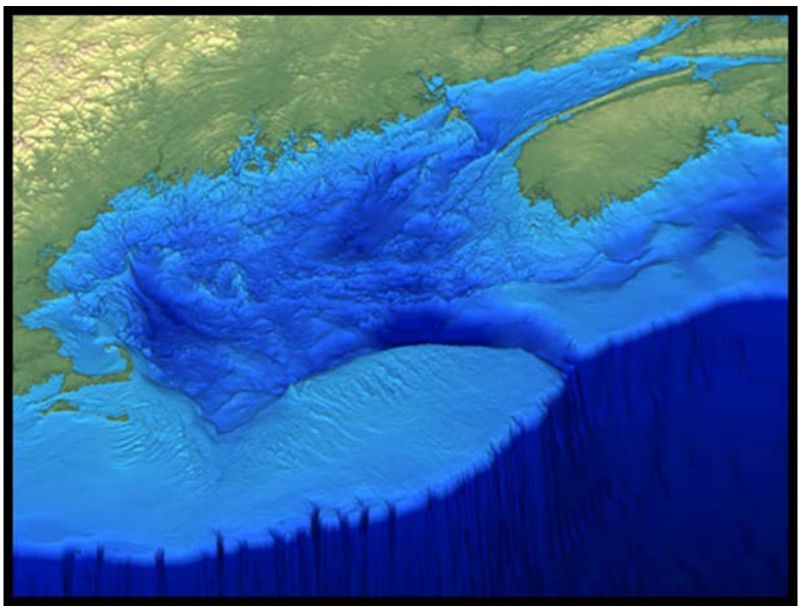
DOCUMENTING SAND AND GRAVEL RESOURCES ON THE INNER CONTINENTAL SHELF: MERRIMACK EMBAYMENT, NEW ENGLAND

A report for:
United States Minerals Management Service



Duncan M. FitzGerald
Christopher J. Hein

Department of Earth Sciences
Boston University
Boston, MA 02215

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I. EXECUTIVE SUMMARY

A suite of data, including shallow seismic, single beam, multi-beam, backscatter, bottom sediment samples, and current meter data were used to document the sand and gravel deposits in the inner continental shelf of the Merrimack Embayment in the Western Gulf of Maine. These data shed new light on the emplacement of the fluviodeltaic sequence deposited by the Merrimack River during the lowstand (12 kya in -45 m) and its subsequent partial reworking through the Holocene transgression to the present time.

Following the deposition of ice-contact deltas at +33 m during a relative sea level highstand at 14.5 kya, crustal isostatic rebound forced a regional regression. During this time, the Merrimack River deposited coarse sands and gravel in the area presently located between 0.5 and 8 km offshore of Plum Island and the mouth of the Merrimack River. These sediments were subsequently reworked alongshore to form the Merrimack braid plain delta (MBPD), a broad plain consisting of 1.4×10^9 cubic meters of moderately to poorly sorted sediments dominated by sands and gravel with a median grain size of 0.1 phi (coarse sand).

Immediately offshore of these braid plain deposits, a fluvial delta of similar volume (1.3×10^9 m^3; Oldale et al., 1983) was deposited during the later stages of the regression and relative sea level lowstand. New shallow seismic through this area confirm the existence of shallowly-dipping clinoforms diagnostic of deltaic forest beds. As shown by Edwards (1988), these foresets are composed of silty fine sand and are overlain by modern offshore muds.

During the subsequent transgression, these Pleistocene sediments were driven onshore, exposing shallow bedrock and boulder lag deposits from offshore drumlins. Additionally, buried cut and fill structures indicate the presence of riverine and inlet systems active in several locations throughout the Embayment during the transgression. The topsets and upper foresets of the paleodelta were eroded and combined with sediment winnowed from the upper portion of the braid plain and additional sediment delivered from the Merrimack River. These finer sediments were reworked onshore and alongshore to form the modern barrier system, fill the backbarrier, and form a broad mobile sand sheet in the nearshore region. Driven south by the dominant northeast storms, this sand sheet discontinuously overlies the braid plain sediments in the north and is up to 9 m thick in the south (in Ipswich Bay). This deposit is composed of approximately 1.21×10^8 cubic meters (Barnhardt et al., 2009) of moderately to poorly sorted fine sand (median grain size of 2.4 phi). Results of a nearshore (20 m depth) deployment of a suite of current meters confirm the reason for the existence of a suite of bedforms seen across the sand sheet – this deposit is actively reworked during moderate to strong winter storms.

Due to the diverse nature of sediments comprising local beaches, two potential sources for nourishment sediments have been identified: the Pleistocene braid plain and the Holocene sand sheet. The braid plain was identified as the most readily available source for sand and gravel. SWAN wave models were employed to study the effects of removal of up to 5 m of sediment from this region; the results confirm the minimal impact incurred by the removal of up to 157 million cubic meters of sand and gravel from the Merrimack Embayment.

II. INTRODUCTION

A. Work Statement

The inner continental shelf and nearshore zones form a region of sediment flux between the land and the sea (Murray and Thieler, 2004). A fundamental understanding of processes in this region is crucial for predicting the behavior of the nearshore zone, and long-term erosional-depositional processes along barrier islands and sedimentation patterns in backbarrier systems. The barriers, marshlands, tidal inlets, and waterways comprising the Merrimack Embayment in the western Gulf of Maine are some of the most important economic and recreational resources and wildlife habitats of the north shore of Massachusetts. The beaches, barriers, and estuaries of this region are dynamic systems that experience seasonal and longer-term shifts in their sediment reservoirs associated with rising sea level, varying wave climate, storm frequency, and human influences. In spite of these changing conditions, there is growing pressure in the public and private sectors to further develop and utilize these barrier and tidal inlet systems. A two-fold increase in tourism during the past 10 years has led to an increasing number of shoreline stabilization structures, dwellings, and commercial marinas. While the usage of the barriers is growing, many of the area beaches are beginning to retreat due to a continuing trend of sea-level rise, which in the future may accelerate as a result of global warming. In addition, the construction of dams, jetties, and other engineering structures, and a natural depletion of glacial and riverine sediment sources have combined to diminish the supply of sediment to the coastal zone.

Numerous beaches along the Merrimack Embayment and extending into the New Hampshire have experienced long-term erosion as indicated by Massachusetts' Coastal Zone Management historical shoreline survey data. Some of these shorelines are retreating at rates as high as 0.5 m/yr. Evidence of erosion and depleted sand sources exists along this entire section of coast:

1. Rye Beach, NH is largely a gravel beach when once it contained large areas of sand.

2. Hampton Beach, NH has been nourished with sand in the past. Presently, the recreational beach is narrow to non-existent during periods of spring high tide.

3. Salisbury Beach, MA is sediment starved and numerous houses along this shore heavily damaged during major storm events due to its narrow and eroding beach.

4. The northern end of Plum Island, MA is experiencing extensive erosion and numerous houses and infrastructure have been destroyed during the past several years. Presently, federal and state agencies are studying at this site and have employed a temporary soft solution until a more permanent long-term plan can be implemented.

5. The central section of Crane Beach, MA has retreated more than 20 m in the past 10 years due to diminished sand supplies.

6. Coffins Beach, MA has lost extensive dune systems in recent years due to erosion.

These examples illustrate the eroding condition of much of the northern Massachusetts and New Hampshire coast and the eventual need for sand nourishment to maintain recreational beaches and protect existing dwellings, facilities, and infrastructure. It should be emphasized that most of the beaches along the Merrimack Embayment extending from Cape Ann, MA northward to Great Boars Head, NH are public beaches or owned by trusts who maintain public access to the beach.

The majority of Late Quaternary stratigraphic models of the inner continental shelf come from coastal plain settings. The stratigraphy of these deposits consists of a number of stacked clastic sequences that are related to eustatic sea-level changes and varying rates of sediment supply. In contrast, the inner shelf stratigraphy in paraglacial settings is a result of complex interactions of glacio-isostatic, as well as eustatic sea-level changes, pronounced basement controls, and variable rates and types of sediment contribution (fluvial, deltaic, and *in situ* glacial deposits).

The study of paraglacial settings is important because these settings have wide geographical extent (>30% of the Northern Hemisphere shelves; Forbes and Syvitski, 1994) and are better analogues for rocky and embayed coasts than the shelves of coastal plain settings. The inner continental shelf in northern Massachusetts provides an excellent opportunity to study the Late Quaternary sedimentary record along a glaciated coastline due to its: 1) well-established sea-level history (see Fig. 3); 2) relatively shallow shelf depths; 3) variable basement relief (bedrock), and 4) diverse sediment sources.

B. Previous Work

Despite the existence of an expansive body of work devoted to the Merrimack Embayment, most of these investigations have dealt with the very nearshore or onshore regions. For example, Stone et al (2004) have used a variety of data sources to construct a new sea-level curve that incorporates rheological considerations (Koteff et al, 1993; Stone and Ashley, 1995). Abele (1973) provides information on the region's wave regime, influence of northeast storms and sediment transport patterns. Other authors have studied the development of the Merrimack Embayment barrier island chain, using mostly sediment core data (Rhodes, 1973; McIntire and Morgan, 1964; Boothroyd and FitzGerald, 1989). More recently, the sedimentology and facies architecture of the barriers has been utilizing ground penetrating radar and new dating techniques (Dougherty, 2004; McKinlay, 1996). Finally, several papers have examined the relationship between the offshore paleo-delta, its reworking, and the contribution of this sand to barrier construction (Oldale et al, 1983; Edwards and Oldale, 1986; Edwards, 1988; FitzGerald et al, 1994). The results of these studies are discussed in detail in a later section of this report.

C. Objectives & Scientific Questions

There is an obvious need to identify new sources of sand that can be used to nourish and maintain the beach systems in northern Massachusetts as well as New Hampshire. In the past land-based sand sources have been utilized to nourish beaches, such as the Revere Beach, MA and Hampton Beach, NH projects. This sand has come primarily from glacial meltwater stream deposits and other glacial sediments.

However, these local sources of sand are mostly depleted and are problematic in that they contain small quantities of silt and gravel and do not match the quality of beach sand. Inner shelf sand bodies usually contain higher quality sand because the sediment has been reworked by wave action during the Holocene transgression and thus it is well-sorted and contains a high percentage of quartz. The effect of sand removal from the inner continental shelf may affect the redistribution of wave energy on the landward shoreline, and thus this potential impact would have to be studied.

The Merrimack River has supplied sediment to the embayment since deglaciation including the formation of a lowstand delta, deposition of fluvial and estuarine sediments inshore of the delta, and contribution of recent nearshore sands at the mouth of the river. This study focuses on the paleodelta, the glacio-fluvial sediment (braided stream deposits) landward of the delta, and the modern mobile sand sheet overlying these two deposits. The major objectives of this study include:

1. Determination of the type and extent of sedimentary units comprising the Merrimack Embayment inner shelf region, including the depositional units formed during the Holocene transgression when the riverine and deltaic sequences were reworked by storm waves and tidal currents as well as by modern day processes.

2. Determination of the volume and quality of the different sedimentologic units.

3. Assessing the sedimentological character of the various facies and determine the microfaunal assemblages that define various present day and paleo-environmental settings

4. Defining the chronology of the sedimentary sequences through age-dating techniques and produce stratigraphic models for the region.

5. Production of an evolutionary model for emplacement of the Merrimack paleo-delta and associated deposits, and their reworking during late Pleistocene and Holocene transgression through the present time.

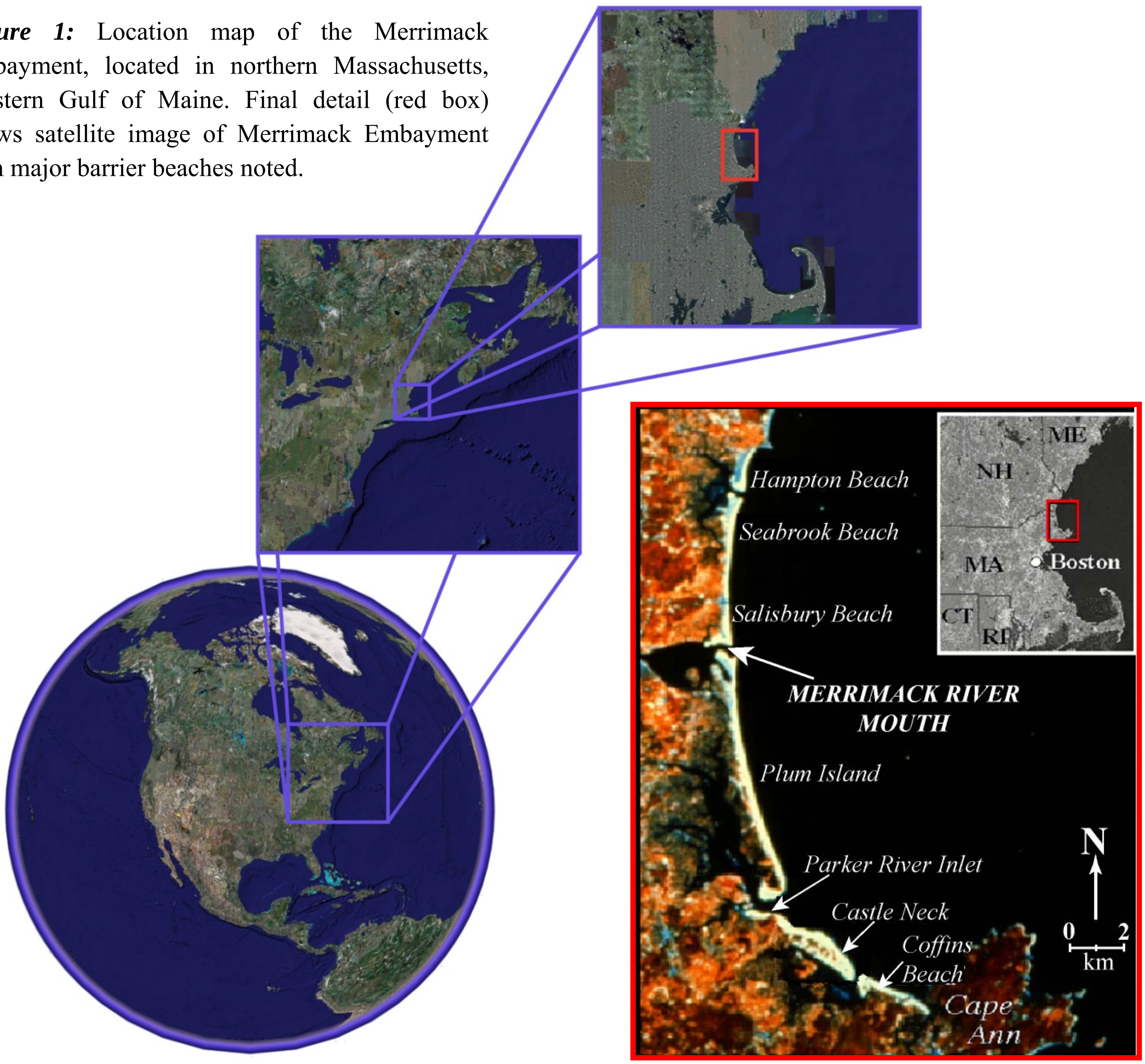
6. Conduct a wave analysis of the study area to look at potential effects of wave focusing following sediment removal.

III. PHYSICAL SETTING

A. Modern Physical Setting

The Merrimack Embayment is located along a mixed-energy, tide-dominated coast in northern Massachusetts extending from Cape Ann north into New Hampshire to Boar's Head (Fig. 1). The Merrimack Embayment contains the longest barrier island chain in Massachusetts (approximately 34 km long), backed primarily by marsh and tidal creeks that often enlarge to small bays near the inlet openings (Smith & FitzGerald, 1994). The barrier islands are pinned to bedrock or glacial promontories and tidal inlets are situated in drowned river valleys. Though several of these inlets have freshwater influx from nearby streams (e.g. Parker and Essex Rivers) the only true estuary is the mouth of the Merrimack River.

Figure 1: Location map of the Merrimack Embayment, located in northern Massachusetts, Western Gulf of Maine. Final detail (red box) shows satellite image of Merrimack Embayment with major barrier beaches noted.



The Merrimack River has its headwaters in the White Mountains of New Hampshire and its catchment is approximately 13,000 km^2 along its 180 km course to the ocean. The Merrimack watershed drains regions dominated by granitic plutons that have produced sandy glacial deposits. The lower part of the river contains extensive coarse sand to gravely glacial drift and several glacio-marine deltas that formed following the Wisconsin sea level high stand of about 13 kya (Oldale et al, 1983). Edwards (1988) identified two paleo-deltas at +16m and +33m, both in the vicinity of Newburyport, MA. Subsequent work by Stone et al (2004) has recognized addition glaciomarine deposits. Sediment discharged from the mouth of the Merrimack ranges in size from fine top coarse sand and granules. These sediments are subsequently reworked in a southeasterly alongshore direction as a result of strong northeasterly storm waves associated with Northeasters (Fig. 2 & Table 1).

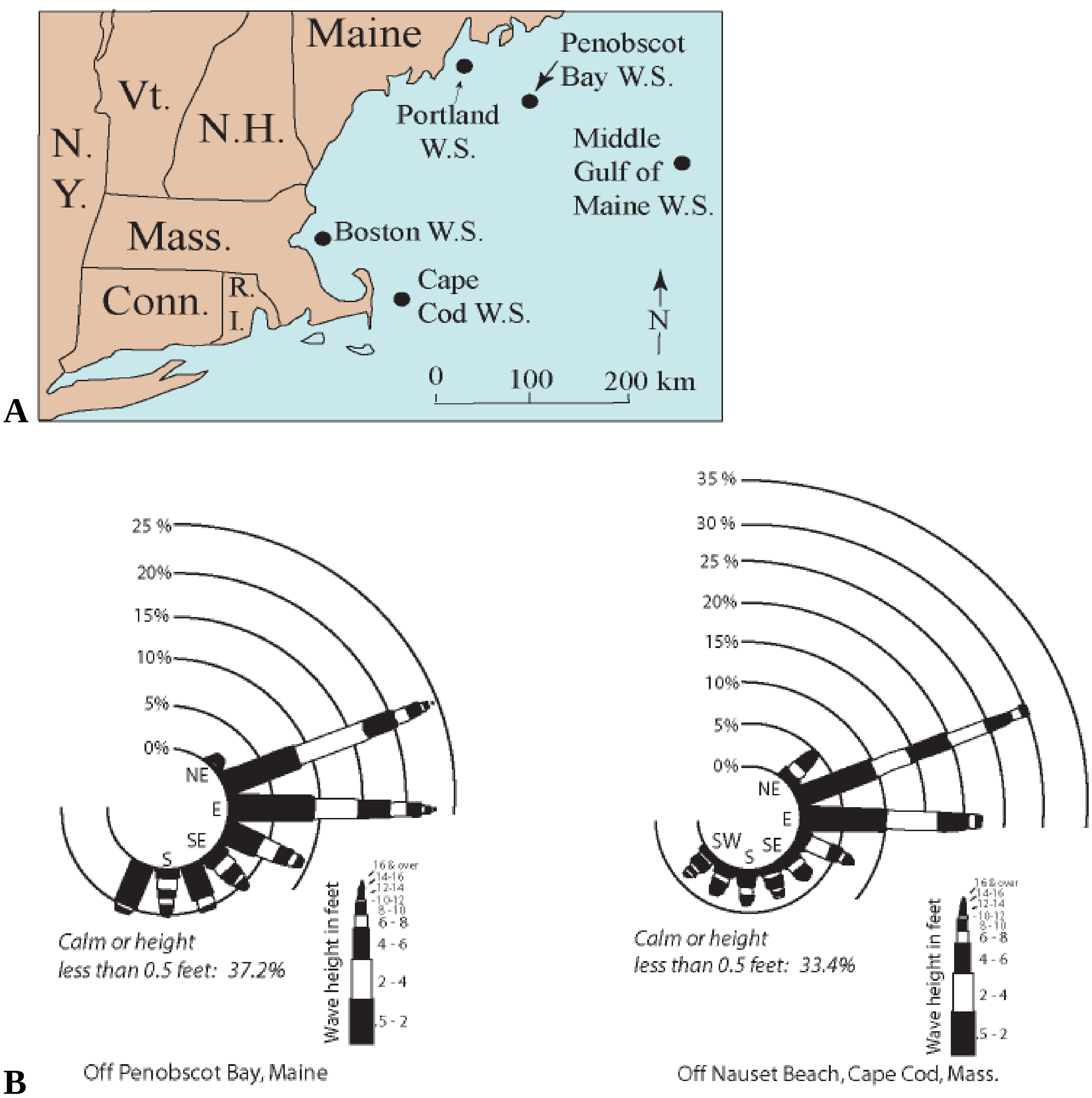


Figure 2: Wave data from areas near Merrimack Embayment (modified from FitzGerald et al, 1993).
A) Map of New England showing locations of wave stations.
B) Wave rose diagrams from Penobscot Bay, Maine and Cape Cod, Massachusetts.

Station Location	Lat / Long (deg)	Water Depth (m)	Wave Heights (m)				Modal Wave Period (s) Range
			Mean Annual	Lowest Monthly	Highest Monthly	Extreme Wave	
Middle Gulf of Maine	42.7N / 68.6W	190	1.7	0.9 (July)	2.4 (Jan)	10	3.5 - 7.5
Portland	43.5N / 70.1W	80	0.9	0.6 (July - Aug)	1.2 (Jan)	7.5	7.6 - 11.5
Boston	42.4N / 70.8W	30	0.7	0.4 (July)	1.2 (Apr)	5.0	7.6 - 11.5

Station Location	Winds					
	Dominant			Prevailing		
	Direction (deg)	Velocity (kt/hr)	Duration (%)	Direction (deg)	Velocity (kt/hr)	Duration (%)
Middle Gulf of Maine	300	15.6	10.9	210	12.6	14.7
Portland	030	11.5	7.2	210	11.5	15.1
Boston	300	14.3	10.9	270	13.9	13.9

Table 1**:** Wave data from wave buoys located in the Gulf of Maine, Portland, ME, and Boston, MA. Locations noted in Figure 2. (modified from FitzGerald et al, 1993)

B. Sea Level History

The Holocene sea level history of the Merrimack Embayment results from the combined forcings of global eustatic sea level rise and regional isostatic adjustments. Following the last glacial maximum (approx. 20 kya), sea levels in Massachusetts rose rapidly in response to the global influx of glacial meltwater. Isostatic depression of the crust below modern sea levels allowed marine submergence to occur contemporaneously with ice front retreat (Bloom, 1963). The maximum marine limit is identified by a glaciomarine delta at +33 m (Edwards, 1988; Fig. 3); this sea level highstand is dated at 14 kya (uncalibrated radiocarbon age). Subsequently, this region experienced rapid isostatic rebound resulting in a -45 m lowstand at 12 kya. Oldale et al (1993) estimate the depth of this lowstand from the change in slope of a drowned delta located offshore of the Merrimack River and date it using submerged shoreline features interpreted as drowned barriers east of Cape Ann. This delta was truncated and drowned during the subsequent Holocene marine transgression. For the first 6,000 years this transgression occurred relatively rapidly and episodically. Approximately 6 kya, sea level rise slowed to approximately modern rates (Oldale et al., 1993). During this time, the upper-most portions of the sediments comprising the lowstand paleodelta and the nearshore braidplain deposits were reworked by shoreline processes. These these reworked sediments now comprise what is referred to as the "mobile sand sheet", the finer, more mature reworked sediments of the Holocene transgression (Barnhardt et al., 2009).

The shoreline reached its modern position by approximately 3-4 kya. Since that time, the barriers of the Merrimack Embayment have been aggrading, elongating, and prograding as additional sediments have been delivered from the Merrimack River.

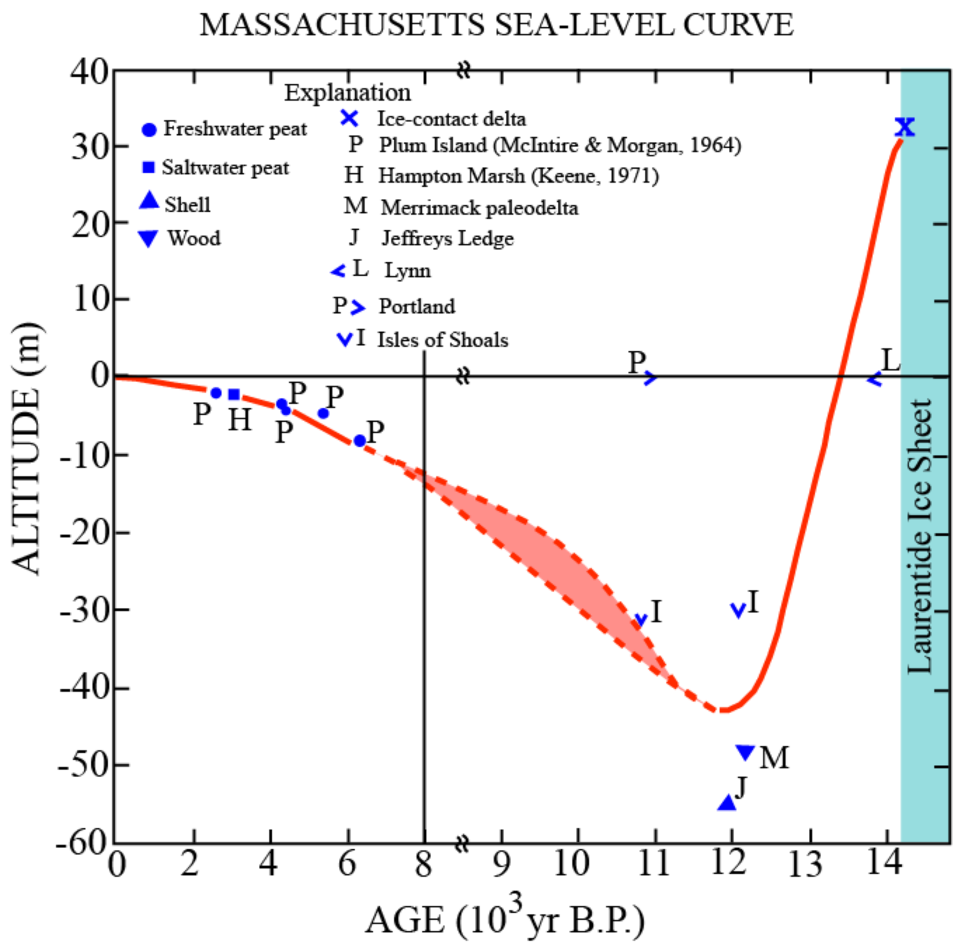


Figure 3: Relative sea level curve for north-eastern Massachusetts and the adjacent inner continental shelf. The envelope (crossed line) represents the range within which the actual curve may run. Note scale change at 8000 yr BP. (modified from Oldale et al, 1993)

C. Formation of the Lowstand Paleodelta

The initial geophysical examination of the Merrimack paleo-delta (Oldale et al, 1983 and Edwards, 1988) revealed that the Merrimack paleodelta is located approximately 6 to 7 km offshore and trends parallel to the present coast (Fig. 4). The paleo-delta is 20 km long, 4 to 7 km wide, up to 20 m in thickness, and resides in -45 m of water (Oldale et al, 1993). The delta was deposited during the regional sea level low-stand at approximately 12 kya and contains about 1.3 billion m^3 of sediment (Oldale et al, 1983). Seismic records show that the upper portion of eastwardly-dipping reflectors, which represent delta foresets, are truncated indicating that the surface of the delta was reworked during the early Holocene transgression of this region (Oldale et al, 1983). They also reported that the delta foresets are underlain by gently sloping bottomset beds and overlain by sediments interpreted as fluvial and estuarine deposits in the landward part of the delta and post-glacial marine silt and clay in the offshore portion of the delta (Edwards, 1988).

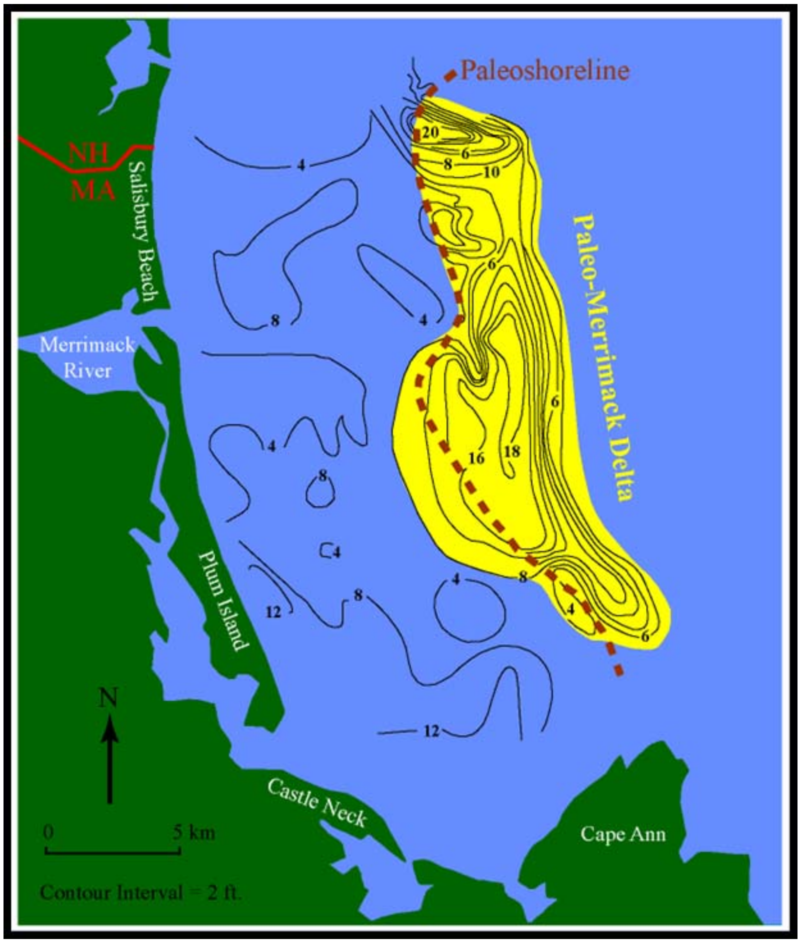


Figure 4: Inferred location of –45 m Merrimack Paleodelta (modified from Oldale et al., 1983)

The volume determinations and early observations of the delta were based on the interpretation of seismic data collected along track lines that were spaced 2 km apart, including only one shore-parallel transect. This investigation has built on these earlier studies adding new and more detailed observations through the interpretation of additional, more closely spaced seismic lines, side scan sonar backscatter imaging, multi-beam bathymetric surveys, and bottom sampling. The goal of this work is to examine the 3-dimensional architecture of the inner shelf depositional sequence as well as determine the sedimentological nature of the sandy inner shelf bodies.

Granularmetric analyses indicate that the delta sediments are bimodal containing poorly sorted silt and fine sand components, which is characteristic of fluvio-deltaic sediments (Giosan and Bhattacharya, 2005). Shallow seismic profiles show a basal unconformity located immediately below a set of regressive fluvial / deltaic deposits. Capping these deposits is a pronounced ravinement surface, which extends from the delta to the nearshore of the Merrimack Embayment, indicating extensive reworking of the fluvial-deltaic lithosome during the Holocene transgression.

Landward of the paleodelta, extensive (18 km x 7 km) Pleistocene regressive braid plain deposits are intermixed with more recent estuarine sands. The braid plain likely built seaward during the regression and ultimately fed sediments to the paleodelta during the late regression and lowstand. Large reworked portions of this feature have been exposed due to shoreface reworking during the Holocene transgression. Surficial bottom samples indicate that braid plain deposits are composed of coarse-grained sand and fine gravel. Edwards (1988) described this unit as “flat-lying to gently dipping, showing large-scale cross-bedding and channel features”, 8-12 m thick, blanketing much of the nearshore area (18 km x 7 km), and grading into the deltaic deposits. Recent shallow seismic survey data show extensive channel cut and fill features in this unit, many of which are truncated at the surface, suggesting that the braided stream deposits themselves were reworked during the Holocene marine transgression.

D. Holocene Transgression and Sediment Reworking

Much of the surface of the delta exhibits a ravinement surface that is inferred to be a time transgressive marine unconformity cut during the Holocene marine transgression and overlain by possible beach or bar deposits at some sites (Oldale et al, 1983). Edwards (1988) described these sandy deposits as a discontinuous, planar, palimpsest shelf surficial sand sheet of varying thickness and in disequilibrium with present-day processes. Edwards (1988) also reported “linear ridges” that he attributed to having formed during the transgression or as post-transgressive features; i.e. either degraded barriers that formed as sea level rose and sediments were reworked in an onshore direction or active shoreface-connected ridges that form in the present day in response to peak flow conditions during northeasters.

Cores through the paleo-delta (Edwards, 1988; Appendix E) generally show intercalated silty clays and fine to medium silty sands. The upper 20 to 30 cm of the cores consists of medium sand with coarse pebbles and shell fragments (Edwards, 1988). These cores that extend between 3 and 8m in depth confirm that the delta is composed largely of fine-grained sediments. Oldale et al (1993) attributed the coarse-grained sediments at the surface of the cores to a “sandy Holocene marine transgressive deposit, too thin to be resolved in the seismic profile, unconformably [overlying] the delta deposits.” Recent backscatter data indicate that Edwards’ (1988), and Oldale and other’s (1993) sandy areas coincide with alternating high and low backscatter regions of the Embayment, evidence of a mobile Holocene fine to medium sand unit that discontinuously overlies Pleistocene regressive deposits. Specifically, in the delta region, the mobile sand sheet sediments are finer (coarse silt to fine sand) and represent the reworking of the truncated forest beds. Landward, the Holocene mobile sand sheet is coarser-grained (fine to medium sand) and originates from the winnowing and reworking of the upper-most portion of regressive braid plain deposits. Where exposed, the braid plain deposits are composed of coarse-grained sand and fine gravel, which have been molded into ripples and megaripples by present marine processes. The overlying Holocene sand sheet is finer, composed of mobile fine and medium sands that are actively reworked by waves, as evidenced by the existence of pervasive 3-D ripples and hydrodynamic measurements collected at the site (see Results section).

The mobile Holocene sand sheet was likely generated during the Holocene transgression when shoreface processes reworked both the lowstand delta and the regressive braided stream and braid plain delta deposits. Additional sand may have been derived from the Merrimack River As will be discussed in more detail later in this report, the Holocene sand sheet contains approximately 1.21 x 10^8 m^3 (Barnhardt et al., 2009), which is one order of magnitude less than the sand comprising the lowstand delta or the Pleistocene braid plain deposits.

IV. DATA ACQUISITION

A. Mapping

A variety of geophysical and sedimentological data has been collected in cooperation with the United States Geological Survey (USGS) Woods Hole Science Center (Woods Hole, MA) for the purpose of assessing the sand and gravel content of the inner continental shelf within the Merrimack Embayment as well as determining the region's depositional history. During several research cruises in 2004 and 2005 the sea floor of the Merrimack Embayment (323 km^2 area) from the nearshore zone to about 17 km offshore (Fig. 5) was mapped using a variety of geophysical techniques. Data was collected during two cruises, each using different techniques. The first cruise was conducted in the offshore part of the study area (water depths 25-91 m) by Science Applications International Corporation (SAIC) between February 23 and March 23, 2004. A second cruise was conducted by the USGS in the nearshore part of the study area (water depths 2-30 m) from September 8-20, 2005.

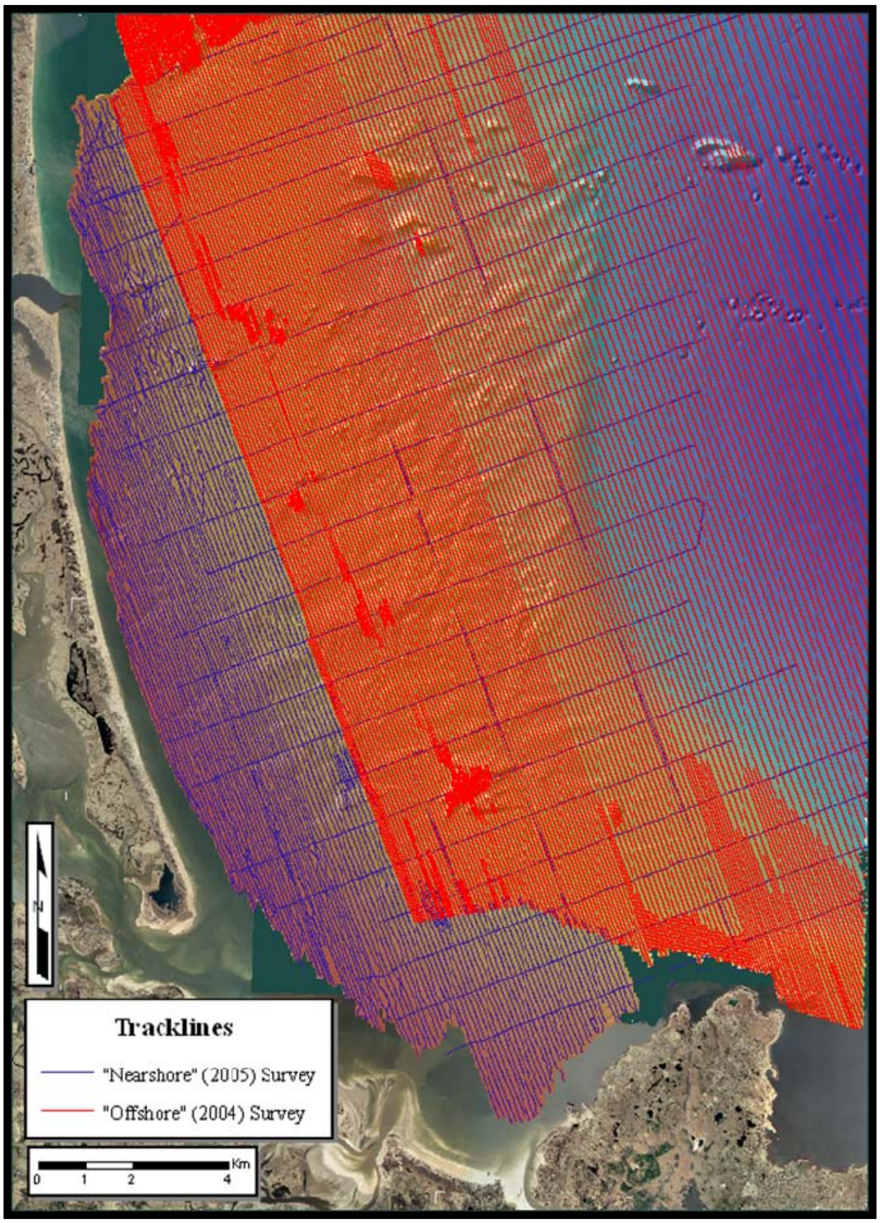


Figure 5: Tracklines from 2 mapping cruises to Merrimack Embayment overlain on bathymetric map (Fig. 6). Red track lines (100 m line spacing) are from 2004 SAIC cruise. Blue lines (variable line spacing, based on depth) are from 2005 USGS cruise. Cross shore lines (2005) are spaced approximately 1 km apart.

