to coastal management regulations, have contributed to a severe reduction in the natural supply of sediment to beach systems, resulting in shoreline erosion and loss of dunes—which magnifies the vulnerability of the natural and built environment to coastal storms now and in the future. With accelerated rates of sea level rise and more frequent and intense storms, low-lying coastal areas are increasingly vulnerable to erosion, flooding, and inundation (Woodruff et al., 2013).

Nourishment has significant appeal over armoring approaches that interrupt natural sediment transport. Massachusetts sediment assets, within its nearshore navigation channels and offshore ocean areas, as well as adjacent federal waters, offer great potential for addressing the sediment deficit on beaches. While marine sediments are routinely extracted for beach nourishment and shoreline stabilization projects in other areas of the United States and across the globe, Massachusetts experience has been limited primarily to the beneficial re-use of compatible dredged material and nourishment using upland sources.

The Commonwealth of Massachusetts is now proactively promoting beach nourishment throughout the state. For example, the importance of this issue was recognized by the Coastal Hazards Commission, which was mandated by the state legislature to develop recommendations for addressing coastal hazards issues in Massachusetts. In 2007, the Commission recommended that Massachusetts should ***implement a program of regional sand management through policies, regulations, and activities that promote nourishment as the preferred alternative for coastal hazard protection*** (see www.mass.gov/czm/chc for background, more information, and the full list of recommendations). The 2011 Massachusetts Climate Change Adaptation Report also explicitly promotes the use of soft engineering approaches that supply sediment to resource areas, such as beaches and dunes, to manage the risk to existing coastal development while minimizing adverse impacts to coastal processes (see www.mass.gov/environment/cca for the complete report). In addition, the scope for updating CZM's 2009 Ocean Management Plan includes ***a task to identify appropriate locations for offshore sand resource areas for use as sources of sand for beach nourishment projects***.

Currently, there is an urgent need to assess the viability of nourishing threatened public beaches in the state. In order to advance the analysis and assessment regarding the potential use of offshore sand resources as a beach-nourishment and erosion-management tool, the stage needs to be set with a comprehensive characterization of the shoreline vulnerability and beach nourishment needs. The beach characterization work presented in this technical report focuses on characterizing publicly owned beaches with a history of storm damage. These beaches also have threatened infrastructure and no active management plan for considering the beneficial use of clean, compatible sediments from off-shore sources.

Beach characterizations are designed to provide critical data for informed determinations regarding the volume of sediment that will be required to nourish public beaches currently in the greatest need of protection. An accurate assessment for the viability of any future beach nourishment project therefore requires detailed grain size statistics of the native beach material.

Further, the needed fill volume for a beach is dictated by a beaches' slope and equilibrium profile extending off-shore to the depth beyond which changes in bottom elevation are minimal over seasonal-to-annual time scales (i.e. the depth of closure, Nicholls et al., 1998). The grain size distribution of a native beach is one of the primary parameters dictating this equilibrium profile (Dean, 2002), and in turn the volume of sand required to produce a desired extension in beach width. Currently grain size statistics for beaches at greatest risk along the Massachusetts coast are either limited or non-existent, thus placing significant restrictions with respect to assessing the volume of sediment required for their nourishment.

Grain size characterizations of native beach material are also vital to any environmental impact assessment for future nourishment, and critical for assessing potential use conflicts when initially evaluating the overall viability of a project. For example, rocky substrate is commonly viewed as critical habitat for native benthic flora and fauna, which presents a potential roadblock when seeking borrow material to nourish gravel and cobble beaches. Indeed, two of the most recent nourishment projects in the state were rejected due to local concerns on impacts to local benthic habitats. This included a nourishment project on the island of Nantucket that required 2.6 million cubic yards of material from an off-shore borrow site and the nourishment of a beach in the city of Winthrop.

Further, the process often most detrimental to a barrier beach is periods of extreme coastal inundation (Sallenger, 2000). The reoccurrence frequency of extreme coastal flooding must therefore be considered when making any long-term decisions on any nourishment project. Sediments along and behind a barrier beach provide critical information regarding past periods of extreme inundation (e.g. Boldt et al., 2010; Brandon et al., 2013; Donnelly and Woodruff, 2007; Mann et al., 2009; Toomey et al., 2013; Wallace et al., 2014; Woodruff et al., 2013; Woodruff et al., 2008a; Woodruff et al., 2008b, and abstracts by Brandon et al., 2013a; Brandon et al., 2013b). This project uses techniques employed in these past studies to provide regional assessments on the long-term reoccurrence frequency of extreme inundation along Massachusetts coastline.

Methods

All Massachusetts beaches included in this study were selected through close collaboration with the Massachusetts Office of Coastal Zone Management. All fieldwork was performed with permission of local and state authorities and scheduled based on guidance from the Massachusetts Department of Fish and Wildlife and Department of Conservation and Recreation to avoid endangered nesting shorebirds.

