Reconstructing Submerged Paleoenvironments: Mud Hole, RI Sound and Greenwich Bay, RI

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RECONSTRUCTING SUBMERGED PALEOENVIRONMENTS:
MUD HOLE, RI SOUND AND GREENWICH BAY, RI

BY
BRIAN J. CACCIOPPOLI

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
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Abstract

Interpretations of high-resolution geophysical data and analysis of the physical properties of vibracores from separate, but closely related study sites have contributed to our understanding of the Late Quaternary paleoenvironments of southern New England. Two submerged areas, Cedar Tree Beach located in the northwest corner of Greenwich Bay and the Mud Hole, a deep bathymetric depression located at the southern edge of the Rhode Island Sound have been designated as study sites for the Bureau of Ocean Energy Management (BOEM) Paleocultural study, which seeks to develop best practices methodology when developing the continental shelf for renewable energy projects. Reconstructions of a post-glacial, pre-marine inundation paleoenvironment is a critical step in the development of an archaeological predictive model to better understand potential for habitability and preservation of cultural material.

The first chapter is focused on interpreting post-glacial depositional environments of the Mud Hole study area. High-resolution geophysical data consisting of 37 survey lines with 500 m spacing and covering ~130 km² including CHIRP seismic reflection and interferometric side-scan and swath bathymetry data were collected in 2012. Side-scan imagery was inspected for sedimentary features. Megaripples were interpreted as areas of modern sediment reworking due to storm-induced bottom currents. Erosional outliers and scour depressions were interpreted as net-erosional sedimentary
environments. Featureless, low backscatter areas were interpreted as non-erosional or depositional.

Several seismic reflectors were identified in the processed seismic reflection lines, representing changes in depositional environments. Identified reflectors and seismic units were correlated with the regional seismic stratigraphic framework of Rhode Island Sound. Five depositional environments were interpreted based on the seismic stratigraphy. A highly eroded Atlantic coastal plain remnant underlies the study area. Glacial deposits ranging from glacial moraine to glaciolacustrine depositional environments unconformably overlie the coastal plain. The draining of pro-glacial lake Rhode Island eroded two distinct channels to depths of 60 m below present sea level. Sea level is constrained to have inundated the study area between 12.8-10.7 kyBP. Topographic tidal constriction by adjacent moraine deposits may have intensified tidal scour, removing up to 10 m of sediment. A prominent ravinement surface truncates glacial deposits, and Holocene marine sediments drape much of the deeper (>40 m) portions of the study area. Preliminary analysis of two vibracores collected August 2015 indicate lithological agreement with interpreted seismic reflection profiles.

Chapter 2 details ongoing investigations of a submerged paleocultural site at Cedar Tree Beach. Approximately 400 artifacts spanning nearly 10,000 years have been documented along the shoreline located in northwest Greenwich Bay, Warwick, RI. A previous study identified a pro-glacial lake depositional environment, and subsequent drainage by paleostream adjacent to the study
area. The collection of seven vibracores and a high-resolution CHIRP seismic reflection survey were conducted to aid in our understanding of the sub-seafloor lithology, and contribute to the reconstruction of the post-glacial pre-marine inundation paleoenvironment.

Vibracores were split, imaged and the physical properties were logged using a Geotek Multi-sensor core logger. Seismic reflection data were predominantly poor in quality, however, several reflectors were identified and correlated with the seismic stratigraphic framework of Greenwich Bay. Down-core changes in magnetic susceptibility, density, P-wave travel time and reflection coefficients helped to constrain four distinct lithologies. Lithology 1 is characterized by high magnetic susceptibility and represents estuarine deposition modified by anthropogenic activities. The basal age is constrained to be 130-340 yr BP. Lithology 2 is interpreted as estuarine deposition prior to degraded water quality. Lithology 3 represents the ravinement surface, due to the presence of coarse sand to gravel sized sediment, and depth correlation with an interpreted reflector from seismic reflection profiles. Lithology 4, recovered in only one vibracore is inferred to be subaerially exposed glaciolacustrine sediment based on its stratigraphic position below the ravinement surface.
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CHAPTER 1

Reconstructing Late Quaternary Terrestrial Paleoenvironments of the Mud Hole, Rhode Island Sound: Implications For Habitability
1.1 Introduction

1.1.1. Statement of the Problem and Research Questions

The inner continental shelf just south of southern New England, including Rhode Island, Block Island and Long Island Sounds has been extensively studied for several decades. With the arrival of seismic reflection techniques in the 1920's, and studies of the Atlantic coastal margin beginning as early as 1940, the geologic structural framework of southern New England has largely been characterized. The earliest studies described and traced a deeply buried bedrock surface, and described the bedrock drainage configuration (e.g. Ewing, 1940; Oliver and Drake, 1952). Subsequent episodes of deposition and erosion have been characterized with the improvement in seismic reflection technologies. Several studies have provided superficial descriptions of the study area, which is the focus of this thesis. The study area (Figure 1.1.) has more recently adopted the name “the Mud Hole or Mudhole” from local anglers and shark fishermen to which they have long referred to this locally deep offshore area east of Block Island and adjacent to Cox Ledge.

Oakley (2012) first hypothesized that the Mud Hole served as a lower spillway for glacial lakes occupying the modern day Block Island and Rhode Island Sounds. His work relied on digital topographic models using modern bathymetry, a constructed relative sea level curve, and assumed that the magnitude of post-glacial erosion and deposition is negligible. Recent acquisition of high-resolution geophysical data that provides nearly complete spatial
coverage of the Mud Hole will help to characterize and interpret the sub seafloor geology. The goals of this thesis chapter are to determine:

1. How strongly the seismic stratigraphy from the CHIRP seismic reflection data correlates with previous studies of regional seismic stratigraphy.
2. The modern sedimentary environments.
3. If the high-resolution geophysical data support the hypothesis that the Mud Hole served as a spillway.
4. How significantly episodes of erosion and deposition have modified the post-glacial landscape.

1.1.2. Justification for and Significance of the Study

A hypothesis that the Mud Hole would have rapidly transitioned to a low-energy depositional environment has been of particular interest to the field of marine archaeology. The Bureau of Offshore Energy Management (BOEM) in 2012 awarded the University of Rhode Island a 5-year, $2 million grant to develop best management practices for the assessment of submerged paleocultural resources in federal waters (King, 2012). This initiative falls under Section 106 of the National Historic Preservation of Act of 1966, as amended, that seeks to identify and protect prehistoric archaeological sites during the development of renewable energy projects in federal waters. A critical component of the project is to evaluate submerged, offshore areas for archaeological sensitivity (Figure 1.2.). Much of the presently submerged continental shelf was above sea level for thousands of years following the retreat
of the Laurentide ice sheet, making this paleolandcape suitable for human habitation.

Evaluation of the archaeological sensitivity must also consider the preservation potential of the paleolandcape. Studies of marine inundation in offshore New England indicate that up to 2 m of sediment is subject to removal in a slow inundation scenario (Koteff et al., 1993). For this reason, areas that transitioned quickly to a low energy basin are favorable for the preservation of paleolandscapes. Based on digital elevation modeling, the Mud Hole had been a freshwater lake in a subaerially exposed valley until approximately 11,000 yr BP, when it rapidly transitioned from a post-glacial lake to a presumably low-energy estuarine environment (Figure 1.3.) (Boothroyd, 2012). A preliminary assessment of the Mud Hole suggests potential for the preservation of the paleolandcape due to approximately 10,000 years of it being both ice-free and above sea-level and its rapid transition to a low-energy marine environment.

There is an apparent convergence of shared goals in better understanding the geologic framework of the Mud Hole and its suggested role as a spillway and the evaluation of the Mud Hole in an archaeological sensitivity context. A critical step to improving understanding in both areas of research is to reconstruct a post-glacial, pre-inundation paleolandcape. Additionally, Holocene relative sea-level rise curves in New England are only well constrained back to about 8,000 yr BP (Engelhart et al., 2010). It is expected that sediment core data from the Mud Hole will better constrain relative sea-level rise and the position of paleoshorelines beyond 8,000 yr BP.
The reconstruction of a post-glacial, pre-inundation paleolandscape will rely heavily on high-resolution geophysical datasets. As part of the geophysical surveys done for the RI Ocean Special Area Management Plan (OSAMP) in 2012, URI collected an abundance of interferometric side-scan and sub-bottom geophysical data, including from the Mud Hole (Figure 1.4.). The abundance of high-resolution data generated by these surveys should prove valuable for better characterizing the geomorphology, understanding the geological framework, and reconstructing a post-glacial paleolandscape of the Mud Hole.

1.1.3. Regional Geologic Framework From Previous Studies

Bedrock Geology of Block Island and Rhode Island Sound

Several early subsurface investigations utilizing geophysical survey techniques (Ewing et al., 1940; Oliver and Drake, 1951) provided the first look at the structure of the continental shelf between New Jersey and Cape Cod, Massachusetts. These early studies revealed a crystalline bedrock surface dipping towards the southeast and overlain with unconsolidated sediment thickening towards the southeast. Garrison (1970) identified the same crystalline basement surface, noting that it is the deepest prominent regional seismic reflector. He also reported steepening of this dipping surface from east to west, in agreement with an earlier study by Woodworth and Wigglesworth (1934). Previous works in the Long Island Sound Basin (e.g. Lewis and Stone, 1991) identify crystalline bedrock east of New Haven, CT as Precambrian to Paleozoic gneisses and granites associated with the accreted Paleozoic
microcontinent of Avalonia. Other studies, including McMaster and Ashraf (1973a) describe this same bedrock surface more generally as pre-Mesozoic “intrusive igneous masses and lava flows, schists and gneisses, and a wide variety of sedimentary rocks, most of which are highly metamorphosed”.

The bedrock geology of the Rhode Island Sound differs from the adjacent Block Island Sound due to seaward extension of the Narragansett Basin at least 16 – 22km offshore (McMaster et al., 1980). Low seismic velocities and magnetic evidence suggests metasedimentary rocks fill a pre-Pennsylvanian structural half-graben. Offshore seismic surveys have described the submerged bedrock surface as an irregular and channeled continuous surface. This surface gently dips towards the south-southeast (Figure 1.5 A,B.) with a prominent change in slope between the 100 m and 125 m sub-bottom contour below sea level (McMaster et al., 1968). In plan view, this slope change generally strikes ENE occurring several kilometers north of Block Island.

Coastal Plain and Cuesta

Unconsolidated remnants of coastal plain strata have been identified to unconformably overlie bedrock along the Atlantic coastal margin including New Jersey, Long Island and Block and Rhode Island Sounds (Flint, 1963; McMaster et al., 1968). Regional sub-surface studies reveal a south-southeast dipping, thickening wedge of semi-consolidated to unconsolidated sediment composed of sands, silts and clays reaching thicknesses of more than 400 m south of Long Island, NY (Denny, 1982). Relative dating techniques constrain the age of the
coastal plain sediments to be Late Cretaceous. Lithological analysis of boreholes approximately 5km south of Block Island describe semi-consolidated to unconsolidated non-marine and marine interbedded sands, gravels and clays (Sheldon, 2012). Sheldon correlated the lithostratigraphy of the boreholes to the regional Magothy and Matawan formations.

The shoreward extent of the coastal plain strata was traced in Block and Rhode Island Sounds by McMaster et al. (1968), revealing an irregular east-northeast striking, north-facing escarpment or cuesta (Figure 1.5. A.). The interface of the coastal plain cuesta and bedrock surface creates an inner lowland, referred to as the Fall Zone (Flint, 1963). Flint argues that coastal plain strata had once extended an unknown distance inland, though a long period of uplift and subaerial erosion down to the basement surface has removed any trace of coastal plain sediments north of the current cuesta (Figure 1.5. B.).

The seismic character of the unconformity marking the uppermost coastal plain strata is a prominent regional reflector and has been described consistently in numerous studies (e.g. Flint, 1963; McMaster et al., 1968; Needell and Lewis, 1984). In Block Island Sound, the northern edge of the cuesta is highly irregular, with several erosional remnants existing north of the cuesta. The upper coastal plain surface is deeply incised by fluvial erosion and later eroded further by episodes of Pleistocene glaciation. The coastal plain strata contain well-defined internal reflectors, which generally parallel the southward dipping coastal plain unconformity (Needell and Lewis, 1984), likely representing different strata of semi-consolidated to unconsolidated sediment.
Last Glacial Maximum and Formation of End Moraines

There is uncertainty regarding how many episodes of glacial ice sheet advance covered southern New England and the inner continental shelf. At a minimum, the Laurentide ice sheet advanced to the modern day inner continental shelf during Illinoian time (200 – 120 kya) and during late Wisconsinan time (Stone et al., 1998). The terminal position of the most recent Wisconsinan glaciation is delineated by the Ronkonkoma-Nantucket (R-N) terminal end moraine. Terminal end moraines are glaciotectonic landforms composed of faulted and folded till, glaciofluvial deposits and older displaced sediments, and are subaerially exposed on the south shore of Long Island, NY, Block Island, RI, Martha’s Vineyard and Nantucket, MA (Balco et al., 2002). Submerged portions of the R-N end moraine are characterized by shallow bathymetric ridges capped by boulders and gravel (Poppe et al., 2011). The R-N terminal end moraine position (Figure 1.1.) was reached by 24-26 kyBP (Balco et al., 2002; Oakley, 2011). A brief readvance of the Laurentide ice sheet occurred approximately 21 kyBP forming the Harbor Hill-Roanoake Point-Charlestown-Buzzards Bay recessional end moraine (Balco et al., 2002). Recent high-resolution seismic reflection evidence from Poppe et al. (2012) argues a glaciotectonic origin similar to the R-N end moraine (Boothroyd, 2001).

Modification of the pre-glacial landscape was mostly confined to the coastal plain valleys that were significantly widened and subsequently filled with glacial deposits during at least two glacial advances. A thin veneer of till covered the interfluvus, which were minimally modified during ice sheet advance (O’Hara
and Oldale, 1980; Stone et al., 1998). Incised coastal plain valleys predating glaciation were often reoccupied by glacial meltwater streams and subsequently filled by meltwater deposits consisting of unconsolidated to stratified sands and gravel (McMaster and Ashraf, 1973c).