A-1. Bathymetry

Offshore bathymetric data were acquired using a Reson 8101 multibeam echosounder (MBES). Survey lines were run at an average speed of 9 knots in a NW– SE orientation (Fig. 5). Cross lines spaced 4 km apart were run across the entire survey area for data-quality control. A total of 2,904 km of survey lines were occupied. Data were processed by the USGS using SAIC's SABER software with a 5-m Pure File Magic (PFM) grid for areas based editing (Barnhardt et al, 2009).

Nearshore bathymetry and backscatter data were collected with a SEA SwathPlus 234 kHz bathymetric system. A total of 1,184 km of survey lines were run at an average speed of 5 knots. The lines were spaced 100 m apart to ensure overlap of adjacent swaths and obtain 100% coverage of the seafloor. Bathymetric data along 322 km of cross lines allowed comparison with the 2004 MBES data. Data were processed and gridded by the USGS using the SwathEd software package (UNB, 2005). The bathymetric data have a vertical resolution of between 0.5% and 1% of water depth. The final bathymetric grid (Fig. 6) was mapped at a resolution of 5 m/pixel (Barnhardt et al, 2009).

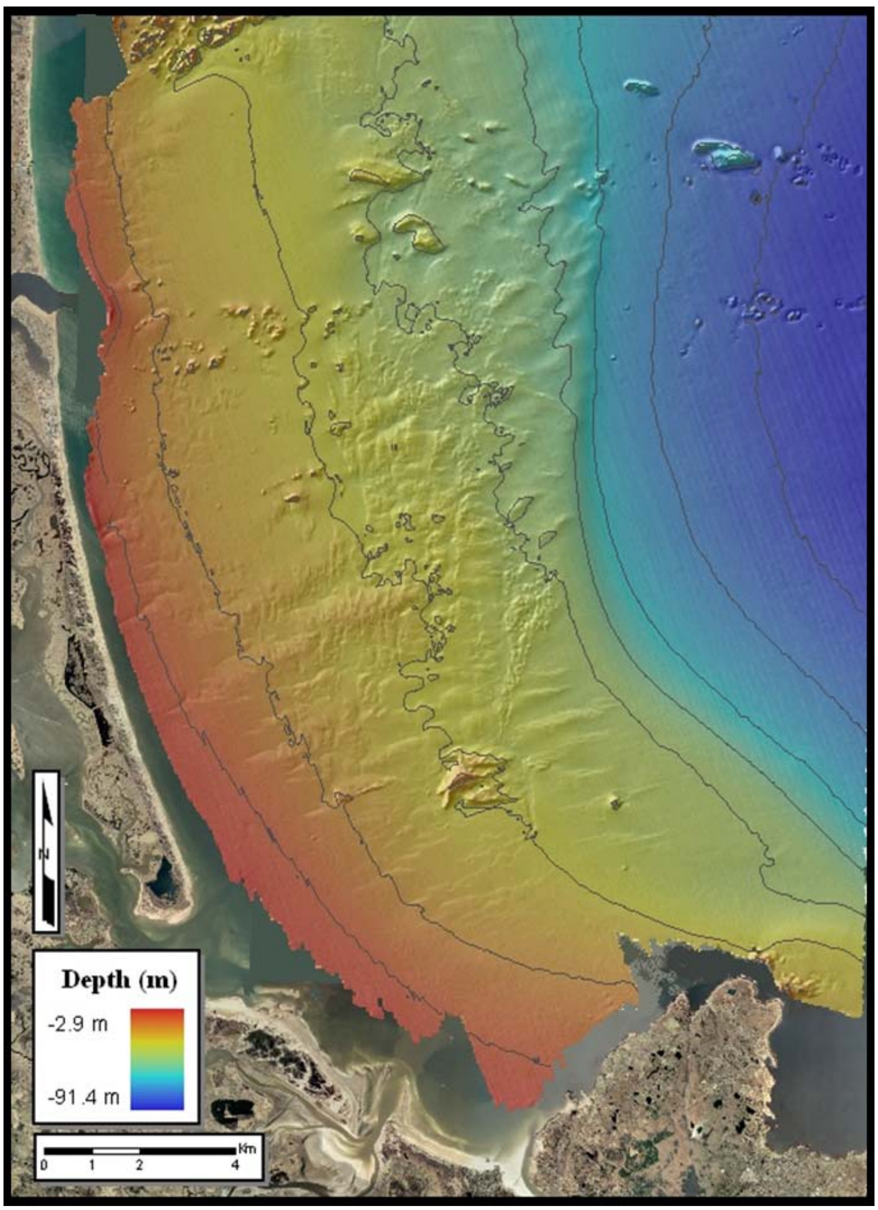


Figure 6: Bathymetric map of Merrimack Embayment. Black lines are 10 m contours, from -10 m to -90 m.

A-2. Backscatter Surveys

Backscatter intensity, as recorded with sidescan sonar, is an acoustic measure of roughness of the seafloor. Acoustic backscatter data were collected with a Reson MBES and a Klein 3000 dual frequency sidescan sonar. All sonar data were later processed for beam angle and slant range correction by the USGS using LINUX based Xsonar/Showimage as described in Danforth (1997). Sonar data from each survey line were mapped in geographic space in Xsonar and then imported as raw image files to Geomatica GPC works and mosaiced line by line. The resulting high-resolution backscatter image (Barnhardt et al, 2009) shows distinct patterns of high and low backscatter regions (Fig. 7). High backscatter features cover approximately 40% of the sea floor in the study area and another 35% of the sea floor is low to medium backscatter. The darkest (low backscatter) regions comprise the final 25% of the sea floor and occupy the northeast quadrant and represent low reflective ocean mud offshore of the paleodelta. Within this offshore mud several sizable (up to ~1km) high backscatter bedrock outcrops occur.

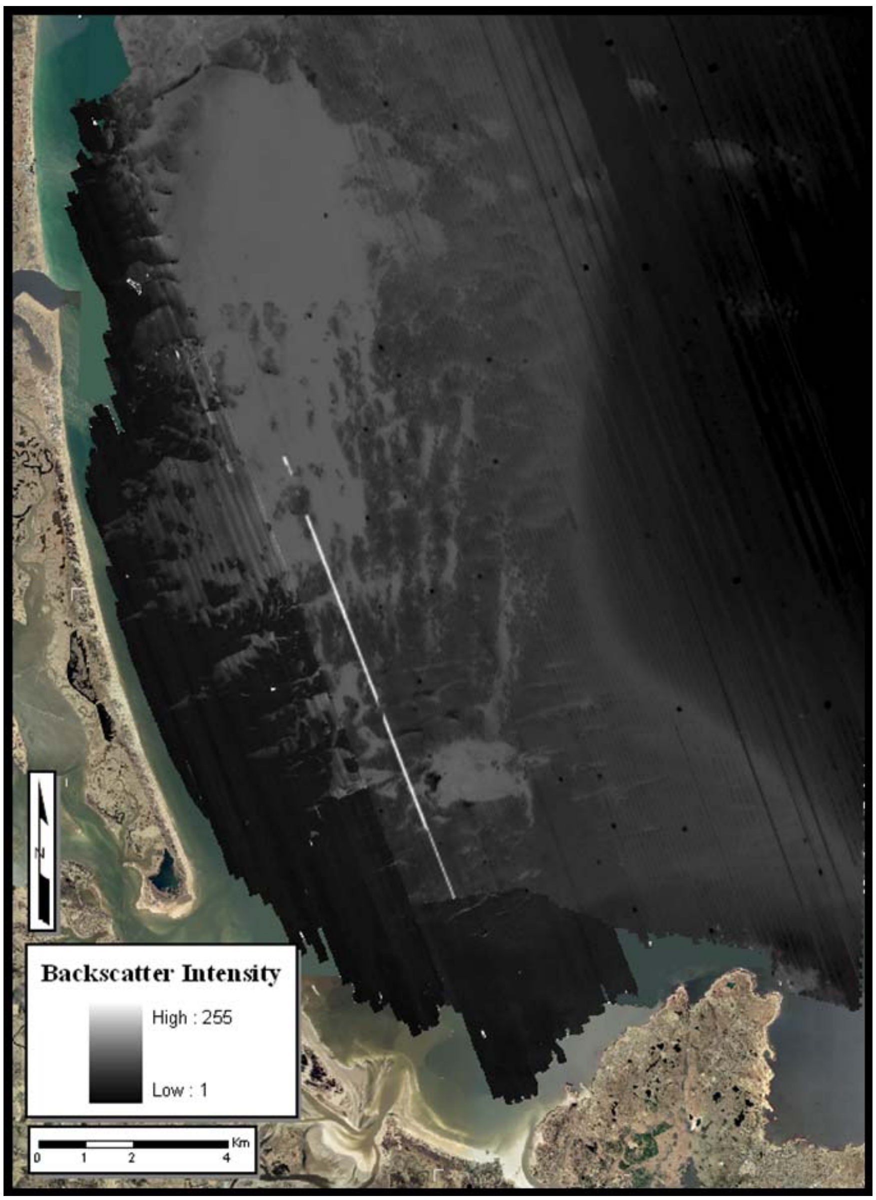


Figure 7: Backscatter map of sea floor. Lighter colors represent high backscatter and darker colors represent low backscatter. The Holocene shelf surficial sand sheet, linear and cuspate ridges, and the delta front are all visible as high backscatter features in this image.

The high backscatter features visible in Fig. 7 are likely the same sandy areas that Edwards (1988) referred to as a “sand sheet” and “linear ridges”. The sand sheet is centered off the mouth of the Merrimack River and is approximately 18 km (N-S) x 7 km (E-W). Bedrock dominates the sea floor north of the sand sheet. The sand sheet becomes diffuse in a south and offshore direction transitioning into a series of linear to cuspate features surrounded by low backscatter sediments. Relatively large, coarse-grained linear features dominate the northern sector and are oriented in a NNE-SSW direction. Within the surrounding fine-grained sediment these forms have a sharp edge on their eastern side and are diffuse along their western edge, suggesting movement in an ESE direction. Elsewhere, subordinate forms are oriented in ENE-WSW and ESE-WNW. The geometry and orientation of the largest positive bed features suggest that the sand sheet is being reworked in an offshore (easterly) direction. In the southern part of the embayment, the smaller high-resolution features appear to be migrating northward. Parts of the sand sheet itself also show evidence of northerly transport, notably in the northwest corner where large features of the sand sheet have sharper northern leading edges.

A-3. Shallow Seismic Surveys

In September 2005, approximately 1100 km of high-resolution chirp seismic-reflection profiles (Fig. 8) were collected using an EdgeTech Geo-Star FSSB system and an SB-0512i towfish (0.5-12 kHz). Post-processing was again provided by the USGS. The SeisWorks (Landmark Graphics Inc) software package was used to digitize tops of geologic units and unconformities to produce two way travel time horizons. Isopachs (Appendix D) were derived from these digitzed layers.

These data build and expand upon previous work done by Edwards and Oldale (1986) and increase our understanding of the Merrimack paleodelta. The track lines normal to the coast show a consistent pattern of seaward dipping clinoforms and a pronounced ravinement surface, confirming previous observations that the upper portions of the delta were eroded during the Holocene transgression. However, it is still not known how much of the upper delta was removed during the reworking process.

The shallow seismic profiles also reveal the existence of channel cut and fill structures. These features trend in an E-W direction. They are commonly several meters in thickness and vary in width from about 25 to several hundred meters. These cut and fill features are prevalent in the entire region onshore of the delta and may be related to braided streams that carried sediments in the Merrimack to the lowstand delta during the late Pleistocene and early Holocene.

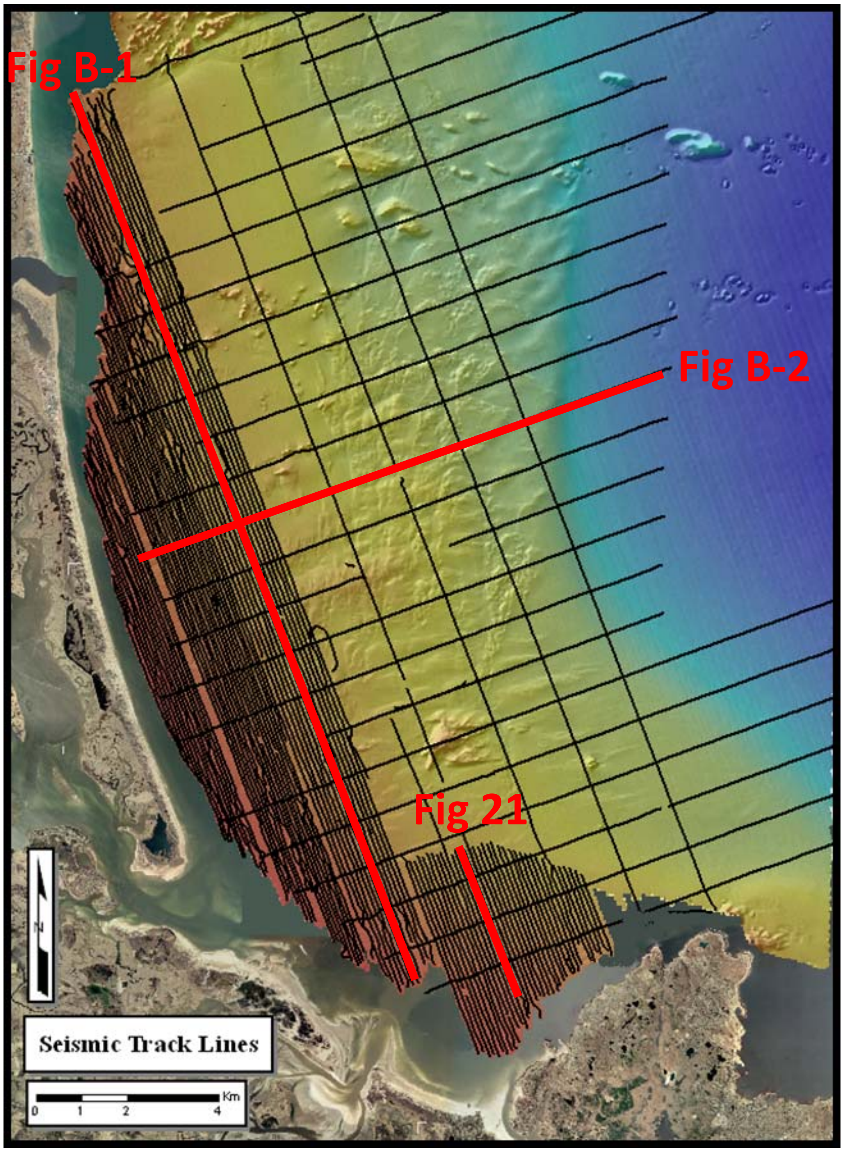


Figure 8: Shallow seismic track lines overlain on bathymetry. Red lines indicate location of Fig. 22 and of strike (Fig. B-1) and dip (Fig. B-2) lines are shown in Appendix B.

B. Bottom Sampling

During three separate research cruises from 2005-2006, 107 bottom sediment samples were collected in both nearshore and offshore regions of the Merrimack Embayment (Fig. 9). 79 sites were sampled during the September 2005 USGS research cruise with the USGS SeaBoss instrument package that also collected bottom video and still photos. The primary study locations were the zones of transition between regions of high and low backscatter (Pleistocene braid plain deposits and mobile sand sheet, respectively); areas in the vicinity of bedrock outcrops provided another priority target area. The SeaBoss was further utilized during a September 2006 cruise that focused on the sediment distribution within a single bedform field. Samples were collected along several transects in a set of long wavelength (600-700 m), north-facing bedforms situated 4-6 km north of Cape Ann. Samples were taken along the stoss face of the bedform, at the crest, in the high backscatter trough, and at regular distances from the crest and trough. Data from this cruise are being used to determine possible present-day reworking of sediments and to instruct positioning of the instrument

In all cases the upper 2 cm of sediment were scraped from the surface of the sediment sample for textural analysis. All samples were analyzed for grain size at the USGS Sediment Laboratory in Woods Hole, MA. Poppe and Polloni (2005) describe the standard procedure for textural analysis.

On September 6, 2005, two transects of box-core samples were collected north of Cape Ann aboard the UNH research vessel *Gulf Challenger*. Samples were collected at approximately 10-m intervals perpendicular to the shore, along two shore-normal transects (Fig. 10). The northern transect is offshore of the Merrimack River, and the southern transect is 5-km south, offshore of Plum Island. Dr. Larry Ward, a Research Professor at UNH provided the ship-time. These samples were further used in the analysis by S. Nathan, M. Leckie, and S. Mabee in their evaluation of microfossil assemblages in the Merrimack Embayment (Appendix B).

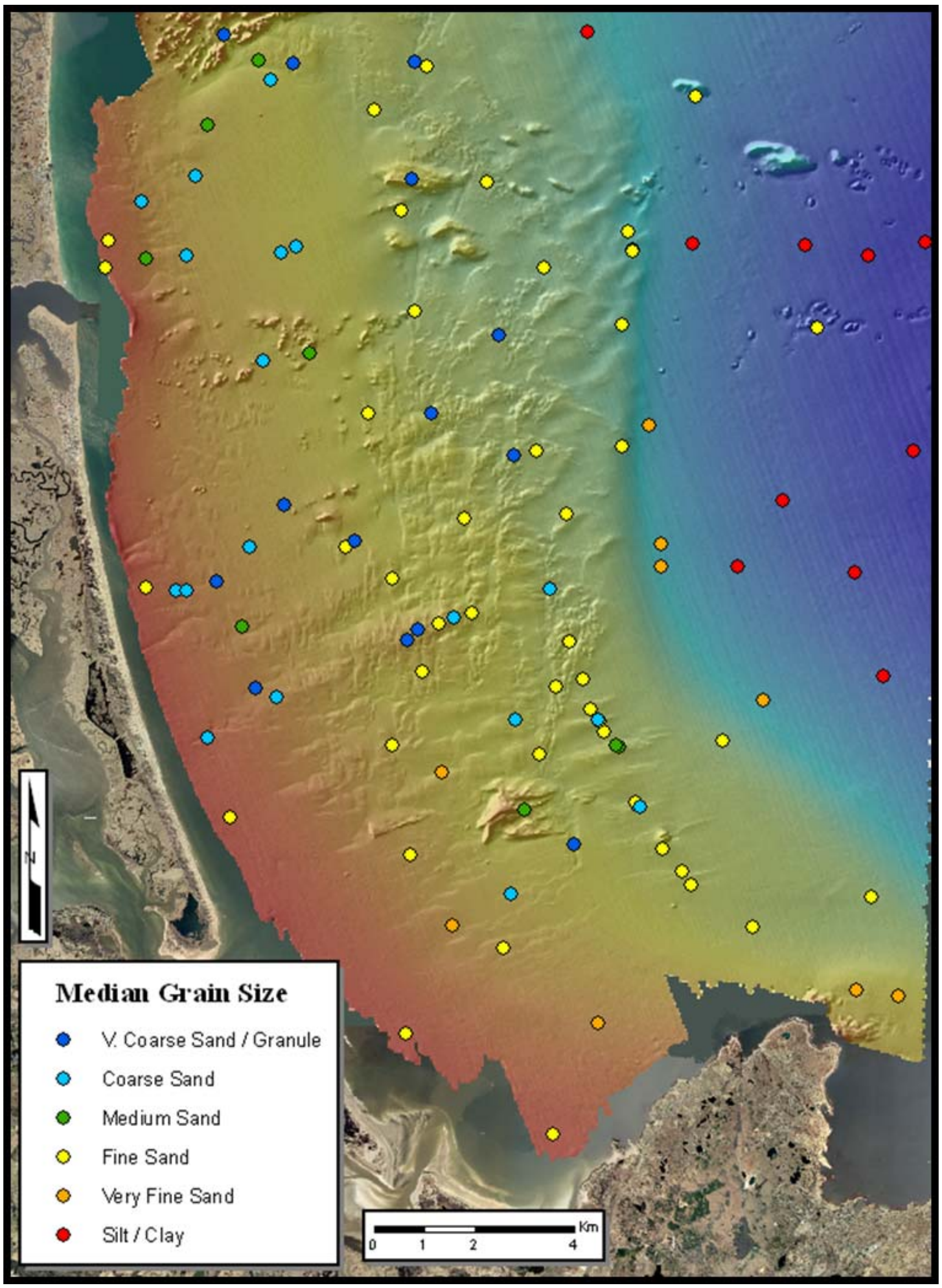


Figure 9: Locations of bottom sediment grab samples. Sediment type classified by median grain size according to Wentworth grain size class. Sample locations overlain on bathymetric map.

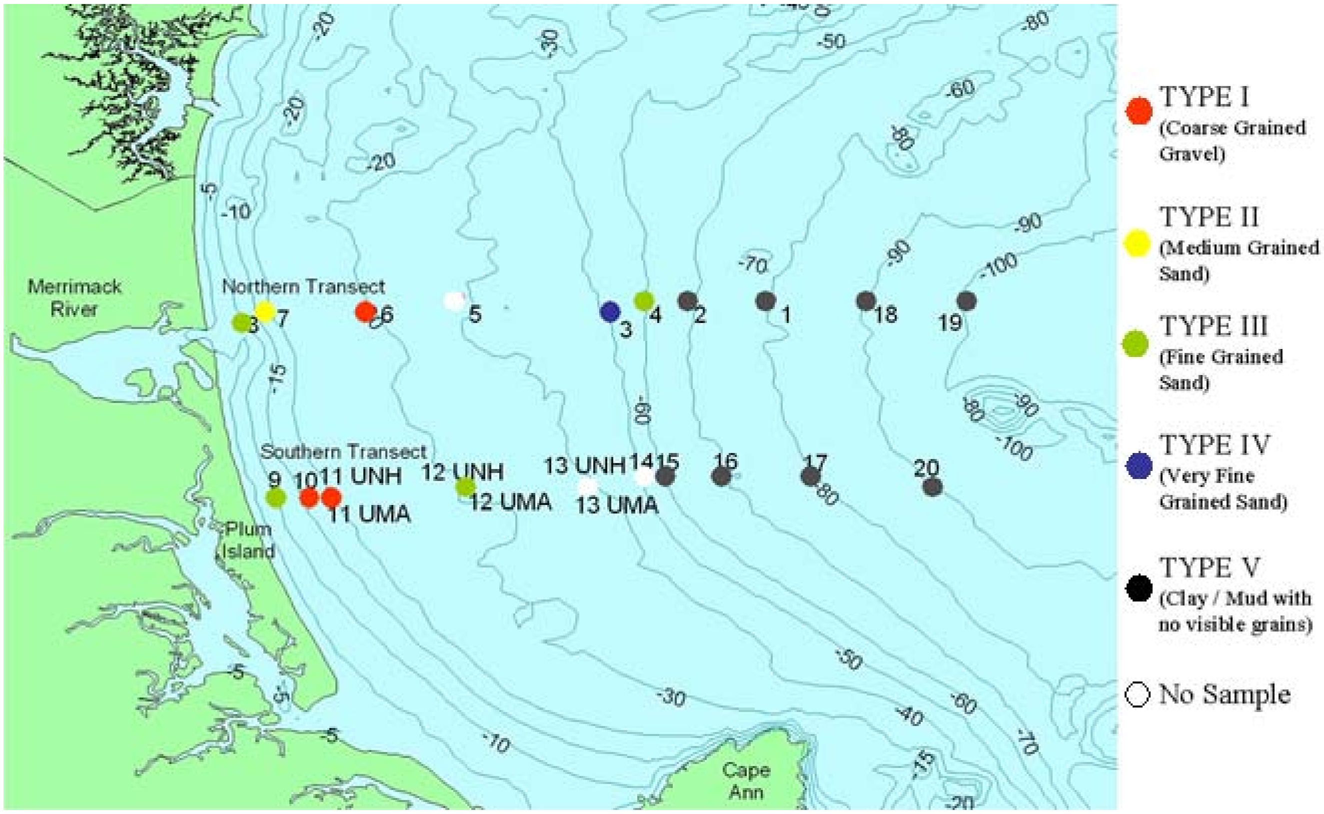
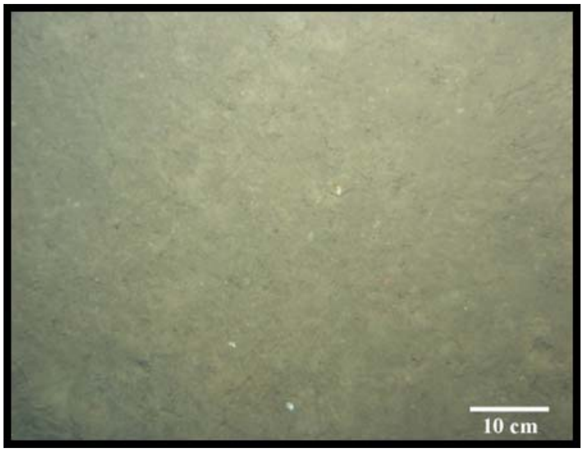


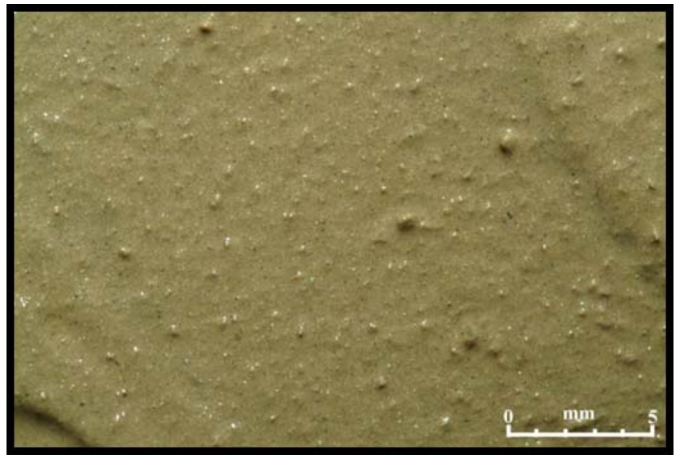
Figure 10. Locations and general categorizations of bottom sediment samples collected by L. Ward (University of New Hampshire), August 2005. Samples that fall within Merrimack Embayment study area are included in Fig. 9.

Raw sedimentological statistics for all bottom sediment samples are grouped by backscatter bottom type (high, low, or intermediate) where the sample was collected; this data is presented in Appendix E. Sample bottom photos and moist sediment sample photos (taken in the lab) are provided in Figure 11.

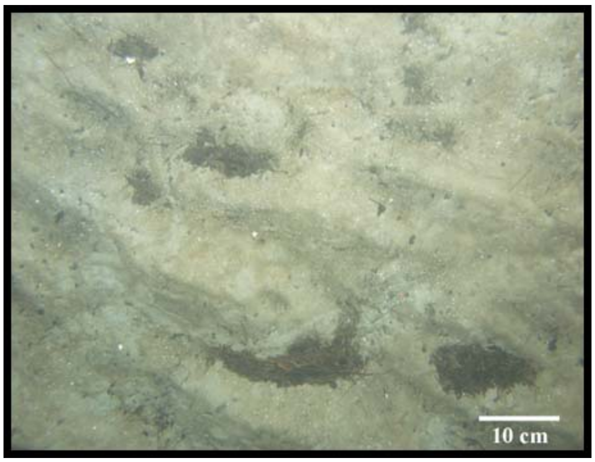
Sediments in regions of high backscatter are composed of coarse-grained sands to fine gravels (mean φ is 0.61; mode φ is 0.53). These regions are dominated by two dimensional megaripples with wavelengths of about 1 m. The troughs of these megaripples are commonly filled with shell hash. Low to medium backscatter areas contain fine- to medium-grained sand (mean φ is 2.42; mode φ is 2.34) dominated by three dimensional, cuspate ripples with wavelengths of about 20cm. Contacts between these regions of coarse and fine sands are very sharp and fine sands are commonly at slightly (<1m) lower elevations. Both the fine and coarse sands were moderately well sorted. Sediments from the delta front are fine grained sands (mean φ is 3.62; mode φ is 4.00) and deeper seaward regions consist of fine-grained mud (mean φ is 5.84; mode φ is 5.71). Mud also drapes bedrock outcrops and inhibits bedform formation in these areas.



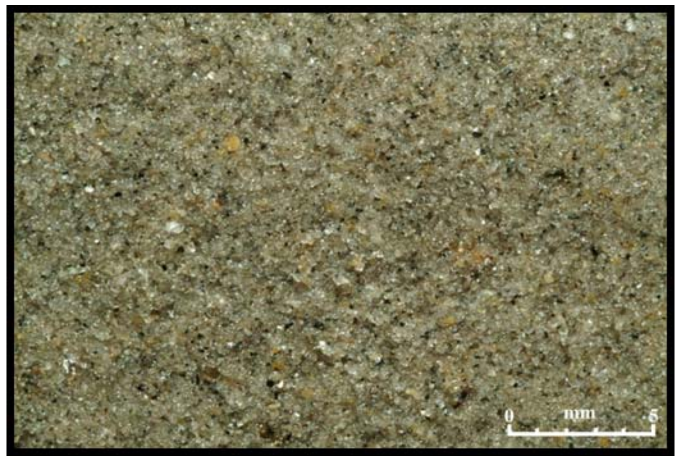
A) Bottom Photo



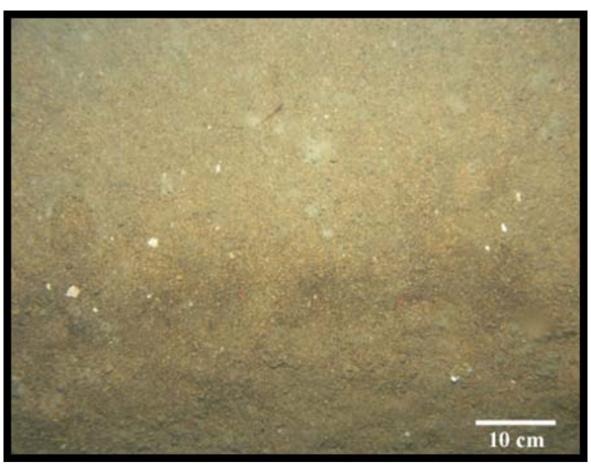
A) Sediment Sample Photo



B) Bottom Photo



B) Sediment Sample Photo



C) Bottom Photo

C) Sediment Sample Photo

Figure 11. Photos of sediments representing each major category of sediment size. Vertical bottom photos taken during the September 2005 USGS cruise are on the left. Sediment photos associated with each bottom type are on the right. A) Delta front mud (low backscatter) B) Fine to medium grained sand (low to intermediate backscatter) C) Coarse grained sand to gravel (high backscatter)

C. Instrument Deployment

The detailed maps produced for this report reveal a complex sediment distribution patterns in the nearshore zone of the Merrimack Embayment (see "Results" Part A). Over time, successive northeast storms drive sediment to the south, depositing it in Ipswich Bay. During the transgression, storm processes reworked and winnowed the regressive braid plain sediments, exposing a large sand sheet to the north, and depositing a 6-9 m thick fine to medium sand sequence to the south (121 million m^3 of sediment; Barnhardt et al., 2009). However, this simplistic approach to nearshore sediment transport does not account for the distribution of sediments comprising the mobile Holocene sand sheet. It also does not address the question of whether these features are relict transgressive features or are the result of modern waves, tides and currents. Present day storm data are needed to answer these questions.

On 25 February 2009, an aluminum tripod frame containing various instruments to measure waves, currents, and suspended sediment was deployed on the seafloor off central Plum Island, in 20 m of water. This site was chosen due to its location in a coarse sand / gravel depression immediately adjacent to several fine / medium sand ridges (Fig. 12).

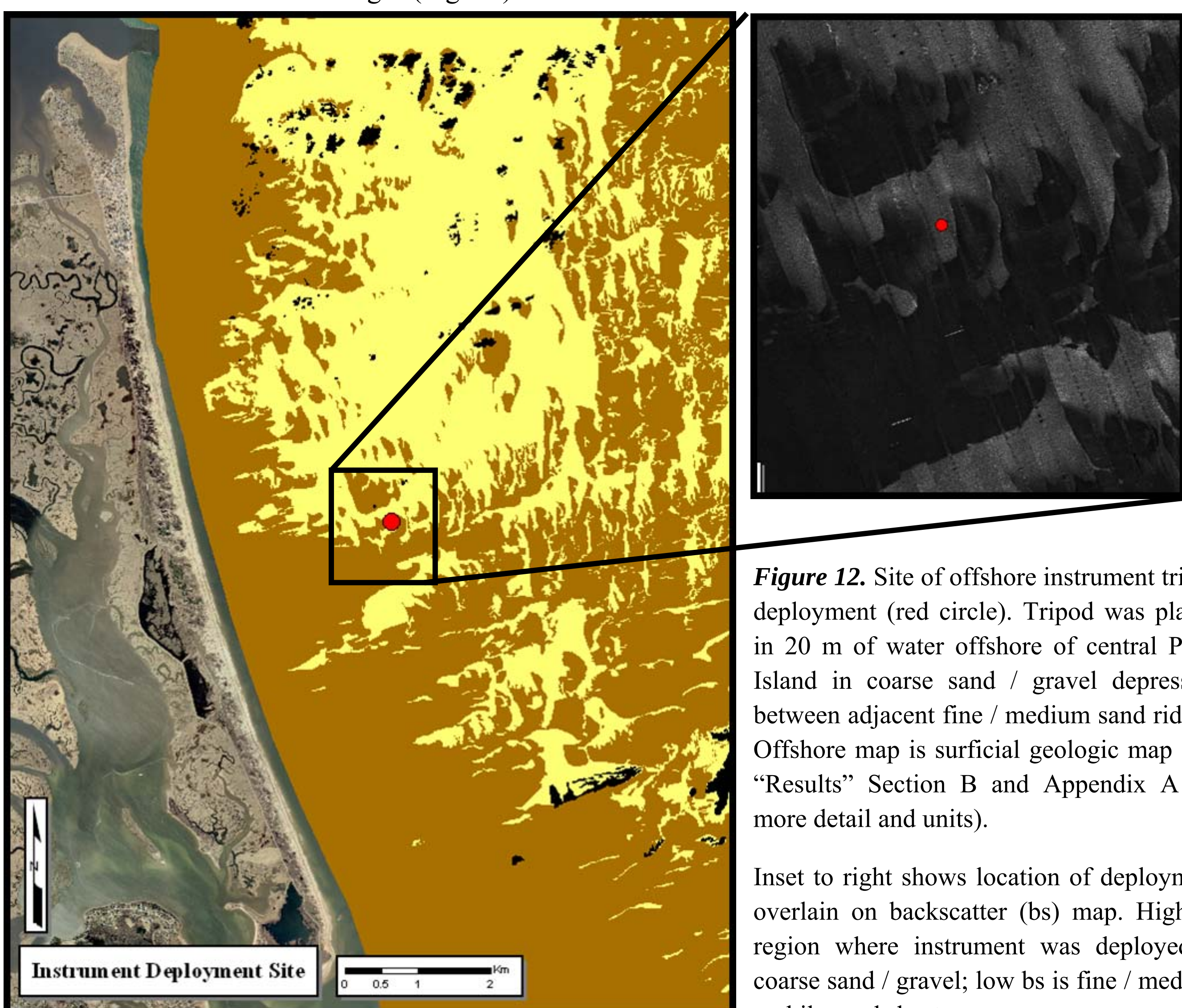


Figure 12. Site of offshore instrument tripod deployment (red circle). Tripod was placed in 20 m of water offshore of central Plum Island in coarse sand / gravel depression between adjacent fine / medium sand ridges. Offshore map is surficial geologic map (see "Results" Section B and Appendix A for more detail and units).

Inset to right shows location of deployment overlain on backscatter (bs) map. High bs region where instrument was deployed is coarse sand / gravel; low bs is fine / medium mobile sand sheet.

This deployment included a suite of instruments designed to measure waves, currents, and suspended sediment concentrations (Fig. 13). Instruments included on this deployment were:

- Downward-Looking Current Profiler: A 2 MHz Nortek Aquadopp Acoustic Current Profiler was used to measure the velocity field through the bottom 1 m of the water column (i.e. within the bottom boundary layer). Velocities and directions are measured by observing the Doppler effect of particles traveling through the water column. Set on high-resolution mode, this unit employed three acoustic beams to collect three-dimensional current measurements in 24 separate 5 cm cells between the tripod and the sea floor. Measurements were made for 1 minute durations once every 10 minutes. This key region is where wave-induced turbulence and tidal / wave-influenced currents interact with sediment on the sea floor and move sediment and is the primary depth of interest for sediment transport. The beam source of this instrument was mounted 100.4 cm from the sea floor.
- Upward-Looking Acoustic Doppler Current Profiler (ADCP): A Teledyne RD Instruments Workhorse Sentinel ADCP was mounted on the tripod frame to provide current measurements through the entire water column, from its blanking distance (approximately 2 m above the instrument head) to the water surface. Similar to the Aquadopp, this instrument employs 4 acoustic beams (1 extra to provide a redundant data source in the case of a blocked or damaged beam) that measure the doppler effect of particles in the water column to provide three-dimensional current measurements. This instrument recorded 50 pingers every 5 minutes for entire length of the deployment. In addition, this instrument was used to provide wave measurements. Wave bursts (continuous for 17 min, once an hour) were used to provide wavelength, frequency, and wave height data. The beam source of this instrument was mounted 150.5 cm from the sea floor.
- Upward-Looking Current Profiler: A second 2 MHz Nortek Aquadopp Acoustic Current Profiler was used to measure the velocity field within the 2 m blanking distance of the RDI ADCP (e.g. between the top of the tripod and 3 m above the tripod). This unit employed three acoustic beams to collect three-dimensional current measurements in 30 separate 20 cm cells. 3 m of overlap was provided between the Aquadopp measurements and the RDI ADCP measurements. Current measurements were made for 1 minute durations once every 10 minutes. This unit also collected wave bursts (512 samples at a 1 Hz sampling rate) once every 8 hours as a check for comparison to the RDI ADCP). The beam source of this instrument was mounted 140.6 cm from the sea floor.
- Optical Backscatter Sensors (OBS): Two Seapoint Turbidity current meters were placed 24.0 cm and 80.7 cm from the sea floor. These were mounted to the leg of the tripod, looking outward. The Seapoint Turbidity Meter measures turbidity by using a photodiode to detect scattered light from suspended particles in water. It senses scattered light from a small volume within 5 cm of the sensor windows. Two sensors recorded turbidity at two locations in the water column (an logarithmic profile of exponentially decaying suspended sediment concentrations from the bottom upward are assumed) for 5 sec every 5 minutes. The upper sensor was placed on 20x gain and the lower on 5x gain, due to assumed variations in turbidity through the lower water column. This data will be useful to determine the wave and current conditions during which various concentrations of sediment are suspended.

