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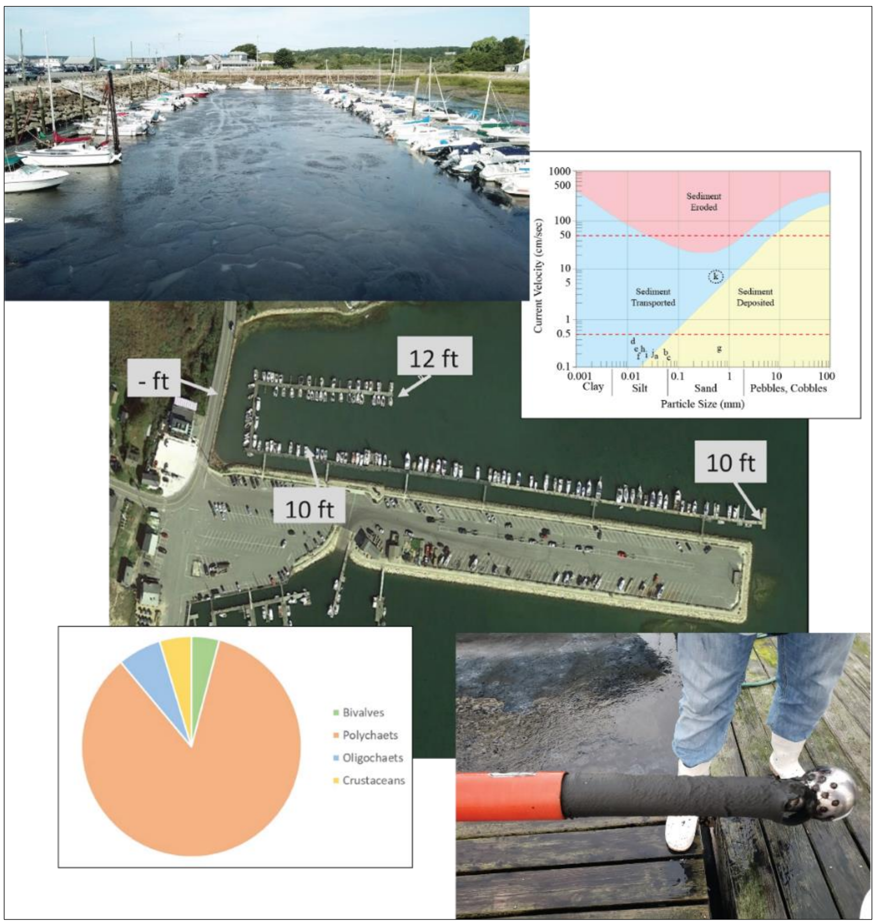
‘Black Mayonnaise’ in Wellfleet Harbor: What is it and where does it come from?



May 2020

Report prepared for the Natural Resources Advisory Board, Town of Wellfleet by the Coastal Processes and Ecosystems Laboratory at the Center for Coastal Studies.

Report: 20-CL02

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1. Key Findings

- "Black Mayonnaise", a common term for black, fine sediment, has an informal definition attached to it: "A dispersion of fine-grained, highly contaminated particles that is devoid of all normal aquatic life, and is composed of human waste floatables, oily slicks, chips of asbestos, arsenic, copper, lead, and mercury and industrial garbage" (United States Army Corps of Engineers 2001). While this description is not peer-reviewed, it speaks of "black mayonnaise" in terms of anthropogenic pollution that is not only toxic for humans but also for any aquatic life. It is therefore important to state that **the material in the Wellfleet Harbor marina is not "black mayonnaise"**. For lack of a better term it will be referred to as "black custard" in this report.
- The material analyzed was **high in organic matter** (derived from marine vegetation) and **low in species diversity** compared with data sample at a control station at "The Gut" and data previously collected in 2015. A total of 13 species were found, 6 of which are worms common in silty, low oxygen sediment.
- Core sampling showed that the size of the layer of *black custard* varies between 8 feet, south of the pier, and 12 feet in the center of the Wellfleet Harbor basin. The grain size of the material analyzed shows a clear difference between samples collected north and south of the pier (silt-sized particles) and samples collected at "The Gut" (sand-sized particles). Based on the locations of the sampling stations of this project, ***black custard* is predominantly in and around the town pier.**
- Stable isotope analysis showed **marine plants** such as algae, to be the main source of carbon in the sediment. Stable nitrogen isotopes were traced back to **rain and soil runoff**. Results of the stable sulfur isotope analysis were obscured by high activity of sulfur reducing bacteria which has the potential to deplete stable sulfur isotopes by as much as 20 - 60‰, however, **the overall sources of the material analyzed are marine** in nature.
- Sediment sizes are coarser in the lower parts of the core samples indicating that stronger current velocities were at work when the channels were deeper. **Sediment deposition in the boat basin is likely a result of the *flocculation* of clay and silt-sized material**. Flocculation can be promoted by several factors and understanding those drivers may be a direction of possible future work that could provide insights to managers into future depositional events in the boat basin and other places in the Harbor.

2. Introduction and Study Area

2.1. History of Wellfleet Harbor

The morphology of Cape Cod in general, and Wellfleet Harbor in particular, is primarily the result of late Pleistocene glacial deposition by the retreat of the Laurentide ice sheet, and coastal processes in response to climate change and subsequent sea level rise (Uchupi et al. 1996). The ice at the last glacial maximum (28,000 – 26,000 years ago) in New England was approximately 500 m thick, and the sea level was approximately 120 meters below present sea level (Oldale and Barlow 1986, Uchupi et al. 1996, Peltier and Fairbanks 2006).

The local ice sheet consisted of three lobes controlled by the topography of underlying bedrock (figure 1-A). The Narraganset Bay – Buzzards Bay lobe occupied the Narraganset Basin, and retreated generally westward. The Cape Cod Bay lobe occupied Nantucket Sound and Cape Cod Bay (Oldale and Barlow 1986).

Glacial meltwater streams formed the expansive and relatively flat plains of Truro, Wellfleet and Eastham (figure 1-B). Near the ice margin, sediment was deposited over and around stagnant ice. When the ice melted back, these deposits collapsed, forming a surface of irregular topography with steeply sloping topographic highs and lows (Oldale and Barlow 1986).

Wellfleet Harbor occupies a part of a large ice block depression that formed as stagnant ice melted (Oldale and Barlow 1986). Sediment deposited in holes or depressions in the ice formed Griffin Island, Great Island and Great Beach Hill. By about 14,000 years BP northeastern Massachusetts was ice free (Uchupi et al. 1996).

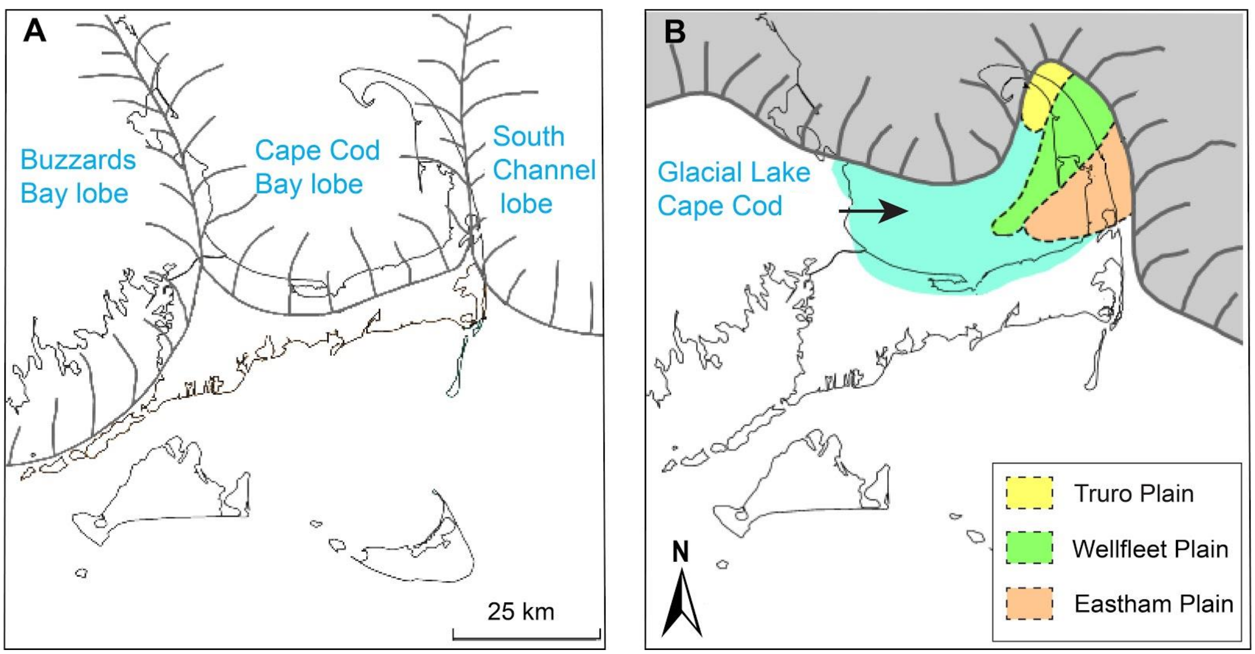

Figure 1. A. The three lobes of the Laurentide ice sheet in the Cape Cod Region at approximately 21,000 BP (modified from Oldale and Barlow 1986). **B**. Glacial Lake Cape Cod and the formation of the plains of lower Cape Cod, at approximately 18,000 BP, (Poppe et al. 2007, Balco et al. 2009), modified from Oldale and Barlow (1986).