Formation and Draining of Glacial Lakes

As the ice margin retreated towards the northwest from the terminal position, meltwater drained towards the south and became impounded by the elevated end moraine ridges. Early studies including Lougee (1953) and Newman and Fairbridge (1960) hypothesized the formation of Pleistocene freshwater lakes, with the understanding that sea level was significantly lower during the Pleistocene and that enclosed topographic depressions along the modern day inner continental shelf of southern New England existed above sea level during the lowstand, providing an environment where freshwater could pool. Early reports of rhythmically layered clay and silt couplets (varves when the couplets are annually deposited) and associated clay concretions recovered in sediment cores from freshwater proglacial environments are numerous and provide physical evidence of the expansiveness of this freshwater-lacustrine depositional environment (from Massachusetts: Ashley, 1972; from Block Island Sound: Frankel and Thomas, 1966; Bertoni, 1974; Bertoni et al., 1977; from Long Island Sound: Williams, 1976). The meltwater formed expansive glacial lakes, which occupied the modern day Long Island, Block Island and Rhode Island Sounds (Bertoni et al., 1977; Lewis and Stone, 1991; Lewis and DiGiacomo-
Cohen, 2000). In more recent studies the lakes occupying Long Island, Block Island and Rhode Island Sounds have been referred to as Glacial Lake Connecticut (GLCT), Block Island (GLBI) and Rhode Island (GLRI), respectively (e.g. Oakley, 2012) and the naming convention has been adopted within this paper.

The formation and extent of GLCT, BI and RI are inferred from isostatically compensated topographic models (Oakley, 2012). GLBI formed as the ice sheet began to retreat from the terminal position ~26kyBP. GLRI began to independently form, separated by the retreating Narragansett Bay Lobe of the Laurentide ice sheet. Connection between GLRI and GLBI occurred at 21 kyBP, and formation of GLCT began when ice was at the recessional end moraine position. As the lakes expanded in volume, water levels were controlled by spillways, which formed at topographic lows in the moraines. The Race has been implicated as a spillway for GLCT, as it breaches the Fishers Island-Charlestown recessional end moraine segment. The Block Channel spillway likely served as the spillway for glacial lakes Block Island and Rhode Island. Erosion at the Race to the water level of Block Channel Spillway (-25 m below present MSL) led to interconnectedness of GLCT, BI and RI (Oakley, 2012). Much of what is known about paleolake levels comes from measured elevations of delta topset/foreset contacts. The Mud Hole was implicated as a spillway due to a projected water level that failed to intersect the Block Channel Spillway, necessitating a spillway at a lower elevation. It is hypothesized that spillway control switched from Block Channel Spillway to the Mud Hole, due to a 5 m drop in lake level when GLBI and GLRI coalesced.
Drainage of glacial lakes resulted from erosion at the spillways and the regional isostatic rebound. Recent studies have favored delayed isostatic rebound in southern New England, beginning 16 kyBP, with only 30 m of isostatic depression at the terminal edge (Oakley and Boothroyd, 2012). Drainage of GLCT completed by 15.5 kyBP (Lewis and DiGiacomo-Cohen, 2000).

**Sea Level History and Marine Inundation**

Retreat of the Laurentide ice sheet at 26kyBP, caused sea level to rise from its global lowstand -120 m below present sea level, and rapidly accelerating by 15 kyBP (Peltier and Fairbanks, 2006; Oakley and Boothroyd, 2012). There remains some uncertainty regarding how quickly isostatic rebound began following the retreat of the ice sheet. Oakley and Boothroyd (2012) favor a delayed onset ~16 kyBP, whereas geophysical models support concurrent rebound and retreat (Roy and Peltier, 2015). Regardless, by 16 kyBP, isostatic rebound as likely outpacing sea level rise for 2,000 years at the Late Wisconsin terminal margin near Block Island. In coastal New England, uplift followed a 0.85 m/km rebound profile towards the northwest at 331 degrees based on measurements of delta elevations representing formerly horizontal water levels in proglacial lakes (Koteff et al., 1993; Oakley and Boothroyd, 2012).

By the earliest Holocene, sea level was still rising rapidly in southern New England, and isostatic rebound had been mostly completed (Engelhart and Horton, 2012; Oakley and Boothroyd, 2012). From 8-4kyBP sea level rise still remains poorly constrained, however reconstructions of sea level from basal sea
level index points from salt marshes in Connecticut reveal sea level rise had slowed to 1.7 mm/yr between 6 and 4 kyBP (Engelhart and Horton, 2012). The Atlantic Ocean began to inundate the stream systems cut into the drained lake-beds in present day Long Island, Rhode Island and Block Island Sounds, marking a transition to an estuarine depositional environment. Estuarine sands, silts, clays and freshwater peats are thought to overlie fluvial channel fill (O’Hara and Oldale, 1980; Needell, O’Hara and Knebel, 1983; Needell and Lewis, 1984).

A prominent ravinement surface, a transgressive wave-cut surface is observable in regional seismic reflection data (from Rhode Island Sound: O’Hara and Oldale, 1980; Needell, O’Hara and Knebel, 1983; from Block Island Sound: Needell and Lewis, 1984; from Long Island Sound: Lewis and Stone, 1991). Fine-grained marine sediment conformably drapes the ravinement surface in deeper basins that are less prone to erosion by bottom currents. Shallower regions are more commonly covered with coarser reworked beach sand and gravel (O’Hara and Oldale, 1980; Needell, O’Hara and Knebel, 1983; Needell and Lewis, 1984; Lewis and Stone, 1991).

Troughs in the modern seafloor bathymetry are reported by McMaster and Ashraf, (1973c), but are not discussed in detail. These features are broad and enclosed, relatively shallow depressions that do not necessarily exhibit superposition with an underlying drainage surface. The Mud Hole is clearly indicated as one of these troughs. The Race is a well-studied series of troughs connecting Long Island and Block Island Sounds. The Race originated as a spillway connecting Glacial Lakes Connecticut and Block Island, and transitioned
to a narrow tidal constriction connecting the Long Island and Block Island Sounds during marine inundation (Lewis and Stone, 1991). Bottom currents resulting from tides have long scoured The Race, which reaches depths exceeding 300 feet.
1.2 Methodology

1.2.1. Data Acquisition

A suite of geophysical data including interferometric side-scan (swath bathymetry and backscatter) and Compressed High Intensity Radar Pulse (CHIRP) seismic reflection data were collected in August, 2012 on the EPA operated Ocean Survey Vessel (OSV) Bold. It is worth noting that the geophysical survey predates the author’s involvement in the study and therefore the details of data acquisition are from personal communication with watchstanders that had been present during the survey, logbooks and sonar header files. The combined Teledyne Benthos C3D/CHIRP III pole-mounted sonar system allowed for simultaneous collection of interferometric and sub-bottom data, respectively. Data from a total of 37 survey lines spaced 500 m, trending WNW – ESE, surveyed perpendicular to the deep channel-like portions of the Mud Hole were collected (Figure 1.4.). No data from crossing lines (lines run perpendicular to the trend of the survey) were obtained. Side-scan swath width was approximately 500 m, providing nearly complete coverage of the study area. Bathymetric swath width was significantly narrower than side-scan swath width, depending on water depth. Data acquisition was controlled by Ocean Imaging Consultants GeoDAS software for the interferometric side-scan data. Chesapeake Technologies SonarWiz software was used for CHIRP seismic reflection data acquisition. Position, heading, attitude, heave and velocity data were obtained by an Applanix POS MV Inertially-aided Real-Time Kinematic Global Positioning
System. Nearly 260 km of sub-bottom data and ~130 km² of interferometric side-scan data were collected.

CHIRP seismic reflection data achieved a maximum of 90 m penetration. The system produced a CHIRP waveform with a 2-7 kHz frequency band transmitted at a 1/8 second repetition rate. Raw data were recorded in SEG-Y format.

Interferometric side-scan raw data were recorded in .OIC file format (Ocean Imaging Consultants proprietary file format).

1.2.2. Sub-bottom Profile Post-processing and Interpretation

Raw SEG-Y files were imported into Chesapeake Technologies SonarWiz 5. Navigation shot points were geospatially plotted as tracklines in the projected UTM Zone 19N coordinate system. A qualitative visual inspection of the sub-bottom profiles revealed a non-systematic, irregular navigation error. The error was first noticed when the maximum seafloor depths from each sub-bottom profile did not match the deepest position from simultaneously collected swath bathymetry. Inspection of shot point positional data using the Navigation Editor tool in Sonar Wiz 5 revealed erroneous navigational excursions. The Navigation data interpolation tool was used to correct and smooth the excursions such that the shot point tracklines were approximately linear. Additionally, each trackline had a substantial and erroneous linear offset, such that the position of each sub-bottom shot point lagged from 0 to ~1900 m behind the true shot point position. The erroneous linear offset was calculated for each of the 37 sub-bottom survey
lines by measuring linear offset of the maximum depth recorded in the sub-
bottom data from the maximum depth recorded in the swath bathymetry data. The linear difference between maximum depth in the two datasets was tabulated (Table 1.1), and corrections in the sub-bottom data were made by using the “cable layback” and “cable out %” post-processing tools in SonarWiz 5. The non-
systematic and irregular nature of these positional errors is difficult to explain and is considered to be a technical glitch. URI GSO Marine Research Scientist Rob Pockalny was present during data acquisition and confirmed that the navigational error was noticeable and unresolved (personal communication, August 2015).

The turns connecting each survey line were manually clipped and removed leaving 37 nearly parallel survey lines. The seismic reflection images were processed to adjust for signal attenuation and to reduce environmental and background noise. Bottom tracking was performed using SonarWiz’s automated bottom tracking tools, though some manual tracking was required where the seafloor was a weak reflector. Data artifacts due to vessel heave were removed by estimating the swell period and applying the Swell Filter tool (typically 3-5 seconds performed well). A combination of automatic gain control and user defined gains were applied to all seismic images, with each image considered independently.

A persistent diagonal striping data artifact across all seismic images was unable to be removed through bandpass filtering or gains. Similar to a seafloor multiple, the inability to remove these unwanted artifacts did not detract from
the interpretation of the seismic images. The source of the data artifact has not been determined.

Seismic reflectors identified in each processed image were traced using the SonarWiz Digitize Reflectors tool. The reflectors were also displayed in map view such that the 2D spatial extent and continuity of the reflectors could be ascertained.

1.2.3. Side-scan and Swath Bathymetry Post-processing and Interpretation

Side-scan data had been previously post-processed using Ocean Imaging Consultants (OIC) CleanSweep processing software by Monique LaFrance-Bartley, URI Marine Research Assistant. Automated bottom tracking was performed, and manual corrections were made when necessary. Along and cross-track gain equalization was applied to improve imagery. Data at the distal edges of the swath were poor, and swath width was trimmed to reduce edge noise. For this reason, there was no data overlap resulting in incomplete coverage within the survey area. Side-scan swaths were mosaicked with 1-meter/pixel resolution and exported as a GeoTIFF spatially referenced in the Universal Transverse Mercator (UTM) Zone 19N projected coordinate system.

Each swath was carefully inspected for changes in sedimentary environment and demarcated using the Cleansweep contact tool. Each contact created was exported as a separate GeoTiff (Figure 1.6.). The side-scan mosaic GeoTIFF of the study area was imported into ESRI ArcMap 10 GIS software, and each digitized contact was layered above the background side-scan mosaic. An
initial interpretive map delineating areas of high, medium, low and mixed backscatter helped to identify sedimentary environments (Figure 1.7.). Next, the distribution of each digitized contact guided the delineation of different surficial sedimentary environments. An interpretative map was created by mapping the spatial extent of each sedimentary environment (Figure 1.8.). The integration of these maps with seismic reflection data is useful for determining which portions of the study area are most likely to have been significantly modified in post-glacial times.

Swath bathymetry was processed using OIC Cleansweep processing software. The range of each swath (width) was trimmed to remove noisy and sparse data along the beam edges. A quality filter was applied which uses a vertical distance criterion between adjacent sonar pings to filter out erroneous data. Corrections for ship roll and pitch, mount angle corrections and sound velocity were applied to further improve the data. Despite the improvements in bathymetric data quality, swath bathymetry failed to improve our understanding of the seafloor morphology within the study area due to a narrow swath width leading to poor overall data coverage and relatively small vertical changes in seafloor morphology. The swath bathymetry, however, was very useful for alignment of the seismic reflection data, which as previously discussed required numerous non-systematic corrections in positioning. Areas of very high slope and maximum water depth in the swath bathymetry were used as tie-points to align the seismic reflection profiles to true positions. For visualization, the RI Ocean SAMP “RI Coastal Bathymetry” raster dataset produced by the University
of Rhode Island Environmental Data Center (URI EDC) was preferred, which features data extracted from the National Geophysical Data Center (NGDC) (currently known as the NOAA National Centers for Environmental Information) NOAA Coastal Relief Model. The dataset features a 266.69(X) by 266.69(Y) ft cell size with one-foot vertical resolution, projected in the NAD 1983 Stateplane Rhode Island FIPS 3800 Feet horizontal coordinate system.

1.2.4 Comparison of Relative Sea Level Curves of Southern New England

A brief comparison of relative sea level curves from southern New England was required to better understand the uncertainty associated with marine inundation of the Mud Hole study area (Figure 1.9.).

A commonly cited relative sea level curve for southern New England, produced by Oldale and O’Hara (1980) used radiocarbon dates from peat and shells recovered in vibracores from Vineyard Sound and eastern Rhode Island Sound near Martha’s Vineyard. Plotting the radiocarbon age against the depth location from the vibracore, and assuming the dated material remained in place, a best-fit relative sea level curve was constructed. Since this study reported radiocarbon ages, the online CALIB v 7.1 Radiocarbon Calibration tools based on the published calibration curve produced by Reimer et al. (2013) were used to calibrate selected radiocarbon ages. Localized marine reservoir corrections were computed by choosing the three nearest points in the Marine Reservoir Database, and averaging reported ΔR values. A weighted mean ΔR value of 140 was used for radiocarbon age calibration. Since both terrestrial (peat) and marine (shells)
samples were used for the construction of the relative sea level curve, the Mixed Marine and Northern Hemisphere curve was preferred. The percentage of marine samples (65%) was computed by counting the number of marine samples (13) and dividing by the number of samples reported in Oldale and O’Hara (1980), but omitting two samples >35,000 radiocarbon yr BP (20).