- CTD Sensor: In addition to its use in logging the OBS data, a Sea-Bird Electronics SEACAT Profiler was used to measure conductivity (proxy for salinity), temperature, and pressure (depth). Temperature and pressure were also collected by both Aquadopps and the RDI ADCP; this instrument provides a check on those data.

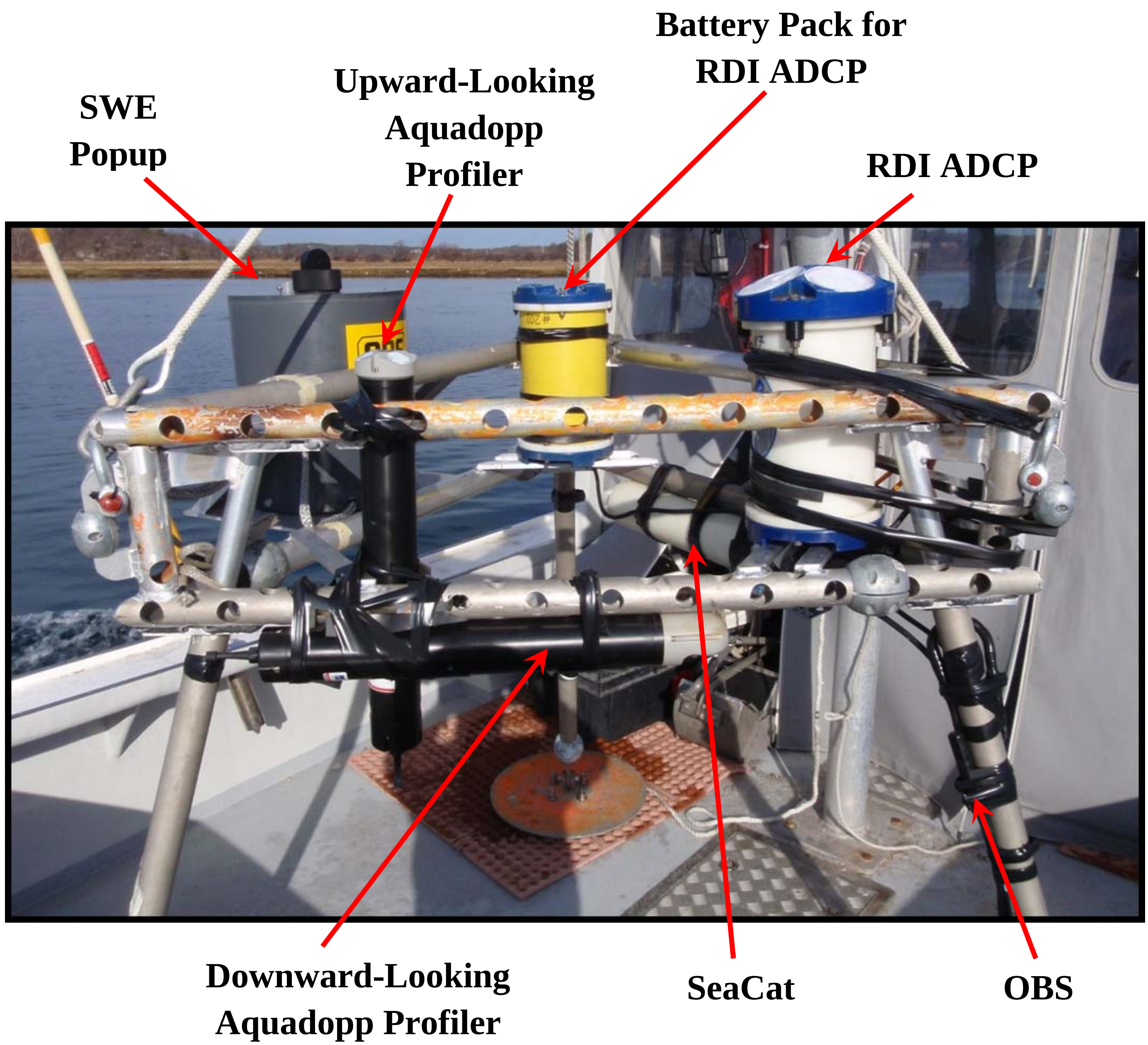


Figure 13. Aluminum frame instrument tripod with various instruments identified. Tripod frame is 1.3 m tall with feet and 100-lb lead weights attached to undersides of feet. Tripod shown here on 25 February 2009, prior to deployment, on Massachusetts Marine Fisheries vessel.

This scheme was designed to provide input for bottom shear stress calculations and determinations of current-induced combined bottom flows and will provide a characterization of the local seabed prior to, during, and after storm conditions. Also included on the instrument tripod were instruments designed for the successful recovery of the tripod, including an ORE Offshore SWR Pop-up (Fig. 13).

The tripod was successfully recovered on 4 May 2009. All instruments recorded data that can be used for analyses during the entire time of the deployment. Additionally, during both the deployment and recovery, three sets of grab samples of bottom sediments were collected to compare suspended sediment concentrations to known sediment types at the location of the tripod.

Analyses of the data from the instrument tripod deployment are presented in the Results section. Additionally, this data was used to calibrate and validate SWAN (Simulating WAves Nearshore) models used to determine the impact of borrowing sediment from the nearshore zone.

V. RESULTS

A. Surficial Sediment Classification of the Merrimack Embayment

All data collected and post-processed from the 4 research cruises were georeferenced and imported into ArcGIS. Sediment samples were classified and mapped based on grain size (median, Fig 9 and mean, Fig. 14), sorting (Fig. 15), and percentage of clay, silt, sand and gravel (Fig. 16). Observations of bottom type were made based on the sediment classifications (Fig. 14-16), bathymetry, and backscatter data.

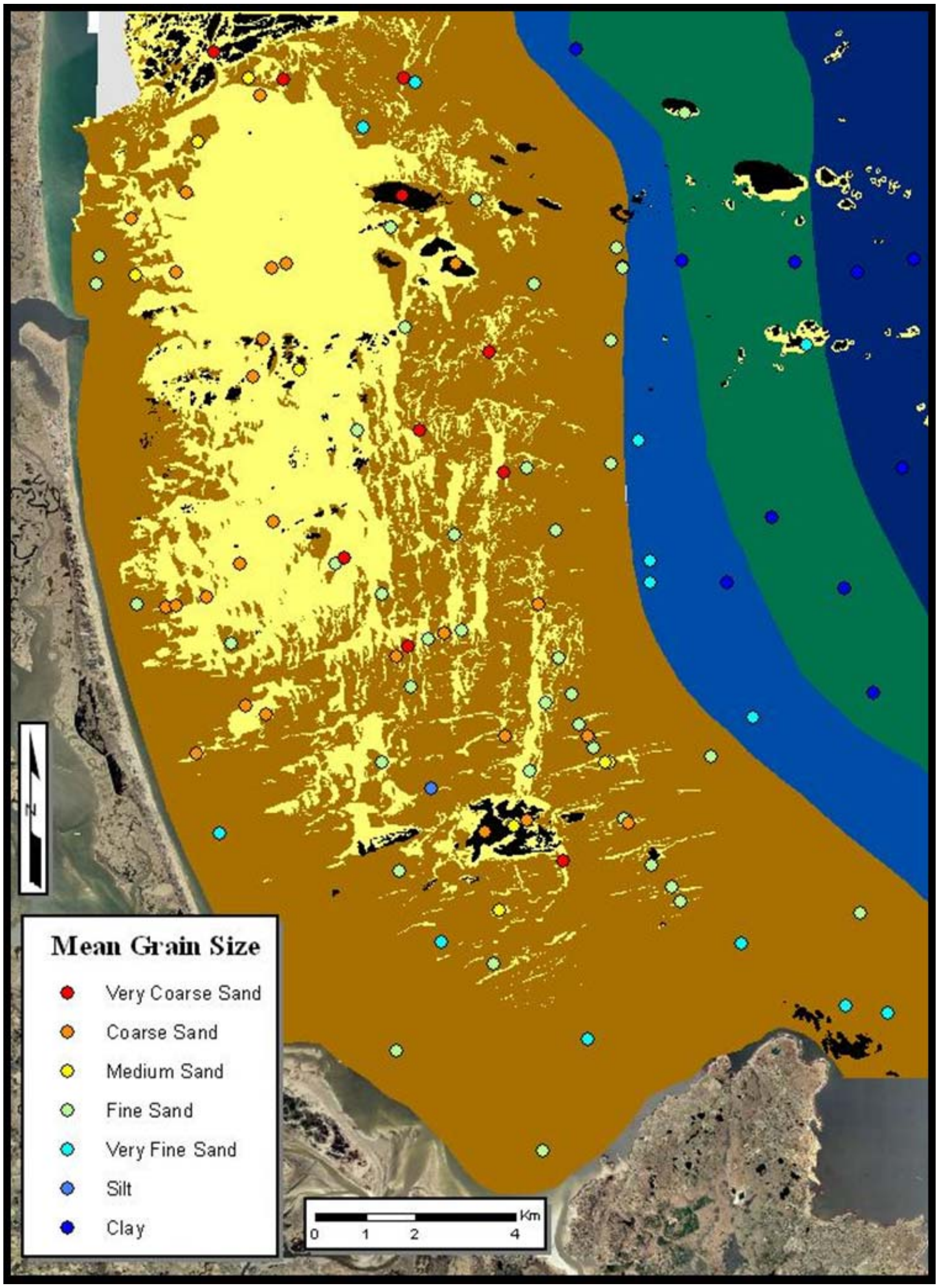


Figure 14. Sediment bottom samples classified by mean grain size according to Wentworth sediment classification. Classification overlain on surficial geologic map (see Part B and Appendix A).

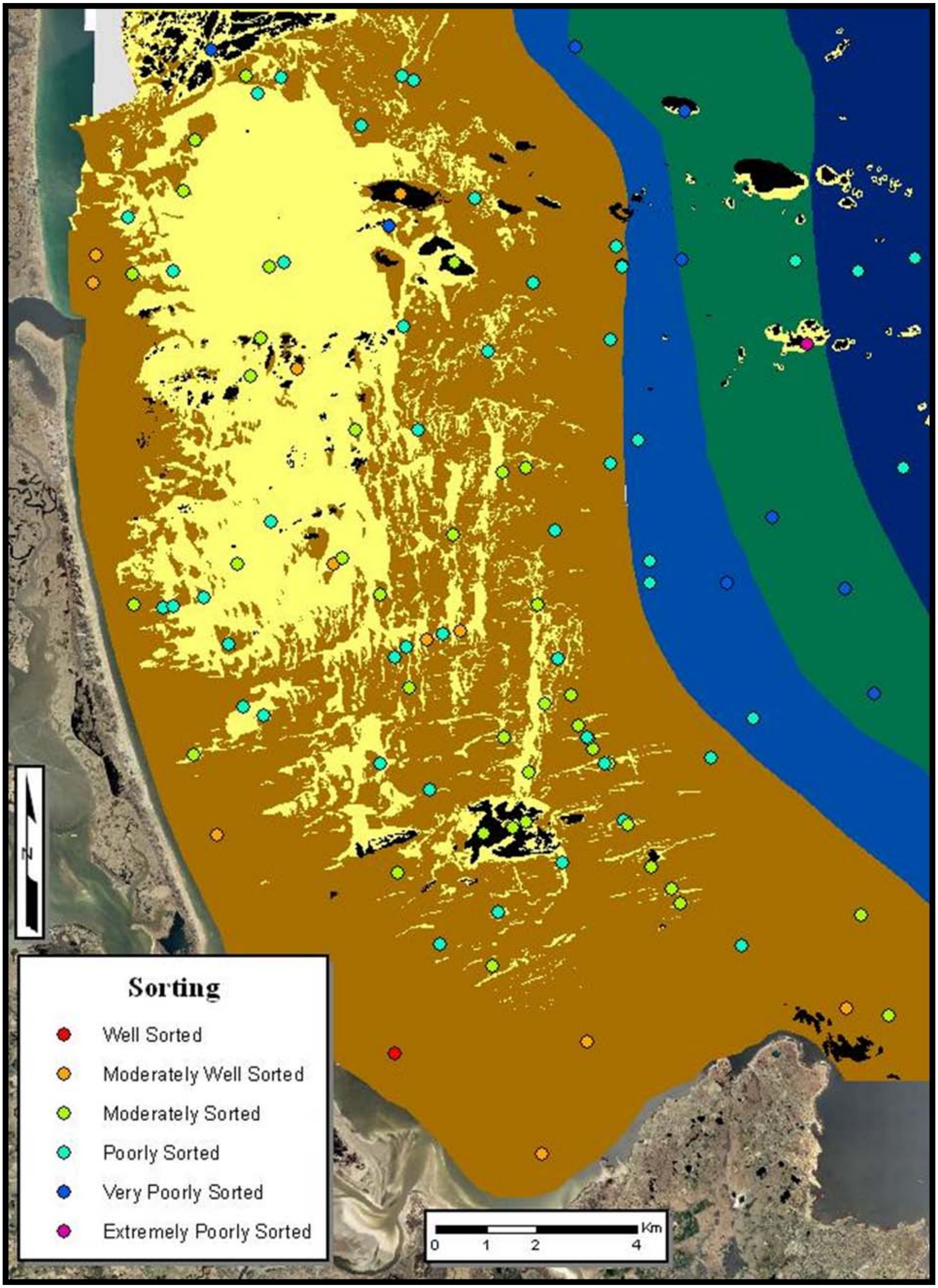


Figure 15. Sediment bottom samples classified by sorting according to Wentworth sediment classification. Classification overlain on surficial geologic map (see Part B and Appendix A).

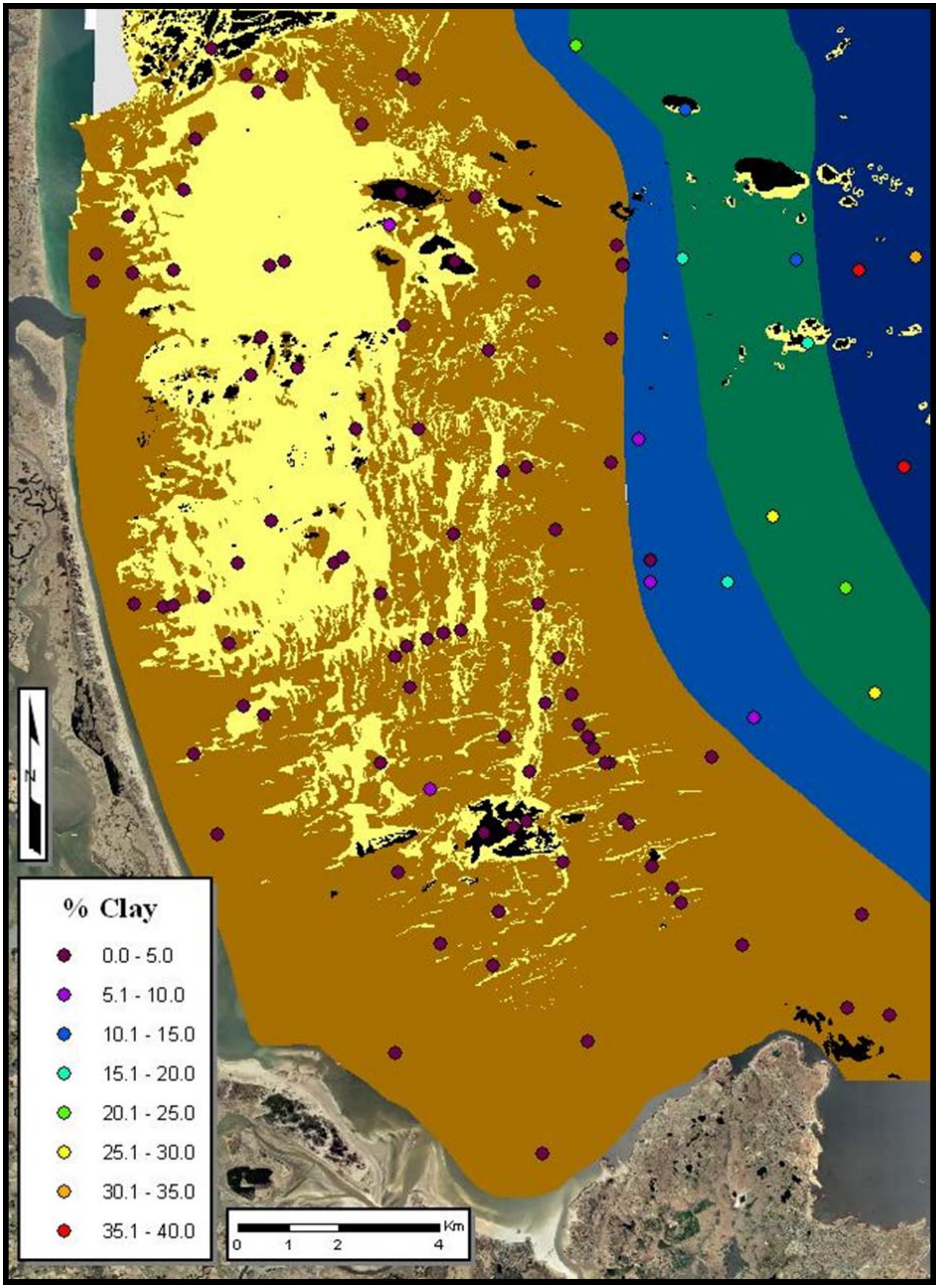


Figure 16a. Sediment bottom samples classified by percent clay (finer than 8 phi) in the samples Classification overlain on surficial geologic map (see Part B and Appendix A).

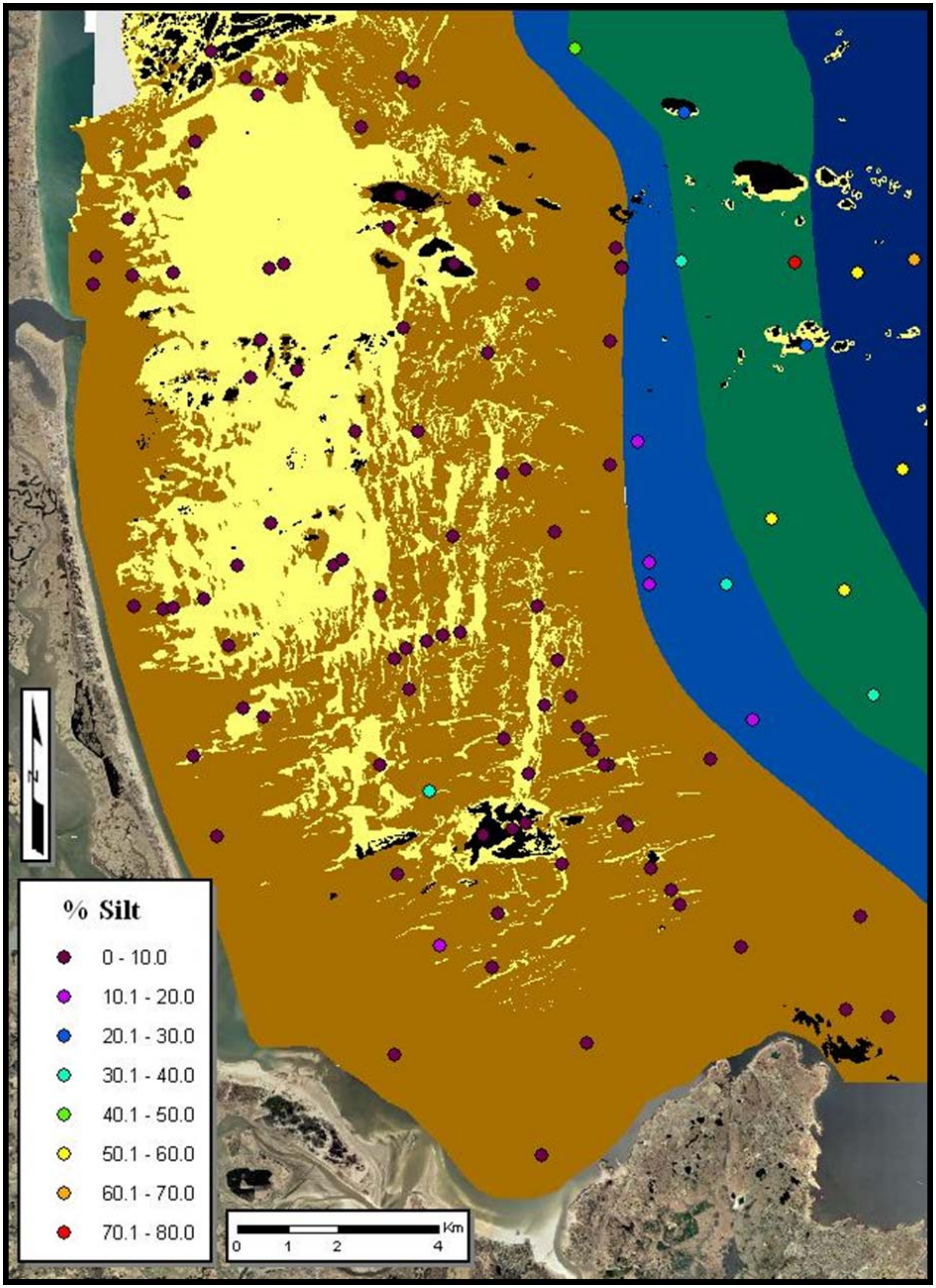


Figure 16b. Sediment bottom samples classified by percent silt (4 phi to 8 phi) in the samples Classification overlain on surficial geologic map (see Part B and Appendix A).

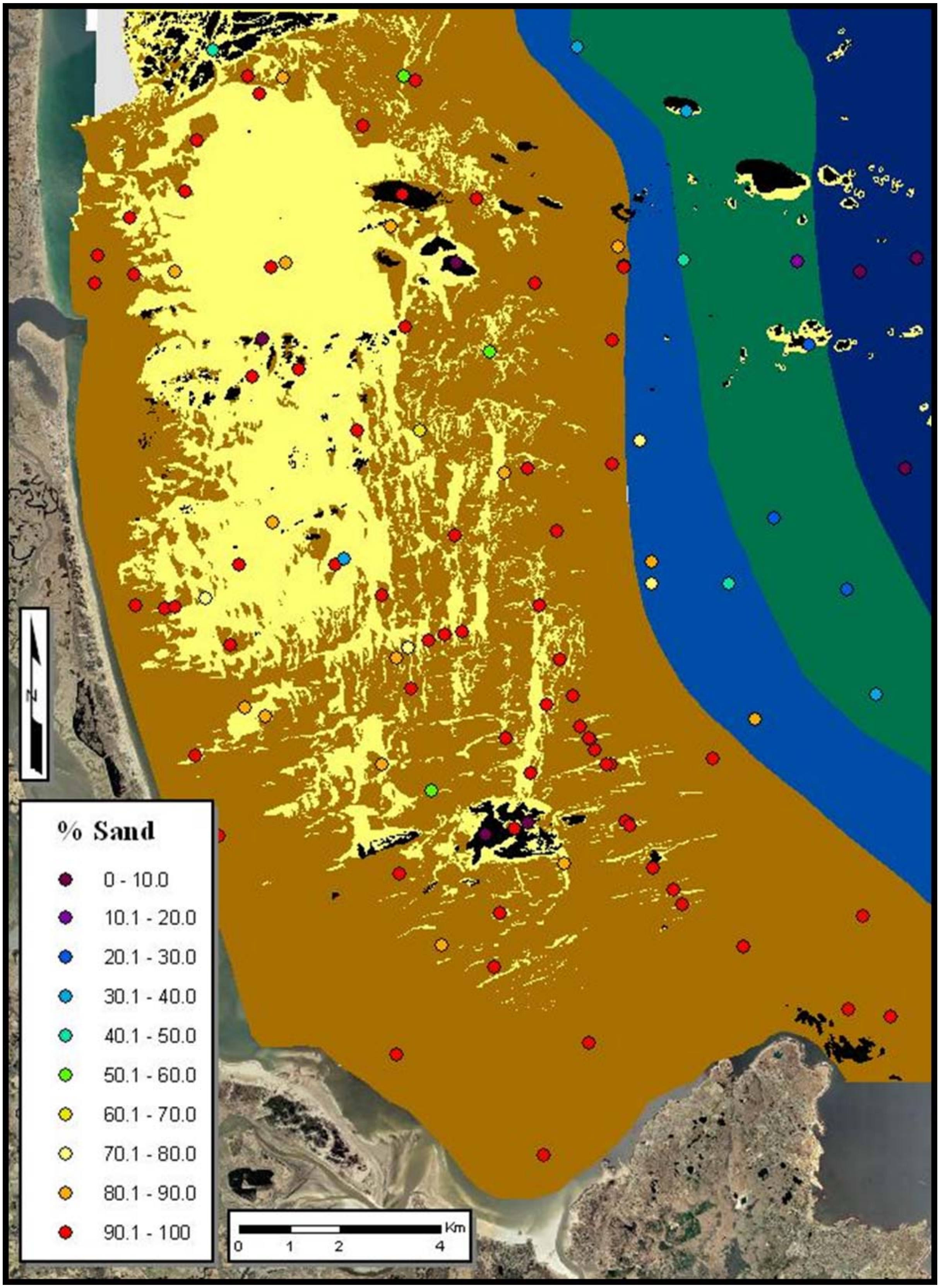


Figure 16c. Sediment bottom samples classified by percent sand (4 phi to -1 phi) in the samples Classification overlain on surficial geologic map (see Part B and Appendix A).

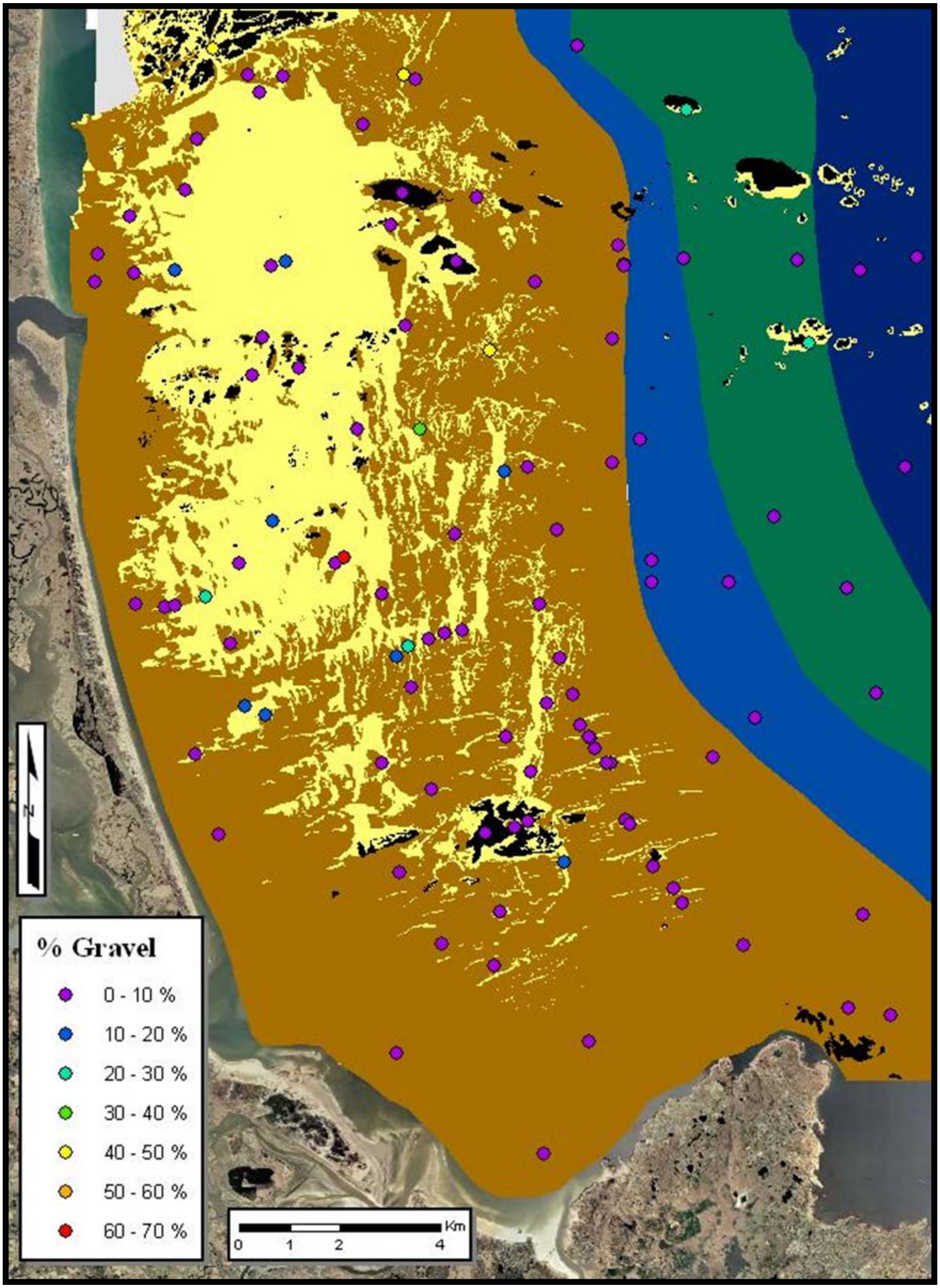


Figure 16d. Sediment bottom samples classified by percent gravel (coarser than -1 phi) in the samples Classification overlain on surficial geologic map (see Part B and Appendix A).

The inner region of the Merrimack Embayment is sand-dominated and has been subdivided into several distinct regions on the basis of morphology and grain size (Fig. 17). A continuous, flat-lying coarse sand deposit (Region A, Fig. 17) is centered off the mouth of the Merrimack River and is approximately 8 km (N-S) x 4 km (E-W). These are the coarse-grained regressive braid plain deposits described earlier in this report. Bedrock dominates the sea floor to the north. The high backscatter regions become diffuse in a south and offshore direction transitioning into a series of linear to cuspate features surrounded by low backscatter sediments. In these locations, the fine-grained sands of the Holocene mobile sand sheet discontinuously overlie coarser deposits that are nearly identical in size to the sand sheet sediments.

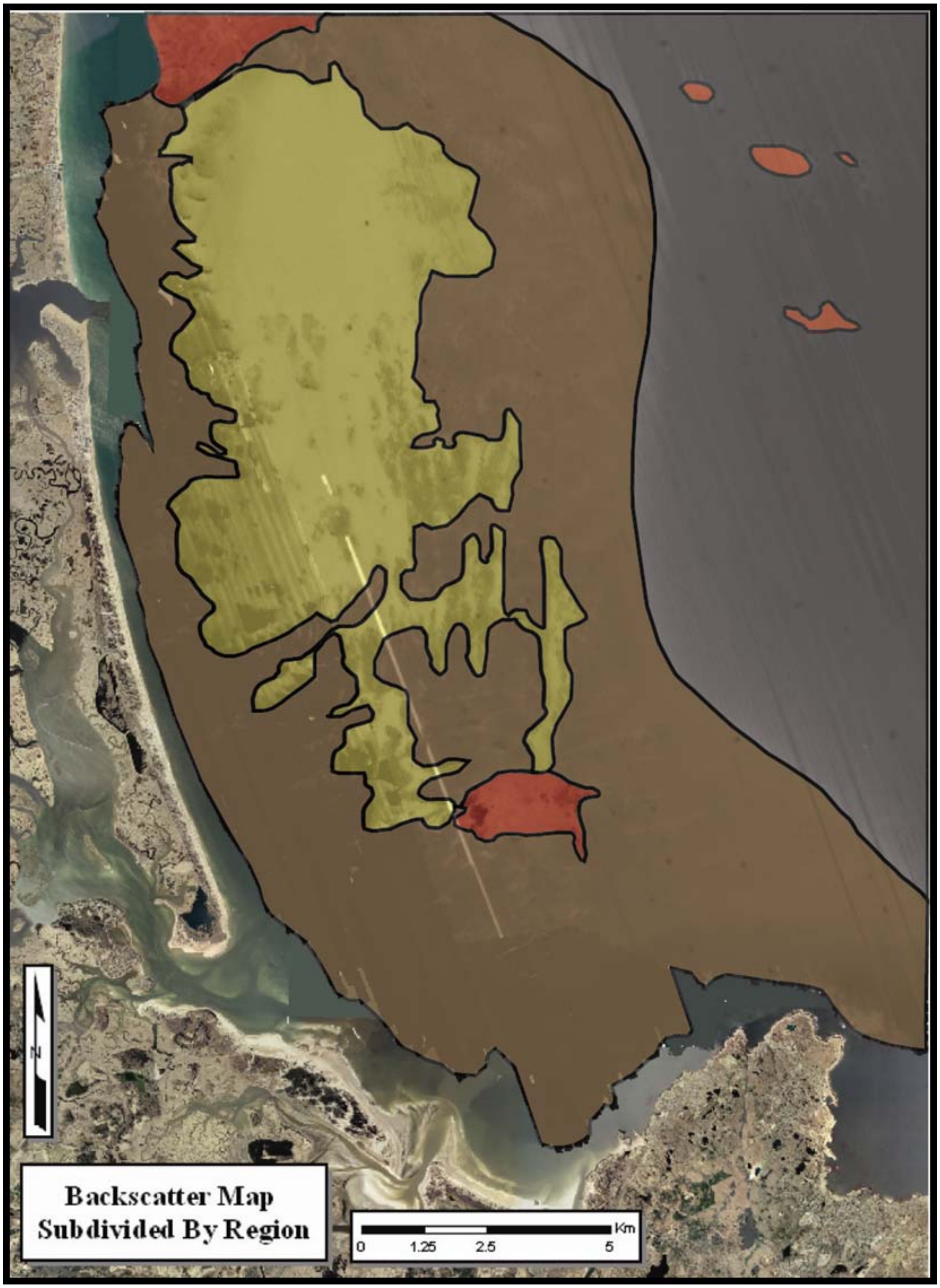


Figure 17. Backscatter map of Merrimack Embayment. Regions of the sea floor mapped based on the backscatter data. Area divided into coarse-grained sandy deposits (yellow), fine- to medium-grained sand (brown), delta front and offshore (gray) and bedrock (red). (modified from Hein et al., 2007a).

Low to medium backscatter areas (Region B, Fig. 17) contain fine- to medium-grained sand (mean φ is 2.42; mode φ is 2.34) dominated by three dimensional, cuspate ripples (small 3D dunes, Ashley, 1990) with wavelengths of about 20 cm. Contacts between these regions of coarse and fine sands are sharp, representing a rapid transition from the Pleistocene braid plain deposits to the overlying finer grained Holocene mobile sand sheet.

The lowest backscatter intensity regions (darker pixels in backscatter imagery) comprise 25% of the sea floor, mostly in water deeper than about 50 m depth and represent low reflective ocean mud offshore of the paleodelta. These sediments consist of fine-grained sands (mean φ is 3.62; mode φ is 4.00) and deeper seaward regions consist of fine-grained mud (mean φ is 5.84; mode φ is 5.71). Mud-draped boulder fields (Region C, Fig. 17) are found throughout the study area and are interpreted as either bedrock outcrops, or closer inshore, boulder lag deposits from eroded drumlins. Mud deposits represent post-transgressive deposition.

It is worthy to note here that sediment grain size characteristic determinations are based solely on surfical bottom grab samples that penetrate no more than 10 cm below the sea floor surface. These sediments represent that section that is in a state of active reworking by waves and currents and likely do not directly match sediments that underly the surface. Cores taken by Oldale and others and published in Edwards (1988) are provided in Appendix E, but are all taken within the paleodelta forsets. As seen in Edwards' (1988) published seismic lines, these cores penetrate the foreset beds of the paleodelta. The sediments contained in these foreset beds are recognized to be of poor quality to serve as borrow sites; rather the more proximal braid plain deposits and mobile Holocene sand sheet are recognized as the higher quality borrow sediments.

B. Surficial Geologic Map

Determinations of sea floor type were based on the analysis of backscatter, bathymetry, and sediment data. Classification of bottom types utilized methods outlined in Barnhardt et al. (1998) having four end member units (rock, gravel, sand, and mud) and twelve composite units that represent combinations of these four end members. Barnhardt et al (1998) mapped regions of the Gulf of Maine having each of the 12 units, although their maps often lump features of various types into a single composite unit. For example, if a small (<300 m^2) patch of coarse sand to granule sized sediment occurs within a larger unit of fine sand, the two would be grouped as Sg (sand with subordinate gravel). The scheme employed for the Merrimack Embayment modifies that outlined by Barnhardt et al (1998). The region of interest is much smaller, the data are of significantly higher resolution, and bottom samples are more numerous. Hence, higher resolution mapping could be achieved. Units as small as 20 m^2 were resolved and mapped with a high degree of confidence.