Beaches were surveyed along transects perpendicular to the shore following Massachusetts Office of Coastal Zone Management (CZM) beach nourishment guidelines (MassDEP, 2007). Spacing of transects was designed to capture full variability within these field areas and ranges from less than 100 meters in small field areas to approximately 800 meters between transects in large areas (Table 1). Transects for each beach were initially laid out in the office on the most recent orthophoto images available from MassGIS and equally spaced along the beach providing between 2 and 10 transects per beach. Transect heads were identified in the field using the orthophotos as a guide and then adjusted as needed depending on access and other obstacles or moved to capture beach characteristics. Once transect heads were identified and marked in the field, each transect head was located using a Trimble GeoExplorer 2008 series GPS unit to obtain UTM coordinates (UTM Zone 19T). Flags were set out from the transect head normal to the shore. Spacing of flags were set to capture breaks in slope and changes in surface material

Beach	Town	Coast	Months observed	Surface Material	Length (m)	# Tran-sects	Spacing (m)	# Sam-ples
Horseneck	Westport	south	August-September 2014, March 2015	sand-cobble	700	5	150	44
East	Westport			sand-cobble	400	4	80	34
Barges	Gosnold			sand-boulder	500	5	90	43
Surf	Falmouth			sand-gravel	650	5	150	40
Town	Oak Bluffs			sand-cobble	650	5	120	41
Sylvia	Oak Bl./Edgartn.			sand-gravel	3500	9	350	81
Miacomet	Nantucket			sand	1500	5	350	45
Low	Nantucket			sand	500	5	110	48
Salisbury	Salisbury	east	August-September 2015, March 2016	sand	5500	9	600	90
Plum Island	Newbury(port)			sand	3000	10	300	100
Long	Rockport			sand	900	4	220	24
Long/Nahant	Nahant			sand	2200	6	360	60
Revere	Revere			sand	3800	6	800	50
Nantasket	Hull			sand-cobble	5000	10	600	80
Peggotty	Scituate			sand	200	2	110	20
Humarock	Scituate			sand-cobble	4600	9	500	82
Brant/Fields.	Marshfield			sand-cobble	3000	9	380	54
Long	Plymouth			sand-cobble	4900	9	450	72

Table 1. Summary of surface material, total transect length and average spacing, and number of samples collected at each beach.

along the transect. On slopes, flags were set at the top of the slope, mid slope and at the bottom of the slope. The azimuth of the transect was measured with a Brunton compass so that the transect could be reoccupied in the next season.

In year 1, a TopCon GTS 210 total station and prism were used to survey in the flag positions. A baseline was established for each transect and used to survey the UTM coordinates of each flag. Vertical control was provided by tying the total station into nearby benchmarks in the network of National Geodetic Survey monuments or with local vertical control provided by the town and converted to North American Vertical Datum 1988, if necessary. Horizontal control of the flags is within approximately 1 meter and vertical control within 0.1 meters. In year 2, a Trimble R8 Global Navigation Satellite System, linked to the cellular phone network, was used to survey flag locations. This unit provides direct read out of UTM coordinates (Zone 19T) and elevation in North American Vertical Datum 1988. Horizontal accuracy is within 1 meter and vertical accuracy within 0.1 meters. QA/QC between winter and summer profiles was determined by plotting the profiles in excel and visually comparing the profiles. Any transcription errors were checked against field notes and UTM coordinates in Google earth.

Once data were collected and assembled in a table, the latitude and longitude of each point was calculated using an excel spreadsheet prepared by Steve Dutch, University of Wisconsin-Green Bay dated May 15, 2015. Data used in the conversion included: Datum WGS84, Polar radius 6,356,752.3 meters, Equatorial radius 6,378,137 meters, flattening (f) 0.003353, 1/f = 298.257, UTM Zone 19T, Central meridian -69 degrees, false easting = 500,000, eccentricity = 0.081819, scale factor = 0.9996, mean radius = 6,367,436 meters. The complete method and formulas used to make the UTM to geographic coordinate conversion can be found in Karney, Charles F.F., 2010, Transverse Mercator with an accuracy of a few nanometers, http://geographiclib.sf.net/tm.html Once latitudes and longitudes were calculated the resulting text files were imported into ArcGIS version 10.03 and converted to shapefiles. In addition, Google Earth KMZ files were also exported from ArcGIS to allow easy viewing of transects on Google Earth images.

Low tide, mid tide, high tide, berm crest and dune positions were identified in the field by a field geologist. Procedures for sampling followed CZM guidelines (MassDEP, 2007). Samples were collected from the top 1 foot of the beach using a shovel. The volume of sample collected depended on the coarseness of the beach material and was collected on the following schedule: a) 100% sand beaches, 1 quart sample bag; b) beaches comprised predominantly of sand but contain a trace to a little very fine to fine gravel, 1 gallon sample bag; c) for beaches comprised of more than 25% gravel and a trace of cobbles, a 2 to 5 gallon bucket was collected; and, d) for beaches comprised of greater than 80% gravel, cobbles or boulders, a pebble count, following the method of Wolman (1954) as described by Kondolf et al. (2003), was performed in the field and no sample was collected (http://onlinelibrary.wiley.com/doi/10.1029/TR035i006p00951/epdf). A minimum of 50 stones were tallied for each pebble count.