Also compared were relative sea level curves for Connecticut and Long Island, produced by Roy and Peltier (2015) based on radiocarbon dated material from salt marshes originally reported by Engelhart and Horton (2012). The last relative sea level curve included in this comparison was produced by Oakley and Boothroyd (2012) and was calculated using the algebraic difference between isostatic rebound derived from an uplift profile based on paleolake delta water levels and eustatic sea level. The studies, locations and methods are summarized in Table 1.2.
1.3 Results

1.3.1. Observations From Bathymetry

The Mud Hole study area is noticeably deeper than the surrounding Rhode Island Sound, and forms an elongate trough with two distinct channels (Figure 1.1. B). The channels are deepest towards the center of the trough, with shallower depths on all the surrounding sides, creating an enclosed basin. Towards the north, the channels coalesce into one broad channel with a NE-SW axis that extends well northeast of the study area. Towards the south, the channel splits and assumes a more N-S axis orientation. Broad, fan shaped features are observed at the channel’s southern outlet and are responsible for enclosure at the southern extent. The study area reaches depths of 60 m along the eastern channel, well north of the channel’s outlet.

Directly to the west and east of the study area, bathymetric highs referred to as East Ground on the west, and Cox Ledge on the east form a constriction along the axis of the Mud Hole (Figure 1.1. A). Just north of the study area, the slope of the west and eastern edges of the trough broaden, becoming less steep.

Just west of the Mud Hole, beginning in the north of East Ground, a dendritic channel-like trough cuts through East Ground. Paleodrainage studies utilizing seismic reflection techniques show that the channel observed in the regional bathymetry represents a rerouting of drainage following the last glacial maximum. A well-established paleodrainage valley passed just to the east of present-day Block Island, a route that has connected the Narragansett basin to Block Channel at least since the Late Cretaceous. The Late Wisconsinan glacial
advance filled this paleodrainage valley, and drainage found a path of lower resistance further east through a thinner segment of East Ground (McMaster and Ashraf, 1973c).

1.3.2. Identification of Sedimentary Features From Side-scan Imagery

Megaripples

Megaripples are sandwaves with wavelengths ranging from 2 to 20 m and crest to trough measurements ranging from 60 cm to 2 m (Ashley, 1990). Measurements of observed megaripples were consistent with these dimensions. Wave crests are continuous, linear and approximately parallel. In the side-scan imagery, megaripples are characterized by apparent alternations in high and low intensity acoustic reflection, creating a dark/light-banded appearance along the seafloor (Figure 1.6. A; Figure 1.8.). Dark or low-intensity reflection is thought to occur due to acoustic shadowing of the lee-side by the stoss of the ripple. Megaripples were only observed in shallower regions of the study area (<40 m depth), such that they were observed in all quadrants of the study area with the exception of the NW quadrant. Another predictor of megaripple presence is coarse-grained sediment, which is represented by high acoustic backscatter (light-colored areas). Since deeper portions of the study area (i.e. channels) are dominated by fine-grained sediment and low acoustic backscatter, megaripples are not observed in these portions of the study area.

Megaripples are not static features, migrating perpendicular to the trend of their crests, in response to unidirectional flow. The crests of megaripples
observed in the Mud Hole study area trend WNW-ESE suggesting a NNE migration aligned with storm-induced bottom currents.

**Erosional Outliers and Scour Depressions**

Scour depressions are identified as portions of the seafloor where bottom currents have caused erosion of sediment. These features are typically found adjacent to erosional outliers, which are portions of the seafloor that are more resistant to erosion. According to high-resolution bathymetric studies in central Rhode Island Sound (e.g. McMullen, et al., 2012), scour depressions averaged 0.5 m in depth. Swath bathymetry collected in the Mud Hole could not resolve such shallow depths, however, these features were observed in the side-scan data. Scour depressions are characterized by having high acoustic backscatter relative to surrounding seafloor and erosional outliers. The shape of scour depressions is crescent to elongate, whereas erosional outliers are more rectangular or tabular in shape (Figure 1.6. B; Figure 1.8.). The morphology of scour depressions and erosional outliers is consistent with findings by McMullen et al. (2012).

Scour depressions and erosional outliers, like megaripples are confined to areas of shallow bathymetry and thus are seemingly absent in regions deeper than 40 m. They are nearly exclusively found in the southern portions of the study area, within the mapped extent of boulders, suggesting a formational mechanism reliant on the presence of boulders. McMullen et al., 2012 hypothesizes that bottom currents experience enhanced turbulence due to interactions with coarse (rough) sediment on the seafloor. This turbulence
drives the erosional processes responsible for the formation of scour depressions and inhibits subsequent deposition. Presence of boulders greatly increases seafloor roughness thereby increasing erosional processes.

Due to the contrasting backscatter signatures of erosional outliers and scour depressions, these features have been mapped as areas of mixed acoustic backscatter.

**Boulders**

Boulders are distributed primarily in the southern portions of the study area, with the exception of the deepest locations. Areas of gravelly sediment with boulders are characterized by a mottled or speckled appearance in the side-scan data (Figure 1.6. C; Figure 1.8.). Isolated boulders appear as highly reflective (bright) points due to strong acoustic backscatter. Some of the larger boulders cast acoustic shadows on the adjacent seafloor, perpendicular to the sonar’s NADIR.

**Anthropogenic Features**

Trawl marks are linear, continuous features characterized by very low acoustic backscatter. These features are the results of bottom trawling activities. Analysis of the side-scan data reveals that trawl marks are only observed in the deep channels of the study area, which are dominated by fine-grained sediments exhibiting very low backscatter (Figure 1.6 D; Figure 1.8.). The majority of trawl
marks are constrained to the western channel of the Mud Hole study area within a narrow NE-SW trending corridor.

1.3.3. Seismic Reflection Analysis

Several seismic reflectors and seismic units were identified within the Mud Hole study area. The CHIRP III seismic reflection system performed best where surficial sedimentology was predominantly fine-grained. A maximum acoustic penetration of 90 m was achieved. Where surficial sediments were coarse, attenuation of the seismic signal occurred. Particularly in the southern portion of the study area, acoustic penetration was limited to the upper 5 – 10 m.

Identified discontinuities and seismic units were correlated to the regional seismic stratigraphy developed in earlier studies (Figures 1.10. – 1.17.); the naming convention for discontinuities and seismic units were purposely kept consistent for the convenience of future workers.

Seismic Unit Ku and Discontinuity Fu₂

The deepest reflector identified within the study area, Fu₂ is inferred to be an erosional unconformity, truncating lower seismic unit Ku. The surface is strongly reflective and completely attenuates the seismic signal, effectively making this reflector acoustic basement for the Mud Hole study area. In this study, no internal bedding or structure can be observed below reflector Fu₂. Reflector Fu₂ is only traceable in the northern half of the study area. This lower penetration is controlled by the coarsening surficial geology south of seismic
reflection line 18, since acoustic penetration of the CHIRP III signal greatly improves in fine-grained sediments, whereas areas of coarse surficial geology quickly attenuate the seismic signal.

Reflector Fu2 is a smooth, westward dipping surface in seismic reflection lines 1-5, reaching depths of 80 m. Seismic reflection line 6 (Figure 1.10.) shows Fu2 becoming much more irregular and assumes an incised valley configuration which persists until seismic line 11. Seismic unit Ku shallows and nearly outcrops at the seafloor, but remains shallowly buried as is observed in seismic reflection profile 8 (Figure 1.11.). Seismic line 11 shows that the western side of the incised valley steepens, dipping beyond 90m below sea level where it can no longer be resolved in the seismic stratigraphy. The eastern side of the incised valley also is no longer resolved due to overlying acoustically impenetrable surficial sediments to the east. South of seismic line 17, Fu2 is no longer observable due to the coarse surficial geology.

Seismic Unit Qdo, Qdm and Discontinuity Fu1

Seismic unit Qdo unconformably overlies seismic unit Ku, the boundary represented by Fu2 and shows considerable thicknesses (up to 45 m, line 6) in seismic reflection lines 1-18. In these lines, tightly spaced and continuous parallel internal reflectors mantle discontinuity Fu2. The thickness of seismic unit Qdo is generally controlled by the depth of Fu2, and thus the deposits are thickest where Fu2 assumes a deep incised valley configuration.
Seismic unit Qdm overlies discontinuity Fu$_2$ south of seismic reflection line 18. Acoustic penetration is significantly reduced due to coarse surficial geology, making it difficult to determine the thickness of seismic unit Qdm, however, some seismic lines (lines 29, 32, 33) show a mix of crude, discontinuous stratification and chaotic and parabolic internal reflectors (Figure 1.17).

Discontinuity Fu$_1$ truncates Qdm, forming two distinct paleochannels, referred to as the west and east channels. Fu$_1$ is first observable in seismic reflection line 18, where all lines south are characterized by significantly coarser surficial sediment. The eastern channel axis trends south and continues outside of the study area by line 22. The southwest trending western channel can be observed in seismic lines 16-37. The greatest amount of acoustic penetration in the southern half (south of line 18) of the study area occurs in the western paleochannel, though penetration rarely exceeds 10 m. The depth of reflector Fu$_1$ is approximately 60 m and constant wherever observable in the study area. Both the western and eastern channels are widest in seismic reflection line 16, and become progressively narrower towards the south. The full depths of the channel are difficult to resolve in the CHIRP seismic reflection data due to signal attenuation.

**Seismic Unit Qfe, Discontinuity Mu and Seismic Unit Qm**

Seismic unit Qfe overlies discontinuity Fu$_1$, partially filling the paleochannels. The base of Qfe is strongly reflective, with hummocky, chaotic and discontinuous internal reflectors. This lowermost channel fill obscures the
true channel depth. Acoustically transparent sediment overlies the strongly reflective fill, and is <5 m in thickness.

Discontinuity Mu is a prominent reflector in all lines north of seismic reflection line 17. It is characterized as a continuous, smooth surface that truncates seismic unit Qdo. The contact between the underlying seismic unit Qdo and overlying sediment suggests little disturbance where discontinuity Mu parallels the seafloor. This lack of disturbance suggests that the contact is conformable, with little erosion of Qdo. Mu forms a channel beginning with seismic reflection line 8. Discontinuity Mu reaches a maximum depth of 70 m by line 12, and remains at this depth until line 15. Discontinuity Mu shallows to 60 m in line 16, and is not observable in any lines to the south. Where the channel cut by Mu deepens, increased disturbance of underlying seismic unit Qdo is observed (e.g. line 9, Figure 1.12.).

Over much of the northern half of the study area, a thin veneer of sediment overlies discontinuity Mu. Seismic unit Qm is nearly acoustically transparent and amorphous, though some discontinuous, flat-lying internal reflectors occasionally are seen (e.g. line 15, Figure 1.14.). With the exception of the channel cut by Mu, where Qm thickens ~12 m most of this seismic unit is no thicker than 1-2 m. Qm is not observed where seafloor depths < 40 m.
1.4. Discussion

1.4.1. Evaluating Relative Sea Level Curves of Southern New England

There are significant disagreements amongst relative sea level (RSL) curves for southern New England (e.g. Oldale and O'Hara, 1980; Oakley and Boothroyd, 2012; Roy and Peltier, 2015). For the purposes of understanding the timing and evolution of depositional environments in the Mud Hole, each sea level curve is evaluated below.

Roy and Peltier (2015) produced RSL curves for the U.S. east coast to test iterative improvements of both the ice loading deglaciation history model (ICE-6G_C) and modeling of mantle viscosity (VM6). When coupled, these models predict RSL curves that are in agreement with geological sea level history data presented by Engelhart et al. (2011). This robust dataset consists of 686 sea level indicators with consistent methodology and significant attention given to quality control and estimates of error (Engelhart et al., 2011). Sixteen regional RSL curves along the U.S. east coast were produced using this extensive dataset. In southern New England (Connecticut; Long Island), resulting RSL curves fit well with relative sea level indicators from Engelhart et al. (2011), especially from 4,000 to 0 yr BP. However, beyond 4,000 yr BP the predicted RSL curve falls to the right of relative sea level indicators leading to several misfits. This result suggests that for Long Island and Connecticut, the ages of -60 and -35 m relative sea level may be underestimated, that is, the ages associated with -60 and -35 m are too young.
An important affirmation of the refinement of the models (ICE-6G_C [VM6]) is the ability of the models to describe glacial forebulge collapse during the Late Holocene. In the models’ latest iterations, both the geographical extent and amplitude of glacial forebulge collapse are in agreement with geologically inferences. This important agreement is due in part to drastic improvements in the models’ predicted sea level curves in regions such as the mid Atlantic, especially >4 kyBP, which were most impacted by the glacial forebulge. Southern New England is a transitional area in model performance. Regions such as Maine and northern Massachusetts still have considerable misfits between predicted RSL and indicators. However, it is expected that slight changes in ice loading history will reduce misfits (Roy and Peltier, 2015).

Oakley and Boothroyd’s RSL curve differs methodologically from Roy and Peltier (2015) as it is not dependent on ice sheet loading and the solid Earth geophysics associated with glacial isostatic adjustments. Alternatively, reconstructed RSL considers the algebraic difference between delayed isostatic adjustment and a best-fit eustatic sea level curve. The uplift profile resulting from isostatic rebound is recorded by formerly horizontal water levels of proglacial lakes, which project onto a linear plane. Oakley and Boothroyd argue that no measurable isostatic rebound had occurred prior to 16 kyBP, and may have been delayed as late as 14 kyBP, due to projected water levels and drainage of Glacial Lake Hitchcock (occupying the present day Connecticut River Valley). The mechanisms proposed for delayed isostatic rebound is the lithosphere underlying southern New England behaving as a rigid “crustal block”. This
approach is in disagreement with viscous mantle models, which favor contemporaneous uplift and ice retreat.