Combining data from Fig. 13-15, sediment samples were classified based on dominant sediment type (Fig. 17); categories were labeled with a capital letter indicating dominant grain size. These categories include gravelly sand (gS), sand (S), muddy gravelly sand (mgS), muddy sand (mS), sandy mud (sM), mud (M), and hard bottom (HB). For instance, a sample that is > 90% sand would be classified as "S"; a sample that is 5% gravel, 40% sand, 30% silt, and 25% clay (i.e. > 50% mud) would be classified as sandy mud (sM). Locations of sediment samples are shown on the surficial map and are labeled by sediment classification type. Appendix D provides a compilation of sediment information used in analysis and the production of Fig. 17.

Applying the methods described above, sea floor of the Merrimack Embayment was classified into six unique map units:

- **Unit R – Rock** (Black) – this unit represents all hard bottom. Due to limited camera and sampling sites, hard bottom types, both bedrock outcrops and boulder piles (possibly lag from drumlins) were mapped in unit R. The northeast corner of the study area is bedrock dominated and rock outcrops discontinuously through the rest of the study area.
- **Unit Sg – Coarse Sand / Gravel** (Yellow) – this unit encompasses all sediment samples classified as "sandy gravel", "gravelly sand", and the coarsest regions of "sand". This unit comprises the expansive medium- to coarse- grained sand sheet centered off the mouth of the Merrimack River, which becomes diffuse in a southerly and offshore direction. In these regions, the sand sheet is broken into a series of linear to cuspate coarse-grained features surrounded by fine-grained, low backscatter sediments. Relatively large, coarse-grained linear features dominate the northern sector and are oriented in a NNE-SSW direction. These forms exhibit a sharp edge with the surrounding fine-grained regions on their eastern side and a diffusive western edge, indicating possible movement in an ESE direction. Elsewhere, subordinate forms are oriented in ENE-WSW and ESE-WNW directions. Unit Sg is also found in shallow troughs around many deeper hard bottom regions where it has either been concentrated by flow disturbances resulting from the presence of the high rocky topography, or eroded out from the adjacent bedrock. The primary sand sheet is chosen as the best target for sand and gravel exploitation; this region is presented in greater detail in forthcoming isopach map of coarser deposits.
- **Unit S – Sand** (Light Brown) - sand comprises most of the shallow area of the Merrimack Embayment, out to approximately the depth of the edge of the paleodelta (~ -45m; shallower in the northern most 3 km of the study area). As determined from shallow seismic and bathymetry, this finer grained unit discontinuously overlies the coarser Sg unit to the east and south of the sand sheet. However, the thickness of this finer unit is unclear; therefore the lateral extent of unit Sg beyond the sand sheet is unknown until cores are taken in this offshore region.
- **Unit Sm – Muddy Sand** (Light Blue) **–** this unit is sand-dominated but contains silt and clay (>10%) of the sample. This unit comprises the paleodelta front. Backscatter returns from fine sand through mud are nearly undistinguishable. Therefore, units Sm, Ms, and M are mapped based on sediment samples and bathymetry only.
- **Unit Ms – Sandy Mud** (Teal) **–** this unit is mud-dominated but sediment samples contain a significant (> 10%) sand fraction. This unit is found along the foot of the paleodelta, in depths of about 65 – 80 m.

- **Unit M - Mud** (Gray) – this is the finest grained unit and generally contains >95% silt and clay. These are offshore, deeper continental shelf mud that generally only occur in depths of > 80 m.

The resulting high resolution surficial geologic map is presented in Appendix A.

C. Evidence of Modern Reworking

Bathymetric and backscatter surveys reveal complex patterns of surficial sediment reworking. Features characterized by high backscatter intensity cover approximately 40% of the sea floor in the study area. Sediments in this region are composed of coarse-grained sands to fine gravels (mean φ is 0.61; mode φ is 0.53) and are dominated by two-dimensional megaripples (small 2D dunes, Ashley, 1990) with wavelengths of about 1 m. The troughs of these megaripples are commonly filled with shell hash.

Low amplitude, long wavelength bedforms occur throughout the inner shelf (d < 50 m). Three discrete sets of bedforms are mapped according to predominant orientation in Fig. 18. In the deep portion of the inner shelf (35-50 m) long wavelength, asymmetric, north-northwest-oriented bedforms dominate. In the northern sector, these features are relatively large and are oriented in a NNE-SSW direction. Elsewhere, subordinate forms are oriented ENE-WSW and ESE-WNW. Northwest-oriented bedforms have similar spacing but generally larger heights. Inshore of these features, the bedforms become more closely spaced and exhibit a west to west-southwesterly orientation. These features generally exhibit spacings between 150 and 350 m and heights from 0.5 to 1.5 m. In several locations, bedform sets have orthogonal orientations within 1 km of each other.

Grain size analysis of seafloor samples taken within the bedform fields revealed nearly identical trends where fine-grained sands (+3 phi) comprise the stoss and crestal areas and coarser sands (1 phi) are confined to the troughs. This grain-size distribution can be explained by the common phenomenon of coarser sediment being preferentially concentrated in the troughs (Jopling, 1964); alternatively, erosion in the trough may be exposing the underlying coarser sand beneath the bedforms.

The enlarged troughs, coarse-grained nature of the sediments, and geometry of the inshore bedforms suggest that these features are similar to rippled scour depressions (RSD; Cacchione et al., 1984; Schwab et al., 2000; Green et al., 2004; Ferrini and Flood, 2005) or sorted bedforms (Murray and Thieler, 2004; Gutierrez et al., 2005; Goff et al., 2005). RSD are subtle bathymetric lows (~1 m) consisting of coarse sand, shell hash and ripples (wavelengths on the order of 1 m) surrounded by finer sands. They are commonly oriented oblique or normal to the shore and been observed in sediment-starved and microtidal settings. These features are typically 100-200 m wide and extend hundreds of thousands of meters on the inner shelf (Cacchione et al., 1984). Sorted bedforms, as observed off Wrightsville Beach, NC and described by Murray and Thieler (2004) are asymmetric with coarse sediment forming bathymetric lows on the updrift (in reference to alongshore flows) sides of the features. Additionally, sorted bedforms have sharp contacts along their updrift sides and “wispy” downdrift contacts with surrounding finer sediments.

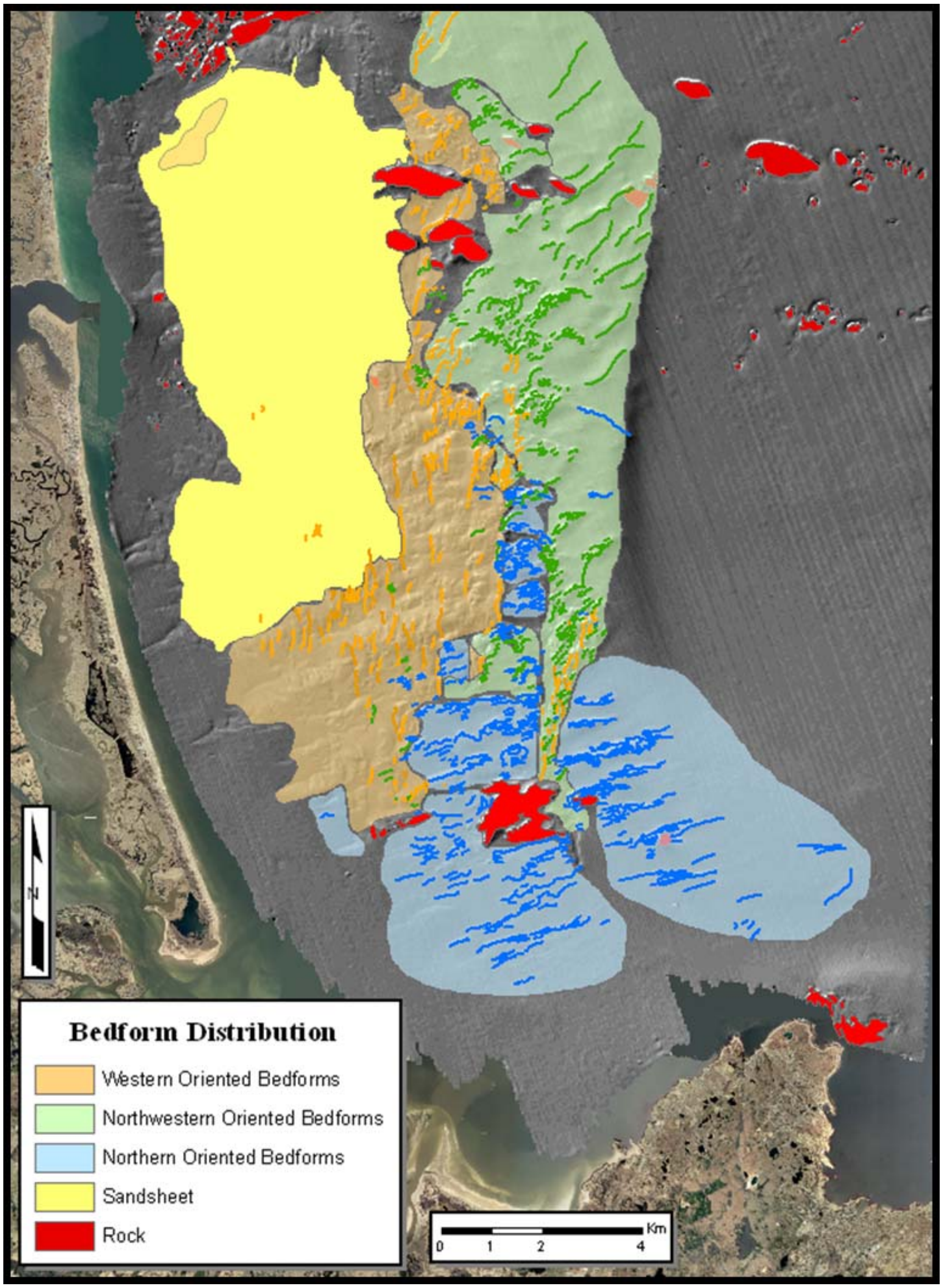


Figure 18. Map of large-scale bedform fields with crests highlighted; overlain on hillshaded bathymetry. Regions of hard bottom are denoted in red. The "sandsheet" (Pleistocene braid plain deposits) is highlighted in yellow. This region is dominated by small (~1 m) 2-D linear wave ripples and contains no large-scale bedforms. Regions highlighted in orange, green, and blue comprise the Holocene Mobile Sand Sheet. Various bedform orientations are shown by colors noted in legend.

Though the coarse-grained bedforms of the Merrimack Embayment are of similar shape and size to RSD, this is a tide-dominated environment with a sizeable sediment supply. These features generally have sharp boundaries around all sides, similar to RSD but dissimilar to sorted bedforms. However, they do contain the 2D ripples common to sorted bedforms. One important difference is that the coarse-grained features of the Merrimack Embayment lack the shore-normal elongated geometry that characterize documented RSD and sorted bedforms.

Cacchione et al. (1984) suggest that RSD are produced by intensified cross-shore flow resulting from storm-induced set-up. These flows preferentially winnow fine material leaving a coarse lag elongated parallel to flow. Schwab et al. (2000) argued that along-shelf processes are responsible; yet both explanations suggest concentrated bottom flows along the primary axis of the features. Murray and Thieler (2004) suggest that sorted bedforms are self-organized; that is they result from the interaction of wave motions with coarse-grained ripples within smaller sorted forms. The turbulence of these interactions is such that finer material remains entrained in the flow while coarser sediments are deposited within the bedforms. This positive feedback perpetuates the formation of the sorted bedforms.

Several processes are probably responsible for the complex patterns of surficial sediment and bedforms seen in the Merrimack Embayment, including storm-generated currents, instantaneous accelerations caused by storm wave orbitals, and return flows associated with large storm surges. The pronounced asymmetry and varied orientation of the features within the Merrimack Embayment indicate that they are long wavelength sandwaves, possibly formed from the same turbulent boundary layer processes proposed for sorted bedforms (Murray and Thieler, 2004). Bedforms occur in fields having a similar height and wavelength, thus suggesting that more than one process or factor controls their geometry and orientation.

Bottom current data from the Gulf of Maine Ocean Observing System (GoMOOS, 2006) Buoy B (Station 44030, Buoy B0102) on the western Maine shelf (approximately 50 km north of the mouth of the Merrimack River) indicate that bottom currents in 60 m of water reach speeds of 20-30 cm/sec during spring tide conditions and even greater magnitude during storms. Intense extratropical cyclones (northeast storms) regularly affect the coast of Massachusetts (FitzGerald et al., 1994); analysis of the GoMOOS buoy data suggests that waves produced by these storms generate bottom shear stresses strong enough to move the sediment that blankets the sand sheet to a depth of at least 50 m (Komar and Wang, 1984). Hydrodynamic data from the instrument deployment (see Results Section D) confirm that during large northeast storms, sediment is suspended by waves and reworked by currents in at least 20 m of water.

Patterns of reworking may also be influenced by the underlying geology and existence of the pronounced Cape Ann promontory (southern border of the Merrimack Embayment). Numerous studies have shown that storm surges can induce coastal set up capable of inducing downwelling and creating horizontal pressure fields strong enough to stimulate near-bottom currents and drive offshore sediment transport (Harper et al., 1988; Gourlay, 1990; Hequette et al., 2001; Hequette and Hill, 1993). Large northeast storm surges in the Gulf of Maine, coupled with the Cape Ann promontory may be significant enough to create a similar system in this region.

Preliminary analysis of shallow seismic reflection data suggests that braided stream deposits and underlying bedrock are spatially discontinuous in the subsurface. Relict topography and sediment distributions related to reworking during the Holocene transgression may also contribute to the patterns of surficial sediment distributions. Analysis of the shallow seismic reflection data is currently underway to investigate the effects of bedrock and paleodelta sequence deposits on bedform field development.

D. Analysis of Instrument Deployment Data

To develop a more complete analysis of the sediment transport regime that has sorted sediments and produced the sea floor features described above, an instrument package was deployed in the nearshore zone of the Merrimack Embayment. This targeted deployment was used to measure bottom currents and sediment suspension during storm conditions. The instruments were deployed during a 10 week period of the most recent winter/spring storm season (February – May) at the border between Unit "S" and Unit "Sg" (Appendix A). The instrument package measured currents, temperature, pressure, and suspended sediment content.

The instrument tripod successfully collected a variety of wave and current data, some of which is presented in Fig. 19 (waves) and Fig. 20 (pressure & currents). Overall, during calm conditions, mean wave periods averaged between 4 and 5 seconds. Significant wave heights averaged approximately 1.0 m during calm conditions; during these periods significant waves generally originated from the ESE (100^o – 110^o). Occasional small, likely locally wind-generated, waves arrive from various other directions including the west. Currents in the 1.4 m closest to the bed were averaged for this analysis. During calm periods currents ranged from 0-5 cm/sec and moved in various directions, likely related primary to the tidal signal. A time series of pressure data (Fig. 20) clearly shows several complex sets of spring and neap tidal cycles during the period of the deployment.

During the period of this deployment, the Merrimack Embayment experienced several northeast storms (there were three instances of wave heights exceeding 2.0 m in 20 m water depth). Higher period and larger significant wave heights correspond to these events. During these times, peak wave heights reached nearly 2.6 m and correspond to wave periods of 8-9 seconds. Additionally, during these peak wave conditions, waves generally arrived from the ENE, driving sediment in the surf and swash zones alongshore to the south (see Fig. 23).

During these storm conditions, currents in the bottom 1.4 m of the water column experienced peaks in flow conditions. During the two largest events, sustained peak flow velocities exceeded 20 cm/sec, the empirical minimum current velocity necessary to transport medium sand-sized (1.0 phi) sediment (Komar, 1976). Current data presented here represent depth-averaged velocities for the bottom 1.4 m; if a standard exponential curve is assumed, then sustained current velocities at the bed are expected to be smaller than those presented in Fig. 20. However, the waves themselves act to suspend the sediment and the storm and tide driven currents would transport them in various directions. Hence, it can be assumed that sediment transport rates are significantly higher than could be interpreted from the current data alone.

Wave data from this deployment was used to calibrate the SWAN (Simulated WAves Nearshore) models to expected quiet water and storm conditions (see Discussion).

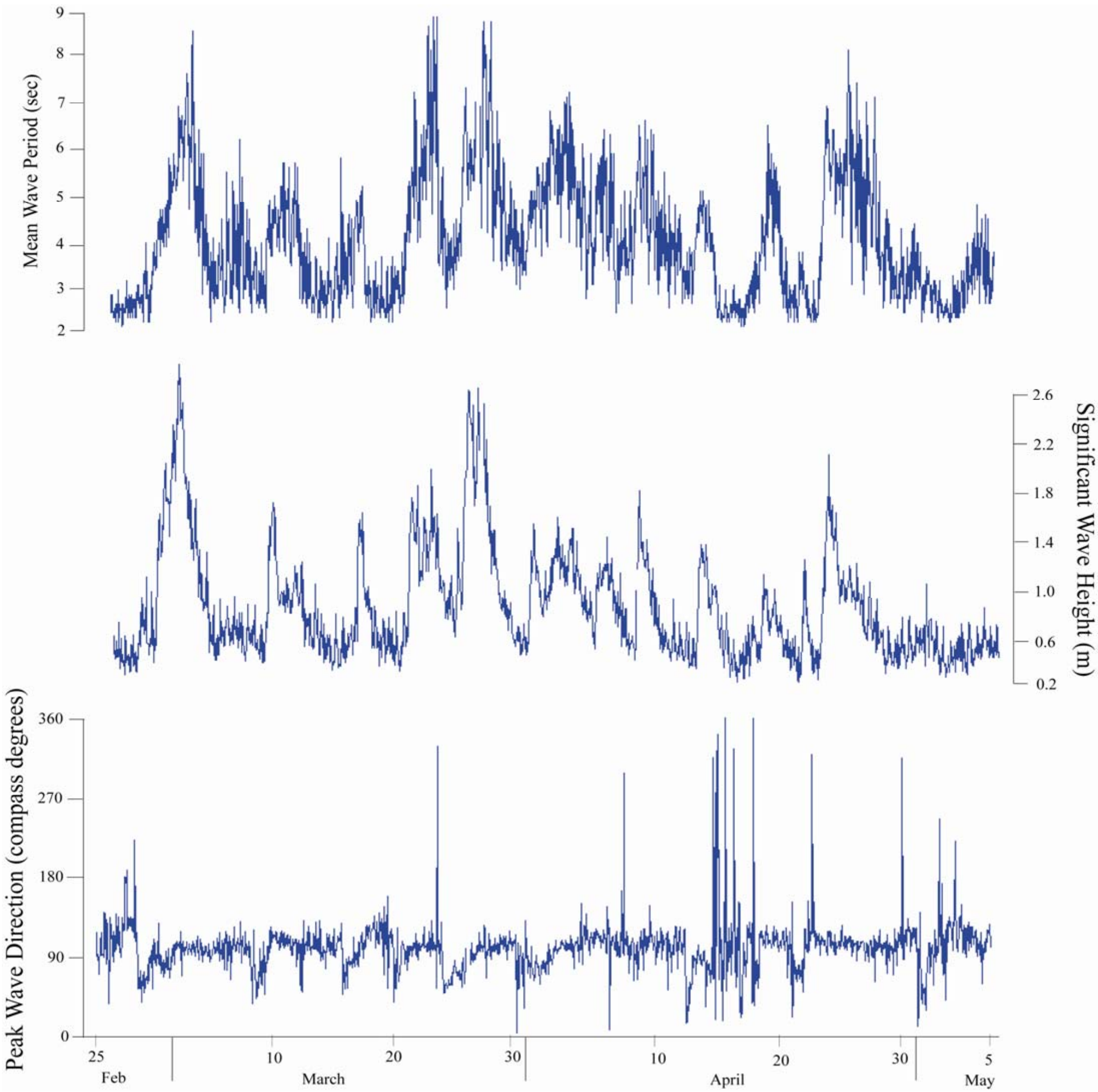


Figure 19. Time series plots of wave data from RDI Acoustic Doppler Current Profiler. Higher period and larger significant wave heights correspond to northeast storms (times when peak wave direction is closest to 45^{o}). Overall, mean wave periods average between 4 and 5 seconds, reaching nearly 9 seconds during occasional (4 events) northeast storms. For the study period, significant wave heights ranged between 0.3 m during calm conditions and 2.6 m during rare storm events, averaging <1.0 m. The direction from which significant waves originated was generally from the ESE (100^{o} – 110^{o}). However, during peak wave conditions, waves arrive from the ENE, driving sediment to the south. Occasional small, likely locally wind-generated, waves arrive from various other directions including the west.

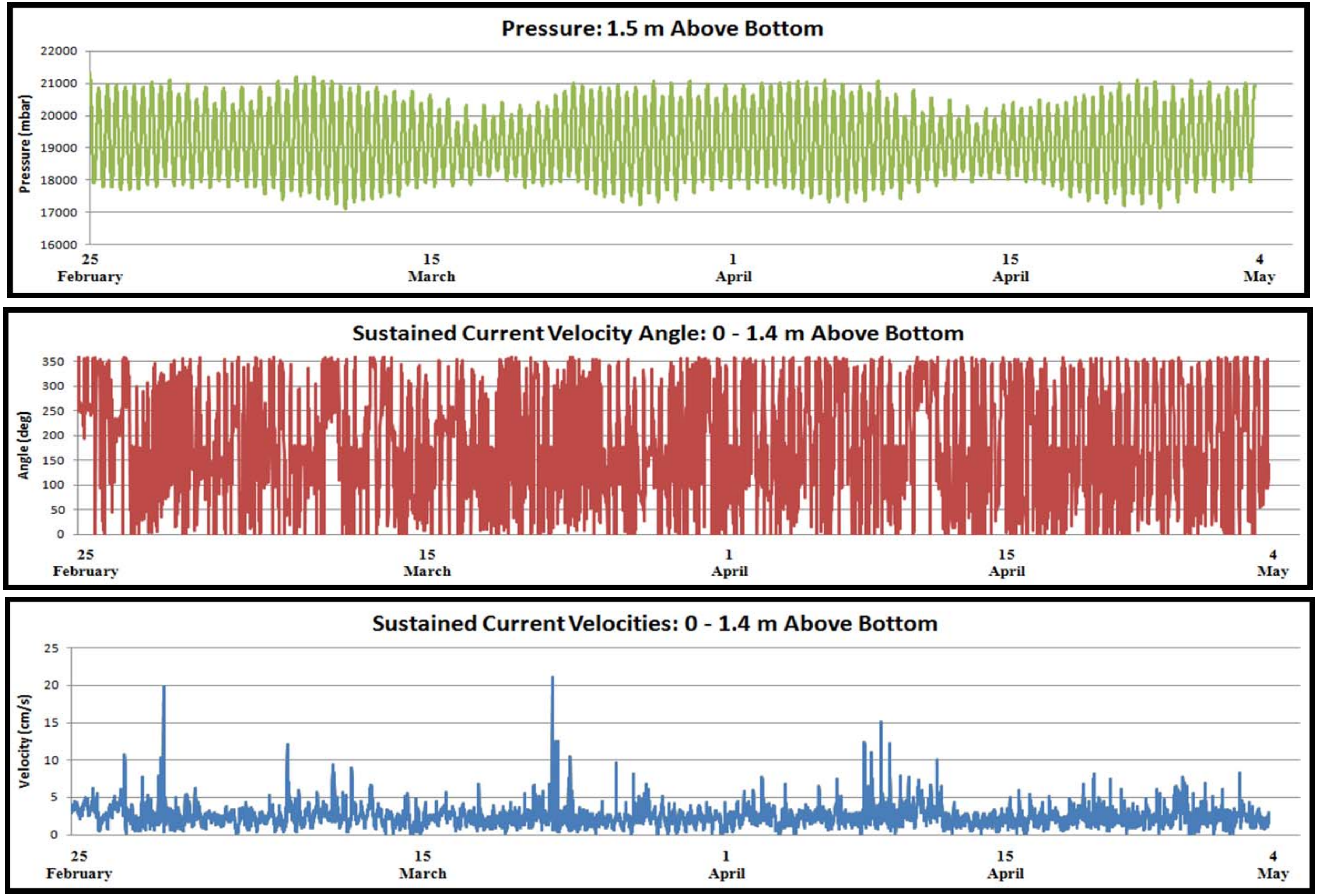


Figure 20. Time series plots from instrument deployment: A) Pressure at 1.5 m above the bottom; B) Sustained current direction (averaged current direction over 15 second intervals); C) Sustained current velocity (averaged current direction over 15 second intervals)

E. Shallow Seismic Analysis

As described in the Methods section above, 1050 km of shallow seismic track lines were collected in the Merrimack Embayment using an Edgetech SB-512 CHIRP sub-bottom profiler. These profiles include both shore-parallel (strike) and shore-normal (dip) sections. Major facies identified in these sections were first published in Hein et al., 2007b (Fig. 21). These facies include the following:

- Bedrock
- Till
- Glaciomarine clay
- Basal Unconformity
- Regressive coarse sands and fine gravel (Braid Plain Sediments)
- Estuarine, channel cut and fill, and fluvial deposits
- Ravinement surface (transgression)
- Holocene sands (sourced from Merrimack River and reworked from deltaic deposits).

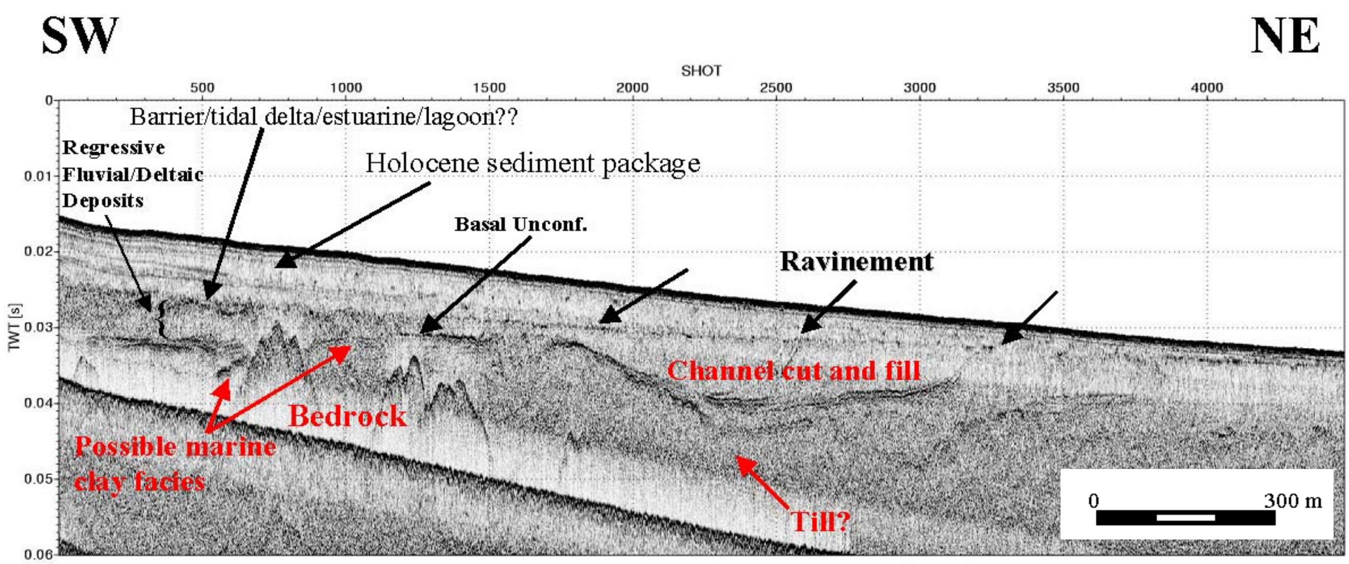


Figure 21. Sample shallow seismic line from the southern Merrimack Embayment. Line trends SW to NE and contains major geologic units described above and used in creation of strike and drip sections (Appendix B). Location of line given in Fig. 8.

Full length strike and dip straigraphic sections are provided in Appendix B.

The SeisWorks (Landmark Graphics Inc) software package was used to map sequence thicknesses throughout the study area. These raw isopachs are presented in Barnhardt et al. (2009). Coverage was limited to regions mapped by shallow seismic (nearshore area only). From these, full coverage isopach maps for the two features of interest, the Plesitocene Braid Plain deposits and the Holocene Sand Sheet, as described in the Discussion) were estimated and are presented in Appendix C.

In addition to the identification and location of major geological facies boundaries (Fig. 21) and the formulation of isopach maps (Appendix C), intense study was focused on channel cut and fill features that were imaged in the shallow seismic records (Fig. 22, Hein et al., 2007b). These E-W trending cut and fill structures were discovered in the shore parallel shallow seismic profile. They are commonly several meters in thickness and vary in width from about 25 to several hundred meters. Several large sets of cut-and-fill features range from 500 to 600 m wide and 10 to 15 m deep. Shore normal seismic lines confirm the nearly shore normal orientation of these features. In some locations, the orientation and geometry of these features closely resembles that of underlying bedrock surfaces. Several of the cut-and-fill features exhibit structures interpreted as the result of river terracing; i.e. sets of parallel horizontal reflectors on either side of a deeper incised channel. Within any given region, the spatial distribution of cut-and-fill features varies from a highly organized network to a random distribution. However, several examples exist of a single structure retaining an identical geometry across numerous parallel profiles representing hundreds of meters in a shore normal direction.

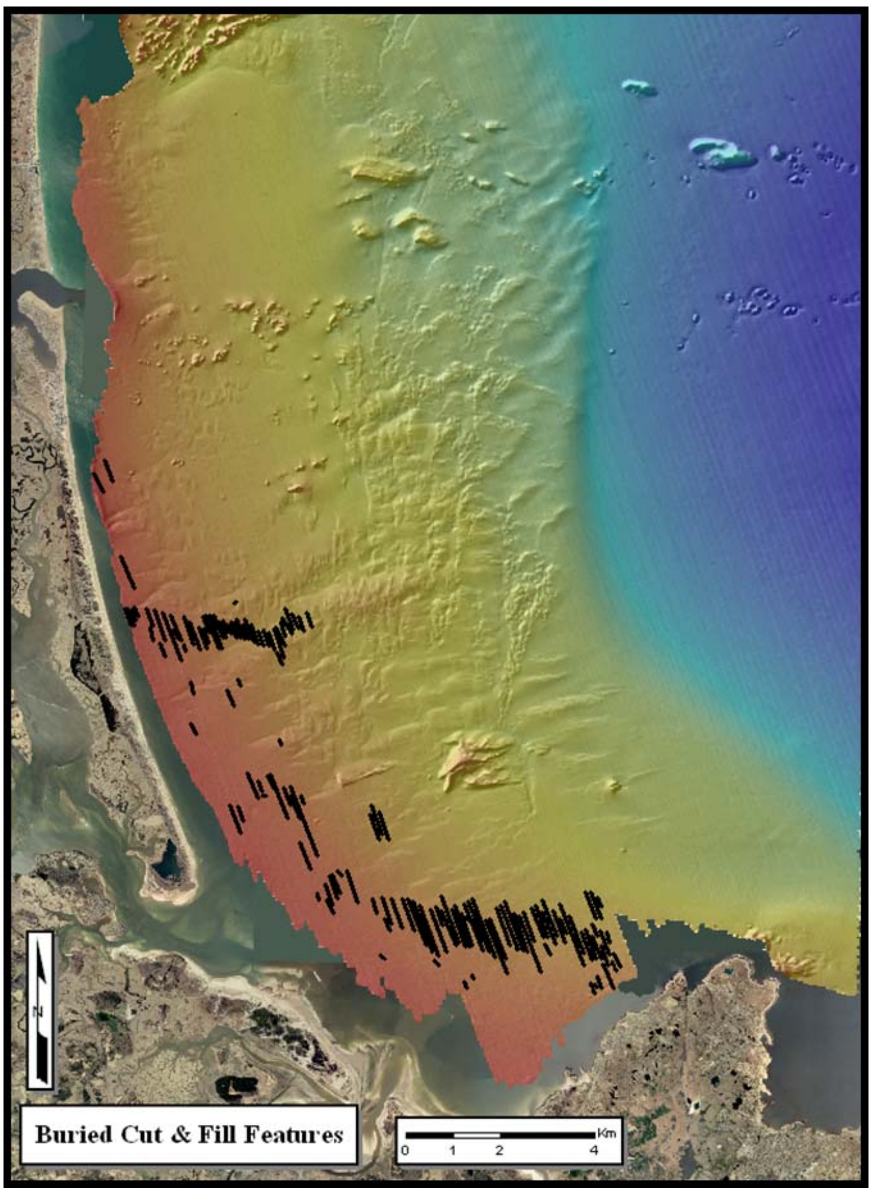


Figure 22. Map of locations where channel cut / fill features were located in shallow seismic records in the Merrimack Embayment. Black lines represent approximate widths of cut / fill features in each shallow seismic record. These features are interpreted as paleo-inlet channels that have removed the overlying braid plain deposits and eroded into the top of the glaciomarine surface. (Hein et al., 2007b)

The channel cut-and-fill structures observed in seismic profiles suggest that the delivery system conveying sediment to the delta consisted of a braided stream complex. Moreover, the size and morphology of the paleo-delta suggest that the delta was deposited in a series of lobes indicating significant river migration and/or avulsion. Present-day topographic evidence supports this conclusion.

Edwards (1988) postulated that distributary drainage through the paleo-Merrimack occurred at or near the present-day mouth of the Merrimack River. Sediment would have been deposited along northern end of paleo-delta and then reworked to the south to form the southern lobe. However, evidence from this study indicates that paleo-drainage of the Merrimack River was indeed to the south through various avulsion channels. Few cut-and-fill features are seen near the present-day mouth of Merrimack River; however thick (>20 m) layering of sediment overlying bedrock indicates a large input of sediment from the present-day Merrimack River.

These buried channel cut and fill structures often contain relatively clean, well sorted sands that are appropriate as borrow sites. However, due to their small and discontinuous extent, they are not considered as part of the Pleistocene braid plain deposits (see Discussion).

F. Litho- and Microbiofacies Maps Defining Sedimentary Environments

The research team from the University of Massachusetts consists of Dr. Steve Nathan (post-doc) and Professor Mark Leckie. They used benthic foraminifers (testate marine protists) as biotic and environmental proxies in the study of sand and gravel deposits of the Merrimack Embayment. Benthic foraminiferal biofacies analysis, coupled with geophysics and lithofacies analysis, can be used to delimit modern depositional environments from grab samples or box cores. Our specific goals of this phase of the study were to: 1) develop a model of foraminiferal distribution patterns to assess depositional environments and establish a modern base-line; and 2) test the applicability of foraminifera as a biotic monitor for seafloor pollution and post-disturbance ecosystem recovery. In addition, they compared the 2005 foraminiferal distribution patterns with a similar study from the late 1940s (Phleger and Parker, 1952).

Unlike benthic macrofossil communities, foraminiferal community structure can be determined with a small sample size due to their sedentary nature, abundance, and tiny size (i.e., and they do not display the patchy distribution characteristic of many benthic invertebrate animals). Foraminiferal populations can be used to monitor biotic recovery on the seabed following disturbance from sand mining operations. These microfossils are also proxies of environmental impact, including test deformities and anomalous changes to population structure.

A full report on this topic was submitted to the Minerals Management Service in December, 2007 by Stephen A. Nathan, R. Mark Leckie, and Stephen B. Mabee; this document was entitled "*A Microfossil Evaluation of Sediment Deposits on the Continental Shelf, Merrimack Embayment, New England*".

VI. DISCUSSION

A. Overview

The beaches, barriers, and estuaries of this region are dynamic and responding to the impacts of rising sea level, increased storm frequency, and pressures of public and private development. The region has seen a significant growth in summer and year-round visitors during the past decade leading to a greater need for public facilities and healthy beaches. Coincident with increasing use of the coast has been a pervasive trend of erosion along most of the Merrimack Embayment coast; beaches are shrinking in size and the retreating shoreline is endangering public and private real estate and infrastructure. Several communities along this section of coast have already implemented beach nourishment projects, and it is likely this need for sand will increase due to widespread beach erosional conditions and public interest in maintaining recreational beaches.

Sources of sand for nourishing beaches along this section of coast have typically come from inland glacial outwash deposits in southern New Hampshire and Maine, but these sediments often contain fractions of silt and clay as well as quantities of fine gravel. This type of glacial sediment was used to nourish Revere Beach located north of Boston. Initially, the community complained about the dust storms produced by wind-blown silt and clay sourced from the beach and also the angular gravel that hurt their feet. These shortcomings were eventually rectified as winter storms reworked the beach sediments burying the gravel and transporting the fines offshore. Still, marine and estuarine mouth sand is preferred for nourishing beaches because the sand is usually texturally mature (well-sorted, quartz-rich, rounded grains) due to the currents and waves action have reworked the sediment. Beachgoers prefer white sandy, quartz-rich beaches.

Sediment dredged from the entrance channel to the Merrimack River is presently being placed several hundred meters offshore along the northern end of Plum Island. This sediment consists of coarse to medium-coarse sand and is an appropriate grain size for this section of the island. However, the dredged sand from Merrimack Inlet is insufficient in volume for the needs of this region and it is too coarse-grained to be compatible with the beach sand along much of this barrier chain. Thus, the sand comprising the offshore sand sheets may become a viable option for beach nourishment projects.

The region immediately offshore of the Merrimack Embayment contains extensive sand reservoirs in the form of a Holocene sand sheet situated in the southern portion of the embayment and a Pleistocene sand sheet located off the mouth of the Merrimack River (Region C in Fig. 16; bottom type Sg in Surficial Geologic Map, Appendix A). These sand resources have different thicknesses and geographic extents, as well as wide ranges in grain size. This variability may actually be may be a positive issue, because the beaches in this region extend along a 30 km stretch of coast and have different grain size requirements for compatibility (Fig. 23). The attributes of these potential sand supplies are discussed below and summarized in Tables 2 and 3.