A barrier spit extending from north to south partially encloses the harbor from Cape Cod Bay (figure 1). The spit is composed of islands connected by sediment entrained and deposited in the direction of net sediment transport, from north to south.

Wellfleet Harbor is a natural harbor providing a safe port for fishing and recreational vessels since 1644. The marina at Town Pier, as well two anchorages, are operated by the Town of Wellfleet and provide major economic benefit for the town. They are used by commercial fishing and charter boats and private boaters. The town marina is located north of the town pier and can be accessed via the south and north access channels. The area has been subject to numerous dredging projects, environmental studies and monitoring effort. The basin was created in the late 1950s when the channel south of Town Pier was extended and dredged to -6 ft MLW. More dredging north of Town Pier occurred in 1958 (300 ft wide, -7 ft MLW), 1968 (-8 ft MLW, 170 ft wide) and 2001(-6 ft MLW).

2.2. Black Mayo definition

The earliest records on "black mayonnaise" can be found in a 1974 hearing on "Sewage sludge Hazard to Long Island beaches" before the subcommittee on environmental pollution of the committee on public works (93rd congress 1974). Dr. William Harris (Geology Dept. at Brooklyn College) describes material in an offshore sewage dump site as resembling "frothy black mayonnaise containing considerable sand." He goes on saying "This is the infamous Dead Sea, or more properly Dead Sea floor."

It is mentioned again in a 1994 letter by the Rhode Island Department of Transportation to the U.S. Army Corps of Engineers concerning a proposed maintenance dredging project in Providence River and Harbor: "The dispersion of fine-grained, highly contaminated particles is a major concern. A previous study by the EPA indicated that fine-grained, high water content dredges materials (anecdotally called "black mayonnaise") was dispersed outside the disposal area study." (United States Army Corps of Engineers 2001).

P. Aarne Vesilind and Thomas D. DiStefano describe "the scum floated to the shore, and the sludge settled to the bottom where it formed a "black mayonnaise" that was devoid of all normal aquatic life." When they talk about the situation at the Deer Island Wastewater Treatment Plant in the 1980s in their book "Controlling Environmental Pollution" (Vesilind and DiStefano 2006).

The San Francisco Estuary Institute states that "Boston Harbor for many years was fouled by human waste floatables, oily slicks, and decaying pier pilings. Sludge turned the outgoing tide black, and the bottom of the harbor was characterized as "black mayonnaise." (Connor 2005).

Most recently "black mayonnaise" is mentioned in connection with the Gowanus Canal, a designated Superfund site with $506 million to fund its clean up: "But before the polluted stew that inhabits the foundation of the canal (called "Black Mayonnaise" and composed of, in part, chips of asbestos, plus some arsenic, copper, lead, and mercury) can be dredged and removed next year, the industrial garbage that’s been dumped into the water over the years has to be plucked out of it first.” (USEPA 2013, Rinn 2016).

While all these instances are anecdotal references and do not offer an official, peer-reviewed definition of “black mayonnaise”, they all speak of it in terms of anthropogenic pollution that is not only toxic for humans but also for any aquatic life. It is therefore important to state that the material in the Wellfleet Harbor marina is not “black mayonnaise”. For lack of a better term it will be referred to as *black custard* in this report.

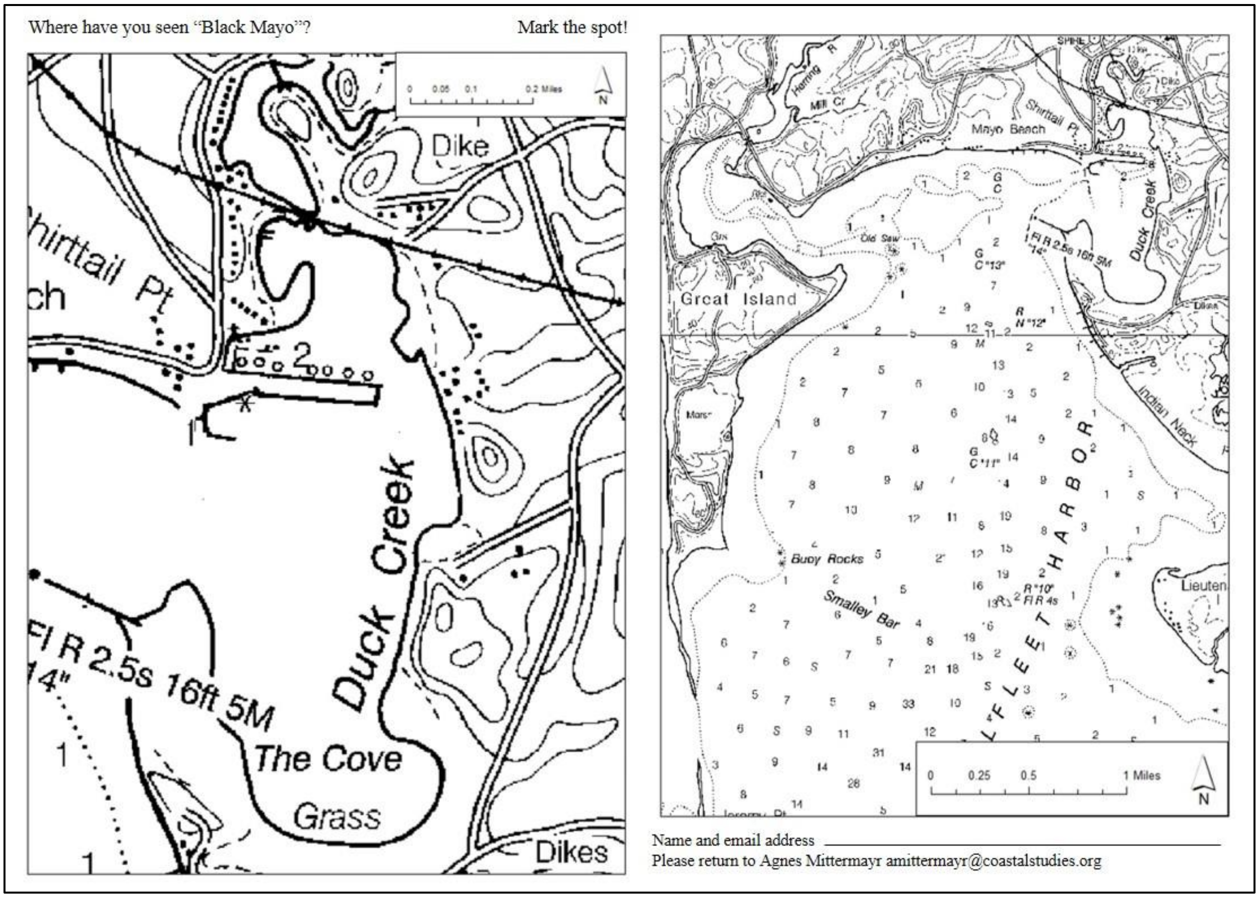

Figure 2. In order to move beyond anecdotal evidence “mark the spot” maps were used for local managers and stakeholders to document affected areas.

2.3. Goals of this project

The Natural Resources Advisory Board from the Town of Wellfleet asked scientists at the Center for Coastal Studies to conduct a study concerning the material that is filling in the boat basin north of the Town Pier in Wellfleet. The goal of this project is to answer the following five questions surrounding *black custard* in Wellfleet Harbor: (1) Where is it? (2) What is it? (3) How dense/thick is it? (4) Where does it come from? and (5) How does it move? To answer the proposed questions, data were collected for biological, geological and chemical analysis from within affected areas and at a reference site. Data from the Center's biweekly water quality monitoring program, run by Dr. Amy Costa, in Wellfleet Harbor will be incorporated to supplement this study.

3. Methods

To address the five questions originally proposed (1. Where is it? 2. What is it made of? 3. How thick is the layer? 4. Where does it come from? 5. How does it move?) invertebrate samples, sediment samples, stable isotope samples and water samples were collected at five locations in Wellfleet Harbor.

Choosing sampling stations was influenced by the first question: Where is it? In order to include anecdotal evidence, we asked local manager, stakeholders, and other interested parties to "mark the spot" on maps of Wellfleet Harbor (figure 2).

Based on their answers and accessibility of the area, we chose three locations in the boat basin (stations 1 - 3), one location by the wharf (station 4) and one control station in "The Gut" (station 5) (figure 3).

Figure 3. Map of the five stations sampled for this project. The star symbol indicates station WH17.

In order to tackle question number 2 (what is it?) core and grab samples were collected at five stations. Surface samples were collected with a ponar grab (sample area: 152 mm x 152 mm, sample volume 2.4 liters). Core samples were collected at depth with a corer. In this case an auger, designed and constructed specifically for this project by Steve Swain and dubbed the 'mud wand' (figure 4). The corer has an auger that rotates within an aluminum tube that has a waterproof stopper at the bottom. Upon arrival at the sample site, a surface grab sample was collected. Then the first core sample was taken at the deepest depth possible. The corer was pushed down into the subsurface, when the corer reached ‘refusal’ depth, the point at which the core could not be lowered further due to hitting ‘a hardbottom’ a sample was collected. Gradations on the outside of the tube allow the user to document depth of sediment, thus answering question number 3 (how thick is the layer?). The material immediately outside of the tube is brought into the tube via the rotation of the auger. The tube is then closed, extracted and the material was returned to the surface without contamination from other layers. The sample is removed from the instrument and the entire device was washed inside and out as to not contaminate the next sample. The core was then lowered to half the depth of the ‘deep’ sample. The ‘middle’ sample was collected, and the process was repeated at the next site.