The relative sea level curve proposed by Oakley and Boothroyd is in poor agreement with the Long Island and Connecticut RSL curves produced by Roy and Peltier (2015) from 4 to 0 kyBP. This disagreement is significant because of the excellent agreement of the Long Island and Connecticut RSL curves with the RSL index points over this time interval. For example, at 4,000 yr BP, RSL is estimated at -7 m in the Long Island curve, versus -3 m the Block Island curve produced by Oakley and Boothroyd. The differences become even more pronounced, especially by 10,000 yr BP, where RSL differs between the two curves by ~25 m (Figure 1.19).

The RSL curve proposed by Oldale and O’Hara was constructed based on radiocarbon dating of terrestrial peats and marine shells identified in vibracores. Each dated sample served as either terrestrial limiting (RSL below) or marine limiting (RSL above). This approach helps to constrain sea level in space and time, and the proposed RSL curve represents a best fit of these limiting dates. Compared to the rigorous quality control measures taken for the RSL index points in Engelhart et al. (2011), each dated sample is subject to more error and uncertainty, including the assumption that the sample had remained in place following deposition.

In the following discussion, the timing of each change in environment is reported as the full range of dates due to disagreement amongst relative sea level curves. Overall, the Connecticut and Long Island RSL curves from Roy and Peltier
(2015) are considered to be most robust due to agreement with RSL index points and the overall performance of the latest geophysical models in all regions along the U.S. East Coast. The Connecticut and Long Island RSL curves tend towards dates that are younger than the Block Island curve for a given RSL, and thus when evaluating the full date range associated with a depositional environment, older dates should be viewed cautiously.

1.4.2. Seismic Sequence Analysis

The analysis of side-scan imagery and 37 CHIRP seismic reflection lines collected in the Mud Hole study area has revealed several episodes of deposition and erosion. Five distinct depositional environments have been interpreted and are discussed in the following section, with each seismic unit and discontinuity correlated to those reported in regional studies. The chronology of each depositional environment has been constrained based on our understanding of deglacial processes including retreat of the Late Wisconsinan ice sheet, isostatic rebound and sea level inundation.

1.4.3. Depositional Environment 1: Pre-glacial Atlantic Coastal Margin

The lower most depositional environment is correlated to the regional Ku seismic unit and represents the highly eroded coastal plain remnant. The coastal plain strata are composed of semi-consolidated to unconsolidated marine sands, silts and clays that were primarily deposited in the Late Cretaceous Period (Flint, 1963; McMaster et al., 1968; Sheldon, 2012). Early lower resolution but more
deeply penetrating seismic reflection studies report parallel internal bedding distinctive of coastal plain sediments, none of which was observed in this study (McMaster et al., 1968). Correlation with Ku is therefore limited to stratigraphic position and expected depth to the truncated surface. Previous works within the Rhode Island Sound report a similar depth to the coastal plain surface in the vicinity of Block Island (McMaster and Ashraf, 1973c). Additionally, crystalline bedrock is expected to occur approximately 200-300m below sea level, depths far greater than the acoustic penetration achieved by the CHIRP III seismic reflection system and thus too deep to be seismic unit Ku (McMaster, 1968; McMaster and Ashraf, 1973a).

The first episode of erosion is recorded by a prominent fluvial unconformity, correlated with Fu₂ in several regional studies (O’Hara and Oldale, 1980; Needell, O’Hara and Knebel, 1983; Needell and Lewis, 1984; Lewis and Stone, 1991). Fu₂ represents the fluvially eroded surface of the underlying coastal plain strata during eustatic sea level lowstands of the Late Tertiary and Early Quaternary periods and subsequent widening and deepening by episodic glaciations during the Pleistocene Epoch. North of the Mud Hole, Fu₂ forms the north facing cuesta.

The possibility that reflector Fu₂ could represent an erosional contact between the most recent glacial deposits and pre-Wisconsinan glacial deposits has been considered, and without direct sampling cannot be fully ruled out. However, the alignment of the valley axis defined by Fu₂ and the direction of glacial advance suggests that the most recent Wisconsinan glaciation would have
likely removed most if not all of the earlier glacial deposits, and continued to widen and scour the pre-glacial valley. In addition, pre-Wisconsinan glacial deposits have only been found locally outcropped on the outer islands (LI, BI, MV, Nantucket), due to glaciotectonic upthrust of pre-glacial material (Poppe et al., 2012). The study area is dissimilar to this geologic configuration, and thus the interpretation that Fu$_2$ represents an erosional unconformity separating pre-glacial and glacial deposits is favored.

1.4.4. Depositional Environment 2: Ice Marginal Terminal End Moraine Setting

Unconformably overlying seismic unit Ku comprises a variety of glacial deposits. A major assumption of this study, and many regional seismic reflection studies is that all glacial deposition prior to the most recent Late Wisconsinan advance have been completely removed north of the terminal end moraine. Regional seismic reflection studies have considered glacial deposits as one seismic unit, Qdo, however these studies recognized that the glacial deposits (Qdo) are made up of unconsolidated tills, stratified outwash and glaciolacustrine deposits (O’Hara and Oldale, 1980; Needell, O’Hara and Knebel, 1983; Needell and Lewis, 1984).

Seismic unit Qdm is correlated to regional seismic unit Qdo, more specifically unconsolidated tills that form the terminal end moraine. As the Late Wisconsinan ice sheet reached its terminal position ~26 kyBP, unconsolidated tills and stratified outwash were deposited at the ice margin. It is expected that moraine deposits unconformably overlie seismic unit Ku, which cannot be
observed due to limited acoustic penetration caused by the coarse surficial sediments. Additionally, it is difficult to determine the thickness of the moraines. Several seismic lines (29, 32, 33) reveal hummocky, laterally discontinuous reflectors that may represent the basal moraine, or alternatively reveal some of the internal structure of the moraine deposits. The observed reflectors suggest that the moraine deposits are at a minimum 10 to 20 m in thickness if the reflectors are interpreted as basal.

1.4.5. Depositional Environment 3: Proglacial Lake Setting

Seismic unit Qdo, occurs in all seismic reflection lines north of line 17 and is correlated with seismic unit Qdo from regional seismic reflection studies (O'Hara and Oldale, 1980; Needell, O'Hara and Knebel, 1983; Needell and Lewis, 1984). The closely spaced, rhythmically layered, continuous internal reflectors draping the underlying topography are diagnostic of glaciolacustrine sediments. Qdo is interpreted to be proglacial delta/lakefloor deposits composed of varved silt and clay. As the ice sheet retreated, meltwater became impounded north of the terminal moraine deposits, flooding areas of low topography. The reflectors interpreted as varves in seismic unit Qdo exhibit vertical heterogeneity. The lowermost varves appear thicker than the uppermost, perhaps representing a transition from proximal to distal deposition as the ice margin retreated (Oakley, 2012; Morissette, 2014).
1.4.6. Depositional Environment 4: Post-glacial Fluvial Setting

Glacial deposits are truncated by an erosional unconformity, seismic reflector Fu₁, sharing its nomenclature with the regional reflector to which it is correlated. Proglacial lakes Block Island and Rhode Island began to drain as meltwater filled the inner lowlands and the isostatically depressed land surface began to tilt the land surface along a NNW-SSE gradient to 0.85 m/km. Horizontal water levels were maintained under hydrostatic forces, forcing drainage at topographic lows along the terminal moraine. It was at this point that the Mud Hole served as a spillway for glacial lakes Block Island and Rhode Island. Two south draining channels were progressively eroded into the end moraine. The western channel formed at the interface of glaciolacustrine and moraine deposits, between seismic lines 17 and 18. The depth of reflector Fu₁ representing the erosional surface of the spillway remains constant at 60 m below sea level through the southern outlet.

1.4.7. Depositional Environment 5: Post-Inundation Estuarine and Marine Setting

The deposits that overlie reflector Fu₁ in both the western and eastern channels are correlated to the regional seismic unit Qfe, a transgressive sequence consisting of channel fill sand, silt and clay, freshwater peat and marsh and estuarine silt and clay (O’Hara and Oldale, 1980; Needell, O’Hara and Knebel, 1983; Needell and Lewis, 1984). Qfe represents a transition from an erosive fluvial environment, to an estuarine depositional environment as marine inundation began. It is likely that the lower portion of Qfe partially fills the
spillway channels with channel-fill gravel, sands and silts. Presumably diachronous estuarine deposits composed of finer silts and clays overlie the emplaced channel fill, as sea level began to inundate the study area.

The eastern channel of the study area differs from the western channel in that the channel does not terminate north of the moraine deposits, but rather deepens to a marine backstripped sub-bottom depth of ~70 m below sea level as seen in seismic line 15. There are several pieces of evidence that suggest that a separate period of erosion continued the eastern channel north of the moraine and that fluvial processes were limited to the south of the moraine. Assuming reflector Fu$_1$ represented the sub-bottom thalweg of the eastern channel north of the moraine, then the depth of reflector Fu$_1$ exhibits a gradient dipping towards the north. The depth of Fu$_1$ would reach ~70 m below sea level in seismic line 15, which is approximately 10 m deeper than in seismic line 20, located 2.5 km south. This reversed gradient is not compatible with fluvial systems and an additional erosional mechanism is required to attain the present gradient configuration. If the eastern channel was only eroded due to fluvial processes, then reflector Fu$_1$ should be present north of the moraine, as well as the overlying depositional sequence, Qfe. There is no evidence of Fu$_1$ or Qfe north of the moraine, although it is possible that a more recent erosional event may have removed these sediments.

North of the moraine, the northward continuation of the eastern channel was likely due to tidal scour, which correlates to regional seismic reflector, Mu. In the study area, and north of the moraine, reflector Mu truncates the
glaciolacustrine depositional sequence. The reflector shows strong lateral continuity and smoothness and is generally flat-lying except where it dips steeply to continue the eastern channel. Reflector Mu represents the wave-cutting ravinement with marine transgression and tidal scour in the eastern channel. Overlying reflector Mu is an acoustically transparent marine depositional sequence correlated with regional seismic reflector Qm. Reflector Qm is a drape of fine-grained silt and clay as the Mud Hole transitioned to a quiet deepwater marine setting during the Holocene. Qm reaches thickness of >10 m in the eastern channel of the Mud Hole, and elsewhere is <2m.

Topographic modeling by Oakley (2012) depicts sea level inundation of the Mud Hole study area while only considering modern seafloor topography and without compensating for the thickness of marine sediments occurring after marine inundation. However, the study does reveal that the Mud Hole transitioned to an estuary with a constriction at the southern extent. The constriction of the flood tide into the Mud Hole estuary would have generated strong currents capable of scouring more erodible sediments. In the case of the Mud Hole, glaciolacustrine sediments were more easily eroded than the coarse sediments that make up the end moraines. This effect can be observed by the deepening of reflector Fu₁ to 70 m (e.g. seismic line 15) with the change in lithology from coarse moraine sediments to glaciolacustrine sediments. A more extreme case of tidal scour occurs at The Race, which connects Long Island Sound to Block Island Sound. The Race served as a spillway for Glacial Lake Connecticut prior to marine inundation, and was eroded to depths exceeding 100 m by strong
tidal bottom currents (>2 m/s) due to a long period of constriction, which is still present today (Poppe et al., 2014). The deep troughs formed as the result of degradational erosion and mass wasting, the latter contributing to large slump blocks composed of glaciolacustrine sediments (Poppe et al., 2014). Assuming a similar lithology underlying Holocene sediments in the Mud Hole, the disturbed and chaotic upper surface of glaciolacustrine sediments (e.g. seismic lines 11 and 12) is interpreted as reworked and slumped blocks of glaciolacustrine sediment.

An alternative explanation for the removal of up to 10 m of glaciolacustrine sediment in a more energetic manner would be due to plunge pool type erosion. Typically a plunge pool describes a highly scoured base of a waterfall, however, this is certainly not only manner in which these features may form. For example, a study by Lee et al. (2002) documents elongate troughs at the base of the west and east coast continental slope that were formed by submarine energetic sediment-laden density flows, with mean trough depths reported to be 21 m. It seems reasonable that an energetic breach of the Mud Hole due to marine inundation could be responsible for the narrow trough eroded to a depth of 10 m.

The timing of marine inundation in to Rhode Island Sound via the Mud Hole has only been considered using modern bathymetry. Seismic reflection evidence has revealed that the western and eastern channels of the Mud Hole spillway had eroded to 60m below present sea level, which is 15 m deeper than the reported 45 m at the southern extent of the basin (Oakley, 2012). Although it is evident that backstripping of marine sediments places the age of marine
inundation earlier than when only considering bathymetry, there remains significant uncertainty in the timing due to disagreement of relative sea level (RSL) curves from southern New England. According to the four RSL curves reported in Figure 1.9., and Table 1.2., the age that sea level reached 60 m below present occurred between 10,700 and 12,800 yr BP. Similarly, the range in age for sea level reaching 35 m below present is between 8,000 and 10,800 yr BP. Although there is a 2,100 year and 2,800 year uncertainty for the 60 m and 35 m below present sea level, respectively, there is less uncertainty in the duration required to transition from initial inundation (-60 m) to full marine (-35 m) conditions. The shortest duration occurs in the RSL curve by Oakley and Boothroyd (2012), taking 2,000 years, whereas the longest duration occurs in the RSL curve for Connecticut by Roy and Peltier (2015), taking 3,100 years. Despite the uncertainties, the physical evolution of the Mud Hole can still be described.