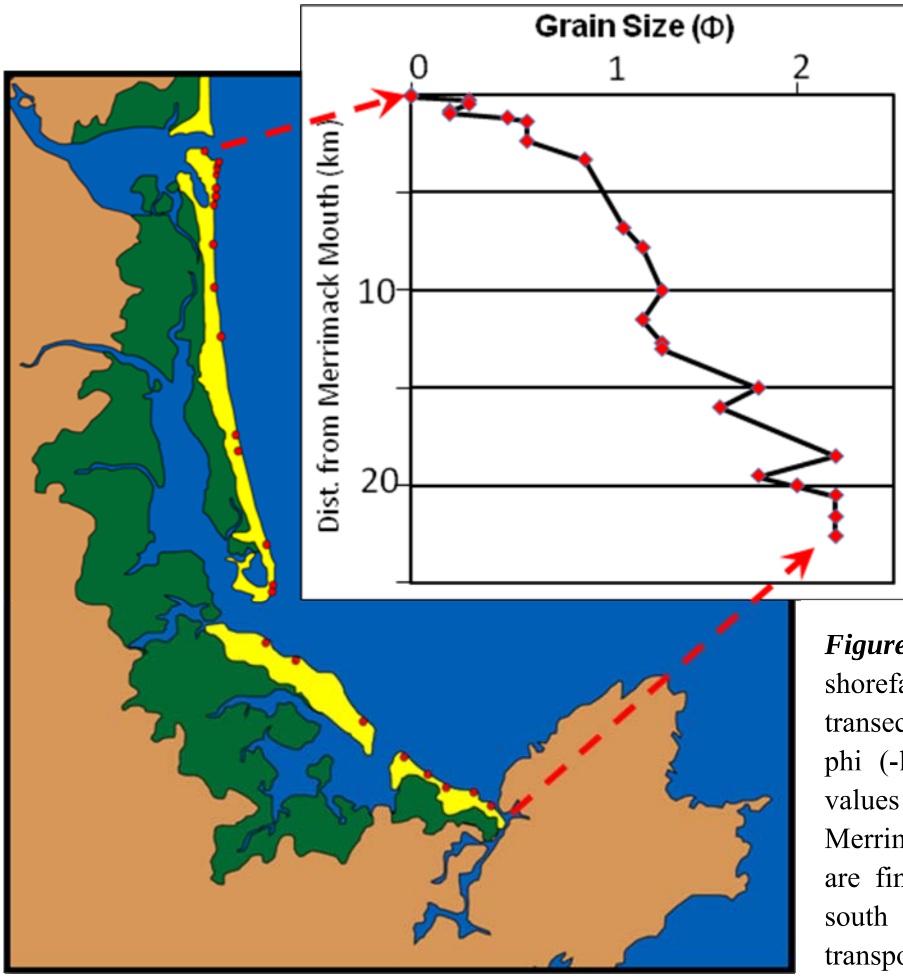


Figure 23. Grain size trends of beach shoreface samples collected along a N-S transect in Merrimack Embayment. X-axis in phi ($-\log_2$[grain size in mm]) where higher values are finer. Sediment proximal to the Merrimack River are coarsest; distal sediments are finest. The gradually fining trend to the south results from southerly longshore transport driven by winter northeast storms.

Deposit	Location	Dimensions			Estimated Volume
		Length	Width	Thickness	
Pleistocene Braid Plain	Between paleodelta foresets and nearshore estuarine unit (0.5 - 8 km offshore); dominant offshore of modern Merrimack	16 km	8 - 10 km	4 - 15 m	1.4 x 10^9 m^3
Holocene Mobile Sand Sheet	Overlying delta foresets & braid plain; thicker to south (Ipswich Bay)	9.4 x 10^7 m^2		0.5 m - 9 m	1.21 x 10^8 m^3 (Barnhardt et al., 2009 in nearshore area where sufficient sub-bottom data exist)
Paleodelta	7 - 6 km offshore; as mapped by Oldale et al., 1983	20 km	4 - 7 km	Up to 20 m	1.3 x 10^9 m^3 (Oldale et al., 1983)
Delta Front	On delta front slope	Intermediate zone between sand sheet and offshore			
Offshore	Marine unit; depths greater than 50 m	Extensive and continuous to upwards of 300 m depth (Kelley et al., 1989)			
Rocky Zone	Surrounding rocky outcrops and boulder lag deposits	Patchy and discontinuous			

Table 2**:** Dimensions and volumes of major subaqueous sediment deposits in the Merrimack Embayment. The Pleistocene Braid Plain and the Holocene Sand Sheet are identified as potential borrow sites and are discussed in detail in the text.

Deposit	Median Grain Size (phi)	Mean Grain Size (phi)	Mean Sorting	Mean Composition			
				Percent Gravel	Percent Sand	Percent Silt	Percent Clay
Pleistocene Braid Plain	0.1	0.2	Moderate to Poor	14.9	84.0	0.8	0.3
Holocene Mobile Sand Sheet	2.4	2.5	Moderate to Poor	0.4	95.6	2.9	1.0
Paleodelta	Silty fine sands; buried and not cored for this study						
Delta Front	3.6	4.2	Poor	0.0	73.7	18.2	8.1
Offshore	6.5	6.5	Poor	0.0	17.4	53.6	29.0
Rocky Zone	1.6	1.8	Very Poor	10.7	72.9	10.6	5.8

Table 3**:** Characteristics of major subaqueous sediment deposits in the Merrimack Embayment. The Pleistocene Braid Plain and the Holocene Sand Sheet are identified as potential borrow sites and are discussed in detail in the text.

B. Pleistocene Braid Plain Deposits

There exists a broad coarse-grained sand deposit offshore of the Merrimack River (0.5 to 8 km) extending from the southern end of Salisbury Beach to southern Plum Island in 15 to 40 m of water (Region C in Fig. 16; bottom type Sg in Surficial Geologic Map, Appendix A). The deposit is 8 to 10 km in width (perpendicular to the shore), 16 km long, and 4 to 15 m in thickness having an estimated total volume of 1.4 x 10^9 m^3 (Table 2, Appendix C). The composition and stratigraphy of the deposit are determined from shallow seismic records collected by the USGS (Oldale et al. 1983; Barnhardt et al. 2009). The sand sheet is interpreted to be an offlap sequence that was deposited as sea level fell during the late Pleistocene regression. It extends offshore of the Merrimack River and thickens seaward as it transitions into the Merrimack lowstand delta identified by Oldale et al. (1983). Shore parallel seismic reflection transects show cut and fill structures that are 50 to 200 m wide and 1 to 7 m deep that have been interpreted as former channels of a braid plain or alternatively, tidal inlet channels associated with a former transgressive barrier island system (Fig. 22). Shore perpendicular shallow seismic transects show a mostly transparent unit exhibiting little structure lying above a glacial-marine clay (Oldale et al. 1983; Barnhardt et al. 2009).

Sediment delivery to the coast during the late Pleistocene by the paleo-Merrimack River was much greater following deglaciation than it is today, primarily due to less vegetative cover, the availability of glacial sediment proximate to the river and its tributaries, and increased roughness of the landscape. The fact that 1.3 x 10^9 m^3 of sediment was deposited in the lowstand delta (Oldale et al. 1983) in a 0.5 to 1.0 ka time span is evidence of the wealth of sediment delivered by the Merrimack River during the post-glaciation period. It is expected during the regression leading to the lowstand, that the Merrimack River would have an equal or higher rate of sediment discharge. During this time sea level dropped from a position along the present coast to the lowstand delta shoreline at a rate of approximately 4.2 m per 100 years. A drop of 45 m in sea level would have slightly reduced the fetch across the Gulf of Maine; however, prevailing wind and storm conditions and the resulting wave energy and longshore sand transport trends would have been similar to the present regime. Sediment would have been deposited at the mouth of river into a regressing sea and would have been dispersed along shore by wave energy. This sediment dispersal pattern coupled with a forced regression, would have produced a seaward building braid plain having one or more distributaries and intervening beach ridges. Bedrock outcrops protruding above the present day seafloor indicate that the geologic framework may have exerted a strong control on shoreline progradation and braid plain delta formation. Pervasive bedrock outcrops immediately seaward of the Merrimack River mouth suggest that the course of the river was tightly controlled during the regression (Edwards, 1988) and that incision of the plain by falling sea level may have been confined to a single valley that was subsequently filled during the transgression. However, to date there is little morphologic or geophysical evidence of a major paleo-valley.

During the deposition of these braid plain deposits, sediments continued to be reworked alongshore. It is estimated that the braid plain was deposited over a period of approximately 4000 years. Assuming a longshore sediment transport rate comparable to the modern rate (150,000 m^3/yr; Abele, 1977), the volume of the Pleistocene Braid Plain deposits (14 x 10^8 m^3) can be roughly (order of magnitude) accounted for by longshore sediment transport (6 x 10^8 m^3) and in situ deposition.

An onshore equivalent of what we term here as the “Merrimack braid plain delta” (MBPD) is found in southern Maine. The Sanford-Kennebunk sand plain delta has been studied extensively using ground-penetrating radar (GPR) and a network of deep and shallow sediment cores (Tary et al. 2001). This delta has a surface area of 125 km^2, a thickness of 5 to 14 m, and a volume of 1.5 x 10^9 m^3 (Tary et al. 2001), which is almost identical in aerial extent (112 km^2), thickness (10 to 15 m), and volume (1.4 x 10^9 m^3) to the MBPD. Throughout the Sanford-Kennebunk braid plain delta, GPR transects exhibit seaward dipping beds ranging from 4 to 15 degrees, which are interpreted as delta foresets (Tary et al. 2001). These sigmoidally-shaped reflectors correspond to the seaward sloping beach and nearshore facies that repeatedly formed as the sea level fell and the shore prograded. Unfortunately, the shallow seismic reflection profiles along the MBPD do not capture the fine scale reflectors that are exhibited in GPR transects. It should be noted that the two deltas formed during similar rapidly falling sea levels.

As the isostatically-forced falling sea level approach a minimum at -45 m, MBPD facies transitioned into the lowstand delta facies. In contrast to the braidplain delta, the seaward prograding lowstand delta foresets are well imaged in seismic reflection transects (Oldale et al. 1983; Barnhardt et al. 2009). Well developed foresets are recorded in all transects traversing the paleo-delta. It should also be noted that the lower portion of the MBPD thickens slightly seaward due to an increase in accommodation space.

Geophysical data (Oldale et al. 1983; Edwards, 1988; Barnhardt et al. 2009) demonstrate that the MBPD is largely exposed at the seabed, meaning that the ravinement surface (transgressive unconformity) coincides with the present ocean floor. Unfortunately, there are no sediment cores through the MBPD and the degree to which the top of the delta has been truncated by the transgression is unknown. Regardless, it can be reasoned that during the erosional trangression surf zone processes would have reworked the surface of the braidplain delta and winnowed the finer grained component of the delta sediments. Numerous grab samples collected in this region contain coarse to medium sand having an average gravel (granules to pebbles) content of 15%. The sediment underlying the surface sand and gravel is expected to have a slightly finer mean grain size because this sediment has not been reworked. The sand removed from the braidplain delta would have been transported southward along the shore by the dominant southerly transport system.

C. Holocene Mobile Sand Sheet

The second major sand sheet in the study area is located primarily south of the MBPD, but sporadically overlies the braidplain delta to the south and east. The sand sheet is approximately 9.4 km^2 in extent ranging in thickness from 0.5 to 9.0 m and a volume of 1.21×10^8 m^3 (Barnhardt et al., 2009; Table 2; Appendix C). It consists almost entirely of fine to medium sand (95.6%) with minor quantities of silt (2.9%) and almost no gravel (0.4%) (Table 3). The sand sheet contains an order of magnitude less sand than the MBPD, but it is a cleaner sand and may be more suitable for beach nourishment in the southern portion of the embayment where the beaches are finer-grained. The characterization of the sand sheet is based completely on geophysical data and surface grab samples.

The sand sheet is primarily a product of the marine transgression and reworking of the braidplain delta. In addition to sand derived through winnowing of the updrift braidplain delta, sediment forming the sand sheet may have come from erosion of the lowstand delta and/or directly from discharge by the Merrimack River. Edwards (1988) has suggested that truncation of the paleo-delta foresets is evidence that the top two meters of delta was removed during the transgression and that this sand may have been transported onshore with the landward migrating shoreface. The seaward excursion of bathymetric contours and thickening of sand sheet to the south (Barnhardt et al. 2009) demonstrate the dominance of the northeast storm regime and ensuing southerly longshore transport system in controlling the geometry of this sand lithosome. The variability in sand thickness is partly a product of the original accommodation space (irregular bathymetry), but also sand being piled against the Cape Ann headland. It is fortuitous that the fine-grained beaches that may need sand nourishment are directly onshore of this fine-grained sands resource.

The mobility of the sand sheet is indicated by the presence of active bedforms (Hein et al. 2007a) and hydrodynamic measurements taken in the winter of 2009. The instrument deployment covered the passage of two northeast storms, which recorded bottom currents well in excess of critical shear velocities needed to move medium sand. It should be noted that the storms that occurred during the March-April 2009 study period were not large magnitude northeasters. Moreover, on a yearly basis the region will experience 15 to 20 storms and they last for 12 to 36 hours. Thus, our data indicate that the MBDP and existing sand sheet will continue to be reworked by storm processes.

D. Impact of Sediment Removal from Borrow Site

Calibrated with data from the instrument deployment, a SWAN (Simulating Waves Nearshore) model was used to determine the effect of removing (via mining operations) sediment from the sea floor of the Merrimack Embayment. SWAN is a third-generation wave model that computes random, short-crested wind-generated waves in coastal regions and inland waters. In its most general form, it calculates wave directions, wave heights, and wave periods. SWAN includes parameters for both shallow and deep water and includes the effects of wind, bathymetry, current and depth induced refractions, wave propagation, bottom friction, three- and four-wave interactions, white-capping, depth-induced breaking, wave-induced set-up, and obstacle-induced diffraction (Booij et al., 1999).

The Pleistocene braid plain sand sheet (region identified in Surficial Map as “Sg”) was identified as a likely target for sediment (sand and gravel) extraction. SWAN model runs were initiated to represent the removal of various quantities of sediment from the borrow site (Fig. 24). Wave characteristics and bottom influence during mean present day storm conditions (as estimated from the instrument deployment data) were compared to those after the extraction of 5 m (Fig. 25) and 2 m (Fig. 26) of sediment from the borrow site. Differences in wave height (Hs, measured in meters), wave energy (E, measured in joules per meter) and approach angle (degrees) pre- and post- extraction were calculated (Fig. 25 & Fig. 26).

Figure 24. Simplified map of Merrimack Embayment used in model runs. Red represents land, yellow the coarse-grained sand sheet (sediment removed for model runs), and white is regions of unaltered bathymetry.

Overall, results of the SWAN model runs for the Merrimack Embayment indicate that a removal of at least 5 m (Fig. 25) of easily accessible sand and gravels from the Pleistocene braid plain deposits (approximately 157 million cubic meters of sediment, as determined by multiplying the area of the borrow site by the thickness of sediment to be removed) from the Merrimack Embayment will produce little to no effect on the wave regime. There is no appreciable change in wave approach angle. Changes in wave energy after this removal of sediment will range from -3 J/m^2 to +6 J/m^2 (corresponding to a change in wave height of -25 and +40 cm, respectively, across the borrow site), with the largest change occurring along the very landward edge of the borrow site. If only a 2 m thick sequence (an approximate volume of 63 million cubic meters) of braid plain sediments are removed (Fig. 26), the changes in wave energy and height are significantly reduced.

Due to the location of the sand sheet >3 km offshore of Plum Island and the mouth of the Merrimack River, any higher magnitude wave energy resulting from the borrow of sediment will be attenuated by the time the waves reach the shore. The removal of 5 m of sediment from the proposed borrow site would create a bathymetric low that would induce the shoaling of waves over the landward edge of the borrow site. As these waves continue to travel the >3 km onshore, they will expend energy as they interact with the sea floor, thereby decreasing in wave height. As per the results of the SWAN analyses, the net effect of sediment removal in the nearshore will be a minor *reduction* in wave height and wave energy along the shoreface.

It should be noted that the SWAN analysis assumes a vertical drop of 5 m from the present sea floor into the borrow site (an "edge effect"). It should be assumed that, upon removal of sediment from the borrow site, slumping will occur along the edges of the site, thereby smoothing the bathymetry and reducing the effects of sediment removal on the wave climate along the shoreface.

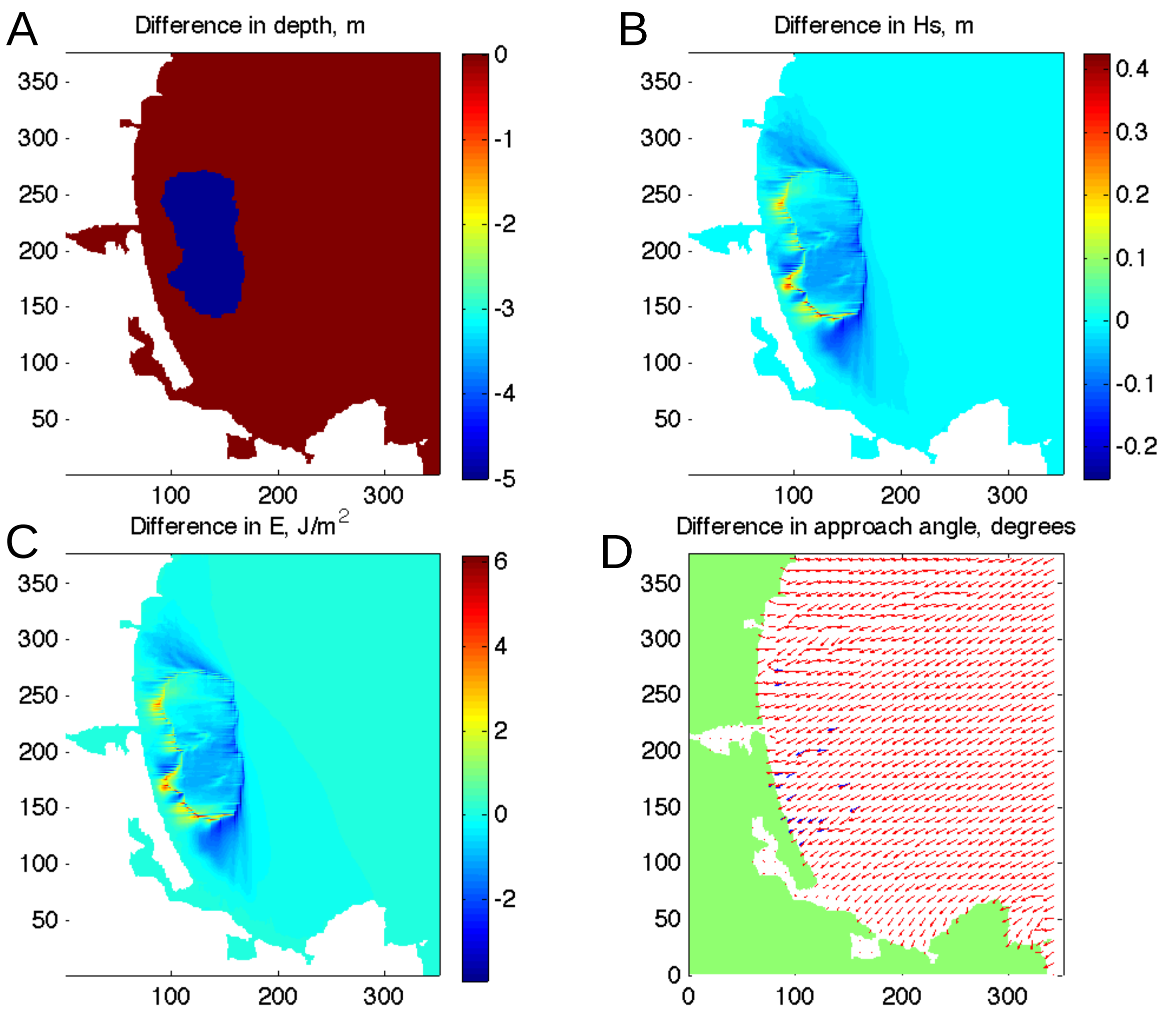


Figure 25. Results of SWAN model removing 5 m of sediment from the coarse grained sand sheet (borrow site).

A) Map of Merrimack Embayment showing region of sediment removal in model run.
B) Difference in wave height (m) due to removal of 5 m of sediment from borrow site.
C) Difference in wave energy (J/m^2) due to removal of 5 m of sediment from borrow site.
D) Difference in wave approach angle (degrees) due to removal of 5 m of sediment from borrow site.

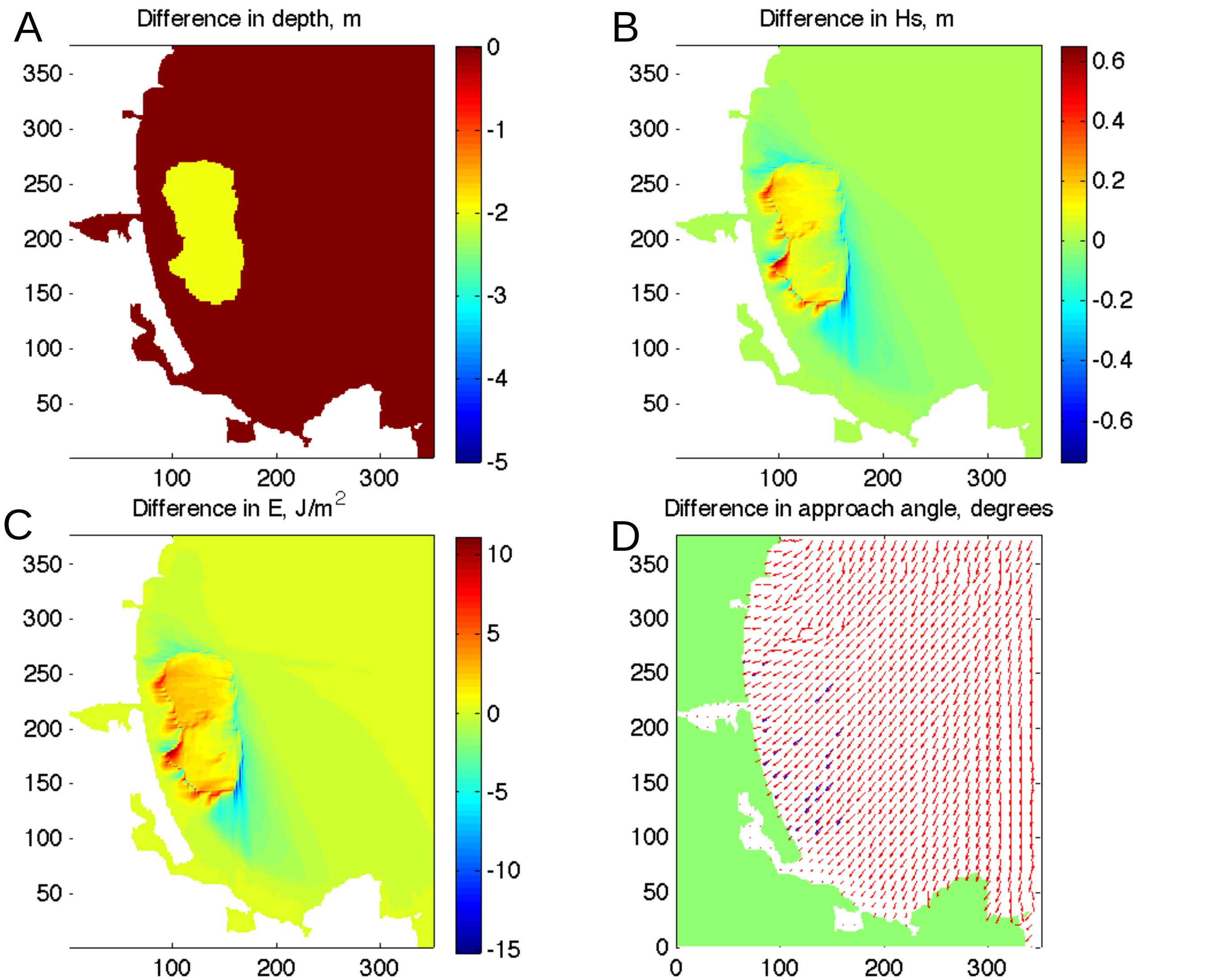


Figure 26. Results of SWAN model removing 2 m of sediment from the coarse grained sand sheet (borrow site).

A) Map of Merrimack Embayment showing region of sediment removal in model run.
B) Difference in wave height (m) due to removal of 2 m of sediment from borrow site.
C) Difference in wave energy (J/m^2) due to removal of 2 m of sediment from borrow site.
D) Difference in wave approach angle (degrees) due to removal of 2 m of sediment from borrow site.

VII. SUMMARY AND CONCLUSIONS

A. The Merrimack Braid Plain Delta and the Lowstand Paleodelta

The –45m Merrimack paleo-delta was deposited around 12 ka (Oldale et al, 1993). The origin of the delta is related to the wealth of sediment discharged from the Merrimack River during the period following deglaciation of this region. The sediment was derived from widespread glacial-fluvial deposits as well as from the reworking of onshore deltas deposited during the regression (i.e., +33 and +16 m elevations; Edwards, 1988). Highstand ice-contact deltas formed around 14.3 ka (Oldale et al, 1993). The lack of vegetation that existed in the region at that time likely contributed to the heavy sediment load of the river. The –45 m depth of emplacement of the delta is a product of rapid isostatic crustal rebound far out-pacing the eustatic sea-level rise during this time as indicated by coral dates (Bard et al, 1993).

Seismic profiles of the region inshore of the delta reveal an irregular basement overlain by channel cut and fills, flat lying reflectors, and acoustically transparent regions. Bedrock outcrops extending through the sediment surface increase in extent to the north. Our records and those collected by Oldale et al (1983) suggest that glacial and bedrock topography strongly controlled the course of the river system while it was delivering sediment to the lowstand delta. Even today much of the lower river and estuary region are stabilized by bedrock outcrops. The channel cut and fill structures observed in the seismic profiles suggest that the delivery system conveying sediment to the delta consisted of a braided stream complex, the Merrimack braid plain delta (MBPD). This feature contains 1.4×10^9 m^3 of sediment; the surface component of this unit consists of reworked moderate to poorly sorted coarse sand and gravel.

Shallow seismic profiles show a basal unconformity located immediately below the regressive fluvial / deltaic deposits. The data from the delta region exhibit pervasive shallow, seaward dipping reflectors that become tangential with sediment bottom in an offshore direction. In most cases, the surface of the clinoforms are truncated and overlain by thin flat-lying deposits. Cores through the paleo-delta generally show intercalated silty clays and fine to medium silty sands. The upper 20 to 30 cm of the cores consists of medium sand with coarse pebbles and shell fragments (Edwards, 1988). These cores that extend between 3 and 8 m confirm that the delta is composed largely of fine-grained sediments. Granularmetric analyses indicate that the delta sediments are bimodal containing poorly sorted silt and fine sand components, which is characteristic of fluvio-deltaic sediments (Giosan and Bhattacharya, 2005).

B. The Holocene Transgression and Reworking of Paleodelta & MBPD Sediments

Capping the deltaic and MBPD deposits is a pronounced ravinement surface, which extends from the delta to the nearshore of the Merrimack Embayment, indicating extensive reworking of the fluvial-deltaic lithosome during the Holocene transgression. Oldale et al (1993) attributed the coarser sediments at the surface of their cores to a "sandy Holocene marine transgressive deposit, too thin to be resolved in the seismic profile, unconformably [overlying] the delta deposits." Recent backscatter data indicate that Edwards' (1988), and Oldale and other's (1993) sandy areas coincide with the medium backscatter regions of the Embayment, forming an extensive (121 million cubic meters), though discontinuous sand sheet which thickens to the south due to long-term transport by winter northeast storms. This feature is composed of medium- to fine-grained sand (median grain size: 2.4 phi) which has been molded into large-scale bedforms with various orientations and small-scale ripples and megaripples by present marine processes.

The earlier studies of the Merrimack inner shelf (Edwards and Oldale, 1986; Edwards, 1988; Oldale et al, 1993) did not report the pervasive channel cut and fill features characterizing the region landward of the delta, and which have tentatively been interpreted as braided stream deposits. The recent shallow seismic survey data show some of these channel cut and fill features are truncated suggesting that the braided stream deposits themselves were reworked during the Holocene marine transgression. The sand sheet was likely generated during the Holocene transgression when shoreface processes reworked both delta and braided stream deposits. Additional sand may have been derived from the Merrimack River.

C. Present Day Processes & Impact of Sediment Removal

Analysis of surface sediment samples show that the fine- to medium-grained sands that comprise the majority of the inner shelf surface sediments (the medium to low backscatter) are significantly finer than the MBPD and associated features that occupy approximately 130 km^2 of the study area and are separated from the landward sandy barrier island system. While surficial sediments provide some information regarding the nature of sediments comprising the MBPD, additional coring is needed to obtain a more complete record of its thickness, volume and variability in extent. Due to its location and coarse-grained composition, these deposits are assumed to be either stable or only very rarely reworked (i.e. during only the largest and most infrequent storms).

The large scale linear to cuspate features comprising the periphery of the sand sheet exhibit variety of orientations. Relatively large NNE-SSW oriented, coarse-grained linear features dominate the northern sector. These forms have a sharp edge with the surrounding fine-grained regions on their eastern side and a diffusive western edge, indicating possible movement in an ESE direction. Elsewhere, subordinate forms are oriented in ENE-WSW and ESE-WNW directions. Bottom videos reveal that the coarse grained sand sheet sediments have a slightly higher elevation (<1 m) than nearby fine-grained sediments. The sand sheet is currently being reworked by modern processes and moving sand in mostly an offshore direction. The evolution of the sand sheet features to their current orientation is the result of waves generated by strong northeast storms. This wave energy will directly rework bottom sediments and, due to the northeast concave shape of the shoreline, produce nearshore water level set-up, triggering offshore currents and transport of coarser grained sediments. However, wave modeling indicates that removal of sediment from the target region is not likely to affect the wave and current regime in the nearshore zone.

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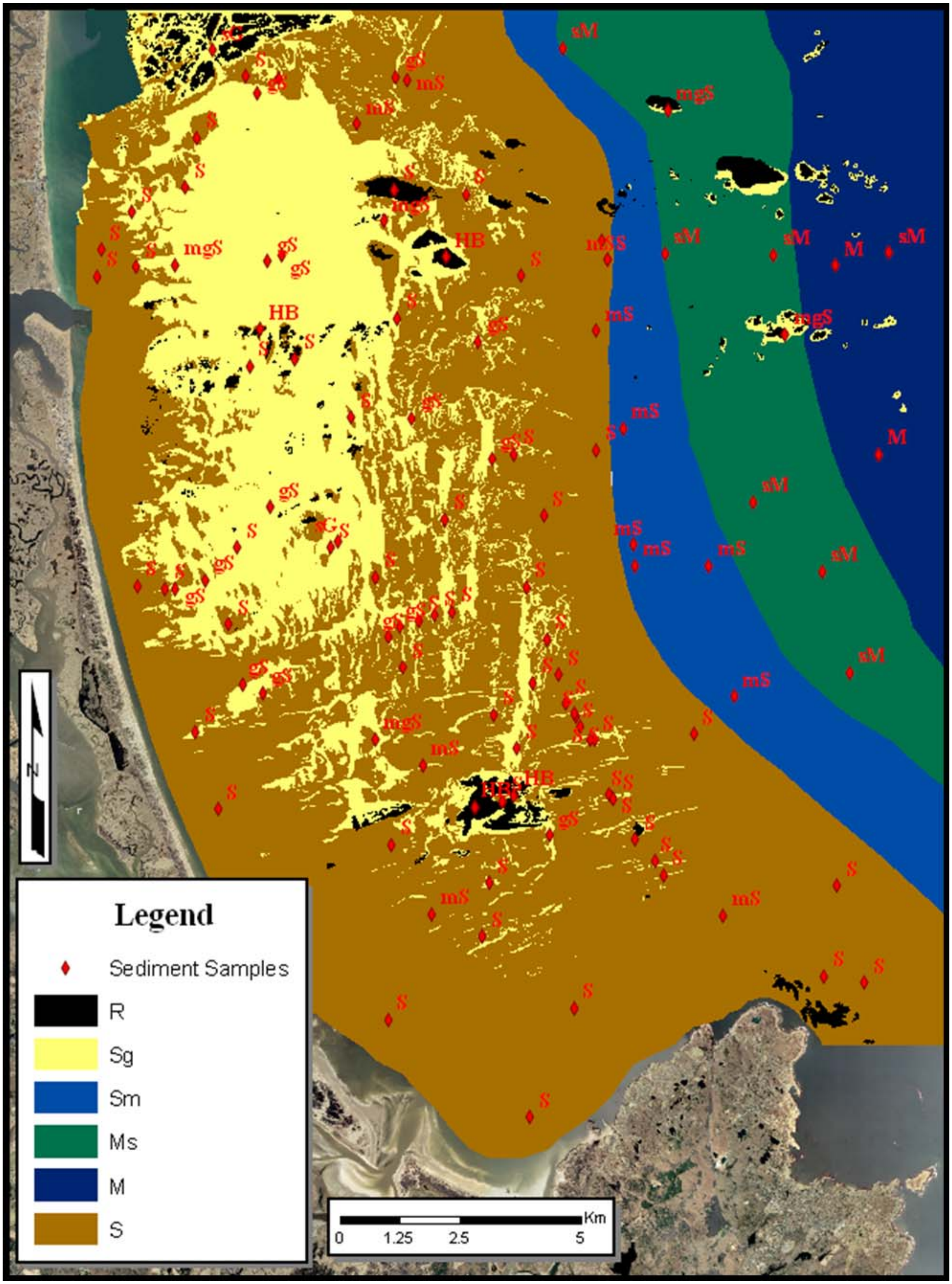
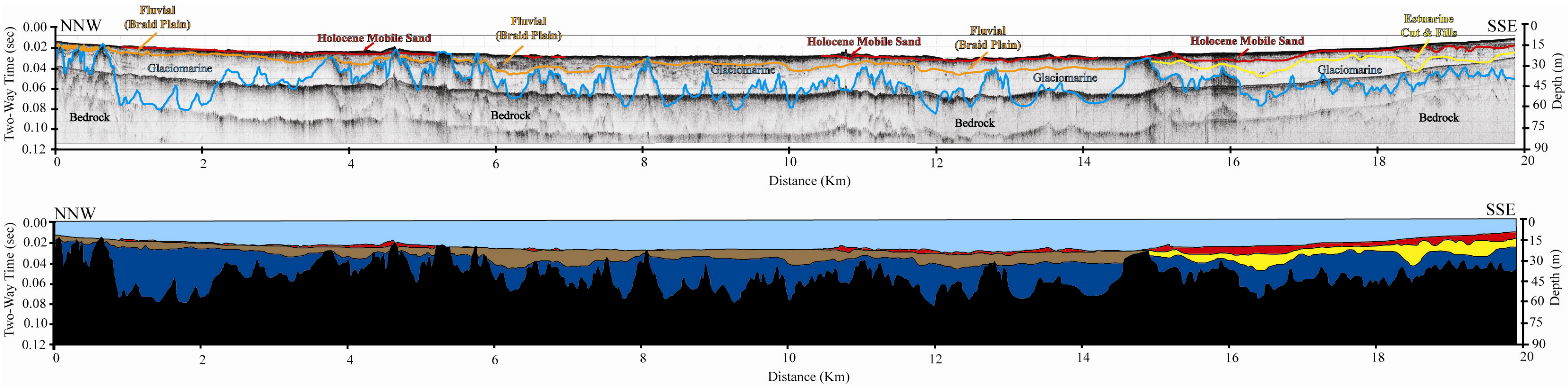
APPENDIX A
Surficial Map for the Inner Shelf Region of the Merrimack Embayment

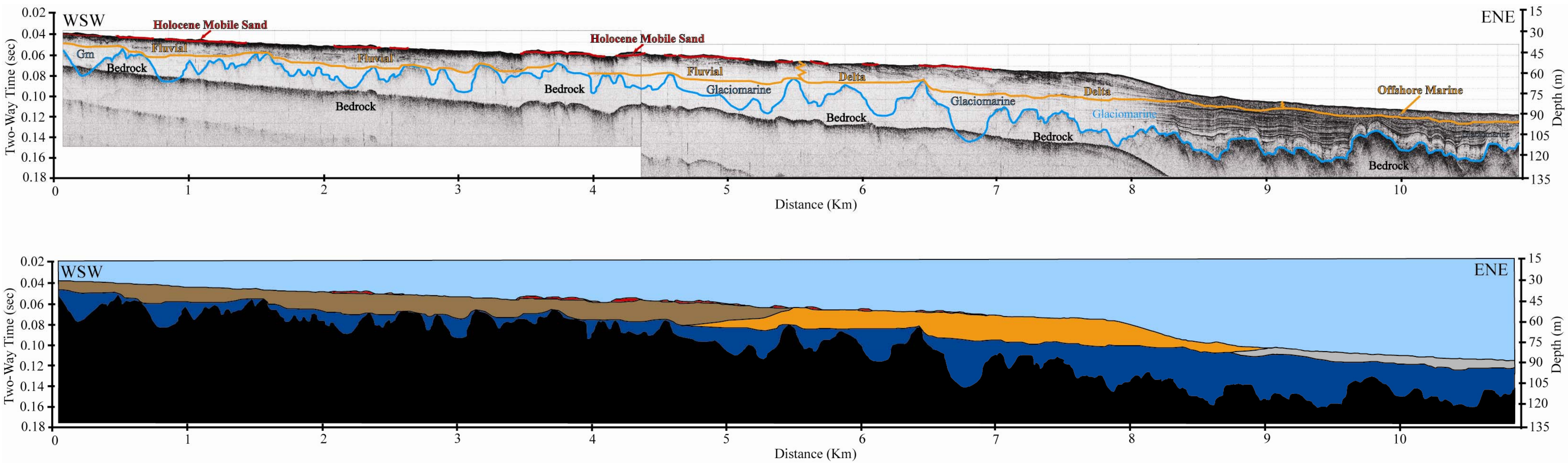


APPENDIX B
Section 1 - Strike Stratigraphic Section



APPENDIX B

Section 2 – Dip Stratigraphic Section



APPENDIX C
Section 1 – Pleistocene Braid Plain Deposits Ispoach

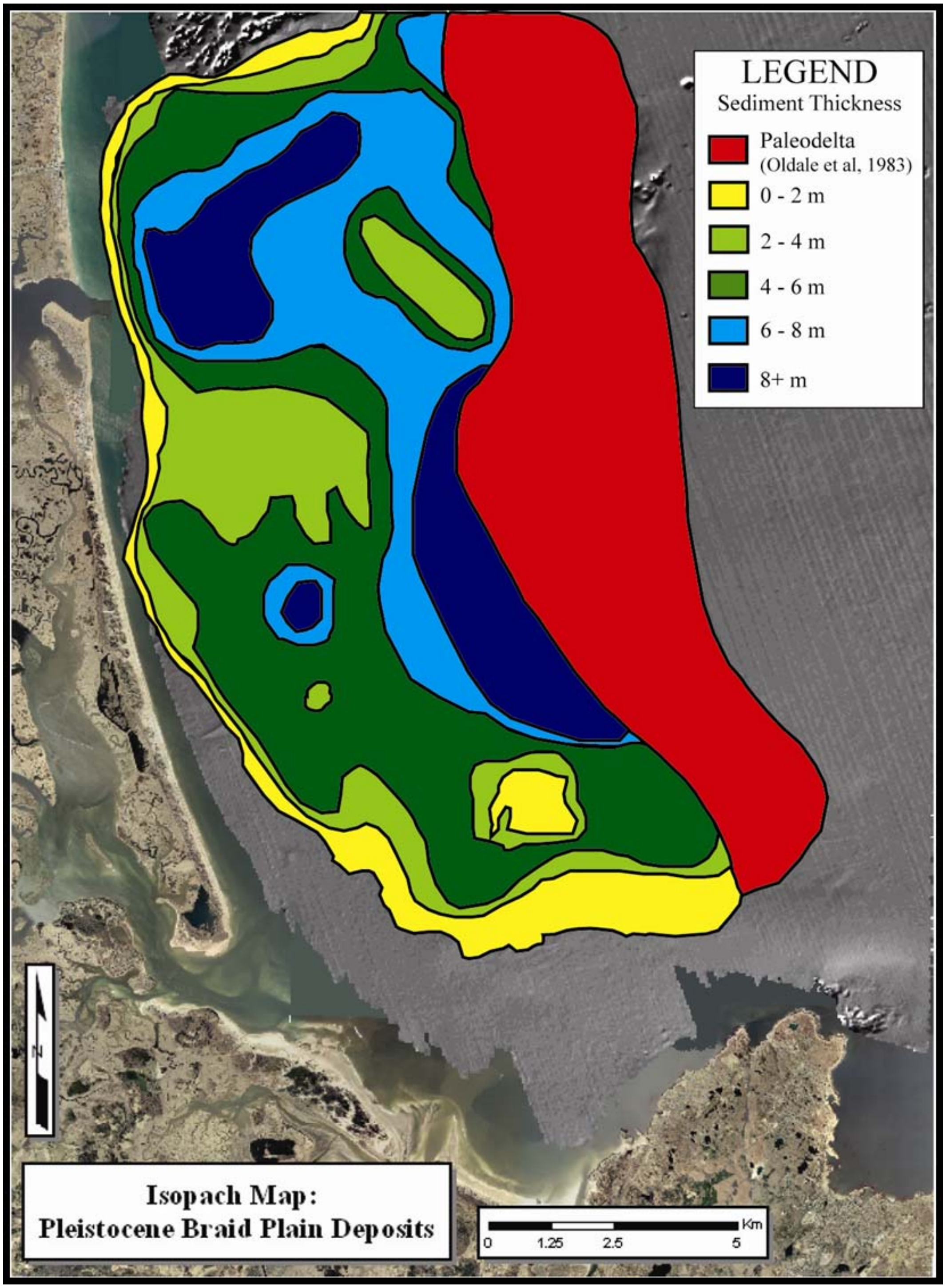


Figure C-1. Isopach map of Pleistocene Braid Plain deposits. Values were interpolated from closely spaced seismic reflection profiles in the nearshore area (Barnhardt et al., 2009) and an isopach map of paleodelta deposits published by Oldale (1983). The red region in this figure represents the region where the deposits are significantly finer and compose seaward-dipping beds; these are interpreted to be the paleodelta foresets. The braid plain deposits, thicker in some regions, are interpreted to have been reworked alongshore as they were deposited. A primary determinant of the location of the thickness of deposits is the topography of underlying bedrock. The region south of the braid plain is dominated by estuarine deposits.