Surface samples were analyzed for invertebrate diversity and abundance. Each replicate was sieved at 1mm (Hemery et al. 2017, Mittermayr et al. 2020), smaller objects were discarded according to laboratory guidelines, larger objects were stored in 70% ethanol and stained with Rose Bengal until later identification. Invertebrates were counted and identified to species level when possible. The specimens are stored in 95% ethanol at the Center for Coastal Studies.

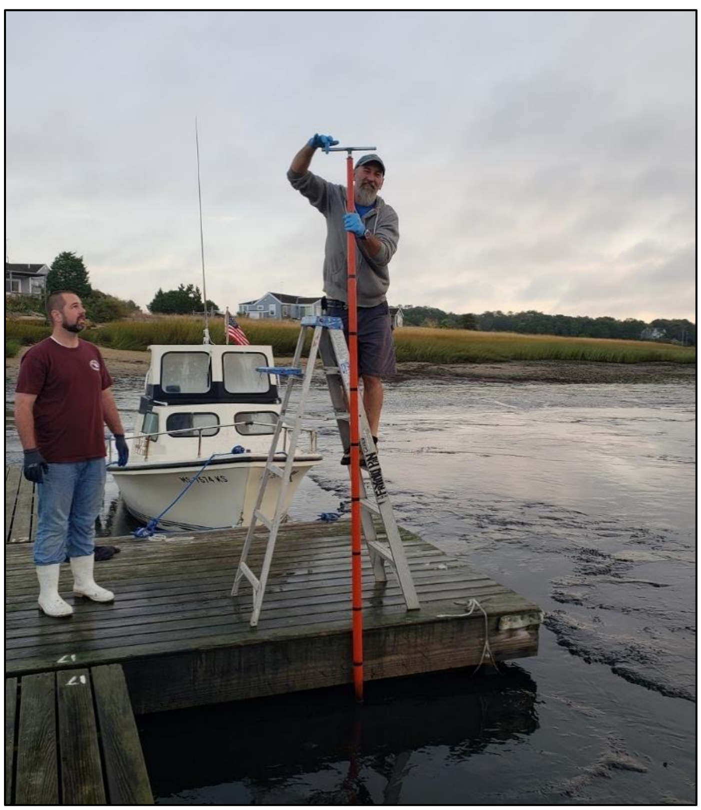

Figure 4. Steve Swain (right) and Bryan Legare from CCS collecting core samples in Wellfleet Harbor

Organic matter content was calculated for each surface sample. 20 - 30 grams of sediment were placed in a drying oven at 105°C for 24 hours (Heiri et al. 2001, Borrelli et al. 2019). Samples were removed from the drying oven and homogenized with mortar and pestle and re-dried. The homogenized samples were weighed and then placed in a muffle furnace at 550°C for four hours and re-weighed to measure loss on ignition (Snyder et al. 2004, Borrelli et al. 2019). After ignition, the percent organic matter was calculated as:

$$LOI(\%) = \frac{(W_D - W_M)}{(W_D - W_C)} \times 100$$

where W_D is the weight of the dried sample and crucible, W_M is the weight of the muffled sample and crucible and W_C is the weight of the crucible.

Grain size analysis was conducted for surface grab samples, using a ponar grab, and core samples using an auger (figure 4). First, all samples were rinsed with water to remove salt, and organic material was burned off in a muffle furnace at 550°C for four hours (Heiri et al. 2001). Then, samples with coarser grain size (> 64 µm; stations 3 and 5) were sieved between 64 µm and 4000 µm before analysis in a Horbia Camsizer. Samples with fine grain size (< 1000 µm; stations 1, 2, and 4) were analyzed with a Beckman-Coulter laser diffraction particle size analyzer. All particle analyzer outputs were then processed in the software GRADISTAT (Blott and Pye 2001) and reported using Wentworth grain size thresholds and classes (Wentworth 1922). GRADISTAT analyzes the outputs from the particle size analyzers and geometrically calculates grain size parameters (e.g. mean, median, mode(s), sorting (standard deviation), skewness, kurtosis) and a range of cumulative percentile values based on a log-normal distribution (Blott and Pye 2001). Additionally, GRADISTAT provides a physical description of the textural class after Folk (1954).

To learn the answers to question number 4 (Where does it come from?) stable isotope analysis was conducted on all sediment samples. The use of stable isotopes of carbon ($\delta^{13}C$) nitrogen ($\delta^{15}N$) and sulfur ($\delta^{35}S$) to trace sources is well documented (Kharlamenko 2001, Grey 2006). Carbon isotopes can be traced back to their primary carbon sources by differentiating by e.g. photosynthesis cycles ($\delta^{13}C$ signature of C3 marsh plants: -23 – -26‰, C4 marsh plants: -12 – -14‰) (Fry 2006, Maier et al.

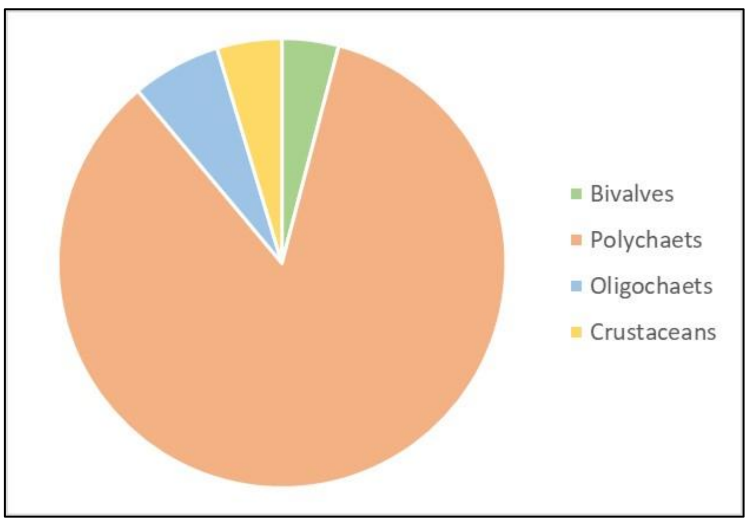

Figure 5. Pie chart indicating the four major groups of invertebrates collected at stations 1 - 5.

2011). Sources of nitrogen can be traced back to e.g. fertilizer (0 - 2‰), septic waste (14 - 18%), animal waste (8 - 12‰), rain (2 - 6‰) (Kendall 1998). Sulfur stable isotopes can be used to differentiate between marine sources and terrestrial sources (Hansen et al. 2009). Samples were dried and prepared according to protocols issued by the Viking Environmental Stable Isotope Laboratory, at Salem State University, where samples were analyzed.

Question number 5 (How does it move?) was answered primarily by taking the results of the grain size analysis, past hydrographic, geomorphologic and bathymetric data and studies (Giese et al. 1994, Borrelli et al. 2019, Smith et al. 2019) and incorporating those into a conceptual framework to explain sediment transport in the area.

4. Results

4.1. Faunal evaluation

Three replicates from each of the five stations were analyzed for their species composition. A total of 171 individuals were found, belonging to 13 species, with 85% of individuals belonging to the group of polychaet worms (figure 5, table 1). While live animals were most abundant at station 3 (outfall pipe) (103 individuals, 86 of which were mud worms), species diversity was highest at station 5 (“The Gut”), where 10 out of 13 species were found.

4.2. Organic matter content

Collecting sediment samples using the *mud wand* resulted in depth measurements for three of the five stations as well as an additional location (boat slip 8 at Wellfleet Marina) that was used as a location to test the equipment. The deepest sample at station 1 was collected at 10 feet, station 2 at 12 feet, station 4 at 8 feet and the testing location at 10 feet (figure 6). The auger was not used at stations 3 (outfall pipe) and 5 (“The Gut”) because sediment was too compact, instead surficial samples were collected with a ponar grab.

Table 1. Organic matter content as Loss on Ignition (LOI) (in %) for stations 1 - 5

Station	LOI (%)
01	21.7
02	21.9
03	1.9
04	22.8
05	1.2

Organic matter content was calculated at every station with stations 3 and 5 containing the lowest amount of organic matter (1.0% and 1.2% respectively) and the remaining stations containing > 21% organic matter.

Table 2. A list of invertebrate species found at stations 1 - 5.

Taxonomic group	**Scientific name**	**Common name**	**Stations**					**Total individuals**
			01	02	03	04	05	
Bivalve	*Crassostrea virginica*	Eastern oyster	0	0	0	0	3	**3**
Bivalve	*Gemma gemma*	Amethyst-gem clam	1	1	0	0	0	**2**
Bivalve	*Mya arenaria*	Soft shell clam	0	0	2	0	0	**2**
Polychaet	*Arabella iricolor*	Opal worm	0	0	0	0	6	**6**
Polychaet	*Capitella* sp.		0	0	4	5	16	**25**
Polychaet	*Drilonereis longa*		0	0	0	0	5	**5**
Polychaet	*Hediste diversicolor*	Rag worm	0	0	9	0	6	**15**
Polychaet	*Streblospio benedicti*	Bar-gilled mud worm	0	0	86	0	8	**94**
Oligochaet	Oligochaeta		0	0	1	0	10	**11**
Crustacean	*Ampelisca macrocephala*	Four eyed Amphipod	0	0	0	0	3	**3**
Crustacean	*Crangon septemspinosa*	Sand shrimp	0	0	0	0	1	**1**
Crustacean	*Palaemon pugio*	Daggerblade grass shrimp	0	0	0	1	2	**3**
Crustacean	Xanthidae	Mud crab	0	0	1	0	0	**1**
	Total individuals		**1**	**1**	**103**	**6**	**60**	**171**
	Total species		**1**	**1**	**6**	**2**	**10**	**13**

4.3. Grain size analysis

Grain size analyses were conducted on samples collected at all five sites (figure 3). Surficial samples were collected at the five sites and cores were collected at depth at sites 1, 2, and 4 (table 3). Median grain sizes (D_{50}) ranged from fine silt (14.19 µm - Site 2: Surface) to coarse sand (659.5 µm - Site 3: Surface). Site 3, closest to the Mayo Creek outfall pipe leading into the boat basin, was collected near low tide at the area where the water leaving Mayo Creek falls directly onto the intertidal flat at low tide. This may have led to anomalous grain size results as the falling water would have removed the finer grain sizes from the flat.