The Wolman method uses a gravelometer for tallying different sizes and ranges from 4 mm to greater than 362 mm. The distribution of the varies sizes is determined by randomly selecting the first stone or grain you touch with your finger near the toe of your foot, picking it up and passing the intermediate dimension through the appropriate opening in the gravelometer. These data are then tallied into a cumulative frequency of the number of stones in different size classes and plotted on a grain size distribution curve. If the sampled stones are of the same density, which is assumed, the results obtained are comparable to the distribution by weight. For more information on how to process and plot pebble count data see:
http://www.gulfofmaine.org/streambarrierremoval/Stream-Barrier-Removal-Monitoring-Guide-12-19-07.pdf

In this study, the Wolman method was used for this planning-level project in place of ASTM D-422 (Standard Test Method for Particle-Size Analysis of Soils) because of the large volume of sample required for sieving cobble and gravel dominated samples. Traditional grain size analysis (ASTM D-422) should be used for any site-specific projects, consistent with MassDEP's Guide to Best Management Practices for Projects in Massachusetts, Technical Attachments (2007).

Collected samples were returned to the lab and washed to remove salt and organic debris. Samples were washed with a volume of water equal to approximately 12 times the weight of the sample. Once washed samples were dried. Dried samples were then sieved at 4 mm to separate very fine gravel and sand from the coarser material. The coarser material was then sieved at 60 mm to separate gravel from cobbles and then at 256 mm to separate boulders from cobble. At each step the masses were weighed. The plus 4mm material was sieved following ASTM D-422 and using the following meshes: 362mm, 256mm, 180mm, 128mm, 90mm, 60mm, 45mm, 32mm, 25mm, 16mm, 12mm, 9mm, 6mm. Each fraction was weighed and the percent passing determined. The less than 4mm fraction was split to reduce the size to about 25 to 100 grams. The final split was passed through a Retsch Technology Camsizer. This instrument provides high resolution grain size and shape information on particle sizes ranging from 4mm to 0.3 nm. Grain size distribution data are considered reliable if the % difference in sample weights prior to processing and after processing is within 1%. If they are not within 1% the error is investigated by the lab technician and resolved. All data in this study are within 1%.

The output from the camsizer provides files in .xle format, which are readable in Excel. Each .xle file in the dataset provides the total mass of the greater than 4mm fraction, total mass of the less than 4mm fraction, percentage of sand fraction, number of splits to reduce size of the less than 4 mm fraction so it can be put into the Camsizer, D_{10}, D_{50}, D_{90} of the less than 4 mm fraction, cumulative distribution, sphericity, symmetry, aspect ratio, proportion (%) of samples with sphericity less than 0.9, proportion (%) of samples with symmetry less than 0.9, proportion (%) of samples with aspect ratio less than 0.9, and number of particle detections.

The camsizer data and sieved plus 4mm fractions were then combined using a script developed in Matlab R2011b (version 7.13.0.564) to produce data tables and plots of grain size versus percent passing. This dataset contains two outputs: 1) a table of data with the grain size, in mm, and the percent passing each grain size; and, 2) a plot showing the cumulative percent passing (percent passing vs. grain size, in mm), a google image showing the transect and location along the transect where the sample was taken including the latitude and longitude of the point, and a profile (cross section) of the beach showing the elevation position of the sample along the transect (Figure 2).

Cores were taken from deposition centers in four back barrier ponds and one marsh. Three cores were acquired from Miacomet Pond on Nantucket, 5 cores at Bartlett Pond behind Whitehorse Beach in Plymouth, 2 cores in Cambourne Pond behind Pebble Beach in Rockport, and a marsh adjacent to Short Beach in Winthrop. Attempts were made to acquire cores in the pond behind East Beach in Westport but too many boulders and cobbles were encountered so the site was abandoned.

Prior to coring bathymetric data was collected in a canoe using a fish finder attached to a hand-held Garmin GPSmap 76S GPS unit. Horizontal accuracy is less than 15 meters. Vertical accuracy with the fish finder is approximately 0.1 meters. The purpose of this bathymetric survey was to locate the best coring locations. Optimal coring sites are those with deep deposition centers that are not in high energy environments and have experienced no human disturbance. Cores were collected using a modified Vohnout/Colinvaux piston corer mounted on a twin canoe coring platform. Typical sediment recovery was 2 to 5 meters. Cores were taken in overlapping ~2 meter sections (ie., D1, D2, etc.). These sections were later cut into 150 cm lengths or less for ease of analysis (ie., 1 of 2, 2 of 2).

Once collected, core sections were transported to the University of Massachusetts and refrigerated until analysis. In the lab, cores were opened and submitted to additional laboratory analyses including X-ray fluorescence (XRF) measurements using a newly acquired Cox Analytical Systems ITRAX XRF core scanner at the University of Massachusetts. The XRF core scanner provides non-destructive, high-resolution (~100 µm) characterization of the bulk elemental composition of sediment and X-radiograph images for cores. This XRF technique has proven to be highly effective by the lead-PI’s lab group in identifying overwash deposition (e.g. Donnelly and Woodruff, 2007; Woodruff et al., 2008a; Woodruff et al., 2009), including event deposits from Hurricane Sandy in backbarrier environments (see published abstracts by Brandon et al., 2013a; Brandon et al., 2013b).