APPENDIX C

Section 2 – Holocene Sand Sheet Deposits Ispoach

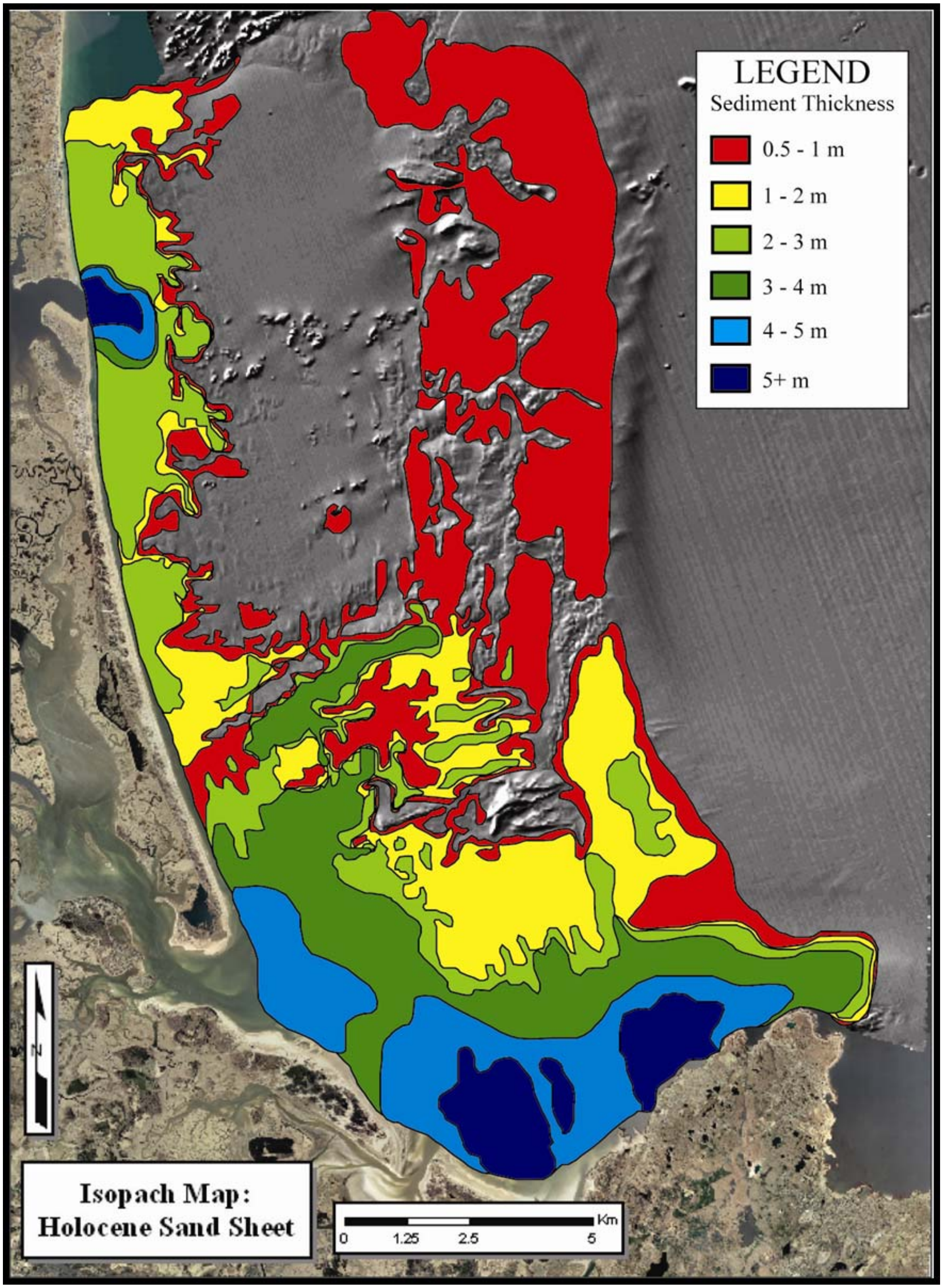


Figure C-2. Isopach map of sandy Holocene sediment (i.e, the sediment above the transgressive unconformity). This is the sediment labeled "S" in the surficial geologic map. Deposits more than 5-m thick (dark blue shading) occur at the mouth of the Merrimack River and in Ipswich Bay. Extensive areas offshore Plum Island and Salisbury Beach are covered by deposits less than 0.5-m thick (no shading). Values were interpolated from closely spaced seismic reflection profiles in the nearshore area (Barnhardt et al., 2009).

APPENDIX D

Section D-1
Sedimentological Data from Bottom Grab Samples

This section contains some of the raw data from granularmetric analyses of the bottom sediment samples retrieved during three bottom sampling cruises: USGS / Boston University Mapping Cruise (September, 2005), University of New Hampshire Lithobiofacies Mapping Cruise (August, 2005), and Massachusetts Division of Marine Fisheries / Boston University Sampling Cruise (September, 2006). Samples have been grouped according to the backscatter region from where they were retrieved. Average median and mean grain sizes have been calculated for each group.

Location Bottom Type	Sample ID	Sediment Class	Sample Location		Water Depth (m)	Median Grain Size (phi)	Mean Grain Size (phi)	Sorting	Skewness	Kurtosis	% Gravel	% Sand	% Silt	% Clay
			Latitude	Longitude										
Pleistocene Braid Plain	2	sG	42.777	-70.740	29.1	-1.2	-1.0	0.98	1.19	10.35	61.3	38.5	0.1	0.0
	4	gS	42.800	-70.722	33.8	-0.7	-0.7	1.34	0.78	10.49	37.3	62.0	0.5	0.3
	5	gS	42.793	-70.701	38.1	-0.4	-0.2	0.97	1.08	12.83	15.1	84.7	0.2	0.1
	7	gS	42.815	-70.705	40.4	-0.9	-0.9	1.77	0.55	3.74	48.0	51.2	0.5	0.3
	14	gS	42.864	-70.728	39.0	-0.8	-0.8	1.32	0.37	2.89	43.9	55.8	0.2	0.1
	16	gS	42.863	-70.757	31.8	-0.3	0.0	1.19	1.42	14.98	9.8	89.2	0.8	0.3
	17	gS	42.860	-70.762	30.6	0.6	0.6	1.04	1.08	16.34	5.6	93.6	0.6	0.3
	19	sG	42.868	-70.774	29.8	-1.0	-0.9	2.75	0.36	0.70	50.0	46.5	2.5	1.0
	22	gS	42.830	-70.756	29.5	0.1	0.0	1.14	0.50	7.26	18.6	81.0	0.3	0.1
	24	S	42.809	-70.763	26.6	0.5	0.5	0.82	0.73	12.11	2.5	97.2	0.2	0.1
	25	S	42.776	-70.765	22.9	0.5	0.6	0.78	1.88	32.49	0.2	99.2	0.5	0.2
	27	gS	42.750	-70.763	18.3	-0.2	0.1	1.28	1.11	7.22	10.1	88.6	1.2	0.1
	28	gS	42.749	-70.758	19.1	0.1	0.3	1.28	0.77	6.05	14.1	84.9	0.8	0.2
	31	S	42.714	-70.700	27.3	1.0	1.0	1.24	0.97	11.37	3.8	94.1	1.6	0.5
	32	gS	42.723	-70.685	32.5	-0.4	-0.2	1.34	1.14	12.22	17.5	81.2	1.0	0.3
	42	S	42.739	-70.694	33.0	2.4	2.4	0.86	1.53	22.22	0.0	98.3	1.2	0.5
	43	S	42.746	-70.700	32.4	0.6	0.8	0.88	2.08	32.22	0.2	99.0	0.5	0.3
	48	gS	42.760	-70.727	24.9	-0.2	0.1	1.34	0.81	6.75	16.9	82.1	0.8	0.3
	49	gS	42.762	-70.724	25.1	-0.4	-0.2	1.18	0.86	9.29	21.8	77.7	0.4	0.2
	51	S	42.764	-70.715	27.3	0.7	0.8	1.26	1.14	11.42	1.8	96.5	1.2	0.5
	53	S	42.769	-70.692	38.1	0.4	0.5	0.99	1.68	24.02	1.5	97.8	0.4	0.4
	67	S	42.837	-70.794	19.5	0.7	0.7	1.09	1.23	15.30	2.7	96.1	0.9	0.3
	69	mgS	42.828	-70.782	24.5	0.4	0.3	1.28	1.09	12.74	11.4	86.5	1.8	0.4
	70	gS	42.783	-70.757	25.6	0.0	0.1	1.20	0.59	6.58	16.8	82.6	0.5	0.1
	71	S	42.768	-70.783	13.7	0.5	0.6	1.17	1.45	15.46	2.5	95.4	1.8	0.3
	72	S	42.741	-70.775	10.3	0.1	0.1	0.77	1.47	25.56	2.7	96.9	0.3	0.1
	84	gS	42.829	-70.759	28.6	0.4	0.3	0.96	0.53	11.77	7.6	92.0	0.3	0.1
	88	gS	42.768	-70.781	15.8	0.1	0.2	1.38	0.50	7.61	8.4	90.2	1.2	0.2
	89	gS	42.769	-70.773	18.4	-0.1	0.0	1.55	0.88	7.28	24.6	73.5	1.5	0.5
	99	S	42.731	-70.670	62.5	0.7	0.7	1.30	0.20	7.71	4.6	94.5	0.7	0.2
	105	S	42.746	-70.679	29.1	0.4	0.7	1.26	1.26	10.78	0.0	98.8	0.8	0.4

Location Bottom Type	Sample ID	Sediment Class	Sample Location		Water Depth (m)	Median Grain Size (phi)	Mean Grain Size (phi)	Sorting	Skewness	Kurtosis	% Gravel	% Sand	% Silt	% Clay
			Latitude	Longitude										
Holocene Mobile Sand Sheet	1	S	42.776	-70.742	27.4	2.3	2.3	0.58	1.99	43.84	0.0	99.3	0.5	0.2
	3	S	42.800	-70.737	31.3	2.3	2.3	0.80	1.51	27.92	0.1	98.7	0.8	0.4
	6	S	42.794	-70.696	38.9	2.1	2.1	0.78	2.24	36.03	0.0	98.8	0.7	0.5
	8	mS	42.817	-70.676	52.0	2.5	2.7	1.62	1.19	7.73	0.4	92.8	3.5	3.4
	13	mS	42.863	-70.725	39.8	2.7	3.0	1.47	1.21	8.52	0.8	91.8	4.4	2.9
	15	mS	42.855	-70.737	37.7	2.8	3.0	1.53	0.82	6.31	1.1	90.0	6.5	2.4
	18	S	42.863	-70.766	31.1	1.5	1.6	1.00	2.30	29.15	0.0	97.6	1.7	0.6
	20	S	42.851	-70.778	25.8	1.3	1.2	0.79	2.26	41.30	0.2	99.0	0.5	0.3
	21	S	42.842	-70.780	25.7	0.8	1.0	0.80	2.58	44.36	0.0	99.1	0.6	0.3
	23	S	42.811	-70.752	26.5	1.7	1.9	0.70	2.45	40.90	0.0	98.9	0.9	0.3
	26	S	42.761	-70.767	19.7	1.9	2.1	1.09	0.64	4.86	0.0	97.8	2.0	0.3
	29	mgS	42.741	-70.729	26.1	2.8	2.7	1.53	-0.15	3.44	3.7	89.8	5.8	0.7
	30	mS	42.736	-70.717	29.1	3.8	4.5	1.92	0.53	0.39	0.0	59.0	33.5	7.5
	33	S	42.719	-70.658	35.9	2.2	2.3	0.95	1.71	20.51	0.1	97.9	1.5	0.6
	34	S	42.741	-70.674	35.8	2.0	2.0	0.77	1.36	23.00	0.0	99.1	0.7	0.3
	35	S	42.743	-70.649	46.7	2.5	2.7	1.15	1.72	15.40	0.0	95.2	3.4	1.4
	38	S	42.715	-70.612	42.2	2.4	2.4	1.00	1.88	23.07	0.1	97.0	1.9	0.9
	39	S	42.697	-70.605	29.2	3.4	3.5	0.74	2.63	38.37	0.0	96.5	2.5	1.0
	40	S	42.698	-70.615	28.7	3.4	3.4	0.55	2.31	52.31	0.0	96.7	3.0	0.4
	41	mS	42.709	-70.641	37.1	2.8	3.1	1.24	1.57	12.02	0.0	93.2	4.7	2.0
	44	S	42.752	-70.690	33.9	2.4	2.3	0.79	1.67	29.45	0.0	98.8	0.8	0.4
	45	S	42.753	-70.683	36.4	2.5	2.6	0.80	2.29	37.05	0.1	98.3	1.0	0.7
	46	S	42.760	-70.687	35.1	2.3	2.1	1.05	-0.29	10.32	2.8	96.5	0.4	0.3
	47	S	42.754	-70.723	27.9	2.4	2.3	0.85	0.75	18.67	0.4	98.4	1.0	0.3
	50	S	42.763	-70.719	25.1	2.2	2.2	0.57	1.59	37.48	0.0	99.5	0.4	0.1
	52	S	42.765	-70.711	29.4	2.4	2.3	0.65	1.58	37.19	0.1	99.3	0.4	0.2
	58	S	42.795	-70.675	49.8	2.5	2.6	1.23	1.36	13.45	0.3	95.2	2.9	1.6
	59	S	42.783	-70.688	40.8	2.4	2.3	1.11	0.95	13.27	0.3	97.1	1.9	0.7
	60	S	42.782	-70.713	33.0	2.3	2.2	0.81	0.81	22.23	0.5	98.7	0.5	0.3
	61	S	42.819	-70.726	39.1	2.8	3.0	1.24	0.98	11.43	0.8	93.3	4.4	1.6
	62	S	42.827	-70.695	46.8	2.6	2.9	1.19	1.76	15.19	0.0	94.8	3.3	1.9
	63	mS	42.834	-70.675	55.7	2.4	2.6	1.80	0.77	4.38	1.2	89.3	6.7	2.8
	64	S	42.842	-70.709	41.9	2.6	2.6	1.03	1.38	17.10	0.2	96.9	2.0	0.9

Location Bottom Type	Sample ID	Sediment Class	Sample Location		Water Depth (m)	Median Grain Size (phi)	Mean Grain Size (phi)	Sorting	Skewness	Kurtosis	% Gravel	% Sand	% Silt	% Clay
			Latitude	Longitude										
Holocene Mobile Sand Sheet (cont)	66	mgS	42.836753	-70.7299624	39.7897	2.4	2.62	2.36	0.49	1.64	4.83	80.93	9.07	5.17
	68	S	42.830334	-70.8012413	10.02	2.72	2.73	0.7	-1.4	22.2	0.67	99.02	0.29	0.02
	73	S	42.727072	-70.7688075	9.4	2.99	3.01	0.57	1.18	25.77	0	98.66	1.19	0.14
	74	S	42.721167	-70.7247682	22.15	2.03	2.09	0.81	1.31	18.18	0	98.81	0.94	0.25
	75	mS	42.709	-70.714	21.5	3.5	3.7	1.02	1.49	13.29	0.0	84.5	14.0	1.5
	76	S	42.705	-70.701	25.4	2.4	2.4	0.82	1.53	21.33	0.0	97.8	1.9	0.4
	77	S	42.692	-70.678	19.5	3.4	3.4	0.69	1.87	32.18	0.0	95.5	4.0	0.6
	78	S	42.671	-70.689	8.2	2.9	2.9	0.64	1.78	30.08	0.0	98.5	1.2	0.3
	79	S	42.689	-70.725	7.0	2.6	2.7	0.47	3.07	64.15	0.0	98.7	1.2	0.1
	82	mS	42.830	-70.673	56.2	2.7	3.1	1.70	1.20	5.63	0.2	88.7	6.6	4.6
	83	S	42.830	-70.673	56.3	2.5	2.6	1.46	0.90	9.55	1.7	92.6	3.6	2.0
	85	S	42.827	-70.792	18.2	1.8	1.9	0.78	1.17	15.74	0.0	99.0	0.8	0.1
	86	S	42.825	-70.802	8.4	2.8	2.8	0.67	0.53	12.77	0.0	97.6	2.3	0.1
	87	S	42.768	-70.790	10.1	2.7	2.7	0.88	-0.19	3.26	0.0	97.8	2.1	0.1
	90	S	42.771	-70.730	28.7	2.6	2.6	0.72	1.02	21.74	0.1	98.6	1.1	0.2
	97	S	42.717	-70.656	62.0	2.4	2.5	0.78	2.34	36.70	0.0	98.2	1.2	0.5
	98	S	42.723	-70.663	28.7	2.4	2.5	0.74	2.15	36.87	0.0	98.5	1.1	0.4
	100	S	42.731	-70.670	59.9	2.6	2.7	1.20	1.26	11.54	0.0	94.9	4.0	1.1
	101	S	42.731	-70.669	42.7	0.8	1.0	0.74	1.68	25.07	0.0	99.6	0.3	0.1
	102	S	42.741	-70.675	19.4	1.3	1.2	1.19	0.27	4.83	3.9	95.5	0.4	0.2
	103	S	42.744	-70.678	61.1	2.6	2.7	0.99	1.76	20.18	0.0	96.9	2.2	0.9
	104	S	42.746	-70.679	21.7	2.5	2.5	0.73	1.39	27.25	0.0	99.1	0.5	0.3
	106	S	42.748	-70.682	69.0	2.4	2.4	0.73	1.29	25.01	0.0	99.3	0.5	0.3

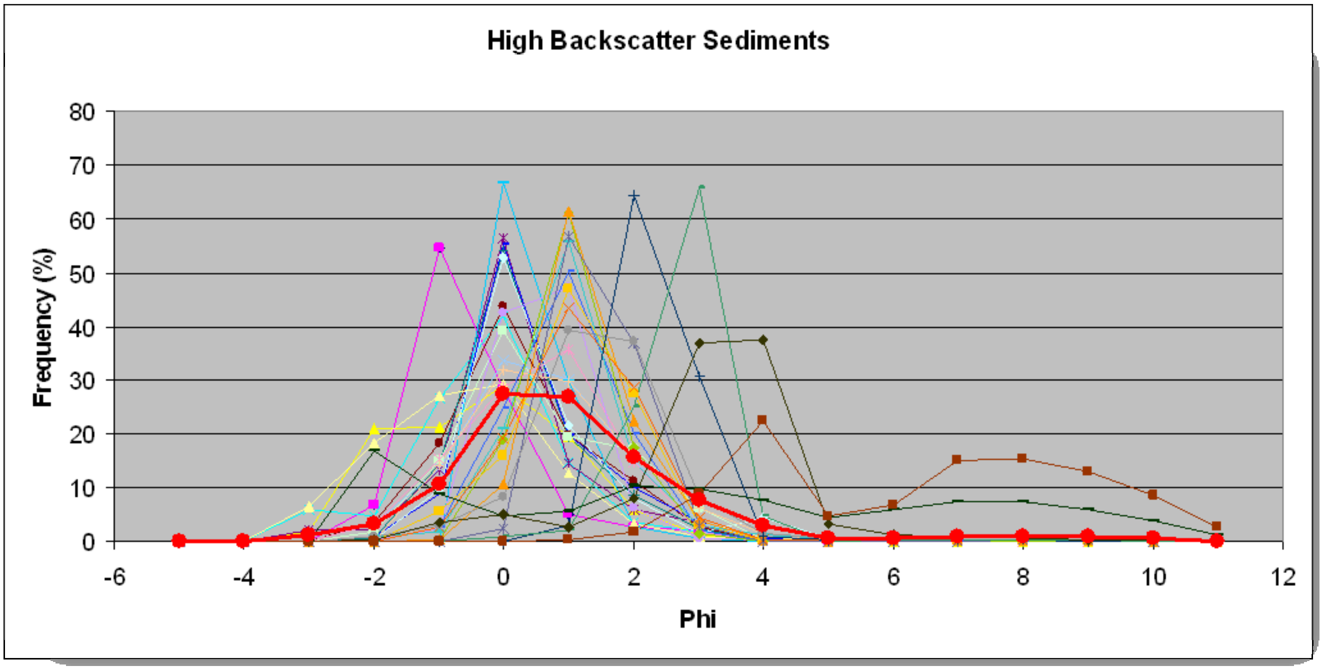
Location Bottom Type	Sample ID	Sediment Class	Sample Location		Water Depth (m)	Median Grain Size (phi)	Mean Grain Size (phi)	Sorting	Skewness	Kurtosis	% Gravel	% Sand	% Silt	% Clay
			Latitude	Longitude										
Delta Front	36	mS	42.750	-70.639	62.0	3.4	3.8	1.75	0.95	3.06	0.0	81.6	12.5	6.0
	54	mS	42.778	-70.665	61.2	3.5	4.0	1.68	0.89	2.64	0.0	80.2	14.9	4.9
	57	mS	42.799	-70.669	62.5	3.4	3.9	1.82	0.81	2.08	0.0	79.7	14.3	5.9
	91	mS	42.774	-70.665	59.9	3.4	4.0	1.88	0.84	1.97	0.0	79.8	12.9	7.3
	92	mS	42.774	-70.646	69.0	4.4	5.3	2.18	0.31	-0.90	0.0	47.4	36.2	16.5

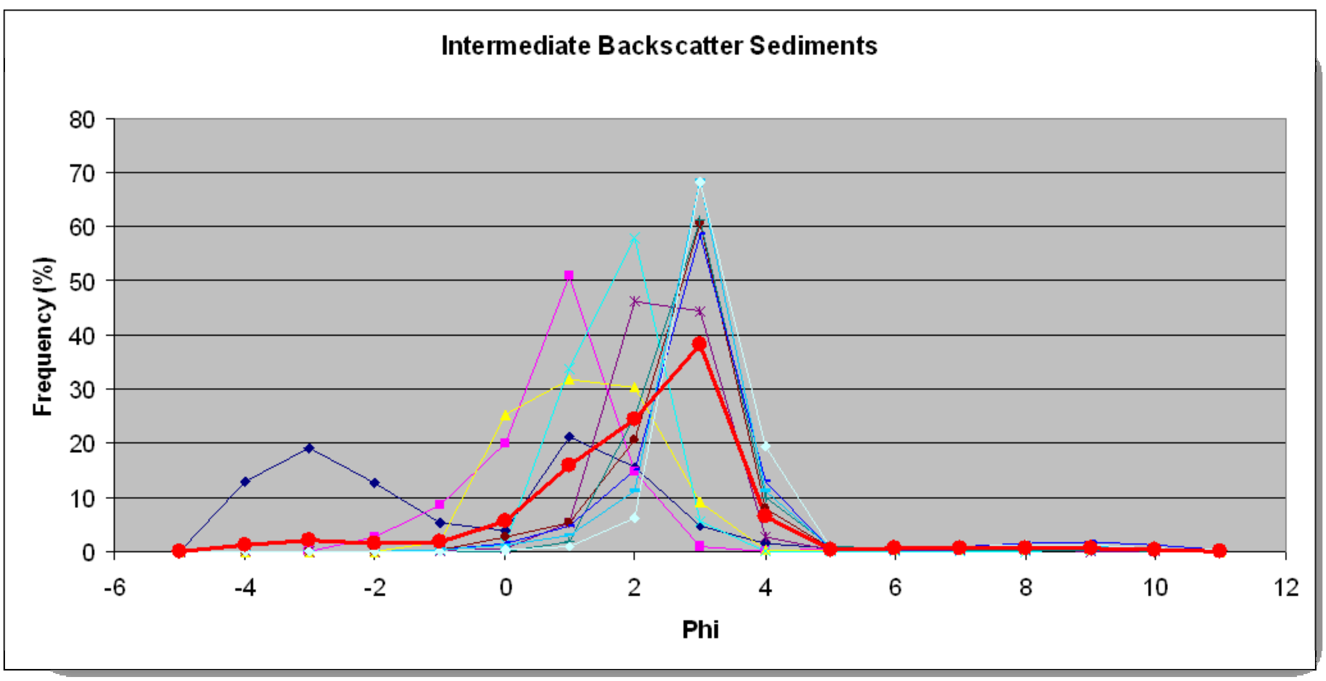
Location Bottom Type	Sample ID	Sediment Class	Sample Location		Water Depth (m)	Median Grain Size (phi)	Mean Grain Size (phi)	Sorting	Skewness	Kurtosis	% Gravel	% Sand	% Silt	% Clay
			Latitude	Longitude										
Offshore	10	M	42.830	-70.616	84.7	7.5	7.5	1.61	-0.15	-0.36	0.0	2.2	59.0	38.8
	12	sM	42.870	-70.686	55.9	6.3	6.0	2.41	-0.02	-1.21	0.0	33.7	42.0	24.3
	37	sM	42.755	-70.610	74.1	6.2	5.9	2.41	0.02	-1.51	0.0	39.0	33.0	28.0
	55	sM	42.786	-70.635	75.4	6.3	6.3	2.06	-0.01	-1.21	0.0	21.4	51.6	27.1
	56	M	42.795	-70.604	87.3	7.5	7.3	1.64	-0.24	-0.28	0.0	4.2	56.8	39.0
	80	sM	42.832	-70.631	78.7	5.1	5.6	1.75	0.38	-0.25	0.0	11.5	74.5	14.0
	81	sM	42.832	-70.659	67.5	4.9	5.4	2.27	0.23	-1.10	0.0	47.8	34.5	17.7
	93	sM	42.773	-70.618	78.7	6.1	6.1	2.07	0.01	-0.81	0.0	20.7	58.8	20.5
	94	sM	42.833	-70.602	89.2	7.0	6.9	1.87	-0.20	-0.17	0.0	7.8	60.7	31.5
	95	M	42.833	-70.571	99.1	7.5	7.4	1.64	-0.03	-0.92	0.0	0.8	60.0	39.3
	96	M	42.772	-70.582	88.4	7.4	7.3	1.71	-0.12	-0.68	0.0	2.8	58.6	38.6

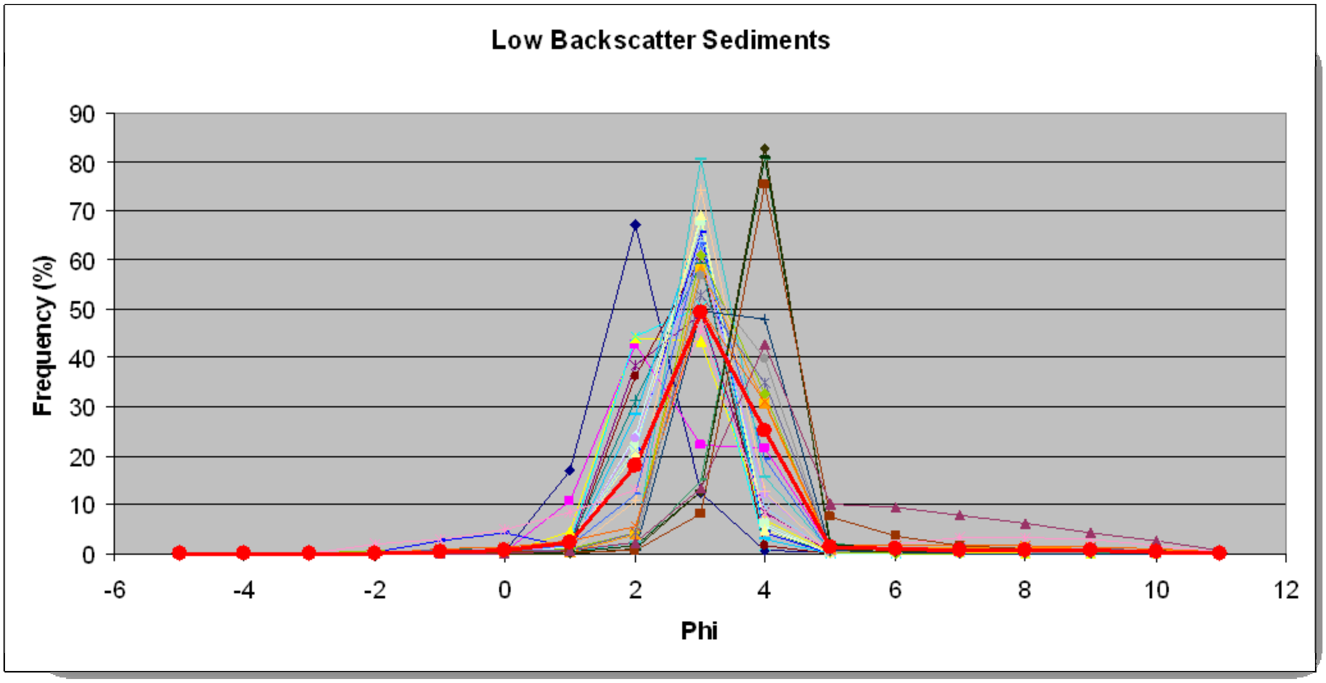
Location Bottom Type	Sample ID	Sediment Class	Sample Location		Water Depth (m)	Median Grain Size (phi)	Mean Grain Size (phi)	Sorting	Skewness	Kurtosis	% Gravel	% Sand	% Silt	% Clay
			Latitude	Longitude										
Rocky Zone	9	mgS	42.817	-70.628	76.7	2.5	3.3	4.29	0.03	-1.52	25.8	29.3	27.2	17.7
	11	mgS	42.858	-70.659	66.5	2.4	2.7	3.86	0.10	-1.19	25.7	38.1	25.2	11.0
	65	S	42.843	-70.727	30.7	-0.3	-0.1	0.58	2.55	54.57	0.1	99.8	0.1	0.1
	107	S	42.730	-70.697	67.6	1.2	1.1	0.75	0.26	11.77	1.7	98.1	0.1	0.1

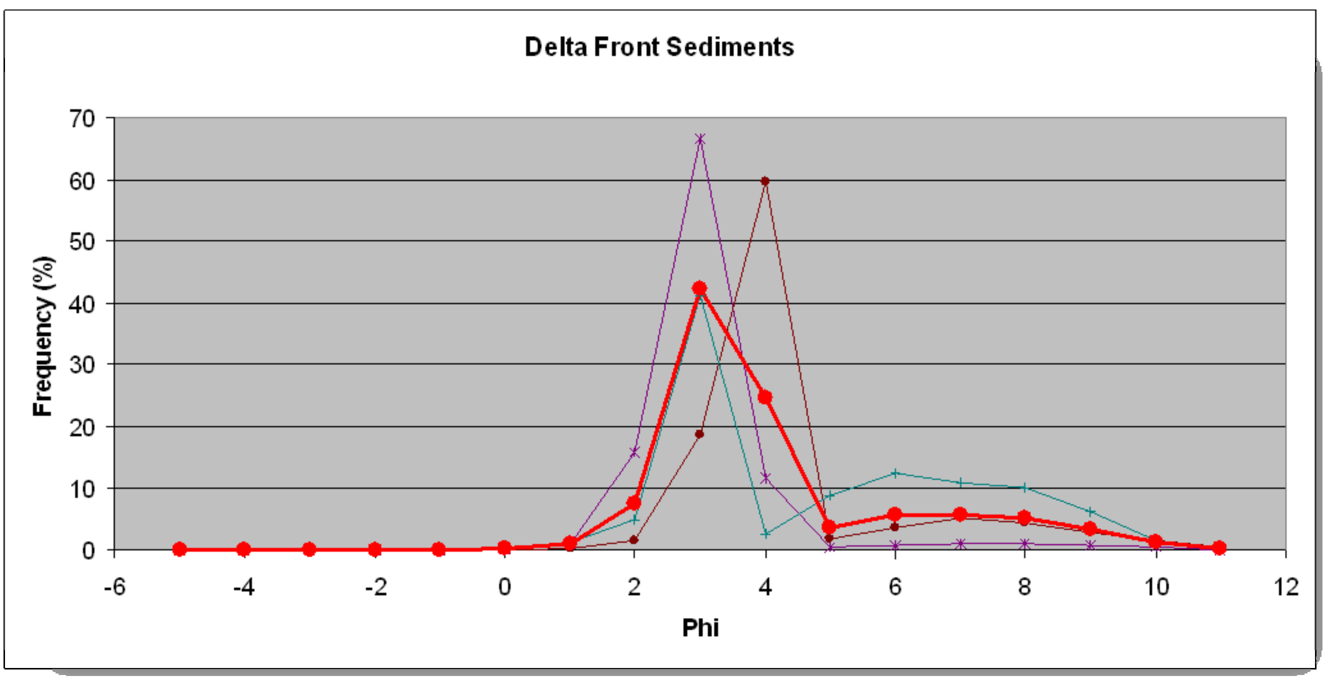
Section D-2
Sedimentological Graphs from Bottom Grab Samples

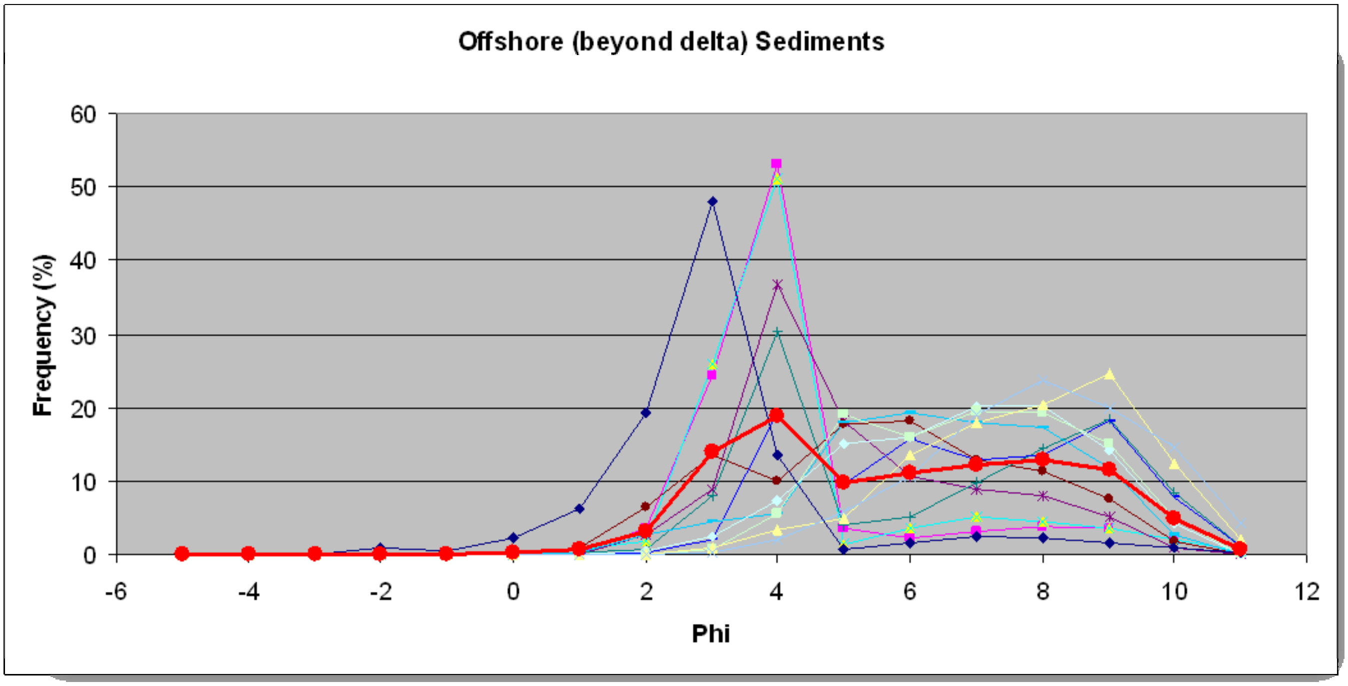
This section contains graphs showing grain size distributions (by percent of phi size) for each bottom sample retrieved during each of the three research cruises. Samples have been grouped according to the backscatter region from where they were retrieved and graphed accordingly. Each graph contains an additional thicker red line representing the mean grain size distribution for each sediment group.