Table 3. Sediment sample locations and grain size analysis results

Sample Location	Sample Name	Median Grain size (D_{50}) (μm)	Sample Depth (ft)	Sediment Description
Site 1: Surface	A	38.97	Surface	Coarse Silt
Site 1: Middle	B	54.22	5	Very Coarse Silt
Site 1: Deep	C	65.16	10	Very Fine Sand
Site 2: Surface	D	14.19	Surface	Fine Silt
Site 2: Middle	E	14.98	6	Fine Silt
Site 2: Deep	F	17.28	12	Medium Silt
Site 3: Surface	G	659.5	Surface	Coarse Sand
Site 4: Surface	H	18.42	Surface	Medium Silt
Site 4: Middle	I	24.42	4	Medium Silt
Site 4: Deep	J	31.63	8	Course Silt
Site 5: Surface	K	542.5	Surface	Coarse Sand

Although the median grain size varies from site to site, a constant seen on all the cores was a coarsening of grains sizes with depth.

4.4. Seismic reflection profiling

Seismic reflection profiling or 'sub-bottom' data were collected for the larger benthic habitat mapping effort (Borrelli et al. 2019, Smith et al. 2019) in 2014 for Wellfleet Harbor. Unpublished data, not used for that project, demonstrate support for the thickness of the *black custard* that is within the bounds of that reported via the coring method (figure 7). A full discussion of the methods, techniques and uncertainties associated with the sub-bottom data collection and analysis can be found in the primary reports for Wellfleet Harbor (Borrelli et al. 2019, Smith et al. 2019, Borrelli et al. 2020).

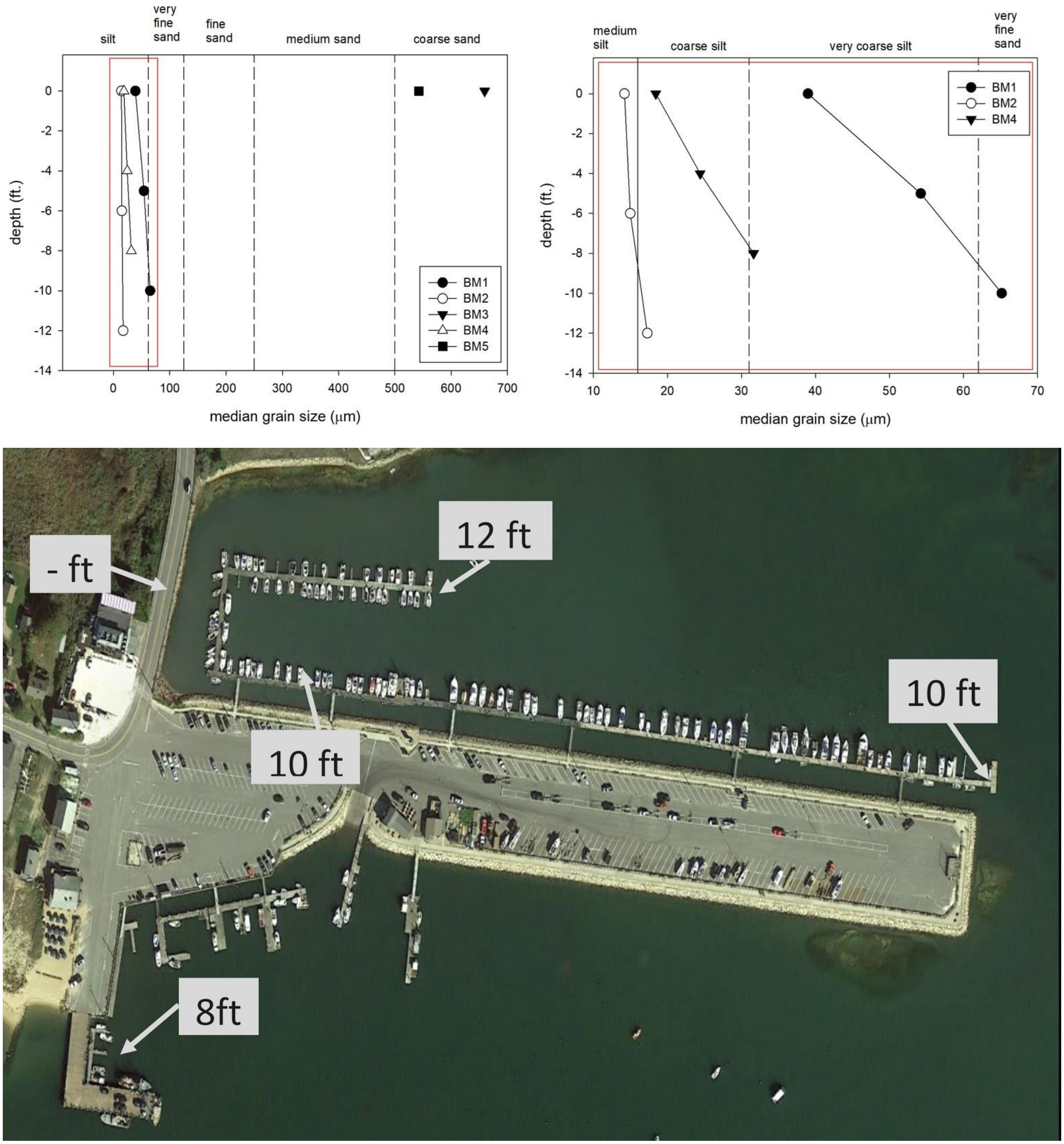

Figure 6. Upper Left: Median grain sizes at all available depths for station 1 - 5. Upper Right: subset that focuses on grain sizes of samples collected at three different depths at stations 1, 2, and 4. Bottom: Depth of accumulated *black custard* at 3 stations and one trial site in Wellfleet Harbor. Picture taken from GoogleEarth.

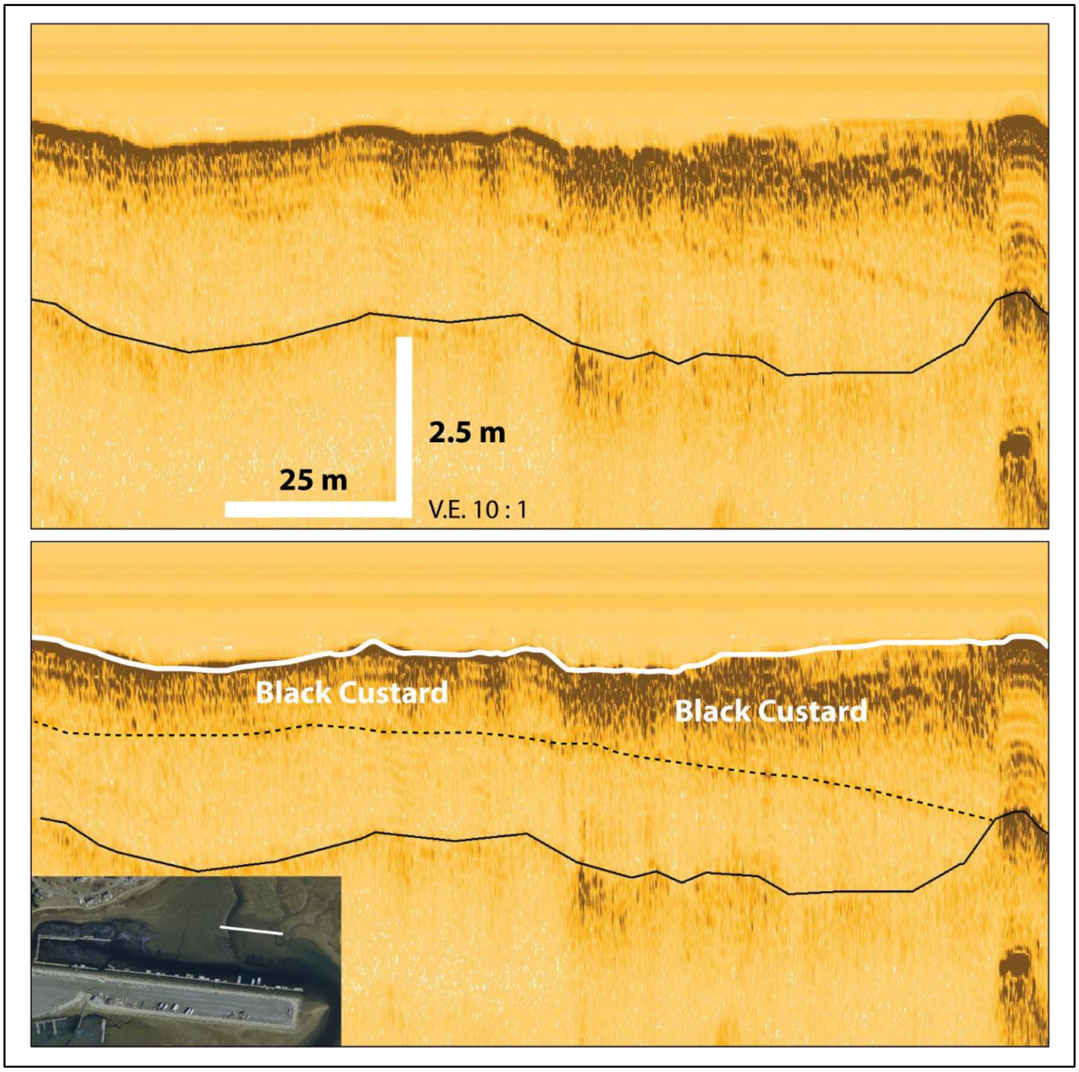

Figure 7. Top. Uninterpreted raw sub-bottom data. The solid black line is a 'multiple' of the seafloor (a common feature of these data) and no information can be used below this line. Bottom: Interpreted sub-bottom data. The solid white line is the seafloor, the dotted black line indicates the likely bottom of the *black custard* and corresponds with the depth of refusal seen in the coring data. Inset, approximate location for sub-bottom data.