As sea level continued to rise above the -60 m level, the Mud Hole transitioned to an estuary with freshwater input from the north and connection to the Atlantic Ocean at the southern channels. The adjacent topographic highs of the moraines constricted the mouth of the estuary. To the north, rising sea level flooded the glacial lakefloor, marking the formation of the Rhode Island Sound. The constriction by the moraines, and the comparatively deeper and broader proto-Rhode Island Sound intensified tidal currents within the channels of the Mud Hole until a transition from estuarine to open marine conditions occurred. Assuming erosion atop the adjacent moraines was minimal, a transition to open marine conditions likely occurred when sea level had risen to 35 m below
present, which according to the regional sea level curve, occurred between 10.8 and 8 kyBP years before present. The preservation of boulder and gravel lag deposits on the adjacent moraines (Figure 1.7; Figure 1.8.) and mixed backscatter suggests some of the fine-grained sediments have been removed. Additional evidence comes from interpretations of sedimentary environments of the moraines. Observations of scour depressions and erosional outliers on the topographic highs adjacent to the Mud Hole are very similar in both size and shape to those reported in the Rhode Island Sound (McMullen et al., 2014). The depths of the scour depressions were reported to be 0.5-0.8 m, and are floored by boulder and gravel, which are thought to enhance near-bottom turbulence due to storm-driven currents and further inhibit deposition.

The scouring of glaciolacustrine sediments in the eastern channel of the Mud Hole study area is constrained to a 2,000 to 3,100 year period and removed a maximum of 10 m of sediment. Ravinement of glaciolacustrine sediments continued as sea level continued to rise, affecting much of the Mud Hole study area. As tidal constriction lessened, the deeper channels of the Mud Hole were progressively less affected by storm-induced and tidal currents, leading to deposition of fine-grained sediment during the Holocene. Evidence of present day sediment re-working is evident in large areas of megaripples found in waters shallower than 40 m. The current perpendicular orientation of the crests suggest south to north transport of sands. It is speculated that resuspension and erosion of sediments sourced from glacial moraine deposits are subsequently sorted, resulting in bedload transport of coarser sands and megaripple formation and
deposition of finer fractions within the deeper areas of the Mud Hole, similar to the findings from surficial geologic studies of the Rhode Island Sound (McMullen et al., 2014).

1.4.8. Paleocultural Significance

Several paleocultural sites dated to the Paleoindian and Early Archaic Cultural Periods have been documented in southern New England, the oldest of which has been dated to 12,000 yr BP (Leveillee, 2012). To date, there have been no archeological findings from the submerged continental shelf of southern New England, though this is likely significantly biased by inaccessibility and/or the burial or erosion of preexisting landscapes. There is no reason to believe that the continental shelf, when habitable, would have been avoided. Supplementing our knowledge of 12,000 years of human habitation, the oral history of the Narragansett tribe describes the existence of permanent human settlements on the continental shelf 15,000 years before present that were abandoned due to a rapid incursion by the sea (Doug Harris, personal communication). Operating under the hypothesis that the subaerially exposed shelf provided suitable conditions for habitation, paleolandscaes aid archaeologists in interpreting how ancient Native American cultures would have interacted with the natural environment.

The reconstruction of a paleolandscape requires a detailed understanding of the modern landscape and the sequence, magnitude and chronology of depositional and erosional events that have led to the modern configuration. At a
minimum, the eligibility of a paleolandscape to be of cultural significance is reliant on the ability of the paleolandscape to support human habitation.

Considering just the most recent interglacial, the Mud Hole study area was first considered habitable when glacial ice had retreated north of the study area. A conservative estimate of the onset of habitability is 21 kyBP, when the ice margin was well north of the Mud Hole at the Charlestown-Point Judith recessional end moraine position (Oakley and Boothroyd, 2012). The end of habitability is controlled by relative sea level rise and inundation of the study area. Earliest inundation, and the establishment of the Mud Hole study area as an estuary is constrained to have occurred between 12.8 and 10.7 kyBP based on the southern New England relative sea level curve and backstripping of marine sediments (Table 1.2). Full inundation of the Mud Hole study area occurred when sea level reached -35 m constrained between 10.8 to 8 kyBP. The date range from 21 – 8 kyBP represents the maximum period of time in which habitable conditions existed at least in part of the Mud Hole study area, however, the habitability of one particular location would likely have been transient as the basin evolved.

The following outlines the limitations to habitability in three distinct phases in the evolution of the Mud Hole while considering the large uncertainties that exist with the timing of marine inundation.

Phase 1: Post-glacial Lake 21 kyBP – 16 kyBP

As the ice retreated from the recessional end moraine position 21 kyBP, meltwater was already becoming impounded behind the moraines, flooding all
areas of the study area north of the moraines with freshwater. Lake water level control was shifted to the Mud Hole by 21 kyBP with coalescence of Glacial Lakes Block Island and Rhode Island (Oakley, 2012). Erosion began at the southern outlets, forming spillways, the path through which the lakes drained towards the Atlantic Ocean. Much of the Mud Hole study area was part of Glacial Lake Rhode Island, constraining the habitable area to the topographic highs along the moraines.

**Phase 2: Accelerated Lake Drainage 16 kyBP – 12.8 kyBP**

The interpreted acceleration of isostatic rebound of the glacially depressed land surface occurred ~16 kyBP. The rebound tilted the land surface, accelerating the drainage of Glacial Lake Rhode Island. Glacial Lake Connecticut was drained by 15.5 kyBP (Lewis and DiGiacomo-Cohen, 2000), which due the connectedness with Glacial Lake Rhode Island suggests a similar timing for drainage of Glacial Lake Rhode Island. Prior to marine inundation, much of the study area would be considered habitable if proglacial lake levels lowered significantly. The amount of drainage and thus the amount of subaerial exposure cannot be determined based on the geophysical data alone. Sediment cores would greatly aid in identifying the extent of subaerially exposed lakefloor suitable for habitation.
Phase 3: Transition to Estuarine Conditions 12.8 kyBP to 8 kyBP

According to the relative sea level rise curve, marine inundation reached 60 m below present between 12.8 and 10.8 kyBP and began to infiltrate the eroded spillways at the southern extent of the Mud Hole study area. Estuarine conditions that were originally confined to the thalwegs of the channels, inundated further into the proto-Rhode Island Sound. Constricted tidal inflow due to the topographically higher moraines led to tidal scour of the eastern channel, eroding up to 10 m of glacial lakefloor sediment. Full marine conditions were established between 10.8 and 8 kyBP when sea level had risen to ~35 m below present, overtopping the glacial moraines, and relaxing tidal constriction. Habitability of the Mud Hole study area began as early as 12.8 kyBP after the complete drainage of Glacial Lake Rhode Island and prior to the beginning of marine inundation, and declined until the study area was fully inundated and uninhabitable.

1.4.9. Vibracoring of the Mud Hole

A total of 16 vibracores were attempted during the RI Endeavor Program funded research cruise EN565, from August 22 – 28, 2015. Fifteen cores were successfully recovered (Figure 1.19.) in 6 m polypropylene lined steel core barrels. The coring targets were selected to ground-truth the identified reflectors and seismic units in the seismic reflection images.

Two of the recovered vibracores were chosen to determine the validity of the interpretations of seismic reflection profiles. Field notes from the research
cruise indicated an observed change in lithology in both VC-7 and VC-15. Additionally, a clay concretion was recovered in the core catcher of VC-7 and a coarse sand was observed on the outside core barrel of VC-15, however, it was not recovered. Both VC-7 and VC-15 were cut into 1.5 m sections, and split into working and archived halves using a core splitter. A change from marine/estuarine sediments to an unvarved clay lithology was observed in VC-7 and VC-15 at 225 cm and 390 cm, respectively. Each core was plotted with its corresponding seismic reflection profile. The change from marine/estuarine lithology to clay lithology showed excellent depth agreement with reflector Mu (Figure 1.20.; 1.21.). Friable clay concretions were observed at a depth of 260 cm, and subangular gravel in a clay matrix beginning at 300 cm. The concretions are hypothesized to represent a period of subaerial exposure, and subjected to episodic freezing and thawing. The subangular gravel, with no evidence of bioturbation is interpreted to be dropstones from the melting of small seasonal icebergs.

Additional lithological analysis of collected vibracores will greatly improve our understanding of the Mud Hole study area and serve to ground-truth interpretations of depositional environments. Several questions remain unanswered due to limitations of geophysical data. Did the proglacial lake completely drain, or did a small confined lake remain isolated in the basin? Subaerial exposure of the lakebed would result in oxidation and the formation of soils, which if preserved, would be recovered in a sediment core. How much time does seismic unit Qm span? Recovery of carbonate shells or other organic
material may help to constrain the transition from an estuarine to a marine depositional environment, and help to constrain Holocene sea level rise. The analysis of sediment cores will give a much more complete understanding of the chronological evolution of the Mud Hole study area.
1.5. Conclusions

- CHIRP seismic reflection images were interpreted and correlated to the regional seismic stratigraphy. The coastal plain remnant (Ku) is truncated by reflector Fu$_2$, which serves as acoustic basement of the Mud Hole study area, though it is only observable in the northern half of the study area due to poor penetration of the signal in coarse-grained sediments. Reflector Fu$_2$ is an unconformity representing fluvial erosion of the coastal plain remnant. Unconformably overlying Fu$_2$ are glacial deposits (Qdm and Qdo) composed of glaciolacustrine sediments predominantly in the northern half of the study area and glacial end moraine tills dominating the southern half. Reflector Fu$_1$ represents fluvial incision of glacial deposits forming channeled spillways that drained Glacial Lake Rhode Island in the southern half of the study area. Depositional sequence Qfe overlies reflector Fu$_1$ and is confined to the spillway channels. The composition of Qfe is inferred to transition from fluvial channel fill to fine-grained estuarine sediments. Reflector Mu truncates seismic unit Qdo, representing a ravinement surface due to marine inundation, and in the eastern channel, includes tidal scour. Unit Qm is fine-grained marine sediment, which drapes much of the Mud Hole where depths currently exceed 40 m.

- Five depositional environments were identified. Depositional Environment 1 is the pre-glacial coastal plain remnant (Ku) that formed in the Late Cretaceous Period. Fluvial erosion (Fu$_2$) deeply incised seismic
unit Ku, forming deep valleys that were widened and deepened by subsequent episodes of glaciation. Depositional Environment 2 is an ice marginal environment that deposited tills and stratified outwash (Qdm) forming glacial moraine deposits when the Late Wisconsinan ice sheet reached its terminal position 26 kyBP. Depositional Environment 3 is a proglacial lake environment, in which distal and proximal varved glaciolacustrine deposits unconformably drape the coastal plain remanant (Ku). Depositional Environment 4 is an estuarine setting in which seismic unit Qfe conformably fills the channeled spillways (discontinuity Fu1) that drained the proglacial lake. Onset of drainage is not well constrained, however it is expected that an interpreted acceleration of isostatic rebound ~16 kyBP accelerated this process. Depositional Environment 5 is an open marine setting. Discontinuity Mu truncates seismic unit Qdo, with minimal erosion from wave-cutting affecting most of the study area with the exception of tidal scour incising glaciolacustrine sediments to 70 m below present sea level. Qm drapes much of the Mud Hole where current seafloor depths exceed 40 m.

- Interpretations of modern sedimentary environments were made from side-scan sonar imagery. Megaripples, erosional outliers, scour depressions, boulders and anthropogenic features were identified and mapped. Megaripples are composed of coarse sands, which are actively reworked by bottom currents. Erosional outliers and scour depressions result in areas of mixed backscatter in the side-scan imagery, and are
formed by erosion of the resuspended finer fraction and inhibited deposition due to turbulence generated by a rough seafloor. Boulders and gravel are found to cap the glacial moraine deposits. Anthropogenic bottom trawl marks are preserved in deep fine-grained sediments.

- Habitability of the Mud Hole spans from 21-8 kyBP, when considering the uncertainty, however, habitability would have been transient. Three phases of habitability were described. Phase 1 details a proglacial lake setting existing from 21-16 kyBP. As the lake expanded, habitability would be confined to the topographic highs of the glacial moraine deposits. Phase 2 details the accelerated drainage of the proglacial lake with accelerated isostatic rebound occurring 16 kyBP. If lake levels lowered, leaving much of the lakefloor subaerially exposed, most of the Mud Hole study area could be deemed habitable, though additional study is required. Phase 3 details the transition of the Mud Hole study area from a drained proglacial lake to an estuarine setting, prior to complete marine inundation between 12.8-8 kyBP, which represents the full range of uncertainty. Habitability during the minimum 2,000 year period would become progressively more confined to higher topography, until full marine inundation of the study area occurred between 10.8 and 8 kyBP.