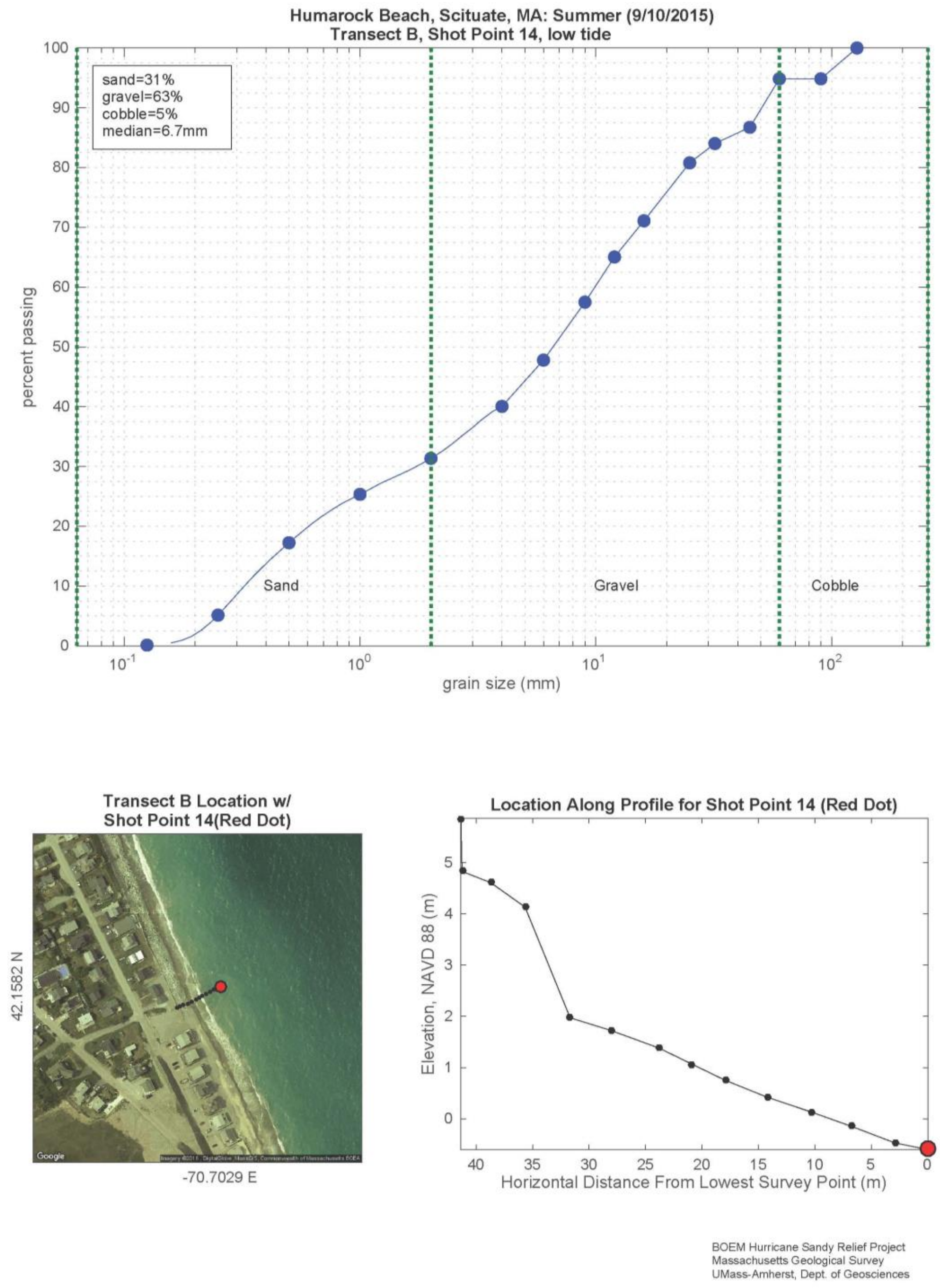

Figure 2. Example of grain size distribution plot (top) from Transect B, low tide sample in summer 2015 collected at Humarock Beach, Scituate, Massachusetts. Also shown is the location of the sample on the transect (lower left) and location of sample along the beach profile (lower right).

The XRF scan provides relative abundances of 33 elements. Elements such as lead are used as proxies to look for changes in lithology, onset of industrialization, changes in energy regime and changes in the source of deposition. X-radiographs provide a means of identifying sandy layers within the core at high resolution. The sand layers indicate individual storm events, which when linked with an age model, extend the coastal storm flood record back in time beyond the instrumental and historic record.

Based on the x-radiographs, the best core exhibiting a clearest record of sandy overwash and no disturbance was core BAP6 from Bartlett Pond. Therefore, all additional analyses were performed on core BAP6. BAP6 was subsampled at a minimum of every 3 cm at 1 cm resolution and sieved for coarse percentage (greater than 32 microns and 63 microns). Coarse percentages greater than 63 microns of sandy deposits were analyzed on a Retsch Technology camsizer to determine grain size distribution. Additional subsamples were taken from the core to determine organic content via loss on ignition. These subsamples were dried, weighed and then burned at 550 degrees Celsius for 5 hours, cooled and weighted again. The change from dry weight to burned weight compared to the initial dry weight is the loss on ignition and assumed to be related to the percent organic matter.