4.5. Stable isotope analysis

Stable isotope signatures of carbon, nitrogen and sulfur were analyzed. Figure 8 compares $\delta^{15}N$ and $\delta^{13}C$ of Wellfleet stations (in color) to results from the literature (black symbols). $\delta^{13}C$ signatures (orange background) of samples taken in Wellfleet are comparable to published signatures of marine organic matter, whereas $\delta^{15}N$ signatures (blue background) are similar to terrestrial organic matter. Marine organic matter is made up of zooplankton, phytoplankton and seston. Seston is defined as the living and non-living matter suspended in the water column.

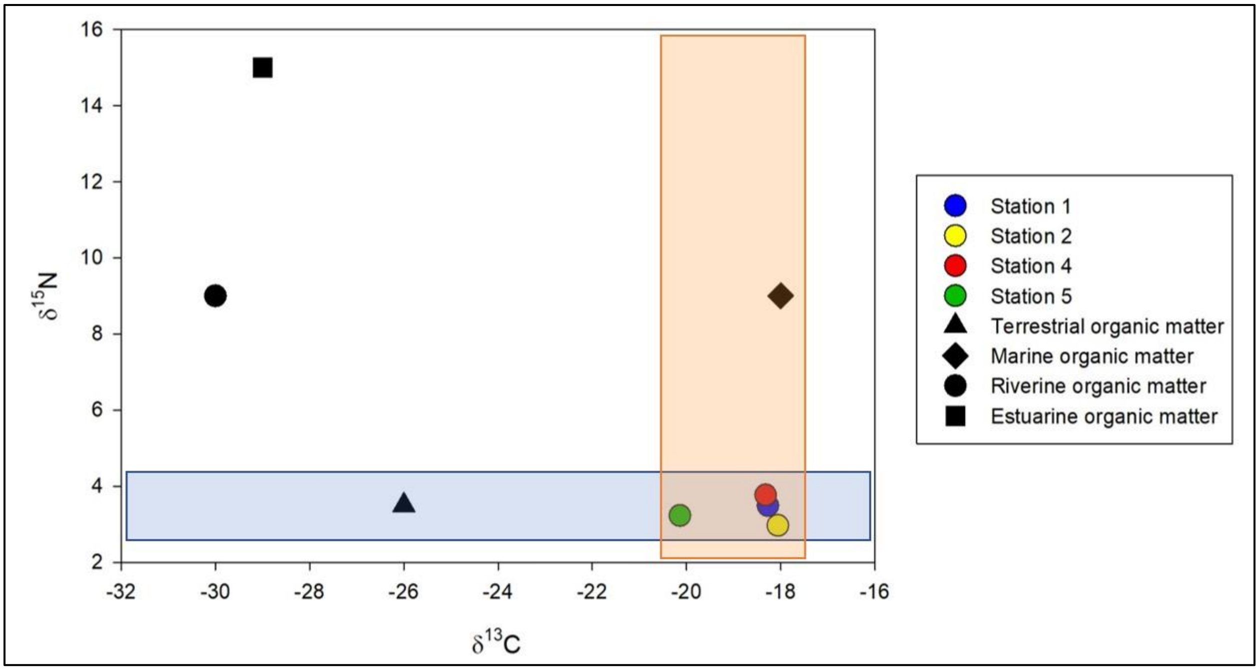

Figure 8. δ15N and δ13C signatures of stations 1, 2, 4, and 5 (colored circles) compared to stable isotope signatures of terrestrial, marine, riverine and estuarine organic matter (from Middelburg 1998) (black symbols).

Taking a closer look at nitrogen from terrestrial sources (figure 9), that enters the harbor through runoff, shows that station 1 (blue), station 2 (yellow), station 3 (red), and station 5 (green), are all within the same narrow range of $\delta^{15}N$ signatures common to fertilized and natural soil, and nitrate and nitrite derived from rain water.

$\delta^{13}C$ signatures indicate marine organic matter as the main carbon sources. Figure 10 shows a comparison of $\delta^{13}C$ signatures from the literature (Kharlamenko et al. 2001, Fry 2006, Grey 2006, Maier et al. 2011, Mittermayr et al. 2014) with signatures measured at stations 1, 2, 4 and 5. Macroalgae, benthic algae, phytoplankton, diatoms and seston were found to have similar signatures, while eelgrass and C3 and C4 marsh plants showed signatures outside the range of this project.

A first glance at the measured sulfur isotope ($\delta^{34}S$) signatures suggests sedimentary sources including pyrite and sapropel (figure 11). Pyrite is generally considered to be the end product of sulfur diagenesis in anoxic marine sediment (Hoefs 2004) and sapropel describes anaerobic sediments that are rich in organic matter.

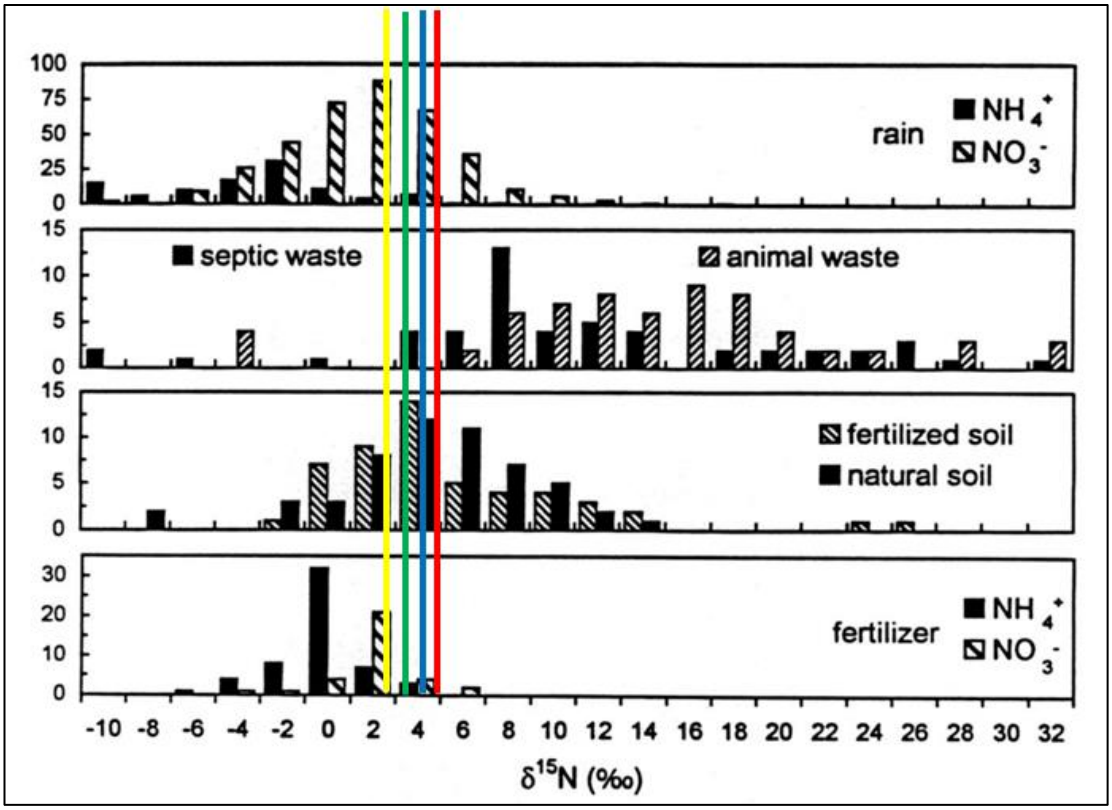

Figure 9. adapted from Kendall (1998) and references therein. Summary of the range of $\delta^{15}N$ values for the major sources of nitrogen in the hydrosphere. The labels on the x-axis are for the high-end of the range plotted within a cell. Colored lines indicate station 1 (blue), station 2 (yellow), station 4 (red), station 5 (green).

5. Discussion

CCS, together with the Cape Cod National Seashore conducted a project aiming to identify benthic habitats in Wellfleet Harbor in 2015 - 2016. One of these stations, WH17, is fairly close to the area studied, north of the town's marina, across the harbor basin (figure 3) (Borrelli et al. 2019, Smith et al. 2019). In the following discussion, WH17 will be used to put results from this study in perspective.

The faunal evaluation showed that species diversity and abundance is low at all five stations, particularly at stations 1, 2, and 4, (St 1. 1 individual, 1 species, St.2. 1 individual, 1 species, St. 4. 6 individuals, 2 species; table 2) compared to WH17 (24 species, 51 individuals). Polychaets were the most represented groups at all stations. Generally, sediment characteristics such as median grain size and sorting as well as organic matter content, are the most important drivers in benthic invertebrate distribution.