- Vibracores recovered from the Mud Hole study area in August 2015 have great potential to ground-truth interpreted depositional environments and improve our understanding of the chronological evolution of the basin. Initial observations of two vibracores show excellent agreement
with the depth of reflector Mu and support interpretations of lithological change.
Figure 1.1. Overview map showing the position of the Mud Hole study area (black inset); Late Wisconsinan terminal end moraine (dashed red line); a recessional end moraine (dashed black line); and adjacent water bodies (A). Fledermaus scene depicting the bathymetry of the Mud Hole and related bathymetric features (B).
Figure 1.2. Proposed study areas for the Bureau of Ocean Energy Management (BOEM) Paleocultural study.
Figure 1.3. Digital topographic models produced by B.A. Oakley and presented in Boothroyd, 2012, using sea level data from Peltier and Fairbanks, 2006. Over a 500-year span, the Mud Hole (indicated by red frame) undergoes a rapid change in depositional environment from a post-glacial lake to an estuary with 10 m of sea level rise.
Figure 1.4. Coverage map of high-resolution geophysical data collected by the URI Graduate School of Oceanography in August 2012. The data includes interferometric sonar and CHIRP seismic reflection profiles. Shown in this figure is a mosaic of side-scan imagery overlaying the RI Ocean SAMP RI Coastal Bathymetry raster dataset produced by the University of Rhode Island’s Environmental Data Center. Numbers correspond to the survey lines, referred to within this text.
Figure 1.5. Bedrock drainage map with 25 m contours and thalwegs of drainage channels (dashed line). Approximate position of coastal plain cuesta indicated by irregular northern trace of red shading. Image adapted from McMaster and Ashraf, (1973a) (a). Generalized cross-section showing the relationship between south dipping bedrock surface, coastal plain strata and the north facing cuesta from Long Island Sound. Although the cross-section is an idealized configuration from Long Island Sound, the general stratigraphic relationships are appropriate for a north-south profile in both Block Island and Rhode Island Sounds. Image adapted from Flint, (1963) (b).
Figure 1.6. Examples of identified sedimentary features from side-scan imagery. Megaripples (a); Erosional outliers and scour depressions (b); Boulders (c); and Trawl marks (d).
Figure 1.7. Characterization of backscatter intensity from side-scan imagery.
Figure 1.8. Mapped spatial extents of sedimentary features identified in side-scan imagery.
Figure 1.9. Comparison of relative sea level curves from southern New England. Red line is the intercept of 60 m below present sea level and reported age. Green line is the intercept of 35 m below present sea level and reported age. Oldale and O’Hara, (1980) relative sea level curve from SE Massachusetts (a); Oakley and Boothroyd, (2012) relative sea level curve from Block Island (b); Roy and Peltier, (2015) relative sea level curve from Connecticut (c); and Long Island (d).
Figure 1.10. Processed seismic reflection line 6, with interpreted seismic reflectors. See text for explanation of discontinuities and seismic units.
Figure 1.11. Processed seismic reflection line 8, with interpreted seismic reflectors. See text for explanation of discontinuities and seismic units.
Figure 1.12. Processed seismic reflection line 9, with interpreted seismic reflectors. See text for explanation of discontinuities and seismic units.
Figure 1.13. Processed seismic reflection line 12, with interpreted seismic reflectors. See text for explanation of discontinuities and seismic units.
Figure 1.14. Processed seismic reflection line 15, with interpreted seismic reflectors. See text for explanation of discontinuities and seismic units.
Figure 1.15. Processed seismic reflection line 18, with interpreted seismic reflectors. See text for explanation of discontinuities and seismic units.
Figure 1.16. Processed seismic reflection line 22, with interpreted seismic reflectors. See text for explanation of discontinuities and seismic units.
Figure 1.17. Processed seismic reflection line 33, with interpreted seismic reflectors. See text for explanation of discontinuities and seismic units.
Figure 1.18. Comparison of the relative sea level curve (black line) proposed for Block Island (Oakley and Boothroyd, 2012) and the relative sea level curve (red line) proposed for Long Island (Roy and Peltier, 2015). Note Long Island curve is only constructed to ~12,000 yBP.
Figure 1.19. Map showing the locations of vibracores collected by the R/V Endeavor (cruise EN-565) from the Mud Hole study area.
Figure 1.20. Vibracore VC-15 location and depth plotted against seismic reflection line 18. A lithology change from marine/estuarine sediments to glaciolacustrine sediments occurs at a sub-bottom depth of 3.90 m.
Figure 1.21. Vibracore VC-07 location and depth plotted against seismic reflection line 14. A lithology change from marine/estuarine sediments to glaciolacustrine sediments occurs at a sub-bottom depth of 2.25 m.
Table 1.1. Seismic reflection lines and layback correction.

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Table 1.2. Comparison of relative sea level curves of southern New England.

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<td>Mantle viscosity model (VM6) and deglaciation model ICE-6G_C combined with Engelhart et al., 2011 relative sea level curves reconstructed from salt marshes</td>
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<td>Mantle viscosity model (VM6) and deglaciation model ICE-6G_C combined with Engelhart et al., 2011 relative sea level curves reconstructed from salt marshes</td>
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CHAPTER 2

Identification of Sub-Seafloor Changes in Lithology From Vibracores and High-Resolution Seismic Reflection Profiles, Cedar Tree Beach, Greenwich Bay, Rhode Island
2.1. Introduction

2.1.1. Study Site and Justification

Cedar Tree Beach (41.687474 N, -71.442135 W) is a southwest facing sandy beach located at the northwest corner of Greenwich Bay, RI. The northwest end of the beach is Cedar Tree Point, a sandspit forming the eastern mouth of Apponaug Cove (Figure 2.1.). The beach is affronted by residential properties of Warwick, RI. Several man-made jetties perpendicular to the beach extend offshore. Baker’s Creek is just east of Cedar Tree Beach, serving as a small freshwater source to Greenwich Bay.

Greenwich Bay is a shallow (2.6 m mean depth), 12-square km estuary, with connection to the west passage of Narragansett Bay. Greenwich Bay is an extremely important recreational and economical resource for Rhode Island, necessitating the protection of its valuable resources. The RI Coastal Management Resource Council (CRMC) has addressed growing concerns of pollution and water quality in Greenwich Bay by creating a Special Area Management Plan (SAMP), authorized under the federal Coastal Zone Management Act of 1972. The Greenwich Bay SAMP serves as an ecosystem-based management strategy and relies on collaboration amongst local municipalities, academic institutions and community organizations (CRC, 2005).

Growing evidence points to the existence of a submerged paleocultural site in close proximity to Cedar Tree Beach due to the large number of stone projectile points and tools that have been found along the shoreline, the oldest of which date to 10,000 yr BP. As a result, Cedar Tree Beach has served as an
inshore study site for the Bureau of Ocean Energy Management Submerged Paleocultural Study. The primary objective for this study is to develop best practices methodology for assessing the archaeological sensitivity of a study area under consideration for offshore energy development. This project necessitates close collaboration amongst federal agencies, academic institutions, private contractors and tribal entities.

2.1.2. Geologic Setting

The bedrock geology underlying Greenwich Bay and Narragansett Bay is the Rhode Island Formation of the Narragansett Bay Group, which is part of the Esmond-Dedham subterrane. The Rhode Island Formation is composed of coarse to fine-grained metasedimentary rocks of Pennsylvanian Age (Hermes, Gromet and Murray, 1994).

The preferential erosion and lowered topography of the Rhode Island Formation led to the establishment of a south-flowing drainage system through Narragansett Bay during the Tertiary Period, representing nearly 60 million years of erosion (McMaster, 1984). A prominent bedrock valley referred to as the (proto-)Blackstone River was traced from north of Providence through Greenwich Bay, connecting to a trunk valley in the west passage of Narragansett Bay (Upson and Spencer, 1964). Subsequent modification by Pleistocene glaciation resulted in the widening and deepening of drainage valleys, followed by deposition of up to 40 m of Quaternary sediments in upper Narragansett Bay, mostly filling the drainage valleys (McMaster, 1984). This thick sequence of
sediment is composed of ground moraine tills, stratified outwash, glaciodeltaic and glaciolacustrine deposits (Peck and McMaster, 1991). The glacial deposits enclosing Greenwich Bay are described by Boothroyd and McCandless (2003), with glacial deltaic deposits to the north and south of Greenwich Bay, ice-marginal deposits to the west and coarse tills to the east.

Twenty-four CHIRP seismic reflection profiles collected by URI GSO in 2006 from Greenwich Bay and interpreted by Morissette (2014) describe the post-glacial depositional environments and sediments of now submerged Greenwich Bay. Acoustic basement was constrained as bedrock or where shallow, a progradational glacial fan. A thick sequence (typically >30 m) of glaciolacustrine deposits was found to overlie acoustic basement throughout the bay, consisting of both a proximal and distal seismic facies. The rhythmic internal reflectors draping the underlying topography are consistent with glaciolacustrine sediments identified in most of Narragansett Bay (Peck and McMaster, 1991; Boothroyd and McCandless, 2003; Oakley, 2012).

Morissette (2014) reports the existence of paleochannels that incise glaciolacustrine sediments. These paleochannels form an organized tributary system, consistent with seismic reflector R2 reported by McMaster (1984), and a regional fluvial unconformity Fu1 (O’Hara and Oldale, 1980; Needell, O’Hara and Knebel, 1983; Needell and Lewis, 1984). The presence of paleochannels is associated with the drainage of Glacial Lake Narragansett, which likely did not begin until the onset of isostatic rebound, but remains poorly constrained (Oakley, 2012). A paleo-stream originating from modern day Apponaug Cove
passed just to the south of Cedar Tree Beach, achieving confluence with an additional paleo-stream approximately midway through Greenwich Bay (Morissette, 2014).

Glacial deposits are truncated by a diachronous ravinement surface representing marine transgression through Greenwich Bay. Marine inundation of Greenwich Bay was originally confined to the paleo-streams, eventually flooding the subaerially exposed lakefloor. The timing of marine inundation of Greenwich Bay is somewhat contested. Based on the relative sea level curve generated by Oldale and O’hara (1980), McMaster (1984) proposed an inundation age of 5,500 yr BP. A study by Vinhateiro, et al. (2007) reported an AMS-dated shell from a sediment core collected in western Greenwich Bay dated to 6,500 yr BP. Morissette conservatively placed the age of paleo-streams as >6,000 yr BP. The reconstruction of paleolandscape prior to marine inundation helped for visualization of the paleo-streams, however the 300 m seismic reflection line spacing led to significant artifacts, mandating closer line spacing. Additional CHIRP seismic reflection lines were collected May 2015, tightening line spacing to 100 m within Greenwich Bay with several crossing lines. This dataset, not reported on in this study should drastically improve the interpolation model.

Estuarine sediments overlie the ravinement surface. Many of the seismic reflection profiles exhibit an acoustically transparent estuarine seismic unit, suggesting the fine-grained nature of these sediments (Morissette, 2014). Benthic geologic habitat mapping by Oakley, Alvarez and Boothroyd (2012)
details the surficial geology of Greenwich Bay. The deeper, central basin of Greenwich Bay appeared as a featureless, low backscatter region in the side-scan imagery and is reported as fine-grained silts. Near the mouth of Greenwich Bay, sand sheets with some tidal/wave bedforms are predominant. Along the margins of Greenwich Bay, a shallow (<1 m) depositional platform composed of sand, some gravel and shells can be traced to the beaches. Cedar Tree Beach falls under this categorization and marks the western most extension of the northern depositional platform. The coves of Greenwich Bay are primarily dredged channels or composed of clay, silt and organic matter.

2.1.3 Paleocultural Context

The presence of freshwater (paleo-stream and freshwater lake) as well as approximately 400 minimally worn lithic artifacts (e.g. projectiles, blades) ranging from 10,000 - 1000 yr BP makes a compelling argument for the existence of a now submerged paleocultural site near Cedar Tree Beach (King, 2012). As part of the BOEM Paleocultural study, archaeological fieldwork including video hydro-probe investigations, magnetic surveys and targeted dredge test pit investigations have been conducted. Within the two dredge pits and sediment video hydro-probe surveys, an oxidized paleosol was identified. In dredge test pit B-17, a 1x1 by 1.8 m excavation, this paleosol was identified ~110 to 140 cm below the seafloor with abundant gravel sized sediment, and preserved Phragmites roots. The video hydro-probe is simply a minimally invasive survey technique for sub-seafloor videography. A similar, thinner paleosol was
identified in the dredge test pit adjacent to video hydro-probe site D3 (Figure 2.2), approximately 125 cm below the seafloor. Quartz chipping debris from stone tool manufacturing was recovered from this paleosol in both dredge test pits (David Robinson, personal communication, November 3, 2015).

It is imperative to understand how the sub-seafloor structure of Cedar Tree Beach connects with the well-characterized sub-seafloor structure of Greenwich Bay. CHIRP seismic reflection data were of poor quality in the vicinity of Cedar Tree Beach due to the coarse surficial sediment of the depositional platform. Additionally, the very shallow (<1 m) water depths along the sandy depositional platform further complicates seismic reflection studies. For this reason, understanding of the sub-seafloor geology directly adjacent to Cedar Tree Beach remains poor. The collection of vibracores in the shallow water off of Cedar Tree Beach should help to reveal the sub-seafloor geology and aid in the characterization of the potential paleocultural site.
2.2 Methodology

2.2.1. Collection of Vibracores

During the spring of 2015, 3-meter vibracores were collected along Cedar Tree Beach, using a pontoon boat as a coring platform (Figure 2.3. C). The shallow draft of the pontoon boat allowed access to the shallow waters, and field operations were primarily conducted near high tide. A submersible Rossfelder P-3 Vibrocoreing head was affixed to a 4-inch PVC tube, into which the sediment was recovered. A metal core catcher and cutter were attached to the PVC tube to aid in penetration and sediment recovery, and were reused when conditions permitted. Successful vibracores were capped and transported to the URI GSO Marine Geological Samples Laboratory (MGSL) and stored near 4 degrees C in a sediment core refrigerator. A total of six vibracores were collected during the 2015 summer field season in the Cedar Tree Beach study area, and one additional core, CTB VC-14 was collected in June, 2014.

Each vibracore exceeding 1.5 m in length was cut into sections to aid in processing. The PVC tubes were split on a core splitter, in which the depth of the routers is set to cut through the PVC tube, minimizing contact with the sediment. A metal wire was guided through the split PVC tube to separate the recovered sediment into two halves. One half of the sediment core was designated as an archive half, to be stored permanently at the URI GSO MGSL. The remaining “working” half was designated for logging of physical properties and imaging on the Geotek Multi-sensor core logger system.
2.2.2. Imaging, Logging of Physical Properties and Initial Core Descriptions

A non-destructive measurement of physical properties of each vibracore was performed using the Geotek MSCL system. Parameters logged included Gamma Ray Attenuation and Porosity Evaluator (GRAPE) density, magnetic susceptibility, electrical resistivity, compressional wave (P-wave) velocity and travel times. The Geotek automatically advances the core by the designated sampling interval, in this case providing one-centimeter resolution. Each core was subsequently imaged using the Geotek MSCL system. Initial core descriptions were recorded noting observed changes in color (referenced to the Munsell system of color notation), lithology, grain-size, and organic matter.

2.2.3. Seismic Reflection Data Acquisition

Seeking a solution to the poor performance of CHIRP seismic reflection systems operated in areas where coarse surficial geology exists, several tests of seismic reflection systems were performed to determine the best approach for a more directed survey. A Falmouth Scientific Bubble Pulser system was manually towed in the shallow waters off of Cedar Tree Beach. The Bubble Pulser system has proven to perform much better than the CHIRP system in coarse sediments, the trade off being less fine-scale resolution. Similarly, a Teledyne Benthos CHIRP III was also tested (Figure 2.3. A,B). No navigational data were collected to supplement the seismic images as the systems were only being tested for their ability to resolve sub-seafloor features and penetration depth. Both systems were tested at different repetition rates, gains, and pulse lengths (CHIRP only).
and feature the sound source suspended just below the water's surface.