Temporal constraints on sediment deposition were determined using radiocarbon, cesium-137 (^{137}Cs), and the onset of industrial heavy metals (such as lead). Bulk heavy metal profiles obtained by the XRF core scans were utilized to identify sediments deposited during the industrial era (e.g. Boldt et al., 2010; Woodruff et al., 2013). The global onset of ^{137}Cs in the sediment record corresponds to 1954, or the start of atmospheric nuclear weapons testing, and the peak in ^{137}Cs dates to 1963, or just prior to the signing of the Nuclear Test Ban Treaty. ^{137}Cs was measured using a Canberra GL2020R Low Energy Germanium Detector. Sediment samples with a dry mass greater than 2 grams were powdered, put in 6 cm diameter plastic jars, and counted for 48-96 hours. ^{137}Cs activities were computed spectroscopically using the 661.7 keV photopeak. In the Northeastern U.S., concentrations of heavy metals increase significantly in sediment between 1850 and 1900, corresponding to the rise of factories during the Industrial Revolution. Depth profiles of lead were employed to identify the depth of this industrial horizon. Lead content was measured in all cores with the ITRAX Core Scanner using a Molybdenum tube and operating at 30 kV and 55 mA for 10 seconds per measurement. Measurements of unsupported ^{210}Pb activity ($t_{1/2}$=22.3 yrs) will provide further temporal constraints over the last 100 yrs (e.g. Woodruff et al., 2013; Toomey et al., 2013).

To extend ages beyond heavy metal and ^{137}Cs derived constraints, radiocarbon dates were obtained at sediment depths of 73.5, 125.5, 223, 289.5 and 482.5 cm. Carbon 14 dates were analyzed at the National Ocean Sciences Accelerator Mass Spectrometry lab at Woods Hole, Massachusetts. The radiocarbon age with 1 sigma uncertainties was converted to calendar age probabilities using the IntCal13 radio- carbon calibration curve. Monte Carlo simulations were employed to derive Bayesian age constraints between chronological controls. For each of the large number of simulations a discrete age is drawn randomly from the sample's obtained probability radiocarbon-derived distribution. A specific age is defined for the 1963 and 1954 ^{137}Cs constraints, and a randomly drawn age between 1850 and 1900 for the heavy metal onset, with probabilities evenly distributed over this 1850 -1900 interval. A date of 2014 was also defined at the top of the core. Random ages were generated at random depths between the radiocarbon, ^{137}Cs, and heavy metal control points such that ages increase monotonically with depth (i.e. no age reversals). The median of all simulations for a particular depth is defined as the most likely age, with bounds presented for 68% and 95% uncertainties. A complete description of the age modeling procedure is described in Brandon, C., Woodruff, J.D., and Donnelly, J.P., 2014, How Unique was Hurricane Sandy? Sedimentary Reconstructions of Extreme Flooding from New York Harbor. Scientific Reports (http://www.geo.umass.edu/faculty/woodruff/Publications_files/Brandon_etal_ScientificReports2014.pdf)

Results

Year 1 - South Coast

Seasonal changes in beach grain size vary with surficial geology (Figure 3). Beaches near till or moraines (East, Horseneck, Barges, Town and Sylvia) are characterized by a mixture of sand, gravel, and cobble, whereas beaches adjacent to glacial outwash (Surf, Miacomet, Low) are cobble free (Table 1). Grain size of berm and dune facies show little change from summer to winter. Cobble armors the high tide/berm facies transition year-round at Barges Beach, East Beach and Horseneck Beach, and fore dunes at Horseneck and Barges Beaches are cobble-veneered (Figure 4). Upper beach facies at Surf Beach, Town Beach and Sylvia State Beach are sandy with gravel interspersed, and berm and dunes at the Nantucket beaches are composed exclusively of sand.

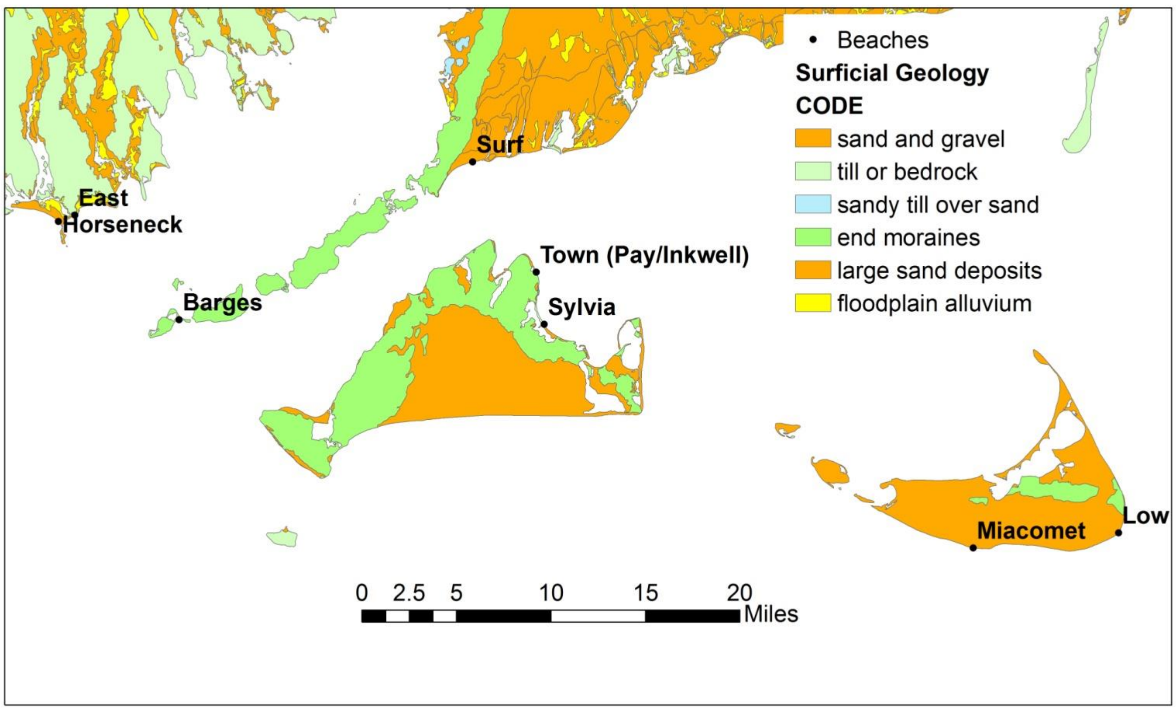

Figure 3. Surficial geology of Massachusetts south coast (Stone and DiGiacomo-Cohen, 2010) showing study sites adjacent to till/moraine and outwash. Figure reproduced from Venti et al. (2015).