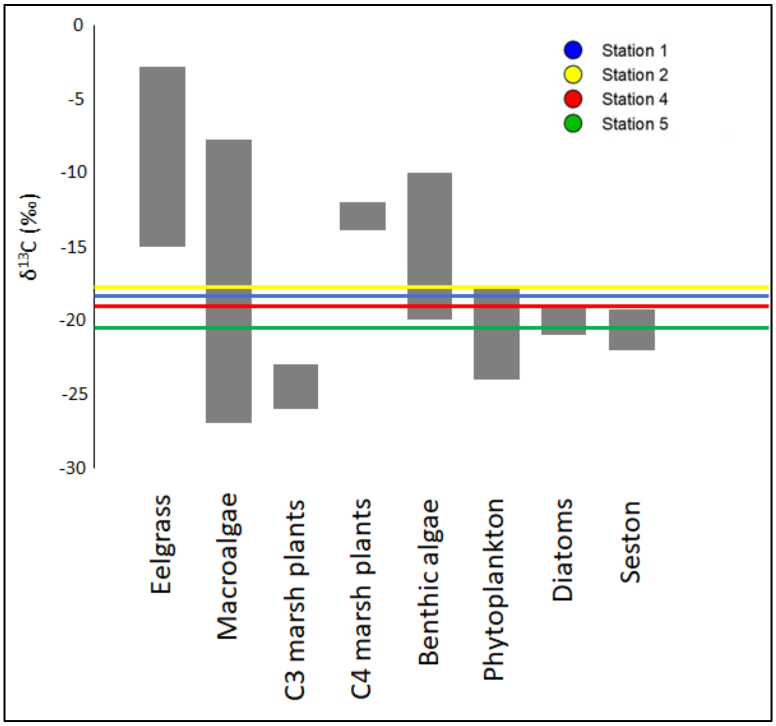

Figure 10. $\delta^{13}C$ signatures of various coastal and marine plants compared to $\delta^{13}C$ of stations 1, 2, 4, and 5

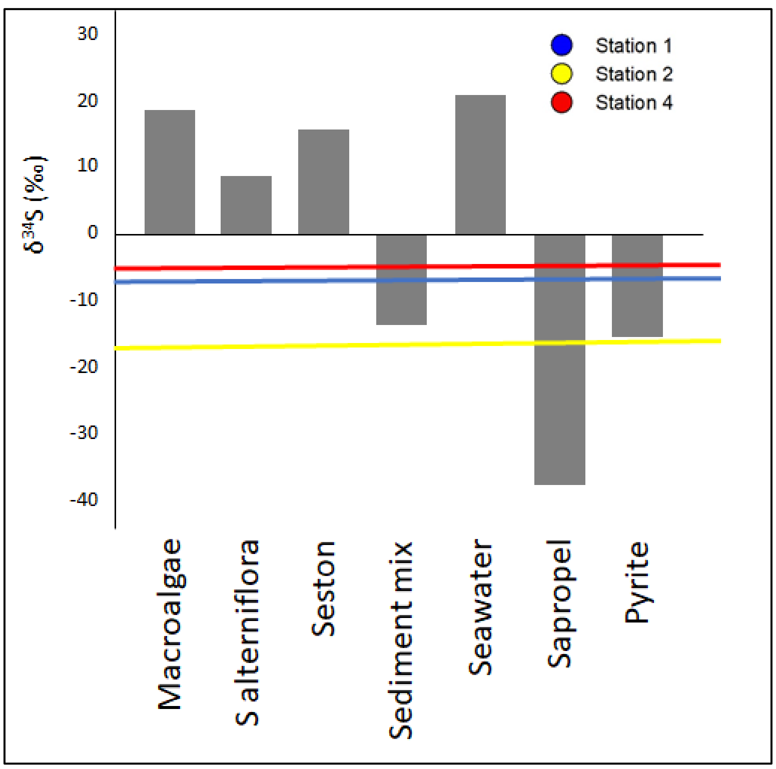

Figure 11 $\delta^{34}S$ signatures of station 1 (blue), 2 (yellow) and 4 (red) compared to $\delta^{34}S$ found in the literature (Hoefs 2004, Hansen et al. 2009, Mittermayr et al. 2014)

Sediment samples at stations 1, 2 and 4, which are also the stations with the thickest layer of *black custard* (10, 12, and 8 feet respectively, figure 6), were composed of coarse, fine and medium silt at the surface respectively, while grain size increased with depth at all three sites. Grain size at WH17 was classified as 96% coarse sand, and is thus more similar to stations 3 and 5. The same pattern emerged when looking at organic matter content: stations 3 and 5 (1.9% and 1.2% organic matter respectively) are similar to WH17 (0.6% organic matter), while samples from stations 1, 2, and 4 are contain > 20% organic matter (table 1).

Stable isotope analysis showed that the organic matter present in the Wellfleet Harbor basin originated from marine sources such as macro algae and seston as indicated by their stable carbon signatures (figures 8 and 10). Stable nitrogen signature of samples analyzed point to rain and fertilized and natural soil as a nitrogen source (figure 9). It is important to note that this study did not measure nitrogen input into Wellfleet Harbor, instead it looked at sources of nitrogen in the sediment. Stable isotope analysis relates heavy to light isotopes (additional neutrons create heavy isotopes) and the resulting ratio (in ‰) is independent of the amount of the element in question (e.g. nitrogen) in the system sampled. However, the CCS Water Quality Monitoring Program collects water samples directly from the duck bill outfall pipe at Mayo Creek on a monthly basis. These data can be accessed here: http://www.capecodbay-monitor.org/ and show a decrease in seasonality and an increase in average total nitrogen (TN) over the years. Average TN in 2018 at Mayo Creek was 1.79 mg/L. The Massachusetts Estuaries Project (MEP) recommends overall total nitrogen (TN) concentrations for Wellfleet Harbor at 0.53 mg/L, to be achieved by reduction of septic load to achieve a reduction in total nitrogen (Howes et al. 2017). However, this project measured nitrogen sources of sediment samples, not water samples. The results of low septic input presented here only refer to sediment samples and therefore cannot be used to infer nitrogen sources of water samples.

Stable sulfur isotopes ($\delta^{34}S$) in sediment samples indicate primary sulfur sources. Samples analyzed in this study all exhibit signatures < 0‰, typical of, among others, sapropel or pyrite (figure 11). However, due to the activity of sulfur reducing bacteria, sedimentary sulfides may be depleted in ^{34}S relative to ocean water sulfide. This depletion can occur in the order of 20 to 60‰ (Hoefs 2004) and is dependent on availability of decaying organic matter, oxygen concentration and temperature. Since these variables are hard to control outside a laboratory setting, no definitive correction factor could be calculated, instead corrected $\delta^{34}S$ signatures of samples collected fall between 2 - 54‰, a range too large to reliably tie to a corresponding primary carbon source.

5.1. Sediment transport

The pattern of increasing coarse-grained material with depth seen in all three cores supports the idea that with greater water depths in an area come increased water current velocities. These increased velocities would, in turn, be able to transport coarser material. As the material is deposited and the channel shoals, there is a commensurate decrease in current velocities because less water needs to be transferred in and out of the area. This decrease in velocity is followed by a decrease in the ability of those current velocities to transport similar sized particles, thus coarser-grained material is deposited. For example, at approximately mid-tide the current velocities are typically at the their highest. At this time, the coarsest-grained material is transported, then as the currents begin to slow approaching slack tide some material is deposited. The coarsest-grained material is then re-transported during the next tidal cycle. Over time if enough deposition occurs in an embayment the volume of water decreases, as do the current velocities, assuming a symmetrical tidal cycle (i.e. ebb and flood duration and velocities are equal). This reduction in water volume reduces the current velocities ability to move sediment it once could. If deposition continues to occur current velocities continue to decrease.

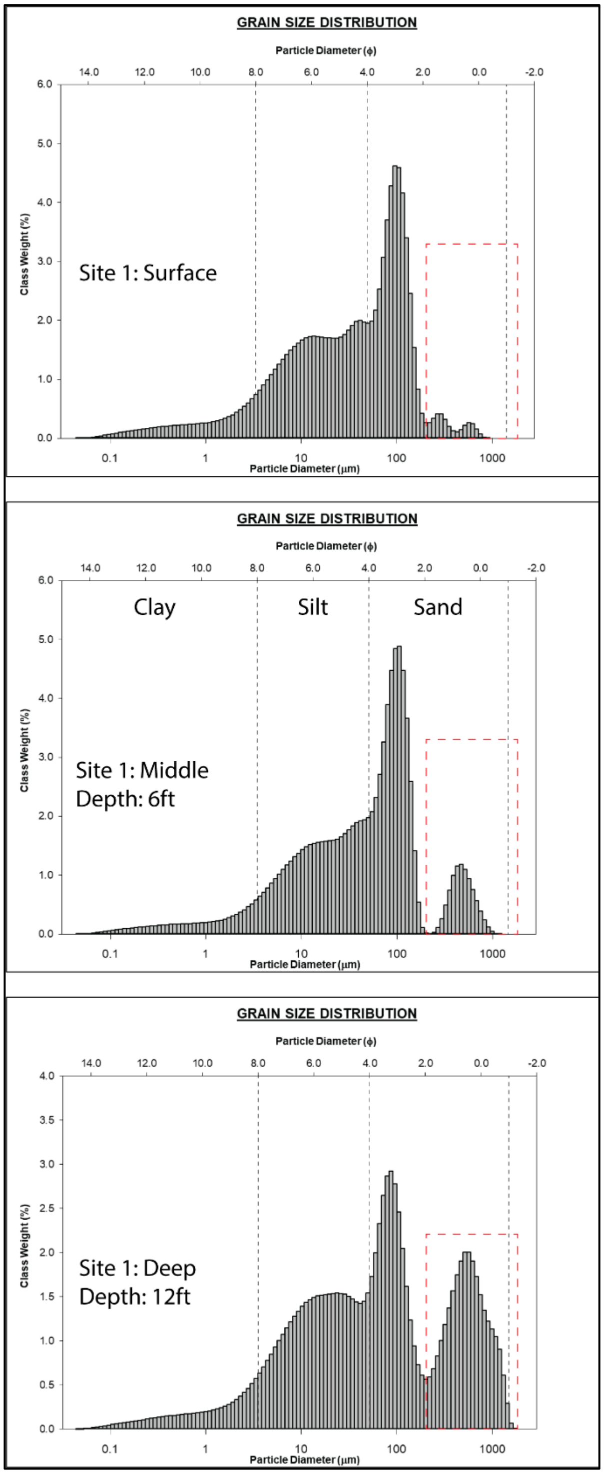

Figure 12. Results from grain analysis at Station 1. Note red dotted boxes highlighting increasing coarse-grained material with increasing depth.