Chesapeake Technologies SonarWiz 5 was used for data acquisition, and files were written in SEGY format. Each seismic image was processed using SeiSee software, which does not require supplemental navigation data to view the seismic image.

The Bubblegun system achieved deep penetration, however, it failed to resolve the upper 10 m. For the Cedar Tree Beach study area, the upper 10 m is expected to be of significance. The signal from the CHIRP III system was strongly attenuated by the coarse-grained seafloor, however several laterally continuous reflectors could be traced within the study area (Figure 2.3. D). For this reason, the CHIRP III system was chosen as more appropriate for the Cedar Tree Beach study area.

A seismic reflection survey was performed within the Cedar Tree Beach study area at 20 m line spacing perpendicular to the shoreline, and crossing lines paralleling the shore (Figure 2.4.). Due to the shallow nature along this depositional platform, and the importance of collecting data as near to the beach as logistically possible, the survey was conducted at high tide. Additionally, the CHIRP III system was towed from the bow of a shallow draft pontoon boat. Two assistants pulled the CHIRP III system very close to the shoreline. The pontoon boat was run in reverse to avoid navigational complications associated with operating in very shallow water. Position, heading, attitude, heave and velocity data were obtained by an Applanix POS MV Inertially-aided Real-Time Kinematic...
Global Positioning System. Cable payout was carefully measured for each survey line, to reduce positional errors.

2.2.4. Post-processing of Seismic Reflection Data

Seismic reflection data were processed using Chesapeake Technology's Sonar Wiz 5 software. Raw SEGY data files were imported and corrections for the amount of cable layback were applied based on field measurements. Files with significant vessel turns were clipped. Image processing included applying various time-varying and user-defined gains. A 1500 m/s velocity was assumed for both the water column and all sediments.
2.3. Results

2.3.1. Seismic Reflection Profiles

The combination of very shallow water depths and a highly reflective seafloor resulted in the poor performance of the CHIRP seismic reflection system. Complete attenuation of the seismic signal occurred by 15 m below sea level, and ringing artifacts predominated through the seismic images. Vertical resolution was approximately 38 cm. Best performance occurred in the western-most study area where water depths were slightly deeper and surficial sediments finer. In seismic line C-C’ (Figure 2.4.; 2.12.), a south dipping, chaotic internal reflector can be traced to a depth of approximately 5 m. The reflector becomes nearly flat lying slightly north of vibracore CTB VC-10_2, and becomes indistinguishable from the ringing artifacts. The same reflector can be observed in seismic line B-B’ (Figure 2.14.). Water depth west of vibracores CTB VC-10_1 and CTB VC-10_2 is approximately 1.75 m, and shallows to <1 m just to the west of these cores. A prominent flat lying reflector parallels approximately 1-1.5 m below the seafloor in the western portion of the seismic line. As the seafloor shallows, this reflector remains at a similar depth. The reflector again becomes indistinguishable from the ringing artifact just east of sediment cores CTB VC-10_1 and CTB VC-10_2.

2.3.2. Physical Properties of Vibracores

Physical properties from the seven vibracores were plotted using Delta Graph 5 software (Figures 2.5 – 2.11). The trends in magnetic susceptibility, P-wave travel time and GRAPE density are reported in the following section.
Additionally, a down-core plot of reflection coefficient was calculated for each vibracore.

**Magnetic Susceptibility**

In all vibracores, magnetic susceptibility is significantly highest in the upper 80 centimeters. The trend within this upper unit is characterized as highly variable, with high amplitude peaks. In several cores (CTB VC-9, VC-6, VC-5, VC-4), at least four distinct peaks are identified. In vibracores CTB VC-10_1, VC-10_2 and VC-14 the peaks are less defined. In all vibracores, a local minima occurs at the base of the variable high amplitude peaks, below which background values of magnetic susceptibility predominate with occasional small amplitude peaks. In vibracores CTB VC-10_1, VC-10_2 and VC-14, another local minima occurs at 233 cm, 250 cm and 218 cm, respectively. Vibracores CTB VC-9 and VC-6 show a large amplitude peak in magnetic susceptibility towards the base of the core.

**GRAPE Density**

Several trends in density exist such that no single trend characterizes all the vibracores within the study area. However, CTB VC-10_1 and VC-10_2 exhibit similar trends in density. The upper 60 centimeters of both cores exhibit high density with moderate variability. Below 60 centimeters, density decreases and becomes more variability to a core depth of 150 cm. Density generally increases below 150 cm, with very low variability in CTB VC-10_2, and high variability in VC-10_1. In vibracore CTB VC-10_1, a local density minima occurs at 233 cm,
below which density decreases. Vibracore CTB VC-10_2 exhibits a similar trend, with a density minima at 250 cm.

Vibracore CTB VC-14 is comparatively lower density than all other vibracores, with density everywhere below 2.0 g/cc. Density increases from 0 – 100 cm, with moderate variability. From 100 to 160 cm, density decreases. From 160 cm to 250 cm, density increases but is highly variable with a local density minima at 250 cm. Below 250 cm, density decreases.

Vibracore CTB VC-9 exhibits high density with low variability, steadily decreasing from 40 cm to 140 cm. From 140 cm to 232 cm, density steadily increases with low variability. Below 232cm density increases with moderate variability.

Vibracores CTB VC-6, VC-5 and VC-4 exhibit similar trends in density. The trend is characterized by a slow steady down-core decrease in density, with slightly higher variability within the upper meter. At the base of these cores, there is a slight increase in density and moderate variability.

**P-wave Travel Time**

P-wave travel times are calculated by the Geotek MSCL system with consideration for the thickness of the sediment. Accuracy of this parameter is reliant on excellent acoustic coupling between the seismic source and the sediment. It is evident that poor acoustic coupling was predominant due to low P-wave amplitudes (<70) with velocities lower than 1500 m/s (compressional wave velocity through water). For this reason, values of travel time or velocity
cannot be considered to be accurate, however, the resulting trends may be valid. Regardless, trends in travel time were not comprehensively reviewed, except where changes in lithology were not strongly described by changes in down-core physical properties.

Reflection Coefficient

Down-core reflection coefficients were calculated between adjacent Geotek sampling points as an indicator for lithological change. For all vibracores with the exception of CTB VC-14, which was sampled at 2 cm, the sampling interval was 1 cm. The calculation of a reflection coefficient log differs from a 1-D synthetic seismogram as there is no convolution with the seismic wavelet (AAPG, 2014). The sampling interval of 1-2 cm is significantly smaller than the vertical resolution of the CHIRP signal trace (>30 cm), and offers the potential to reveal fine-scale changes in sediment that cannot be resolved in the seismic reflection data. In seismic stratigraphy, the reflection coefficient is described by the following equation (Sheriff, 1984):
\[ R_\theta = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1} \]

Where:

\[ R_\theta = \text{Reflection coefficient} \]
\[ \rho_2 V_2 = \text{acoustic impedance of medium 2} \]
\[ \rho_1 V_1 = \text{acoustic impedance of medium 1} \]
\[ \rho_1 = \text{density of medium 1} \]
\[ V_1 = \text{seismic velocity of medium 1} \]

In shallowly buried, unconsolidated sediments, acoustic impedance is dominated by changes in density, due to very low variability in seismic velocity (Chip Heil, personal communication, October 15, 2015). Since changes in seismic velocity are negligible under these conditions, the down-core reflection coefficient was calculated by omitting seismic velocity. It is noted that density alone is not necessarily an indicator for change in lithology, as sediments of differing lithology may have similar densities. In cases such as this, changes in sediment compressibility, may have a large impact on acoustic impedance, and p-wave velocities may need to be considered.

Several prominent reflections were observed in each vibracore, and are described within the following sections.

*CTB VC-10_2*

Two small amplitude reflections occur at 47 and 59 cm. The interval between 100 and 150 cm are characterized by several small to large amplitude
reflections. Below 150 cm, reflections are minimal until a large prominent
reflection at 250 cm, followed by another large reflection at the bottom of the
core.

*CTB VC-10_1*

Several small-scale reflections are observed within the upper meter, with
a large reflection due to the presence of a large chunk of wood recovered in the
core. Below 150 cm, there are no prominent reflections except a large amplitude
reflection at 233 cm, and another at the bottom of the core.

*CTB VC-9, VC-6, VC-5, VC-4*

These vibracores are characterized by several small amplitude reflections
in the upper 100 cm, and a prominent reflector at the bottom of each core.

*CTB VC-14*

From 0-200 cm, numerous moderate amplitude reflections occur, which
may be the result of a 2 cm sampling interval for this particular core. A large
amplitude reflection occurs at 218 cm, with minimal reflections observed
through the remainder of the core.
2.4. Discussion

2.4.1. Correlation of Seismic Reflection Profiles With Previous Investigations

Morissette (2014) provided a comprehensive analysis of the seismic stratigraphy of Greenwich Bay. Similarly, CHIRP seismic reflection data were poor along the depositional platforms, and the shallow water depths prevented data collection along these features. As a result, seismic reflection profiles terminated at the edge of the Cedar Tree Beach study area. Though data from this study were poor, several features were identified in the seismic reflection profiles that could be correlated with the well-established seismic stratigraphy. Seismic reflection profile 2 from Morissette (2014) was chosen due to its proximity to the Cedar Tree Beach study area as well as the good data quality especially near the depositional platform (Figure 2.4.). Several seismic reflectors representing changes in lithology were identified including the ravinement surface (R1), representing Holocene marine transgression and the truncation of underlying pro-glacial lake sediments (Figure 2.12.). A well-defined paleochannel (PC) dissects pro-glacial lake sediments. Overlying the ravinement surface is estuarine sediment (U4). The ravinement surface exists at a depth of approximately 6-8 m below present sea level in seismic reflection profile 2, and more or less parallels the depth of the estuary floor. Extrapolation of R1 to the north, and approximately following the slope of the estuary floor results in good depth agreement with a reflector identified in seismic reflection profile C-C’ (this study) (Figure 2.12.).
A shallow, discontinuous reflector was identified in seismic reflection profile 2, represented by a dashed green line in Figure 2.12. This reflector has not been described in previous studies, likely due to its shallow depth, confinement to the depositional platform and its position within seismic unit 4. This reflector lies ~1 m below the estuary floor and represents a change in physical properties within the estuarine sediment.

2.4.2. Stratigraphic Correlation of Vibracores

Several distinct lithologies have been identified through the analysis of seismic reflection profiles collected for this study, correlation of seismic reflection data with previous studies and analysis of physical properties of vibracores.

2.4.3. Lithology 1: Estuarine Deposition Modified by Anthropogenic Processes

Previous studies have established the usefulness of magnetic susceptibility for stratigraphic correlation of coring sites (Bloemendal et al., 1988; Corbin, 1989). Magnetic susceptibility is the degree of magnetization of a material in the presence of a magnetic field. Changes in the concentration of magnetic minerals in sediments are responsible for changes in measured magnetic susceptibility values, therefore, as sedimentation rates increase at a given site, fluxes of magnetic material will covary based on the concentration of magnetic minerals. Corbin (1989) used this relationship as a proxy for sedimentation rates in Narragansett Bay. Piston cores analyzed in Corbin (1989)
from Apponaug Cove and Greenwich Bay show a very similar trend in magnetic susceptibility, with high values within the upper 40-60 cm, and trending towards a low background value down-core. Vibracores collected from Cedar Tree Beach exhibited high amplitude variability with up to 4 distinct peaks in magnetic susceptibility, with the core logging sampling interval of 1 cm. These peaks were absent from the piston cores in Corbin (1989), which is likely due to the difference in sampling interval (3 cm subsamples). Additionally, the amplitude of peaks in magnetic susceptibility increased with nearness to shore.

Corbin’s thesis reported that metal concentrations reached background values at a depth very similar to magnetic susceptibility, and occurred at the interface of two distinct lithologies. Similarly, magnetic susceptibility of the vibracores from this study reached background values at a distinct density change, indicated by a high amplitude peak in the reflection coefficient. The base of Lithology 1 is correlated with the tie point in Corbin (1989) where magnetic susceptibility and metal concentrations reach background values, which was dated to approximately 1880 A.D. (135 yr BP). This age serves as minimum age of the base of Unit 1, as the increase in magnetic susceptibility predated the increase in metal concentrations in the Apponaug Cove and Greenwich Bay piston cores. The increase in magnetic susceptibility and sedimentation rates are the result of land clearance by European settlers, which increased erosion rates and changed the composition of sediments entering Greenwich Bay (Corbin, 1989). A well-established proxy for European settlement and land clearance is the “Ambrosia rise”, the presence of ragweed pollen grains representing a
vegetation shift due to European settlement. Morissette (2014) reporting on an unpublished study by King et al. (1993) identified an age of ~340 yr BP for the *Ambrosia* rise specific to Gorton Pond, a freshwater kettle pond <2 km from Cedar Tree Beach. It is therefore proposed that 340 yr BP is a maximum age of the base of Unit 1. According to the radiocarbon dated *Rumex* pollen rise observed in sediment cores from Succotash Marsh, East Matunuck, RI, the date of land clearance in southern New England occurred ~209-281 yr BP (1734 – 1806 A.D.). This date range is closer to the widespread and regional European-style agricultural land clearance c.a. 1700 (Donnelly et al., 2001). Based on initial core descriptions, grain size of Unit 1 decreases with distance from the shoreline, with numerous marine shells and shell hash present. The base of this lithology is correlated with green reflector from seismic reflection line 2 (Figure 2.12.).

2.4.4. Lithology 2: Open Estuarine Deposition

Based on initial core descriptions, sediment within this unit fines downward, with increasing fraction of silt and mud. Shells become less common down-core through this lithology. In vibracore CTB VC-10_1, a scallop shell was preserved at the very top of this lithology (Figure 2.5.). In Greenwich Bay, scallops are an indicator species for good water quality. Prior to anthropogenic eutrophication, Greenwich Bay was heavily used for scalloping. Declines in eelgrass due to eutrophication have greatly reduced scallop populations (John King, personal communication, October 25, 2015). This lithology represents the onset of open estuarine deposition within the Cedar Tree Beach study area,
truncated at the top by the onset of estuarine deposition modified by anthropogenic activities in surrounding upland areas.