Low Backscatter Sediments
Frequency (%)
90
80
70
60
50
40
30
20
10
0
-6
-4
-2
0
2
4
6
8
10
12
Phi

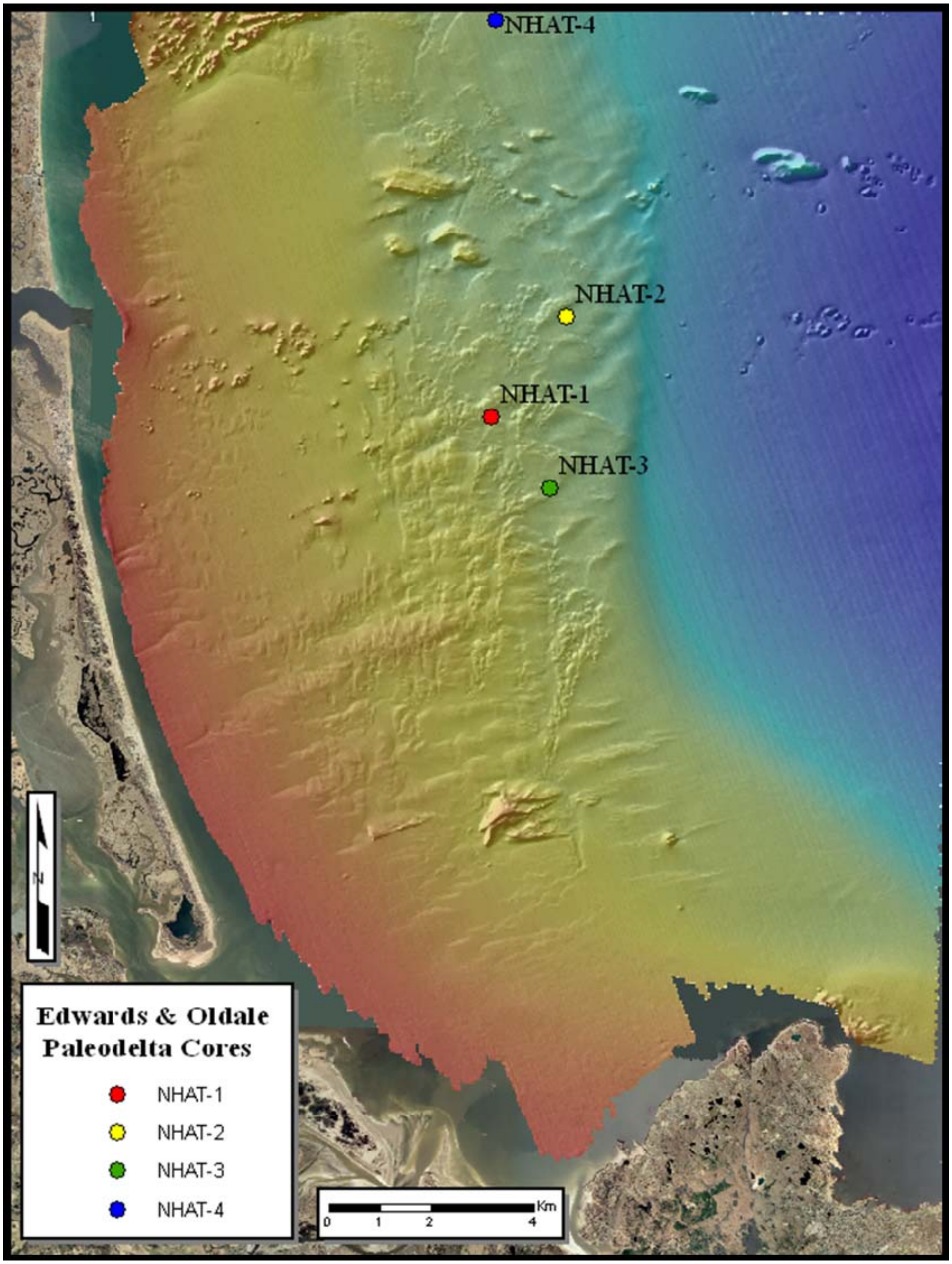

Delta Front Sediments
Frequency (%)
70
60
50
40
30
20
10
0
-6
-4
-2
0
2
4
6
8
10
12
Phi


Offshore (beyond delta) Sediments
Frequency (%)
60
50
40
30
20
10
0
-6
-4
-2
0
2
4
6
8
10
12
Phi

APPENDIX E

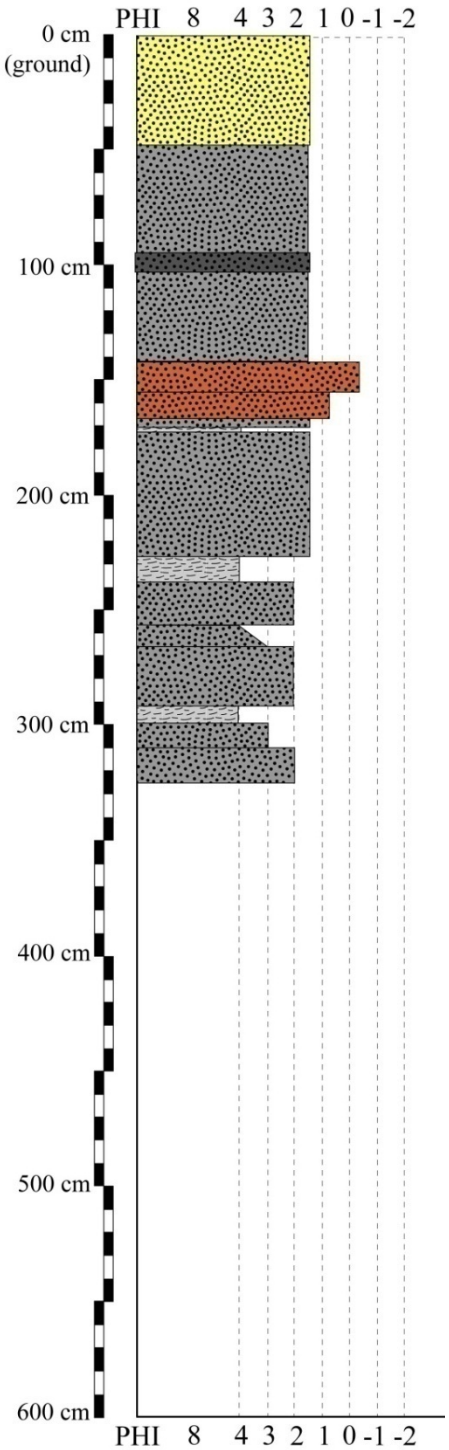
Offshore Core Descriptions

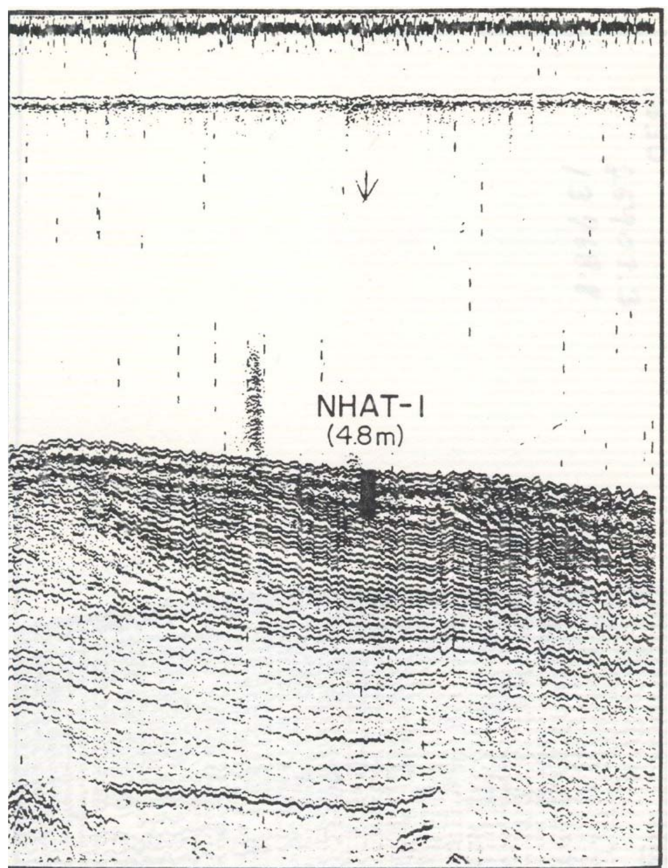
Both graphic and written description core logs are provided from cores taken by Dr. Robert Oldale (USGS) and Mr. Gerald Edwards and published in Edwards' 1988 Masters Thesis. No additional offshore cores have been collected as part of this study due to lack of sufficient funds.



CORE LOG #1 (Core NHAT-1)

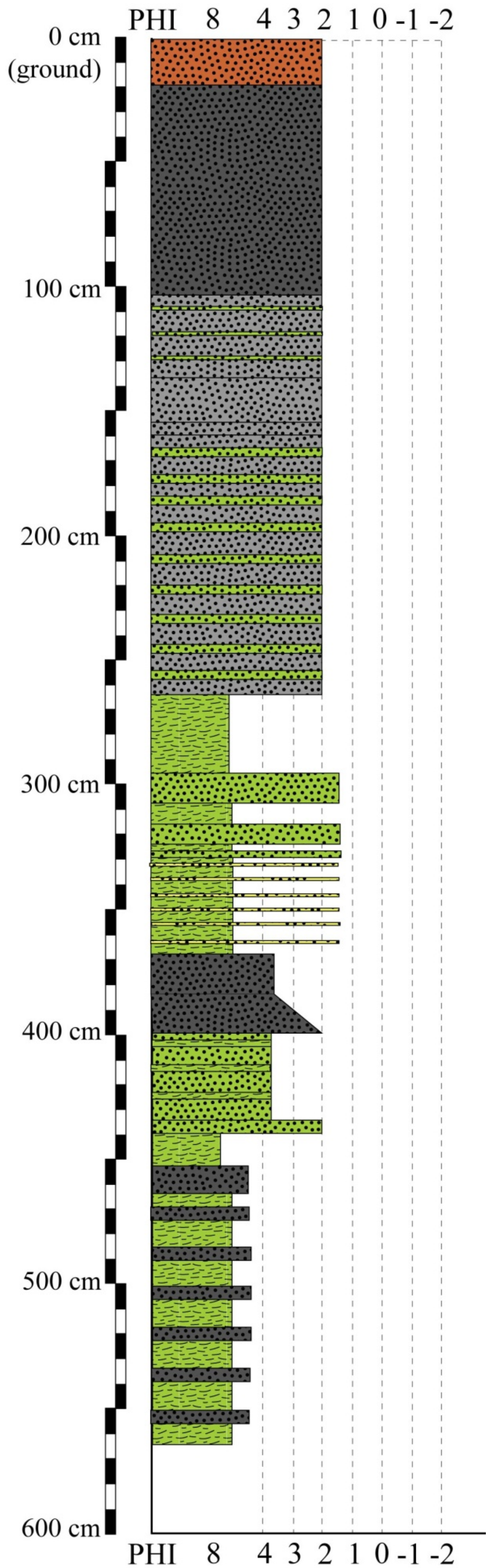
Depth (cm)		Description	Grain Size	Munsell Color
0-48	0-30	shell- bivalves	med grain	2.5Y 8/4
	30-45	Shells noticeably absent, pale yellow sand only		
	45	only 1 shell, concave down		
48-135		light brownish grey sand, grading down through greyish brown, olive fine to med grain sand, abundance of muscovite throughout		
	99-104	small patch of very dark greyish brown sand (bio-organic alteration?)	med grain	2.5Y 3/2
	132	small bivalve		
141-155	105-142	mettled coloring (relative moisture differences?)		
		dark olive brown, poor sorting	med to Very coarse	2.5Y 4/4
156-158		poorly sorted, G. contact(?), top same as above texturally yet has a submatrix of fine light grey sand (mixing during coring?)	med to Very coarse	2.5Y 4/4; 5Y 7/1
165-227		light grey, texturally gradational into upper unit; color difference (sec. G-contact above), prominent layering of biotite and light and dark sands	fine grain	5Y 7/1, layering of 5Y 7/1 and 2.5Y 4/2
	173-179	band of clayey silt		
	A Unit	greyish brown		2.5Y 5/2
	B Unit	drak greyish brown		2.5Y 4/2
227-239		clear interlaminar beds of very fine clayey silts	very fine	
239-259		interlaminations of fine and med grained light grey to light olive grey sands	fine and med	5Y 7/1 and 5Y 6/2
259-268		2 prominent beds of very fine sand to silt, olive, fining upwards, S-contact at bottom	very fine sand to silt	5Y 4/3
268-293		interlaminated med/fine and fine light grey sand	med/fine and fine	5Y 7/1
293-300		interlaminated fines and clayey silts, olive grey, S-basil contacts at 300cm	fines and clayey silts	5Y 4/2
300-308		dark and light sands dominant variant feature	fine and very fine	
308-328		olive grey	med to med/fine	5Y 5/2

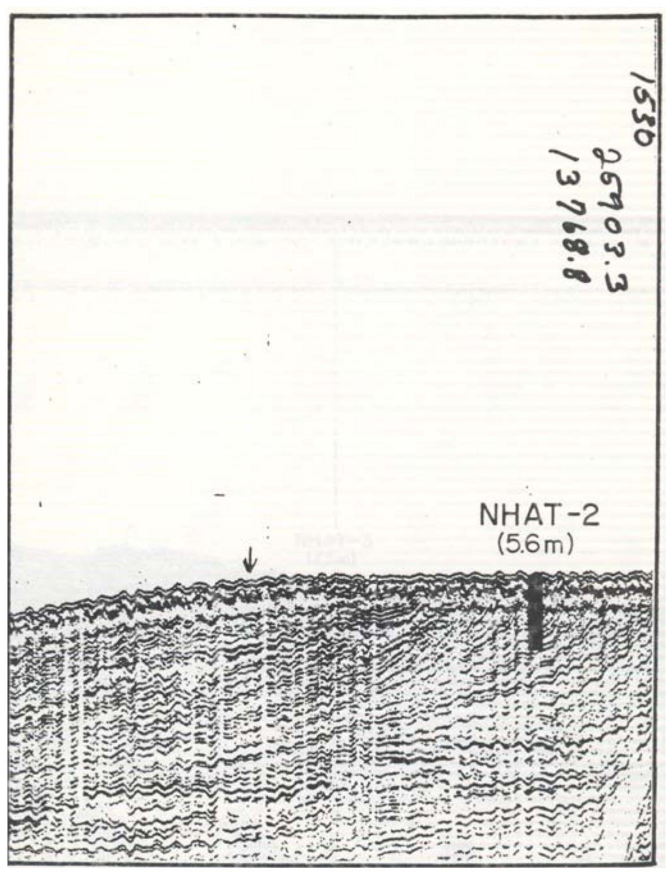

PHI 8 4 3 2 1 0 -1 -2
0 cm
(ground)
100 cm
200 cm
300 cm
400 cm
500 cm
600 cm
PHI 8 4 3 2 1 0 -1 -2


NHAT-1
(4.8m)

CORE LOG #2 (Core NHAT-2)

Depth (cm)	Description	Size	Munsel Color
0-20	olive brown sand, fairly well sorted matrix, larger grains (coarse, up to 8mm), shell material up to 5mm along axis, appears sub horizontal	med grained	2.5Y 4/4
20-103	mottled med sand, dark olive grey silt/sand, biotite layers in sand, some thin mostly biotite sand laminations within sand/silt layers	med sand, fine silt/sand	5Y 6/1, 5Y 3/2
103-135	essentially massive sand with some minor sand/silt layers, light grey	fine/med grained	5Y 6/1
142-155	3mm layers of fine/med pale olive sand- oxidation?	Fine/med, fine/med	5Y 6/1, 5Y 6/8
155-160	light grey	Med/fine sand	
160-264	Alternating layers of light grey med/fine sands with biotite and olive grey sandy silts	med/fine sands, sandy silts	5Y 6/1, 5Y 4/2
264-297	olive grey silty clay with black organic hash, surface color lighter than interior, which is very dark grey. Organic area is black	silty clay	5Y 4/2, 5Y 3/1, 5Y 2.5/ 1
300-308	Ex- olive grey med sand In- Dark grey sand	med sand	5Y 4/2, 5Y 4/1
308-316	olive grey	silty clay to sandy silt	
316-322	olive grey with shells up to 1cm long axis	med sand	5Y 4/2
322-326		silty clay to sandy silt	
326-330		med sand	
330-368	very thin bands of sand and yellow traces	dominantly silty clay	
368-383	dark grey, dark to black and pungent	silty sand	5Y 4/1
383-400	fines upward from med silty sands to fine silty/sands	med to fine silty sands	
400-434	interlayering of sandy silts, silty sands and silty-clays, all olive grey on exterior, dark grey to black interior with high organic hash	sandy silts, silty sands, silty-clays	5Y 4/2
434-440	olive grey	med sand	5Y 4/2
44-453	olive grey, some olive color banding	fine silty clay	7.5Y 4/2, 5Y 4/3
453-464	dark grey, finely laminated sandy silt with prominent biotite laminae	sandy silt	5Y 4/1
464-465	Interlayered silty clays (olive grey) and silty sands (fine/med, dark grey)	silty clays, fine/med silty sands	5Y 4/2, 5Y 4/1

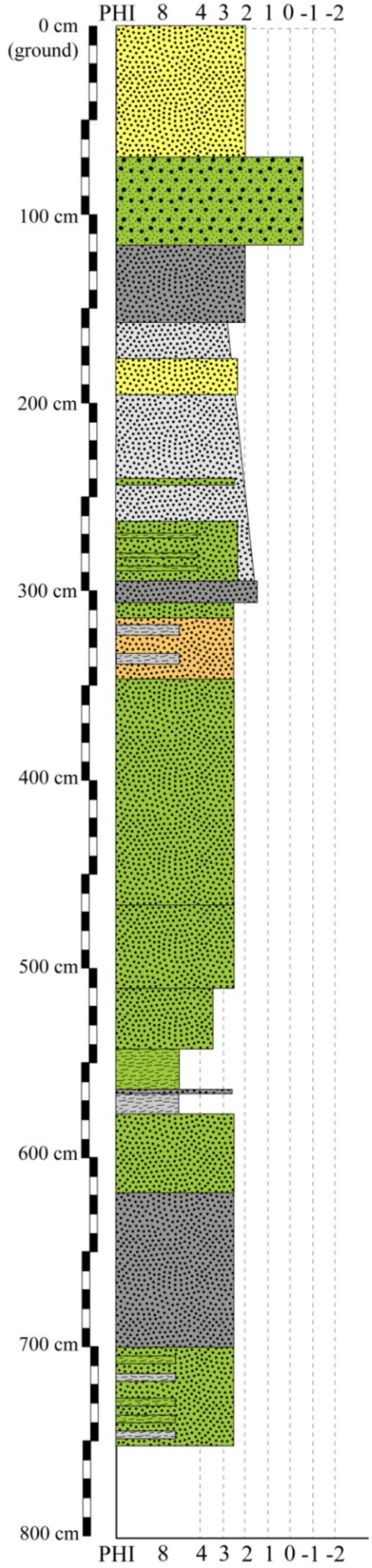

PHI 8 4 3 2 1 0 -1 -2
0 cm
(ground)
100 cm
200 cm
300 cm
400 cm
500 cm
600 cm
PHI 8 4 3 2 1 0 -1 -2

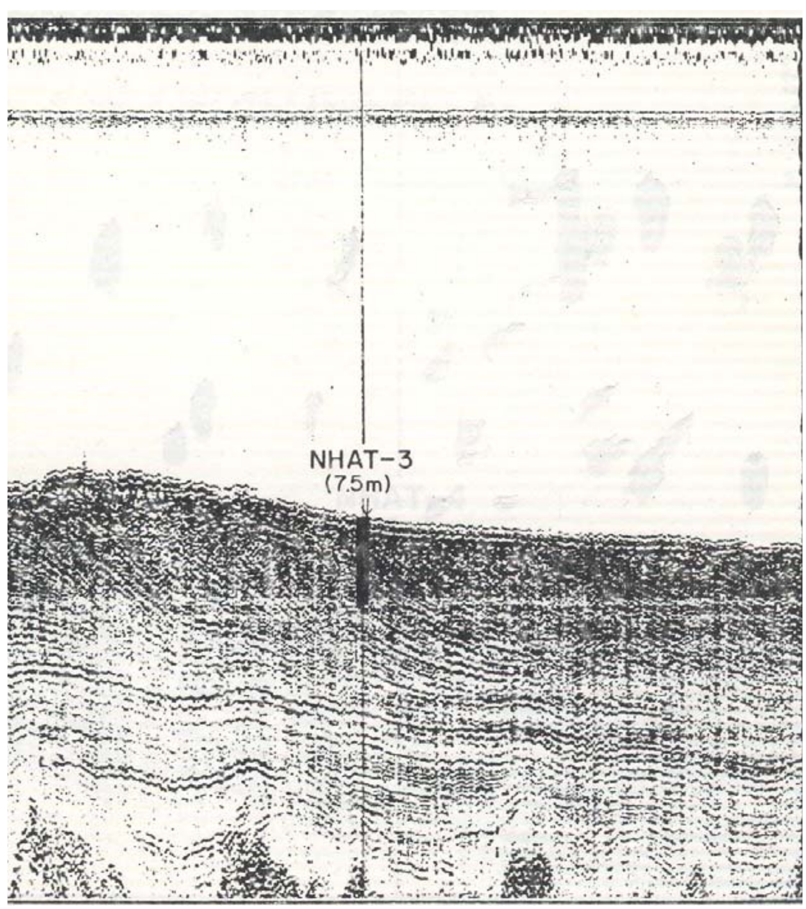

NHAT-2
(5.6m)

CORE LOG #3 (Core NHAT-3)

Depth (cm)	Description	Grain size	Munsel color
0-70	pale yellow, very well sorted with sparse coarse grains (2-3mm), massive, no apparent laminae	Med grain sand	5Y 7/3 to 5Y 8/3
70-118	large pebbles (2-3cm) and abundant thick (up to 4cm) shell fragments grading up into coarse and medium olive sands, appears turbidity in two phases- 70-90cm and 90-118cm, no apparent orientation to shells, very poor sorting	Very coarse	5Y 4/3
118-156	light grey med/fine sand grading up into very fine olive grey sands, some sparse organic blackening	med/fine, fine sand	5Y 7/1, 5Y 5/2
158-308	white sand grading up from med to fine grain size	med to fine (grading)	5Y 8/1 to 5Y 8/2
177-197	pockets of muscovite and biotite hash with peripheral staining of sands to pale yellow		5Y 7/3 (pale yellow)
240-246	pale olive sand, distorted bed plane?		5Y 5/3
262-296	olive sand with interbedded olive sandy silt		5Y 5/3, 5Y 4/3
296-308	light grey		2.5Y 7/2
308-312	olive grey	fine sand	5Y 4/2
312-348	light brownish grey to greyish brown, two prominent bodies of silty clay	fine sand	2.5Y 6/2, 2.5Y 5/2
350-466	semi-well laminated pale yellow to pale olive, some color differences- olive in areas tending towards silty/sand. Heavy content of muscovite and biotite throughout	fine sand	5Y 7/3, 5Y 6/3, 5Y 5/2
476-510	Interlaminated beds of fine sands, light olive grey to pale olive, and silty clays (olive grey). Prominent biotite laminations, sharp basal contacts (?) in bottom of silty clays	fine sands ans silty clays	5Y 62/ to 5Y 6/3, 5Y 4/2
510-541	biotite laminated, grey	very fine sands	5Y 5/1
541-564	olive grey	silty clay	5Y 4/2
565-568	grey	fine sand	
568-576	fine interlaminations of silty clay & biotite hash	silty clay	
576-620	biotite laminated fine sands, olive with olive brown stained laminae		5Y 5/3, 2.5Y 4/9
620-753	fine biotite laminated sands grades down from light grey/grey through greyish/brown to grey	fine sand	2.5Y 5/2, 5Y 5/2
	very heavy biotite laminae		

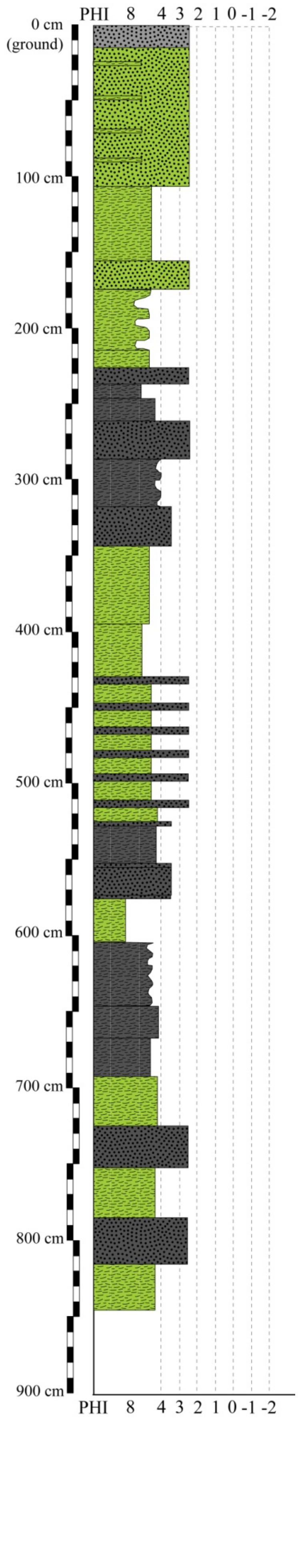
	interlaminated beds of olive grey fine sands and olive brown to dark grey/brown silty clays	fine sands to silty clays	5Y 5/2 (olive grey)





CORE LOG #4 (Core NHAT-4)

Depth (cm)	Description	Grain Size	Munsel Color
0-12/16	fine dark greyish/brown sand		2.5Y 4/?
12/16-107	light grey to light olive grey fine sands interbedded with olive greysilts and clayey silts (olive grey)	fine sands with silts and clayey silts	5Y 7/2, 5Y 6/2, 5Y 5/2
93-104	biotite laminae		
132-153	Olive grey clayey silt (black underneath surface)	clayey silt	5Y 4/2
153-173	Alternating beds of laminar biotite sands (Fine, light olive grey) and clayey silts (olive grey)	fine sands and clayey silts	5Y 6/2, 5Y 4/2
173-214	interbedded clayey silts (olive grey) and silty clays (olive grey)	clayey silts and silty clays	5Y 4/2, 5Y 5/2
215-226	clay silt, olive grey	clay silt	5Y 5/2
226-237	fine, wet, dark grey sand with biotite laminae	fine sand	5Y 4/1
237-246	dark grey silty clay	silty clay	5Y 4/1
246-259	dark grey silt	silt	5Y 4/1
258-261	dark grey silt	silt	5Y 4/1
261-286	dark grey fine sand	fine sand	5Y 4/1
286-319	alternating beds (~2cm thick) of sandy silts and clayey silts	sandy and clayey silts	
319-343	dark grey very fine sand with biotite laminae	very fine sand	5Y 4/1
343-396	olive grey	clayey silt with some sandy silt	5Y 4/2
403-430	olive grey	clayey silt	5Y 4/2
430-515	Alternating beds of fine dark grey sand and olive grey clayey silt to silt to fine sandy silt	sand and clayey silt to silt to fine sandy silt	5Y 4/1, 5Y 4/2
515-523	olive grey	silt	5Y 4/2
523-529	dark grey	very fine sand	5Y 4/1
530-551	dark grey	silt	5Y 4/1
551-555	dark grey	very fine sand	5Y 4/1
555-572	dark grey	very fine sand	5Y 4/1
572-576	dark grey	fine sand	5Y 4/1
577-603	dark grey to olive grey	clay to sub-silty clay	5Y 4/1, 5Y 4/2
603-647	dark grey	alternating clayey silt and silty clay	5Y 4/1
647-669	dark grey	sandy silt	5Y 4/1
pocket	grey	fine sand	5Y 5/1
669-691	dark grey	silty clay and clayey silt	5Y 4/1
691-724	olive grey	sandy silt	5Y 4/2
724-734	very dark grey	fine sand	5Y 3/1
734-783	olive grey	silt grading down to clayey silt	5Y 4/2
783-816	dark grey, biotite laminae following convolutes	fine sand	5Y 4/1
816-849	olive grey, shell and wood fragments	sandy silt	5Y 4/2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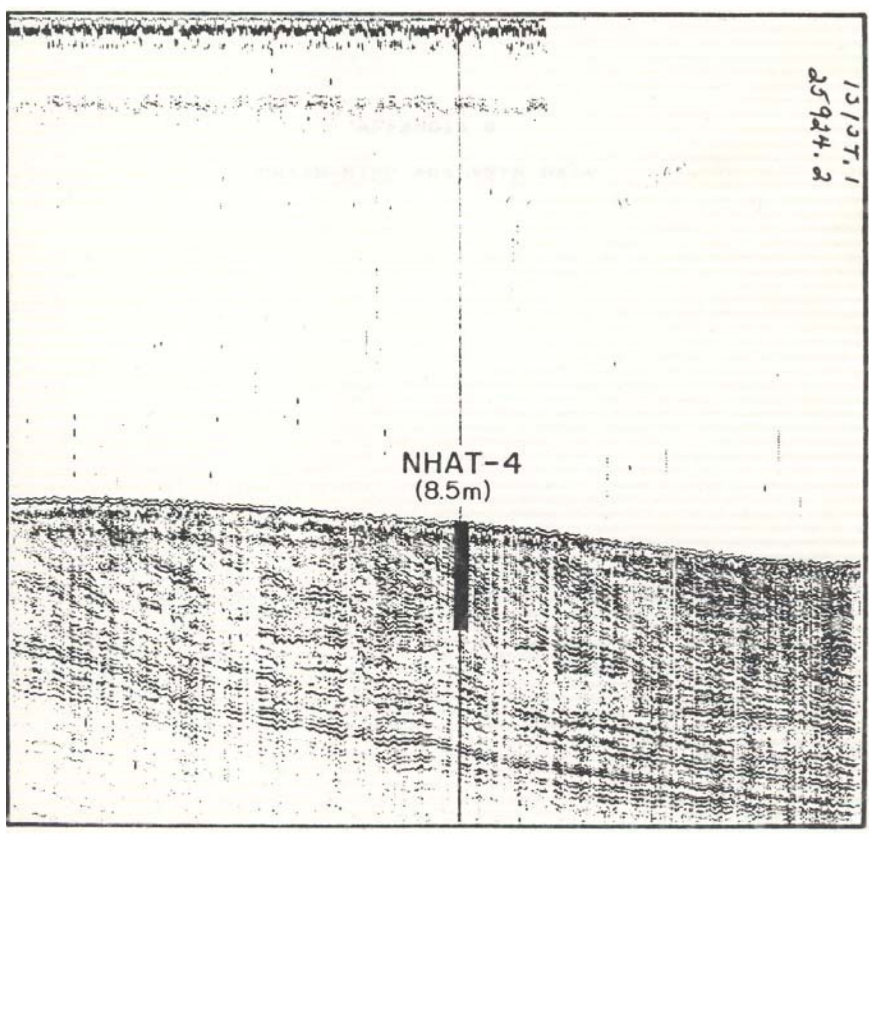
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APPENDIX F
Journal Publications

Journal of Coastal Research	SI 50	pg - pg	ICS2007 (Proceedings)	Australia	ISSN

Holocene reworking of a sand sheet in the Merrimack Embayment, Western Gulf of Maine

C.J. Hein†, D.M. FitzGerald†, and W. Barnhardt‡

†Department of Earth Sciences
Boston University, Boston, MA
02215, United States of America
hein@bu.edu, dunc@bu.edu

‡ United States Geological Survey
Woods Hole, MA
02543, United States of America
wbarnhardt@usgs.gov

ABSTRACT

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Recent bathymetric, backscatter, and seafloor sediment samples demonstrate that a large sand sheet was formed in the inner shelf by the reworking of the Merrimack River lowstand delta (deposited 12 kya; currently at 45 m depth) and braid plain during the Holocene transgression. Asymmetric bedforms and distinct grain size distributions suggest the sand sheet is actively being reworked by inner-shelf processes.

Bottom sediments range from silty sand at the submerged delta to coarse sand and fine gravel in the innermost shelf (depth: 10-50 m). Coarse-grained sand comprises an expansive (32 km^2) featureless sand sheet centered off the Merrimack River. Fine-grained sand discontinuously overlies this sand sheet in many locations and forms long wavelength (100 – 800 m), low amplitude (1-2 m), asymmetrical bedforms. Sets of these bedforms are oriented from slightly oblique offshore to onshore; several bedform sets are located within 1 km and oriented orthogonally to one another. Along the paleo-delta front north-northwest oriented bedforms are dominant. Inshore of these features, the bedforms become more closely spaced and have orientations to the west and west-southwest. Preliminary data suggest that the combined forcings of instantaneous storm-wave generated shear stress and storm-induced currents associated with high energy northeast storm events may be responsible for sand sheet reworking and bedform development.

ADDITIONAL INDEX WORDS: *Backscatter, bedforms, shallow seismic, shelf sediment transport*

INTRODUCTION

The barriers, marshlands, tidal inlets, and waterways comprising the Merrimack Embayment in the western Gulf of Maine are some of the most important economic and recreational resources and wildlife habitats of the north shore of Massachusetts. There is growing pressure in the public and private sectors to further develop and utilize these barrier and tidal inlet systems. However, the construction of anthropogenic structures and a natural depletion of glacial and riverine sediment sources have combined to diminish the supply of sediment to the region. This has caused an increase in the relative importance of the continental shelf as a natural source of sediment to these barrier systems. It is therefore crucial to develop an understanding of the processes responsible for the reworking of inner shelf sediments in the Merrimack Embayment and how these processes may be affected by accelerated sea level rise.

Physical Setting

The Merrimack Embayment in the Gulf of Maine is a mixed-energy, tide-dominated coast, extending from Cape Ann in northern Massachusetts north to Great Boar's Head in New Hampshire (Figure 1). It is the longest continuous barrier island chain in the Gulf of Maine (approximately 34 km long) with a backbarrier system consisting primarily of marsh and tidal creeks that often enlarge to small bays near the inlet openings (SMITH and FITZGERALD, 1994). The barrier islands are pinned to bedrock or glacial promontories and tidal inlets are situated in drowned river valleys (FITZGERALD et al., 2002). The Merrimack River heads in the White Mountains of New Hampshire with a catchment of approximately 13,000 km^2. The river drains regions dominated by granitic plutons, which produced extensive sandy glacial deposits (NHDES, 1986). Sediments discharged from the mouth of the Merrimack are subsequently reworked in a southeasterly alongshore direction as a result of strong northeasterly storm waves associated with Northeasters (FITZGERALD et al., 2002).

STONE et al. (2004) have used a variety of data to construct a late Quaternary sea-level curve for the region. Following the Wisconsin sea level highstand (+33m) at about 17 kya, this region experienced rapid isostatic rebound resulting in a -45 m lowstand at 12 kya. During the late regression and lowstand the Merrimack River deposited a large delta that is currently located approximately 6 to 7 km offshore and trends parallel to the present coast (OLDALE et al., 1983 and EDWARDS, 1988). The paleo-delta is 20 km long, 4 to 7 km wide, up to 20 m in thickness and contains about 1.3 billion m^3 of sediment (OLDALE et al., 1983, 1993). Seismic reflection profiles show that the eastwardly-dipping delta foresets were truncated during the early Holocene transgression of this region (OLDALE et al., 1983). Much of the surface of the delta exhibits a ravinement surface that is inferred to be a time transgressive marine unconformity formed during the Holocene marine transgression. Large areas have been subsequently overlain by beach or bar deposits (OLDALE et al., 1983). EDWARDS (1988) described these sandy shelf deposits as a discontinuous, planar, palimpsest surficial sand sheet of varying thickness and in disequilibrium with present-day processes.

EDWARDS (1988) also reported “linear ridges” that he attributed to having formed as transgressive or post-transgressive features; e.g. degraded barriers that formed as sea level rose and sediments were reworked in an onshore direction or active shoreface-connected ridges that form in the present day in response to peak flow conditions during northeasters.

Several papers have examined the relationship between the offshore paleo-delta, and its contribution to the onshore barrier system (OLDALE et al., 1983; EDWARDS, 1988; FITZGERALD et al., 1994). This paper presents recent bathymetric, backscatter intensity, and seafloor sediment data that provide new evidence for the partial reworking of the paleo-delta deposits that continues to the present time.