When the boat basin was 12 ft deep a larger percentage of sand sized material was being deposited (figure 12). The current velocities were such that this sand-sized material could be transported into the boat basin. As the basin began to fill up, current velocities slowed and less sand was deposited as noted in the samples at 6 ft and at the surface. A question can be asked, if the same volume of water has to be flushed in and out of the boat basin why does the basin fill up, but the many places in Wellfleet Harbor do not? Also, if the source of the sediment in the boat basin is marine, and not terrestrial, doesn't that mean that all of the water in Wellfleet Harbor has this material in it, and if so why does *black custard* fill this area while the Harbor is otherwise free from large deposits of this material?

5.2. Sediment deposition

Sediment is primarily transported in one of two ways: first, as 'bedload' where coarser-grained material such as sand and pebbles roll and bounce along the seabed or, second, as 'suspended load' where fine-grained sediment (silts and clays) float in the water column kept from depositing by near-continuous tidal currents. In more energetic settings such as the bayside on Jeremy's Point, bedload dominates. There is suspended load in the water column, but the current flows are near constant and fine-grained sediment cannot 'settle out' of the water column and deposit on the seafloor. In the Harbor, in lower energy areas, the current velocities are lower and there is a commensurate decrease in sediment size. In these areas, current velocities are such that fine-grained sediment can be deposited on the seafloor and less coarse-grained sediment is transported in these areas.

The seemingly anomalous deposition of *black custard* in the boat basin and other similar areas in the harbor can be explained with several supporting data sets, physical sediment transport concepts as well as past studies in the area. Giese et al. (1994) documented that Wellfeet Harbor is a flood dominated system resulting from longer ebb tidal flow and shorter flood tidal flow. This requires greater flood tidal velocities because the same volume of water must be moved into the system during a shorter time window. Stronger flood tidal currents will resuspend more and coarser sediment into the water column. Slower ebb tidal flow allows that suspended material to be deposited in lower energy areas, thus slowly filling in some areas in the Harbor including the boat basin.

As stated above, the findings from this study demonstrate that the *black custard* in the boat basin is not from a terrestrial source. Current velocities measured by Giese et al. (1994) coupled with findings here support the idea that suspended sediment, very fine sands and silts, are suspended in the water column and transported into the basin during energetic flood tidal flow (figure 13). It should be noted that the velocities shown in Figure 13 are mean (average) velocities and that peak current velocities could be responsible for the bulk of the sediment transport into the basin.

However, if the material in the boat basin is from a marine source then it is reasonable to assume that it is roughly equally distributed throughout the waters of Wellfleet Harbor. The remaining question as to why do certain, but not all - or even a majority, of low energy areas of the Harbor seem to have deep deposits of *black custard* is an interesting one. It is well known that fine grain sediments <62.5 µm (silts and clays) can flocculate or come together and form into small clumps or masses. This allows for their deposition onto the seafloor rather than them remaining suspended in the water column. The mechanism for this flocculation is either the coming together of these particles (direct contact) due to turbulence in the water column, or the particles (together called flocs) 'stick' to each other as a result of biological activity or electrostatic charge caused by interaction with organic matter or changes in salinity (Dyer and Manning 1999, Spearman et al. 2011).

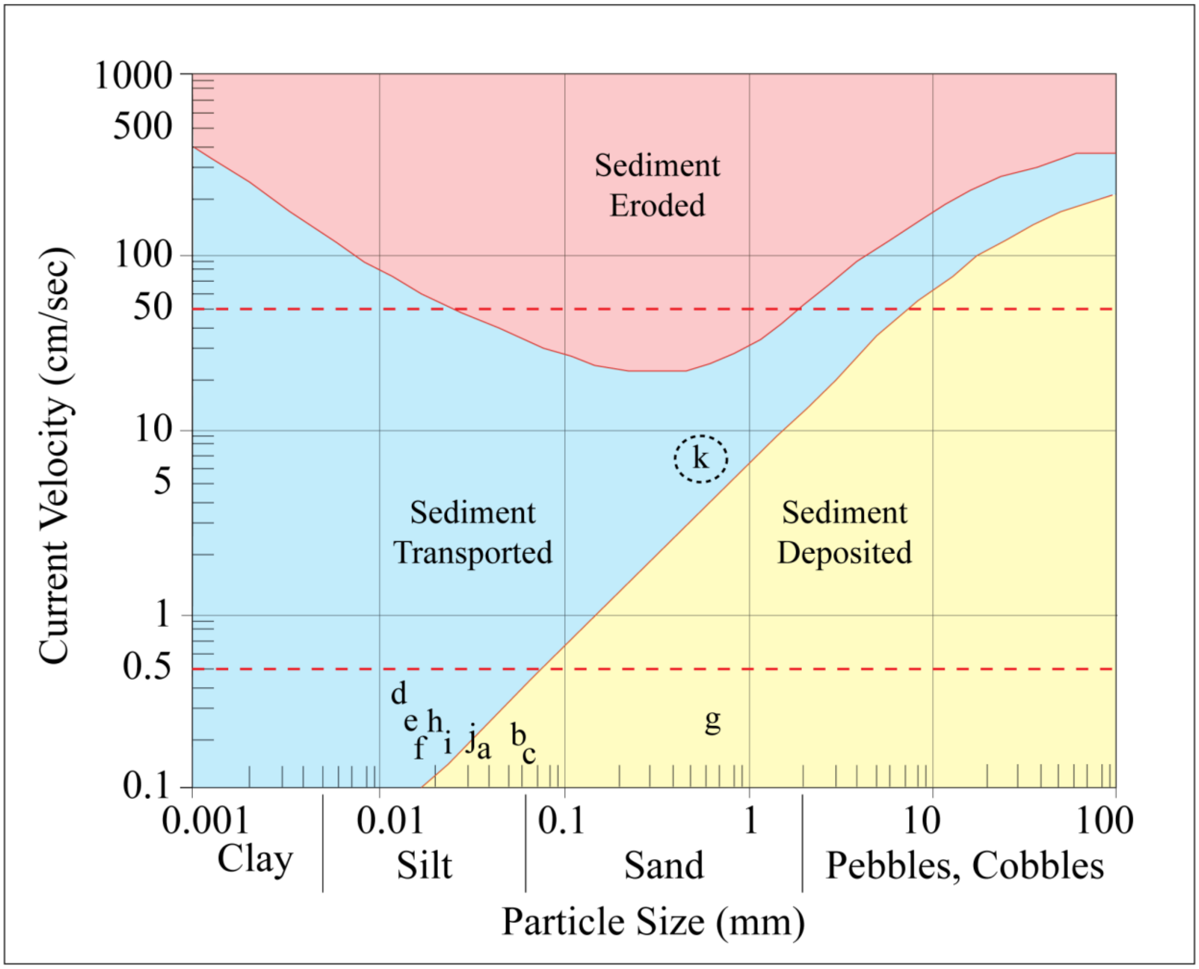

Figure 13. Samples a-k plotted on the Hjulstrom diagram by grain size (see table 3). Red dotted lines are average velocities for areas near the boat basin and away from the boat basin (Giese et al. 1994). Samples 'a-g' were collected in the area near the boat basin and 'k' was collected in "The Gut". Dotted circle around 'k' = no current velocity data was collected at this location.

Clay-sized particles are typically flat, platy-shaped and polar, in that one end of a clay particle is negatively charged and the other end is positively charged. Thus, when clay particles are in suspension, in quiescent settings, oppositely charged ends of the particles can be attracted to each other and bonds are formed between particles, if the process continues flocs become bigger until they can no longer stay in suspension and are deposited on the seafloor. This is primarily how large deposits of mud (silts and clays) are formed. Generally speaking, clay particles are the majority of material in mud deposits that 'settle out' of suspension. It has been shown that flocs deposited from suspension can include some silt particles (Wolanski and Elliott 2015). The majority of material in the boat basin is silt-sized sediment that coupled with the low tidal current velocities directs us toward the idea that flocculation is playing a key role in the sedimentation of the boat basin.

5.3. Future work

As noted above there can be several drivers of flocculation including physical, chemical or biological that may work in tandem or separately to increase the rates of flocculation and deposition. This study did not look at possible drivers of that flocculation. This could be a topic for future work: to ascertain precisely which drivers are responsible for this flocculation in order to better understand potential future scenarios and basin infilling. Brackish inflowing water from Mayo Creek may change salinity enough to promote increased flocculation and deposition. Recent work has shown that certain types of algae can contribute to flocculation even with silt-sized material (Deng et al. 2019).

6. Conclusion

In conclusion, the short answers to the five initial questions are:

1) Where is it?