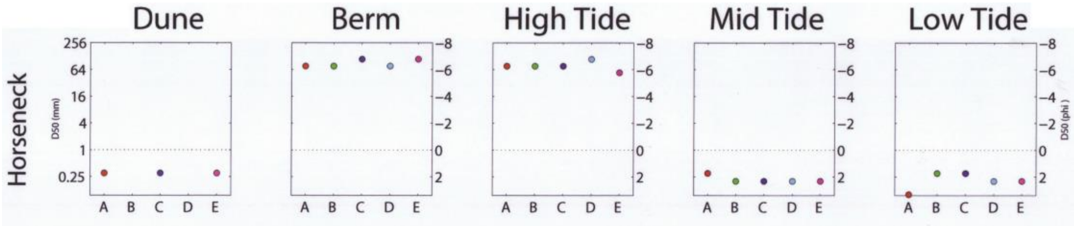

Figure 4. Median grain size at Horseneck Beach, summer 2014. Cobble dominates berm and high tide facies; fine and medium sand characterize low and mid-tide facies (from Venti et al., 2015). Letters are transects, mm on left y-axis, phi scale on right y-axis.

Grain size becomes coarser in the intertidal zone during the winter compared to summer, particularly at the low tide facies (Table 2). Sand or very fine gravel form a veneer at all beaches in the summer but beaches derived from till/moraines (East, Horseneck, Barges, Town) show a significant coarsening in the winter (Table 2). Intertidal zones at beaches derived from distal outwash deposits (Low, Miacomet, Surf) show little to no change in grain size from summer to winter (Table 2).

Table 2: Summary of profile and median grain size changes on south coast beaches in Year 1.

Beach	Range of winter retreat (m)	Average winter retreat (m)	summer low tide grain size (ϕ)	Winter low tide grain size (ϕ)	LT Grain size change (ϕ)
Horseneck	-1 – 4	1	medium sand (1 – 2)	very fine gravel (-2 – -1)	-3
East	-3 – 3	0	coarse sand (0 – 1)	medium gravel (-4 – -3)	-4
Barges	-2 – 5	1.2	medium sand (1 – 2)	fine gravel (-3 – 2)	-4
Surf	0 – 2	1.2	very fine gravel (-2 – -1)	fine gravel (-3 – -2)	-1
Town	0 – 4	2.1	coarse sand (0 – 1)	coarse gravel (-5 – -4)	-5
Sylvia	-5 – 2	-0.7	very fine gravel (-2 – -1)	very fine gravel (-2 – -1)	0
Miacomet	-10 – 20	10	coarse sand (0 – 1)	coarse sand (0 – 1)	0
Low	-10 – 5	0	coarse sand (0 – 1)	coarse sand (0 – 1)	0

Berm and intertidal facies generally migrate landward along the south coast beaches during winter (Table 2). At cobble- and gravel-bearing beaches (Horseneck, East, Barges, Surf, Town, and Sylvia), these facies migrate short distances, <5 m at individual transects, with average landward migration distances between -0.7 and 2.1 meters (Table 2). Seasonal profile variability is more dynamic at beaches that lack these larger, less mobile grains. Facies at Miacomet Beach and Low Beach, composed exclusively of sand, migrate the farthest, up to 20 meters on two transects on Miacomet Beach (Table 2, Figure 5).

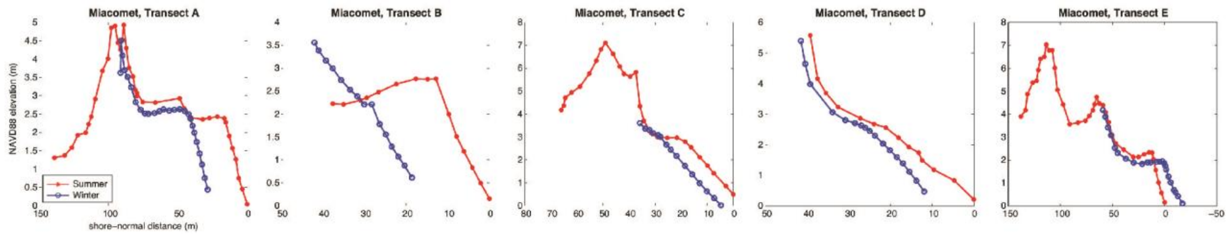

Figure 5. Shore-normal transects at Miacomet Beach illustrate landward retreat of intertidal and berm facies from summer (red) to winter (blue) in an environment lacking gravel and cobble (from Healey et al., 2015).