2.4.5. Lithology 3: Ravinement and Onset of Estuarine Deposition

The identification of Lithology 3 is dependent on observations of coarse-grained sediments during initial core descriptions. In most cores, sub angular to angular coarse sand to gravel are sparsely embedded within this unit, becoming more prevalent towards the bottom of this lithology. In the shore perpendicular vibracore transect (Figure 2.13.), lithology 3 was observed at a down-core depth of 144 cm in CTB VC-6 and at 73 cm in CTB VC-4, decreasing in depth with proximity to shore. Shore parallel down-core depth of lithology 3 is more variable, occurring at 264 cm in CTB VC-10_1, 189 cm in CTB VC-14, 144 cm in CTB VC-6 and 140 cm in CTB VC-9 (Figure 2.14.). The coarse sand and gravel does not exhibit distinct layering in any of the cores. It is hypothesized that rising sea level left a coarse lag deposit prior to onset of estuarine deposition that was subsequently homogenized with finer grained sediment by bioturbation.

The top of lithology 3 is correlated with seismic reflector R1 from seismic reflection line 2, representing the ravinement surface (Figure 2.12.). In the down-core plots of reflection coefficient there are no prominent reflectors that are associated with the ravinement. However, the ravinement surface is clearly observable in seismic reflection profiles 2 and C-C’ (Figure 2.12.). The absence of high amplitude reflectors in the vibracore physical properties representing the ravinement surface is likely due to the small (1-2 cm) sampling interval of the
Geotek MSCL system and the lack of a distinct layer of coarse sand and gravel due to bioturbation effects. Alternatively, the 20-40 cm vertical resolution of the CHIRP seismic reflection system has an averaging effect for the changes in acoustic impedance of lithology 3. The sparsely distributed coarse sand and gravel contributes to a density and/or compressional wave velocity contrast, which generates a reflector. This subject is hypothesized to occur in a similar manner as the internal reflectors observed in varved sediments, where the seismic reflection system cannot resolve individual couplets (<10 cm scale) but averages the acoustic impedance of several couplets resulting in a reflector.

The ravinement surface is a diachronous feature, and therefore the depth at which it is observed corresponds to an inundation age based on relative sea level rise. A previously unpublished study created an age model for a ~7m sediment core collected in western Greenwich Bay (Vinhateiro, et al., 2007) (Figure 2.15.). Calibrated radiocarbon dated shells determined a basal age of ~6500 yr BP. The depth of the ravinement surface at the southern edge of the Cedar Tree Beach study area is estimated to be approximately 5.50 m below present day sea level. Based on the age model produced by Vinhateiro et al. (2007), submergence of Cedar Tree Beach would have begun approximately 6,000 yr BP. This closely agrees with the relative sea level curve constructed for Block Island by Oakley and Boothroyd (2012), which yields an inundation age of ~5,800 yr BP (Figure 2.15.). Comparison with relative sea level curves for southern New England constructed by Roy and Peltier (2015) yields a much younger inundation age, approximately 3,300 yr BP (Figure 2.15.). The
Connecticut relative sea level curve presented in Roy and Peltier (2015) was determined as appropriate for Greenwich Bay, RI based on the measured distance (~2,450 km) from the approximate center of mass of the Laurentide ice sheet near the western shore of Hudson Bay. A plot of the rates of Late Holocene relative sea level rise against the distance from the ice sheet center of mass presented in Engelhart et al. (2009) yields a subsidence rate of ~1 mm/yr at a distance of 2,450 km, a rate which is nearly identical to that of Connecticut (1.1 ± 0.1 mm/yr). As discussed in the previous chapter of this thesis, predicted relative sea level curves from geophysical models fit well with robust relative sea level indicators, especially from 4,000 to 0 yr BP (Roy and Peltier, 2015). For this reason, an inundation age closer to 3,300 yr BP must be strongly considered.

2.4.6. Lithology 4: Terrestrial / Glaciolacustrine Deposition

Lithology 4 was only recovered in vibracore CTB VC-9, however, characterization of the physical properties associated with this boundary suggests that several vibracores likely penetrated, or came very close to penetrating this lithology (Figure 2.8.). At 231 cm sediment depth, a light tan silt and clay unit with oxidation stains and a disturbed appearance was recovered, to a depth of 247 cm. A very high amplitude magnetic susceptibility peak and prominent reflection was observed within this lithology, where background values predominated in the overlying lithology. CTB VC-6 also shows a high amplitude peak in magnetic susceptibility at the very bottom of the vibracore, at a down-core depth of approximately 188 cm (Figure 2.9.). These two vibracores
have a similar density trend at peak in magnetic susceptibility, characterized first by a sharp decrease in density, followed by a sharp increase in density, occurring over a 10 cm interval at the bottom of the core.

Lithology 4 is correlated to terrestrial deposits, most likely glaciolacustrine sediment. Morissette (2014) reported very thick sequences (up to 42 m) of varved pro-glacial lake floor sediments truncated by the ravinement surface. Two distinct seismic units were identified, and hypothesized to represent proximal (Unit 1) and an overlying conformable distal facies (Unit 2). Lithology 4 represents the top of the glacial deposits. Oxidized sediment may represent a period of subaerial exposure, as the pro-glacial lake in Greenwich Bay was drained, and streams cut in to the exposed lake floor as is indicated by the paleochannel identified in seismic reflection line 2.

Due to the poor performance of the CHIRP seismic reflection system along the Cedar Tree Beach depositional platform, no seismic reflector is correlated with this change in lithology.
2.5. Conclusions

Seven vibracores were collected in shore parallel and shore perpendicular transects and a tightly spaced CHIRP seismic reflection profile survey was conducted within the Cedar Tree Beach study area. Down-core physical properties were logged for each core and each core was imaged using a Geotek MSCL. Initial core descriptions including observations of changes in lithology, color and organic matter supplemented the logging data. Down-core trends in magnetic susceptibility, density, compressional wave travel time and reflection coefficient were characterized.

Seismic reflectors and depositional units were characterized in areas of adequate acoustic penetration. Seismic reflection line A-A’ was correlated with the seismic stratigraphy of Greenwich Bay based on work by Morissette (2014).

Four distinct lithologies were identified within the vibracores collected in the Cedar Tree Beach study area:

Lithology 1 represents modern estuarine deposition modified by anthropogenic activities. The basal age of lithology 1 is constrained to be 135 – 340 yr BP based on proxies for European settlement reported by previous workers.

Lithology 2 represents open estuarine deposition within the study area, prior to the degradation of water quality due to anthropogenic eutrophication and pollution.

Lithology 3 represents the ravinement surface due to the presence of coarse-grained sediments and correlation with seismic reflection profiles. Coarse
sand and gravel does not exhibit distinct layering, likely due to bioturbation. The age of marine inundation remains poorly constrained due to remaining disagreement between calibrated radiocarbon ages from previous studies and southern New England relative sea level curves.

Lithology 4 was only observed in one sediment core, although characterization of the physical properties associated with this change in lithology suggest that at least one additional vibracore may have penetrated this lithology, with little to no sediment recovered. Correlation of this lithology with seismic reflection profiles was not possible due to poor seismic reflection data. However, based on the seismic stratigraphic framework in Greenwich Bay, lithology 4 is inferred to be terrestrial glacial deposits, likely glaciolactustrine silt and clay.
Figure 2.1. Overview map of the Cedar Tree Beach study area (top panel) and Greenwich Bay (bottom panel). Aerial imagery prepared by the URI Environmental Data Center, and projected in the NAD83 Rhode Island State Plane Feet 3800 coordinate system.
Figure 2.2. Preliminary results from video-hydroprobe investigations and magnetic gradiometric survey data. Several video-hydroprobe sites contained gravel (top panel, green circles) and evidence of subaerially exposed sediments (bottom panel, blue circles). Data prepared by Carol Gibson, URI GSO.
Figure 2.3. Photographs of fieldwork from Cedar Tree Beach. Several performance tests of the Teledyne Benthos CHIRP III seismic reflection system (A) were performed by manually towing the system to determine the ideal settings for a full survey. A field laptop running Chesapeake Technology SonarWiz 5 was used for data acquisition (B), however, no navigation control was required for these tests. Vibracores were collected using a pontoon boat as a coring platform, allowing access to coring sites in very shallow water (photo by David Robinson, URI GSO (C). Seismic reflection data were processed using SeiSee software, and several reflectors were identified (D).
Figure 2.4. Seismic reflection survey lines from the Cedar Tree Beach study area and the locations of collected vibracores. Survey lines A-A’, B-B’ and C-C’ overlap vibracore transects and are discussed in further detail. Seismic reflection line 2 was collected in 2006 and provides a stratigraphic framework for Greenwich Bay.
Figure 2.5. Physical properties and initial core descriptions of vibracore CTB VC-10_1. Numbers refer to correlated peaks in magnetic susceptibility. Green line represents a down-core transition to background values of magnetic susceptibility. Dashed red line represents a core break. Dashed black line labeled “A” is a tie point with CTB VC-10_2 and CTB VC-14. Red line (R1) indicates a change in lithology characterized by the presence of coarse sand and gravel. See text for interpretations of lithology.
Figure 2.6. Physical properties and initial core descriptions of vibracore CTB VC-10_2. Numbers refer to correlated peaks in magnetic susceptibility. Green line represents a down-core transition to background values of magnetic susceptibility. Dashed red line represents a core break. Dashed black line labeled “A” is a tie point with CTB VC-10_1 and CTB VC-14. See text for interpretations of lithology.
Figure 2.7. Physical properties and initial core descriptions of vibracore CTB VC-14. Numbers refer to correlated peaks in magnetic susceptibility. Green line represents a down-core transition to background values of magnetic susceptibility. Dashed red line represents a core break. Dashed black line labeled “A” is a tie point with CTB VC-10_1 and CTB VC-10_2. Red line (R1) indicates a change in lithology characterized by the presence of coarse sand and gravel. See text for interpretations of lithology.
**Figure 2.8.** Physical properties and initial core descriptions of vibracore CTB VC-9. Numbers refer to correlated peaks in magnetic susceptibility. Green line represents a down-core transition to background values of magnetic susceptibility. Dashed red line represents a core break. Red line (R1) indicates a change in lithology characterized by the presence of coarse sand and gravel. Blue line represents a change in lithology. See text for interpretations of lithology.
**Figure 2.9.** Physical properties and initial core descriptions of vibracore CTB VC-6. Numbers refer to correlated peaks in magnetic susceptibility. Green line represents a down-core transition to background values of magnetic susceptibility. Dashed red line represents a core break. Red line (R1) indicates a change in lithology characterized by the presence of coarse sand and gravel. See text for interpretations of lithology.
Figure 2.10. Physical properties and initial core descriptions of vibracore CTB VC-5. Numbers refer to correlated peaks in magnetic susceptibility. Green line represents a down-core transition to background values of magnetic susceptibility. Dashed red line represents a core break. See text for interpretations of lithology.
**Figure 2.11.** Physical properties and initial core descriptions of vibracore CTB VC-4. Numbers refer to correlated peaks in magnetic susceptibility. Green line represents a down-core transition to background values of magnetic susceptibility. Dashed red line represents a core break. Red line (R1) indicates a change in lithology characterized by the presence of coarse sand and gravel. See text for interpretations of lithology.
Figure 2.12. Processed seismic reflection line C-C', with interpreted seismic reflectors and correlated with seismic reflection line 2 from Morissette (2013). See text for explanation of reflectors and interpretations of lithology.
Figure 2.13. Seismic reflection line A-A’ with N-S vibracore transect. See Figure 2.4 for location of seismic line. Green, blue and yellow core sections represents lithology 1, 2 and 3, respectively. Seismic unit U4 and reflector R1 were originally identified in Morissette (2014) and are correlated with the vibracores from this study. No reflectors were identified in this particular seismic line, and therefore no attempts were made to correlate lithological changes observed in the vibracores with this particular seismic reflection line.
Figure 2.14. Seismic reflection line B-B’ with W-E vibracore transect. See Figure 2.4 for location of seismic line. Green, blue, yellow and red core sections represents lithology 1, 2 3 and 4, respectively. Seismic unit U4 and reflector R1 were originally identified in Morissette (2014) and are correlated with the vibracores from this study.
Figure 2.15. Comparison of an age model for Greenwich Bay (A) and relative sea level curves for southern New England (B, C). The horizontal red lines intersect a depth of 5.5 m below present sea level, representing the depth of the ravinement surface at the seaward edge of the Cedar Tree Beach study area. The Greenwich Bay age model agrees more closely with the relative sea level curve produced by Oakley and Boothroyd (2012), with an inundation age of ~5,800 yr BP.
### Table 2.1. Cedar Tree Beach Vibracore Collection Information

<table>
<thead>
<tr>
<th>Date</th>
<th>Core ID</th>
<th>Lat</th>
<th>Lon</th>
<th>Water Depth</th>
<th>Recovered Length</th>
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<tr>
<td>5/14/15</td>
<td>CTB VC-10_1</td>
<td>41.68702</td>
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<td>2.6 ft</td>
<td>283 cm</td>
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<td>CTB VC-4</td>
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<td>4.3 ft</td>
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<tr>
<td>5/20/15</td>
<td>CTB VC-5</td>
<td>41.68708</td>
<td>-71.44251</td>
<td>3.8 ft</td>
<td>116.5 cm</td>
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<td>CTB VC-9</td>
<td>41.68654</td>
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<td>CTB VC-10_2</td>
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<td>6/27/15</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>306.5 cm</td>
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</table>
Bibliography


CRC (Coastal Resources Center)., (2005). Greenwich Bay Special Area Management Plan. Kingston, Rhode Island: University of Rhode Island Coastal Resources Center and Rhode Island Sea Grant.


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