Out of the five stations analyzed, *black custard* was exclusively found north (at three stations) and south west (at one station) of the pier. The station downstream of Chequessett Neck dike showed much coarser sediment

2) What is it?

The gooey, black, and smelly substance called black custard is made up of 70% fine grained sediments (< 70 µm) and 30% organic material. The color is caused by the high percentages of FeS (iron sulfide) and FeS_2 (iron disulfide or pyrite) in the sediment while the smell stems from bacterial activity commonly found in marine sediments but compounded in Wellfleet due the high iron levels, abundance or organic material and low rates of water exchange.

3) How dense/thick is it?

The thickness of the black custard layer was measured by lowering an auger until hitting refuse and varies between 12 feet (Station 2, north of the pier in the center of the basin) and 8 feet (Station 4, south of the pier).

4) Where does it come from?

Organic material derives from marine sources such as macroalgae and seston while nitrogen is derived from rain, fertilizer and natural soil. It is important to note that this study did not measure nitrogen input into Wellfleet Harbor, instead it looked at sources of nitrogen in the sediment. Sulfur analysis points to sapropel and pyrite are sources, however, the presence of sulfur reducing bacteria alter these results by a large margin impeding a reliable determination of sulfur sources. Overall, the material is rich in decomposing marine plants, small grained pyrite and nitrogen introduced by natural sources and fertilizer.

5) How does it move

Sediment moves as either bedload (along the bottom) or as suspended load (in the water column). When the boat basin was deeper more coarse-grained material was transported into the basin indicating faster tidal currents. As the basin filled, tidal currents slowed and fine-grained sediment was deposited. Flocculation, the coming together of fine-grained sediment (silt and clay) that allows for the deposition of sediment too fine to be deposited individually is a major component of deposition in the boat basin. The drivers of that flocculation are not well understood and could be a direction of future work.

7. References

93rd Congress, Second Session (Aug 2nd, 1974) Sewage Sludge Hazard to Long Island Beaches: Hearing Before the Subcommittee on Environmental Pollution of the Committee on Public Works, United States Senate.

Balco, G., Briner, J. Finkel, C., Rayburn, J.A., Ridge, J.C., Schaefer, J.M. 2009. Regional beryllium-10 production rate calibration for late-glacial northeastern North America. Quaternary Geology, v. 4, p. 93 – 107.

Blott S.J. and K. Pye. 2001. GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments. Earth Surface Processes and Landforms. 26(11): 1237-1248

Borrelli, M., S.E. Fox, E.J. Shumchenia, C.G. Kennedy, B.A. Oakley, J.B. Hubeny, H. Love, T.L. Smith, B. Legare, A. Mittermayr, S.J. McFarland, and G.S. Giese. 2019. Submerged Marine Habitat Mapping, Cape Cod National Seashore: A Post-Hurricane Sandy Study. Natural Resource Report

Borrelli, M., Oakley, B.A., Hubeny, J.B., Love, H., Smith, T.L., Legare, B.J. and Lucas, T., 2020. The Use of Multimodal Data to Augment Shallow-Water Benthic Habitat Maps for Pleasant Bay, Cape Cod, Massachusetts: Stratigraphic Data and Seafloor Maps. Northeastern Naturalist, 27(sp10): 48-75.

Connor, M. 2005. Water Quality Improvements Are Critical to Waterfront Development: Lessons from Boston, San Francisco and Kitayushu. SFEI Contribution No. 422. San Francisco Estuary Institute: Oakland CA.

Deng, Z., Q. He, Z. Safar, and C. Chassagne. 2019. The role of algae in fine sediment flocculation: In-situ and laboratory measurements. Marine Geology. 413: 71-84.

Dyer, K.R. and A.J. Manning. 1999. Observation of the size, settling velocity and effective density of flocs, and their fractal dimensions. Journal of Sea Research. 41(1): 87-95.

Folk, R. 1974. 1974: Petrology of sedimentary rocks. Austin, Texas: Hemphill Publishing Company.

Fry, B. 2006. Stable Isotope Ecology. New York, Springer.

Giese, G.S., T.R. McSherry, and W.D. Spencer. 1994. Wellfleet Inner Harbor: A Summary of Work. Woods Hole Oceanographic Institution.

Grey, J. 2006. The use of stable isotope analyses in freshwater ecology: Current awareness. Polish Journal of Ecology. 54(4): 563-584.

Hansen, T., A. Burmeister, U. Sommer. 2009. Simultaneous d1^{5}N, d^{13}C and d^{34}S measurements of low-biomass samples using a technically advanced high sensitivity elemental analyzer connected to an isotope ratio mass spectrometer. Rapid Communications in Mass Spectrometry. 23(21): 3387-3393.

Heiri O., A.F. Lotter, and G. Lemcke. 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. Journal of paleolimnology. 25(1):101-110.

Hemery, L.G., K.K. Politano, and S.K. Henkel. 2017. Assessing differences in macrofaunal assemblages as a factor of sieve mesh size, distance between samples, and time of sampling. Environmental Monitoring and Assessment. 189: 413pp.

Hoefs, J. 2004. Stable Isotope Geochemistry. Springer-Verlag, Berlin

Howes, B., R. Samimy, E. Eichner, D. Schlezinger, S. Kelley, J. Ramsey, P. Detjens. 2017. Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Wellfleet Harbor Embayment System Town of Wellfleet, Massachusetts, Massachusetts Estuaries Project.

Kendall, C. 1998. Tracing Nitrogen Sources and Cycling in Catchments. Isotope Tracers in Catchment Hydrology C. Kendall and J. J. McDonnell. Amsterdam, Elsevier Science B.V.: 519-576.

Kharlamenko, V.I., S.I. Kiyashko, A.B. Imbs, D.I. Vyshkvartzev. 2001. Identification of food sources of invertebrates from the seagrass *Zostera marina* community using carbon and sulfur stable isotope ratio and fatty acid analyses. Marine Ecology-Progress Series 220: 103-117.

Maier, G.O., J.D. Toft, C.S. Simenstad. 2011. Variability in Isotopic ($d^{13}C$, $d^{15}N$, $d^{34}S$) Composition of Organic Matter Contributing to Detritus-based Food Webs of the Columbia River Estuary. Northwest Science 85: 41 - 54.

Middelburg, J.J., J. Nieuwenhuize. 1998. Carbon and nitrogen stable isotopes in suspended matter and sediments from the Schelde Estuary. Marine Chemistry. 60(3-4):217-225

Mittermayr, A., T. Hansen. U. Sommer. 2014. Simultaneous analysis of δ13C, δ15N and δ34S ratios uncovers trophic importance of epiphytes in an eelgrass (*Zostera marina* L.) community. Marine Ecology-Progress Series. 497: 93-103.

Mittermayr, A., B.J. Legare, and M. Borrelli. 2020. Applications of the Coastal and Marine Ecological Classification Standard (CMECS) in a Partially Restored New England Salt Marsh Lagoon. Estuaries and Coasts. doi: 10.1007/s12237-020-00707-2

Oldale, R.N., and R.A. Barlow. 1986. Geologic map of Cape Cod and the Islands, Massachusetts: Miscellaneous Investigations Series Map I-1763: U.S. Geological Survey.

Peltier, W.R., R.G. Fairbanks. 2006. Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record. Quaternary Science Review. 25(23-24): 3322-3337.

Poppe, L.J., S.D. Ackerman, D.S. Foster, D.S. Blackwood, B. Butman, M.S. Moser, and H.F. Stewart. 2007. Sea-floor character and sedimentary processes of Quicks Hole, Elizabeth Islands, Massachusetts: U.S. Geological Survey Open-File Report 2006-1357, DVD. Available online at: http://pubs.usgs.gov/of/2006/1357/

Rinn, N. 2016. Dredge Report: EPA Contractors Make Show of Canal's Black Mayonnaise and Big Tires. Brooklyn Magazine.

Smith, T.L., A. Mittermayr, B.J. Legare, S.E. Fox, and M. Borrelli. 2019. Benthic Habitat Mapping in Wellfleet Harbor and Vicinity. Tech Rep: 19-CL04, Center for Coastal Studies, Provincetown MA.

Snyder, N.P., J.R. Allen, C. Dare, M.A. Hampton, G. Schneider, R.J. Wooley, C.N. Alpers, M.C. Marvin-DiPasquale. 2004. Sediment grain-size and loss-on-ignition analyses from 2002 Englebright Lake coring and sampling campaigns, USGS

Spearman, J.R., A.J. Manning, and R.J.S. Whitehouse. 2011. The settling dynamics of flocculating mud and sand mixtures: part 2—numerical modelling. Ocean Dynamics. 61(2-3): 351-370.

Uchupi, E., G.S. Giese, D.G. Aubrey, D.J. Kim. 1996. The late quaternary construction of Cape Cod, Massachusetts: A reconsideration of the WM Davis model. Geological Society of America Special Papers 309, 1-69.

United States Army Corps of Engineers. 2001. Providence River and Harbor Maintenance Dredging Project: Environmental Impact Statement. Northwestern University.

United States Environmental Protection Agency. 2013. Record of Decision: Gowanus Canal Superfund Site, Brooklyn, Kings County, New York. Report No 692106

Vesilind, P.A., T.D. DiStefano. 2006. Controlling Environmental Pollution: An Introduction to the Technologies, History and Ethics. DEStech Publications Inc.

Wolanski, E. and M. Elliott. 2015. Estuarine ecohydrology: an introduction. Elsevier.

Wentworth, C.K. 1922. A Scale of Grade and Class Terms for Clastic Sediments. The Journal of Geology. 30(5): 377-392.