External factors might explain cases that do not fit the patterns described above. For example, Sylvia State Beach showed little change between winter and summer profiles and no change in median grain size. It is understood that sand may have been added to a portion of Sylvia State Reservation in October, 2014, between summer and winter surveys, possibly resulting in the minimal change in profile observed. Similarly, transects C and D at Low Beach showed an enhanced winter profile possibly due to the intersection of southward and eastward directed long-shore transport at that location (Figure 3). In general, grain size and profile results indicate a net loss of finer grains (sand) from beaches during the winter.

Year 2 – East Coast

East-facing beaches showed similar trends as observed on south-facing beaches, however, the changes between summer and winter in Year 2 were not as dramatic as Year 1. The difference may be explained by fewer winter storms in Year 2. Gradients, particularly in upper facies (berms and dunes), were steepened due to incision by wave action. However, in many cases the volume removed appears to be redistributed to lower facies resulting in a change in the profile but not a major change in net sediment volume. In select areas, for example, the mouth of the Merrimack River at Plum Island near Transects A and B and also further south in the bluff at Transect I, there was dramatic loss of sediment. In these cases, the loss of material extended into the dune indicating this magnitude of loss exceeds the expected seasonal cycle. A coarsening of material was observed in many locations between summer and winter indicating winnowing of finer sediment (i.e., sand size material) during the winter season. In addition, the most dramatic change in profile corresponds to sections of beach lacking coarser material (cobble and coarse gravel). In general, the pattern of coarse material associated with neighboring source areas of glacial till is generally consistent with that observed on the south shore. However, this pattern is not as well developed as on the south coast. The east coast beaches exhibit greater heterogeneity in the surficial materials than the more expansive surficial deposits found on the south shore.

Coring Results

The cores from Miacomet Pond on Nantucket and Cambourne Pond in Rockport could not be used for detailed analysis. The Cambourne Pond core was too shallow and was located in too energetic an environment. In other words, the deposits were disturbed by every large storm preventing preservation of any record of historic events. At Miacomet Pond, periodic opening of the barrier beach to flush the system eroded the sediments producing a gap in the sedimentary record; the core is not continuous. Only Bartlett Pond core BAP6 provided the best continuous sediment record (Figure 6).

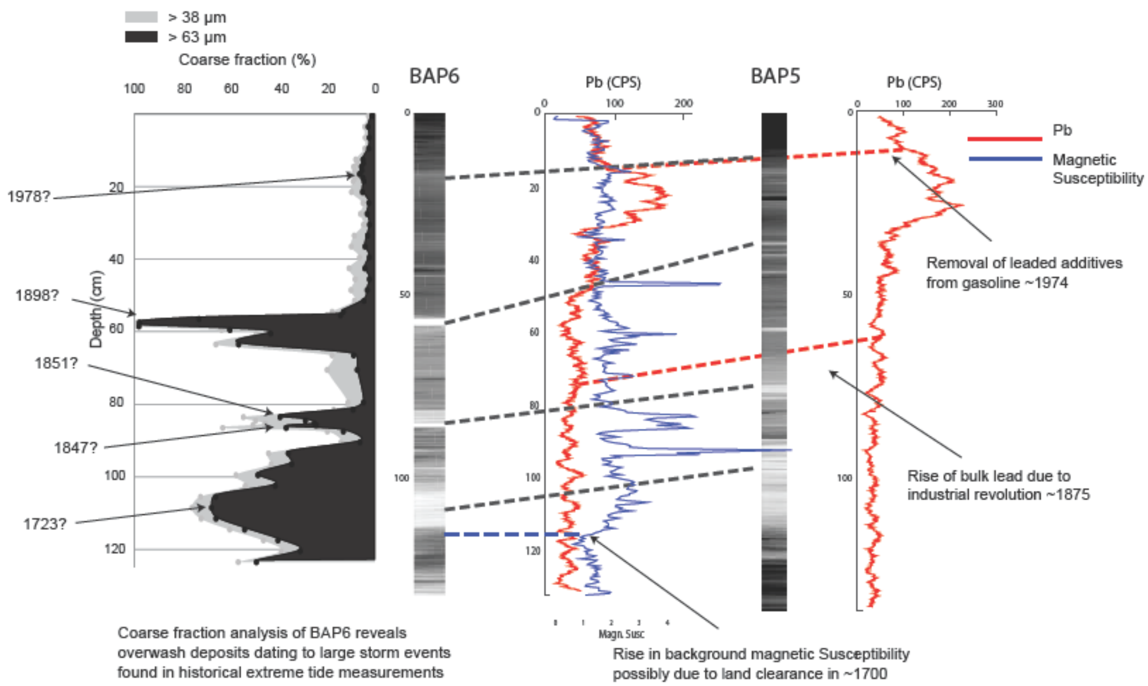

Figure 6. Results of core scans and grain size analyses on cores BAP5 and BAP6 from Bartlett Pond. Grain size analyses on core BAP6 (left) showing sand peaks associated with storm events. Lead and magnetic susceptibility help constrain the age model for each core. Bright sections in core scan represents sandier storm event layers (from Stromer et al., 2015).

Results from Bartlett Pond indicate the pond preserves a 1000-year record of extreme events. Historic coastal flood events recorded in the core, among others, include the Blizzard 1978, the Christmas Storm of 1909, the 1851 Minot Light storm, Benjamin Franklin's eclipse storm of 1743, and a particularly large storm in 1723 recorded by the Reverend Cotton Mather. The data also suggest an increase in extra-tropical events causing large floods north of the Cape prior to 1909. This record of coastal flood events near Boston extends our knowledge of known extreme events back at least 300 years. In addition, analysis of dating, historic records and review of the instrumental tide gauge records on the east-facing shores of Massachusetts indicate that these coastal flood events are dominated by non-tropical cyclone events and generalized extreme value theory (GEV) seems to describe the data reasonably well (Figure 7). However, data from the south-facing shores show that the largest events are predominantly tropical cyclones. Standard GEV analysis fails for the southern facing shore due to the mixture of two different populations of storms (i.e. tropical and extra-tropical), whose flooding behavior is different along southern facing coastlines of New England.

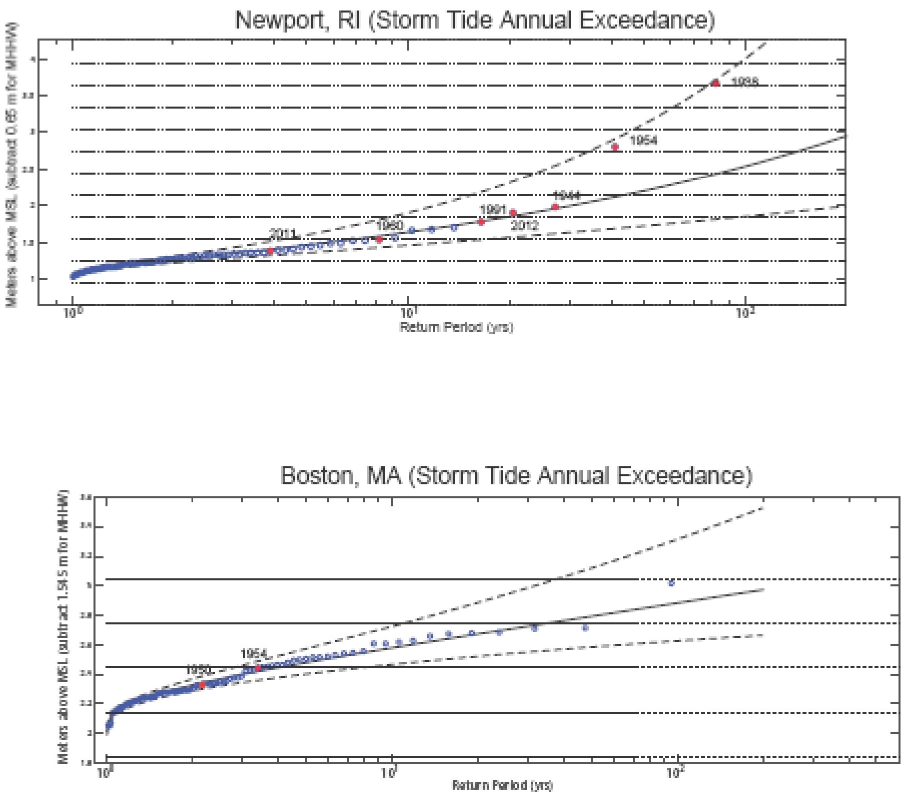

Figure 7. Comparison of storm tide annual exceedance from hourly tide data for Newport, RI (south-facing shores) and Boston (east-facing shores). Blue dots are extra-tropical nor'easters and red dots are tropical cyclones. Curves to the data are fit using the three-parameter Generalized Extreme Value (GEV) function (from Stromer et al., 2015).

Conclusions/Implications

Topographic profiles and grain size analyses performed on sediment samples collected at 18 Massachusetts beaches that are currently experiencing erosion were taken during the summer and winter to evaluate seasonal and spatial variability. This information will be used primarily to match native-beach material with compatible offshore sand resources for beach nourishment projects.

Results suggest that nearly all beaches lose a veneer of sand size particles in the winter but that initial beach grain size distribution and seasonal profile changes are a function of coarseness and proximity to glacial till exposures. Beaches derived from till or moraines are coarser initially, often become coarser in the intertidal zone during winter but show 2.5 meters or less of retreat in the winter. In contrast, beaches comprised exclusively of sand show significant (up to 10 to 20 meters) retreat in winter, depending on location, but no change in grain size with season. Beaches that are comprised of sand but contain more fine gravel and gravel facies fall in between these extremes with some coarsening in the intertidal zone during the winter and some winter retreat. Results indicate that matching native-beach material with offshore sources spans a broad spectrum of grain size distributions that exhibit different seasonal behaviors.

Core BAP6 obtained from Bartlett Pond in Plymouth reveals a continuous long-term sediment record. Analysis of the Bartlett Pond core shows several major storm events that can be linked directly to historic storm events back to 1723. Furthermore, these large events appear more frequent prior to 1909 and are associated with extra-tropical storms, not hurricanes. This is in contrast to the south-facing shores of Massachusetts where storm tides appear to be a mixture of both nor'easters and tropical hurricanes. The implication is that perhaps more attention needs to be paid to understanding the frequency and likelihood of future extra-tropical storm events for Boston and all east-facing shores as these may be the greater flood hazard. This record of coastal flood events near Boston extends our knowledge of known extreme events back at least 300 years. These events suggest an under-assessment of risk of flooding if that risk is based solely on the instrumental record.

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