METHODS

From 2004-2006, several research cruises mapped the sea floor of the Merrimack Embayment (323 km^2 area) from the nearshore zone to about 17 km offshore, using single beam, multibeam, interferometric and sidescan sonar. Additionally, 1050 km of high resolution seismic reflector profiles were obtained in the study area using a CHIRP sub-bottom profiler. Bottom photography and grab samples were used to ground truth the remotely sensed acoustic data at more than 100 locations. After a preliminary analysis of bedform fields in the study area, this study focused on the sediment distribution within a single bedform field.

Samples were collected along several transects in a set of long wavelength (600-700 m), north-facing bedforms situated 4-6 km north of Cape Ann. Samples were taken along the stoss face of the bedform, at the crest, in the high backscatter trough, and at some distance from the crest and trough. All sediment samples were analyzed using standard dry and wet sieving techniques and a Beckman Coulter Multisizer 3 for fine fractions (POPPE et. al., 2000). Raw seafloor geophysical data were processed by the USGS using a suite of software (Swathid, XSonar, Sidseis, and Seisworks). These data were further analyzed using ArcGIS.

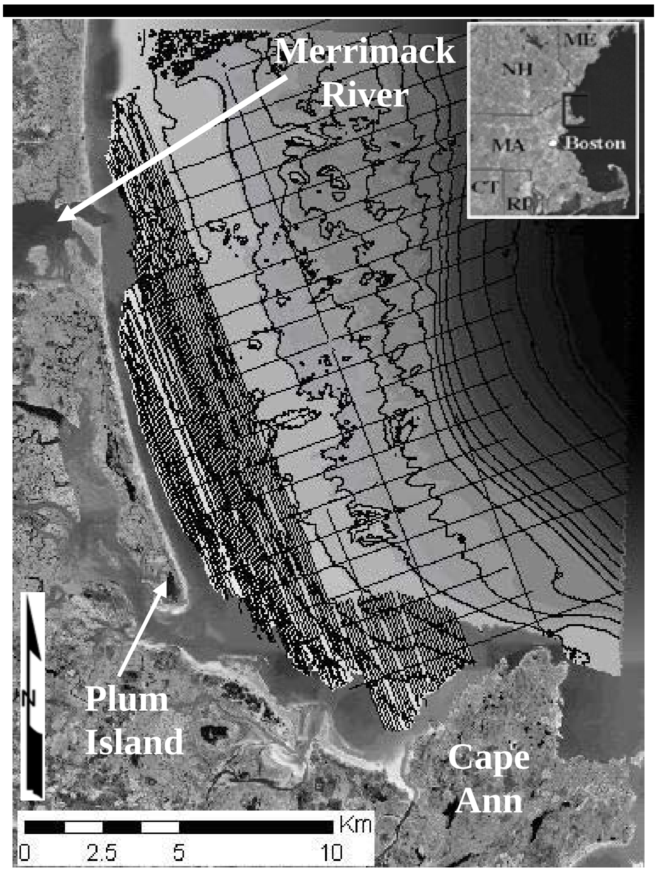

Figure 1. Study area in northern Massachusetts. Offshore study area shown in grayscale bathymetry with black isobath lines (contour interval = 5m). Parallel track lines (black) run NW-SE with shore-normal tie lines.

RESULTS

Bathymetric and backscatter surveys reveal complex patterns of surficial sediment reworking. Features characterized by high backscatter intensity cover approximately 40% of the sea floor in the study area. Sediments in this region are composed of coarse-grained sands to fine gravels (mean φ is 0.61; mode φ is 0.53) and are dominated by two-dimensional megaripples (small 2D dunes, ASHLEY, 1990) with wavelengths of about 1m. The troughs of these megaripples are commonly filled with shell hash.

The inner, sand-dominated area of the Merrimack Embayment has been subdivided into several distinct regions on the basis of morphology and grain size (Figure 2). A continuous, flat-lying sand sheet (Region A, Figure 2) is centered off the mouth of the Merrimack River and is approximately 8 km (N-S) x 4 km (E-W). Bedrock dominates the sea floor north of this sand sheet. The sand sheet becomes diffuse in a south and offshore direction transitioning into a series of linear to cuspate features surrounded by low backscatter sediments (Figure 2B). In these locations, fine-grained sands discontinuously overlie coarser deposits that are nearly identical in size to the sand sheet sediments.

Low to medium backscatter areas (Region B, Figure 2) contain fine- to medium-grained sand (mean φ is 2.42; mode φ is 2.34) dominated by three dimensional, cuspate ripples (small 3D dunes, ASHLEY, 1990) with wavelengths of about 20 cm. Contacts between these regions of coarse and fine sands are sharp. These sands are ubiquitous throughout the study area and are similar in sedimentological character to those that surround the coarse-grained linear depressions.

The lowest backscatter intensity regions (darker pixels in backscatter imagery) comprise 25% of the sea floor, mostly in water deeper than about 50 m depth and represent low reflective ocean mud offshore of the paleodelta. These sediments consist of fine-grained sands (mean φ is 3.62; mode φ is 4.00) and deeper seaward regions consist of fine-grained mud (mean φ is 5.84; mode φ is 5.71). Mud-draped boulder fields (Region C, Figure 2) are found throughout the study area and are interpreted as either bedrock outcrops, or closer inshore, boulder lag deposits from eroded drumlins. Mud deposits represent post-transgressive deposition.

Low amplitude, long wavelength bedforms occur throughout the inner shelf (d < 50 m). Three discrete sets of bedforms are mapped according to predominant orientation in Figure 3 and described in Table 1. When these bedforms are plotted on a height-spacing diagram, (Figure 4), they tend to group according to their orientation. In the deep portion of the inner shelf (35-50 m) long wavelength, asymmetric, north-northwest-oriented bedforms dominate. In the northern sector, these features are relatively large and are oriented in a NNE-SSW direction. Elsewhere, subordinate forms are oriented ENE-WSW and ESE-WNW. Northwest-oriented bedforms have similar spacing but generally larger heights. Inshore of these features, the bedforms become more closely spaced and exhibit a west to west-southwesterly orientation. These features group tightly in Figure 4 with spacings between 150 and 350 m and heights from 0.5 to 1.5 m. In several locations, bedform sets have orthogonal orientations within 1 km of each other.

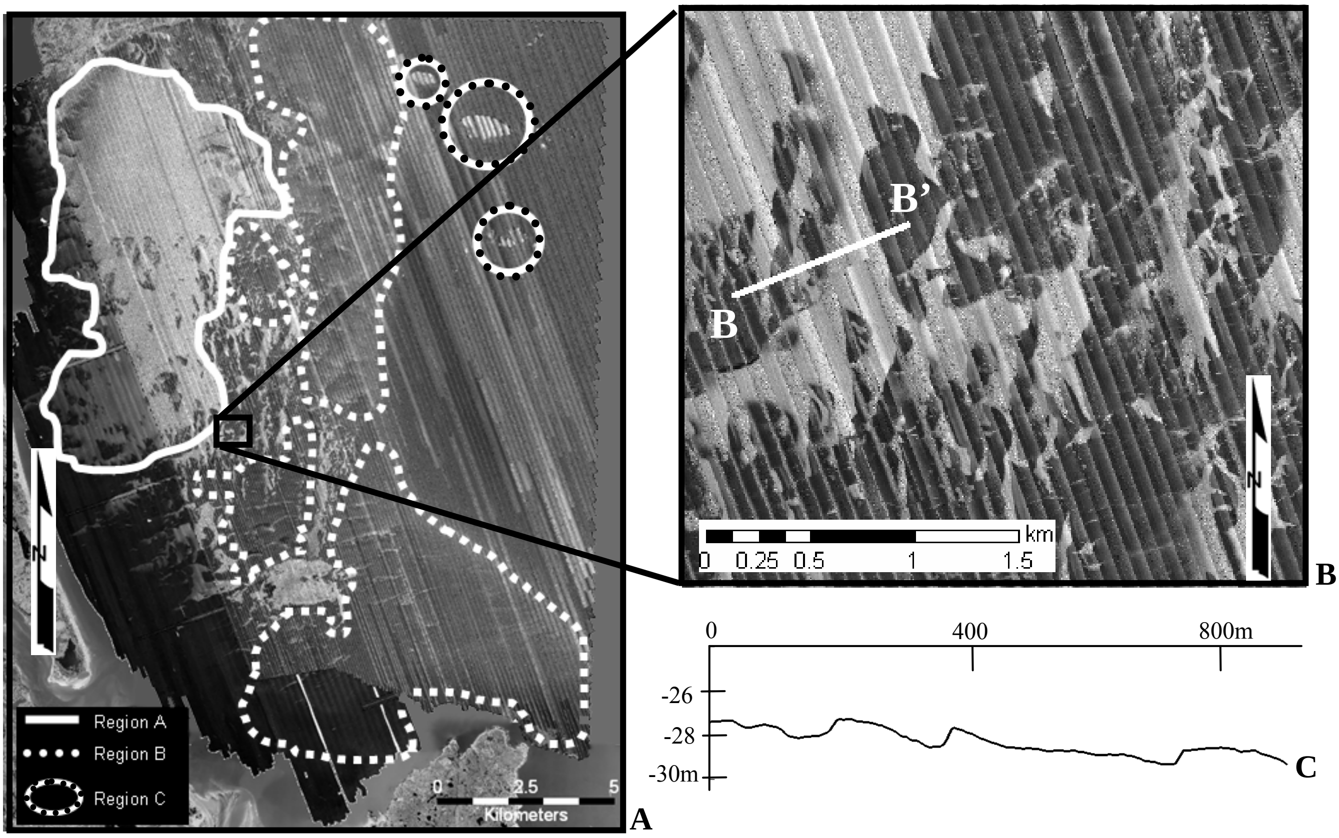

Figure 2. A) Backscatter map of Merrimack Embayment. Regions of the sea floor mapped based on the bathymetric, backscatter, and sedimentological data. Regions indicate the coarse-grained sand sheet (Reg. A), fine- to medium-grained sand (Reg. B), and offshore bedrock (Reg. C). B) Close up of coarse-grained linear depressions. Light color represents high backscatter regions and darker colors represent low backscatter. C) Profile B-B' across coarse-grained linear depressions as marked in (B). Note asymmetric form with steeper lee face oriented to the west.

Grain size analysis of seafloor samples taken within the bedform fields revealed nearly identical trends where fine-grained sands (+3 phi) comprise the stoss and crestal areas and coarser sands (1 phi) are confined to the troughs. This grain-size distribution can be explained by the common phenomenon of coarser sediment being preferentially concentrated in the troughs (Jopling, 1964); alternatively, erosion in the trough may be exposing the underlying coarser sand beneath the bedforms.

DISCUSSION

The enlarged troughs, coarse-grained nature of the sediments, and geometry of the inshore bedforms suggest that these features are similar to rippled scour depressions (RSD; Cacchione et al., 1984; Schwab et al., 2000; Green et al., 2004; Ferrini and Flood, 2005) or sorted bedforms (Murray and Thieler, 2004; Gutierrez et al., 2005; Goff et al., 2005). RSD are subtle bathymetric lows (~1 m) consisting of coarse sand, shell hash and ripples (wavelengths on the order of 1 m) surrounded by finer sands. They are commonly oriented oblique or normal to the shore and been observed in sediment-starved and microtidal settings. These features are typically 100-200 m wide and extend hundreds of thousands of meters on the inner shelf (Cacchione et al., 1984). Sorted bedforms, as observed off Wrightsville Beach, NC and described by Murray and Thieler (2004) are asymmetric with coarse sediment forming bathymetric lows on the updrift (in reference to alongshore flows) sides of the features. Additionally, sorted bedforms have sharp contacts along their updrift sides and "wispy" downdrift contacts with surrounding finer sediments.

Though the coarse-grained bedforms of the Merrimack Embayment (Figure 2B-C) are of similar shape and size to RSD, this is a tide-dominated environment with a sizeable sediment supply. These features generally have sharp boundaries around all sides, similar to RSD but dissimilar to sorted bedforms. However, they do contain the 2D ripples common to sorted bedforms. One important difference is that the coarse-grained features of the Merrimack Embayment lack the shore-normal elongated geometry that characterize documented RSD and sorted bedforms.

Cacchione et al. (1984) suggest that RSD are produced by intensified cross-shore flow resulting from storm-induced set-up. These flows preferentially winnow fine material leaving a coarse lag elongated parallel to flow. Schwab et al. (2000) argued that along-shelf processes are responsible; yet both explanations suggest concentrated bottom flows along the primary axis of the features. Murray and Thieler (2004) suggest that sorted bedforms are self-organized; that is they result from the interaction of wave motions with coarse-grained ripples within smaller sorted forms. The turbulence of these interactions is such that finer material remains entrained in the flow while coarser sediments are deposited within the bedforms. This positive feedback perpetuates the formation of the sorted bedforms.

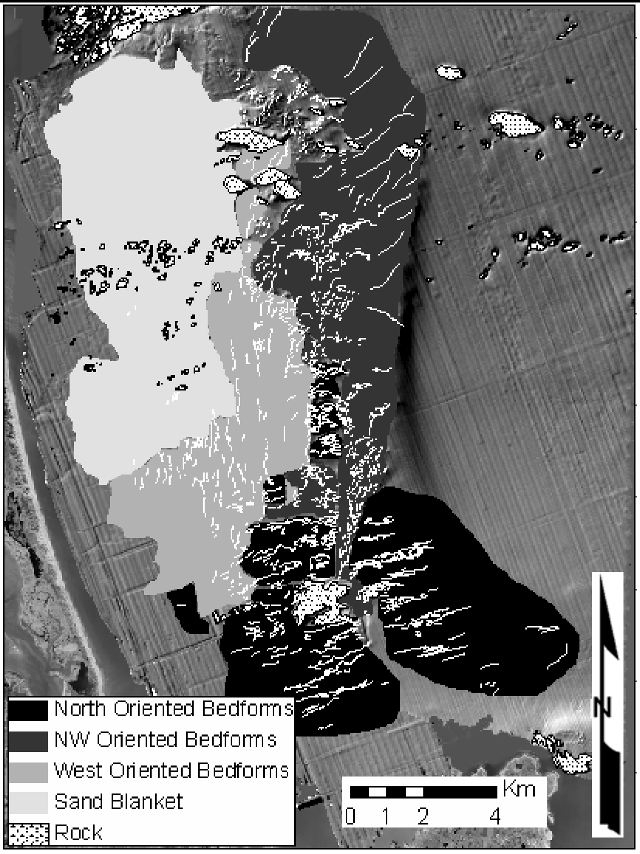

Figure 3. Map of bedform fields with crests traced in white lines.

A number of processes are probably responsible for the complex patterns of surficial sediment and bedforms seen in the Merrimack Embayment. The pronounced asymmetry and varied orientation of the features within the Merrimack Embayment indicate that they are long wavelength sandwaves, possibly formed from the same turbulent boundary layer processes proposed for sorted bedforms (MURRAY and THIELER, 2004). Bedforms occur in fields having a similar height and wavelength, thus suggesting that more than one process or factor controls their geometry and orientation.

Bottom current data from the Gulf of Maine Ocean Observing System (GOMOOS, 2006) Buoy B (Station 44030, Buoy B0102) on the western Maine shelf (approximately 50 km north of the mouth of the Merrimack River) indicate that bottom currents in 60 m of water reach speeds of 20-30 cm/sec during spring tide conditions and even greater magnitude during storms. Intense extratropical cyclones (northeast storms) regularly affect the coast of Massachusetts (FITZGERALD et al., 1994) and a preliminary analysis of the GoMOOS buoy data suggests that waves produced by these storms generate bottom shear stresses strong enough to move the sediment that blankets the sand sheet to a depth of at least 50 m (KOMAR and WANG, 1984).

Patterns of reworking may also be influenced by the underlying geology and existence of the large Cape Ann promontory (south of the Merrimack Embayment). Numerous studies have shown that storm surges can induce coastal set up capable of inducing downwelling and creating horizontal pressure fields strong enough to stimulate near-bottom currents and drive offshore sediment transport (HARPER et al., 1988; GOURLAY, 1990; HEQUETTE et al., 2001; HEQUETTE and HILL, 1993). Large northeast storm surges in the Gulf of Maine, coupled with the Cape Ann promontory may be significant enough to create a similar system in this region.

Preliminary analysis of shallow seismic reflection data suggests that braided stream deposits and underlying bedrock are spatially discontinuous in the subsurface. Relict topography and sediment distributions related to reworking during the Holocene transgression may also contribute to the patterns of surficial sediment distributions. Analysis of the shallow seismic reflection data is currently underway to investigate the effects of bedrock and paleodelta sequence deposits on bedform field development.

Future work in this region will include instrument deployments to measure horizontal and vertical current profiles, turbidity, and wave parameters during large northeast storms. These data will serve as calibration for hydrodynamic modeling (Finite Volume Coastal Ocean Model; CHEN et al., 2003) that will simulate storm generated currents and sediment transport.

Table 1: Description of bedform sets

Bedform Field	Location	Depth	Avg. Wave-length	Avg. Height
North to NNW Oriented	Southern & offshore regions along paleodelta front	35 – 50 m	500 m	1.0 m
Northwest Oriented	Northern reaches of paleodelta front, along -45m contour	35 – 50 m	500 m	1.9 m
WNW to West Oriented	Inshore of delta front; bordering east and southeast of sand sheet	10 – 35 m	250 m	1.0 m

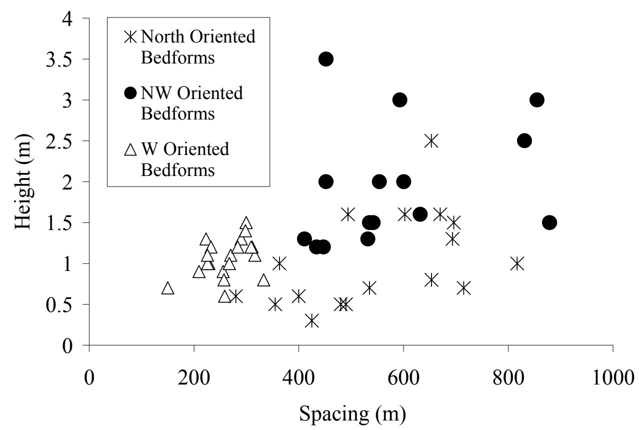

Figure 4. Height vs. Spacing graph of representative bedforms from each of 3 bedform orientation fields.

CONCLUSIONS

1. A broad sand sheet (18km x 7km) extends from approximately 2 km north of Cape Ann to 4 km north of the mouth of the Merrimack River and from the nearshore (10 m depth) to the paleo-delta front (45 m). This sand sheet consists of silty sand in the outer reaches near the delta and coarse-grained sand further inshore. An expansive (32 km^2), featureless, coarse-grained sand deposit is centered off the Merrimack River. Fine-grained sand discontinuously overlies this deposit in many locations and forms asymmetrical bedforms.

2. The surface of the sand sheet shows extensive reworking evidenced by the existence of several, large-scale bedform fields having a variety of alignments. Four km offshore of the southern end of Plum Island, two bedform fields located within 1 km of each other exhibit orthogonal orientations. Grain size analysis of surface samples taken across representative bedforms indicates that either coarser sediment is being preferentially concentrated in the troughs or excavation of fine-sands in the trough may have exposed the underlying coarse sand sheet beneath the bedforms. The geometric and sedimentological diversity of the bedform field likely reflects the forcing of storm-generated currents and the influence of local topography and shoreline geometry.

ACKNOWLEDGEMENTS

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HOLOCENE EVOLUTION OF THE MERRIMACK EMBAYMENT, NORTHERN MASSACHUSETTS, INTERPRETED FROM SHALLOW SEISMIC STRATIGRAPHY

Christopher J. Hein[1], Duncan M. FitzGerald[2], Walter A. Barnhardt[3]

1. Department of Earth Sciences, Boston University, 675 Commonwealth Ave., Boston, MA 02215, USA.
   hein@bu.edu
2. Department of Earth Sciences, Boston University, 675 Commonwealth Ave., Boston, MA 02215, USA.
   dunc@bu.edu
3. United States Geological Survey, Woods Hole Science Center, 384 Woods Hole Road, Quissett Campus, Woods Hole, MA 02543-1598, USA.
   wbarnhardt@usgs.gov

Abstract: Recent multi-beam, backscatter, and bottom sediment data demonstrate that a large sand sheet was formed in the inner shelf by the reworking of the Merrimack River lowstand delta and braid plain (12 kya) during the Holocene transgression. Seismic data reveal the presence of widespread channel cut-and-fill structures landward of the delta suggesting that much of the sand sheet consists of braided stream deposits. These features map into several sets of cut-and-fill structures, indicating the avulsion of the primary river channels, which created the lobes of the paleo-delta. Truncations of these cut-and-fill structures suggest that the braid plain deposits were probably reworked during the Holocene transgression and may have contributed sand to developing barriers that presently border the Merrimack Embayment.

INTRODUCTION

Global warming is causing increased melting of ice caps and mountain glaciers and the expansion of surface ocean waters, which is accelerating sea-level rise (SLR). The 2001 IPCC Report predicted SLR by 2100 to be between 48 and 88 cm (Church 2001). Concurrently, riverine supply of sediment to the coastal zone in northern latitudes has diminished due to dam construction and natural depletion of glacial sediment sources. The lack of new sand sources has led to pervasive beach erosion and shoreline retreat not only in New England, but throughout the US and the world. Thus, the potential sand reservoirs of the inner continental shelf and the mechanisms of sand exchange between beaches and barriers and the offshore are vital topics of research for the coastal community (Pilkey and Field 1972). Presently, the pathways, volumes, and net direction of sand exchange between the nearshore zone and offshore (the inner shelf) are not known (Morton et al. 1994). However, if shoreface sand is being lost to the inner shelf sand sheet, as suggested by several recent studies (e.g. Gayes et al. 1997; Swift and Thorne 1991), then the coastal zone and the populations and infrastructure it supports ($3 trillion along the US East and Gulf Coasts alone [USGS 2006]) may be under serious threat from accelerated SLR.

To investigate the reworking of nearshore sediments in a regime of accelerated SLR, it is crucial to understand the processes that govern the origin and distribution of sand bodies on continental shelves. To understand the source and behavior of these sediments, it is important to understand both their sedimentologic history and the present processes driving sediment transport. This paper presents a preliminary analysis and interpretation of nearly 4,000 km of shallow seismic data from the nearshore region of the Merrimack Embayment in the western Gulf of Maine and provides a sedimentologic framework for developing an evolutionary model of the 34 km-long barrier system within the embayment.

Physical Setting

The Merrimack Embayment in the Gulf of Maine is a mixed-energy, tide-dominated coast, extending from Cape Ann in northern Massachusetts north to Great Boar’s Head in New Hampshire (Figure 1). It is the longest barrier island chain in the Gulf of Maine (approximately 34 km long) with a backbarrier system consisting primarily of marsh and tidal creeks that often open to small bays near the inlet openings (Smith and FitzGerald 1994). The barrier islands are pinned to bedrock or glacial promontories with the tidal inlets are situated in drowned river valleys (FitzGerald et al. 2002). The Merrimack River heads in the White Mountains of New Hampshire with a catchment of approximately 13,000 km^2 (FitzGerald et al. 1994). The river drains regions dominated by granitic plutons, the weathering of which produced extensive sandy glacial deposits. Sediments discharged from the mouth of the Merrimack are subsequently reworked in a southeasterly alongshore direction as a result of strong northeasterly storm waves associated with Northeasters (FitzGerald et al. 2002).

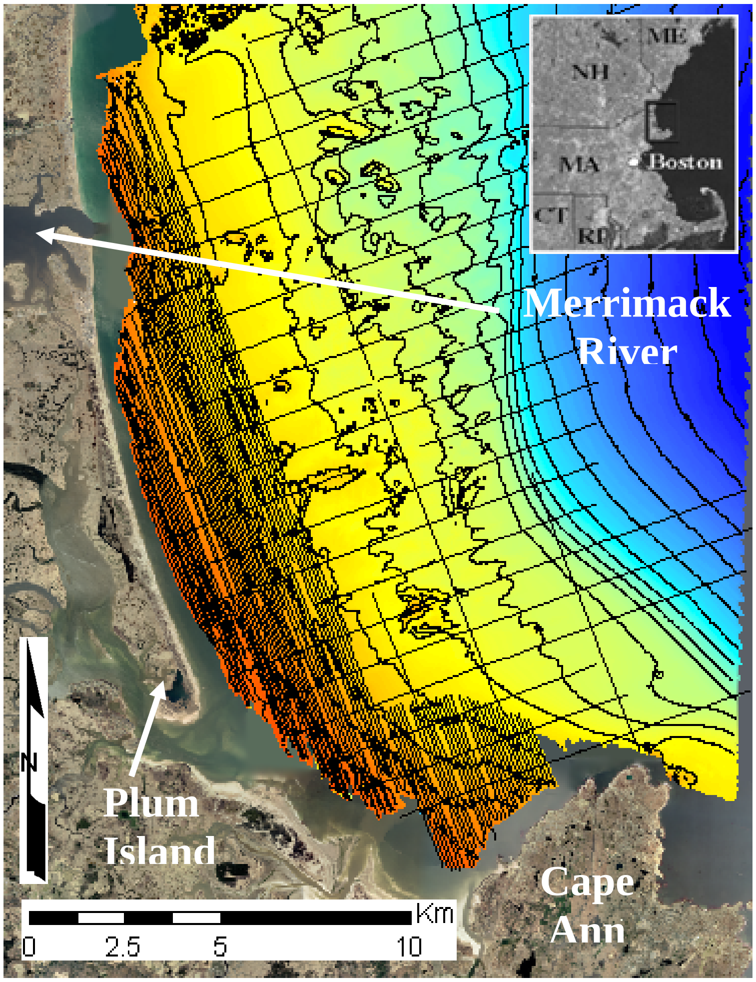

Fig. 1. Study area in northern Massachusetts. Offshore study area shown in grayscale bathymetry with black isobath lines (contour interval = 5m). Parallel track lines (black) run shore parallel with shore normal tie lines.

Stone et al. (2004) used a variety of data to construct a sea-level curve that incorporates a rheological model for the region. Following the Wisconsin sea level highstand (+33m) at about 14 kya, this region experienced rapid isostatic rebound resulting in a -45 m lowstand at 12 kya. During the regression and subsequent lowstand, the Merrimack River deposited a large delta that is currently located approximately 6 to 7 km offshore and trends parallel to the present coast (Oldale et al. 1983; Edwards 1988). The paleo-delta is 20 km long, 4 to 7 km wide, up to 20 m in thickness and contains about 1.3 billion m^3 of sediment (Oldale et al. 1983, 1993). Earlier seismic records showed that eastwardly-dipping delta foresets were truncated during the early Holocene transgression of this region (Oldale et al. 1983). Much of the surface of the delta exhibits a ravinement surface that is inferred to be a time transgressive unconformity formed during the Holocene marine transgression and subsequently overlain by beach or bar deposits (Oldale et al. 1983). Edwards (1988) described these sandy deposits as a discontinuous, planar, palimpsest shelf surficial sand sheet of varying thickness and in disequilibrium with present-day processes. Edwards (1988) also reported "linear ridges" that he hypothesized formed during the transgression or as post-transgressive features; i.e. either degraded barriers that formed as sea level rose and sediments were reworked in an onshore direction or active shoreface-connected ridges that form in the present day in response to peak flow conditions during northeasters.

Several papers have since reexamined the formation and evolution of the barrier system in relation to the offshore paleo-delta (Oldale et al. 1993; FitzGerald et al. 1994). However, these efforts have relied on the interpretation of limited (2 km spacing) seismic data and only 4 vibracores that provided little information on the detailed morphology and nature of the sub-bottom stratigraphy. Recent shallow seismic data provide new evidence for the partial reworking of the paleo-delta deposits that continues to the present time.

METHODS

During February - March 2004, September 2005, and September 2006 the sea floor of the Merrimack Embayment (323 km^2 area) from the nearshore zone to about 17 km offshore was mapped using single beam, multibeam, and side scan sonar. Additionally, 3,857 km of shallow seismic track lines were taken in the study area using an Edgetech SB-512 CHIRP sub-bottom profiler. Shallow seismic track lines were primarily oriented shore parallel and were taken within the first 1-2 km of the present shoreline (depths of less than 30 m) with 100 m spacing between lines (Figure 1). Several sets of shore normal lines with approximately 750 m spacing were also taken.

Shallow seismic data were georeferenced and analyzed using ESRI's ArcGIS Desktop software package. Cut-and-fill features in the shallow seismic profiles were traced across profiles and mapped throughout the study region.

RESULTS

Shallow Seismic Surveys

The locations of shallow seismic profiles analyzed in this section are given in Figure 2. Shallow seismic data from the paleo-delta region exhibit pervasive shallow, seaward dipping reflectors that become tangential with the sediment bottom in an offshore direction. In most cases, the surface of the clinoforms are truncated and overlain by thin flat-lying deposits. Track lines normal to the coast show a consistent pattern of seaward dipping clinoforms and a pronounced ravinement surface, confirming previous observations that the upper portions of the delta were eroded during the Holocene transgression (Figure 3). However, it is still not known how much of the upper delta was removed during the reworking process.

Shore parallel profiles reveal the existence of channel cut-and-fill structures in the region onshore of the paleo-delta. These features trend in an E-W direction and are commonly several meters in thickness, varying in width from about 25 to several hundred meters. Several large sets of cut-and-fill features range from 500 to 600 m wide and 10 to 15 m deep. Shore normal seismic lines confirm the nearly shore normal orientation of these features. In some locations, the orientation and geometry of these features closely resembles that of underlying bedrock surfaces (Figure 4). Several of the cut-and-fill features exhibit structures interpreted as the result of river terracing; i.e. sets of parallel horizontal reflectors on either side of a deeper incised channel (Figure 5). Within any given region, the spatial distribution of cut-and-fill features varies from a highly organized network to a random distribution. However, several examples exist of a single structure retaining an identical geometry across numerous parallel profiles representing hundreds of meters in a shore normal direction (Figure 6).

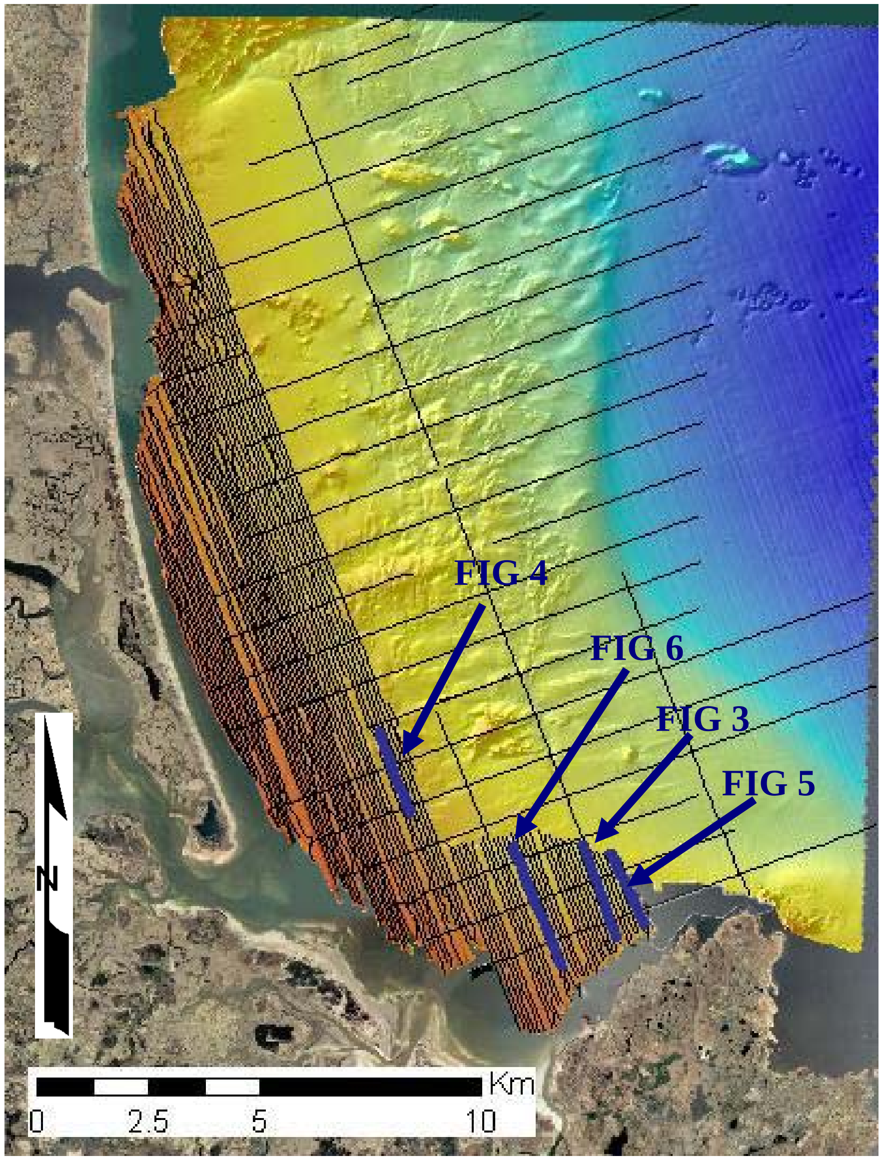

Fig. 2. Locations of tracklines shown in Figures 3-6

A continuous, near-horizontal reflector, interpreted to be an erosive ravinement surface, overlies the cut-and-fill features. This layer is in turn overlain by several (3-8) meters of sediment, interpreted to be Holocene deposits (Figure 3). Generally, the thickness of this Holocene layer decreases in a shoreward direction, resulting in a shallowing of the ravinement surface in the profiles. In the nearshore profiles the channel cut-and-fill features loose their distinct character and are not ubiquitous. In the most nearshore profiles, the cut-and-fill features breach the subsurface and appear to be within a zone of active reworking. These changes in the character of the sub bottom likely reflect reworking during the Holocene.

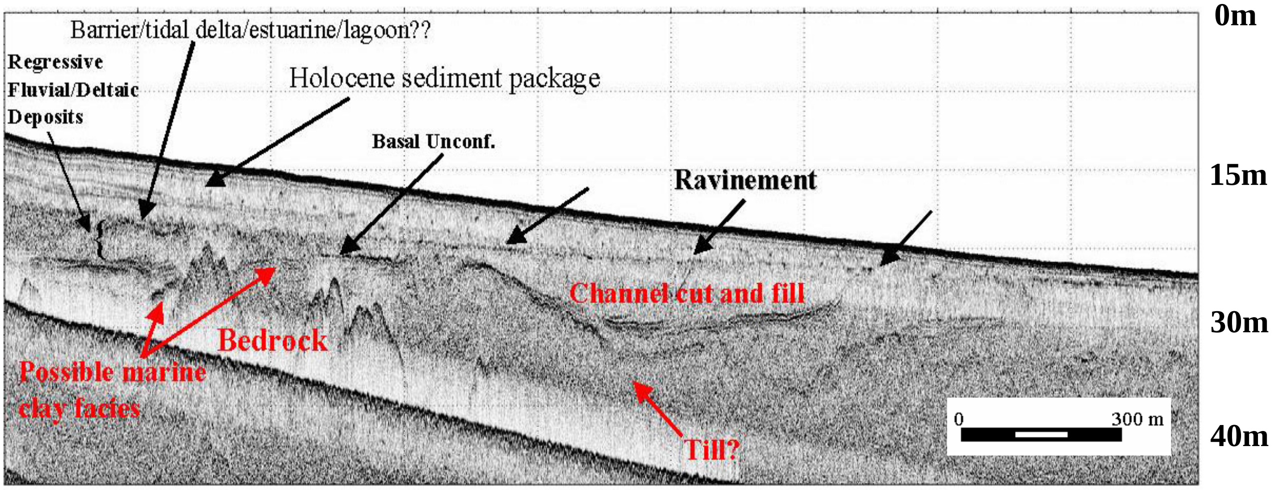

Fig. 3. Sample shallow seismic line indicating general features seen in both shore normal and shore parallel transects (Seismic shot L101f1).

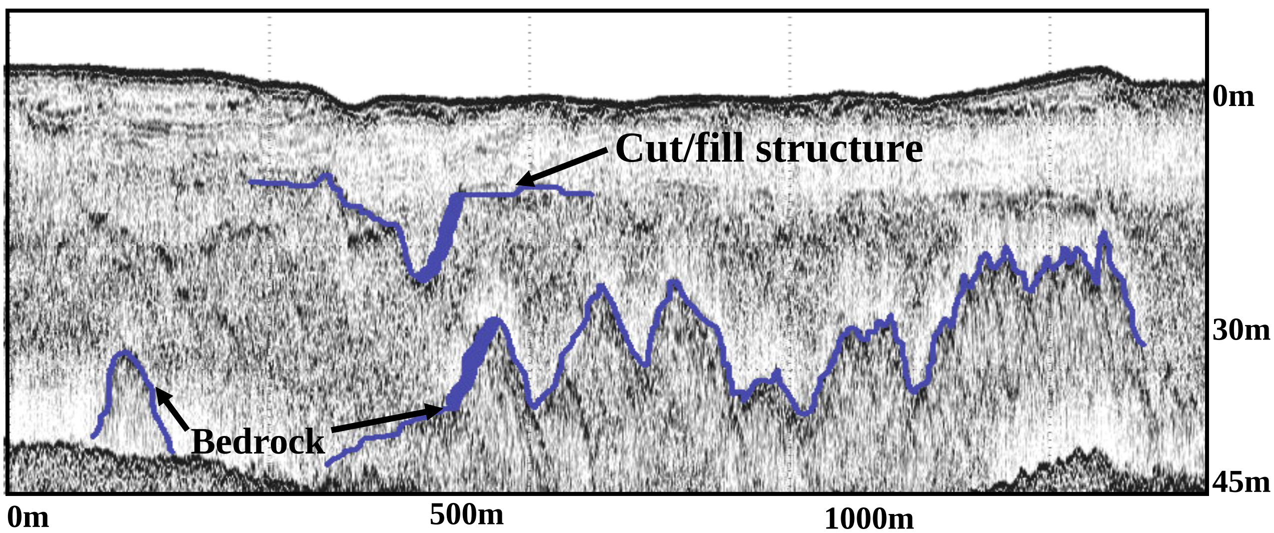

Fig. 4. Sample shallow seismic line indicating a channel cut-and-fill structure overlying bedrock. The bolded lines highlight the close correlation between the geometry of the bedrock and the side of the channel (Seismic shot L5f2).

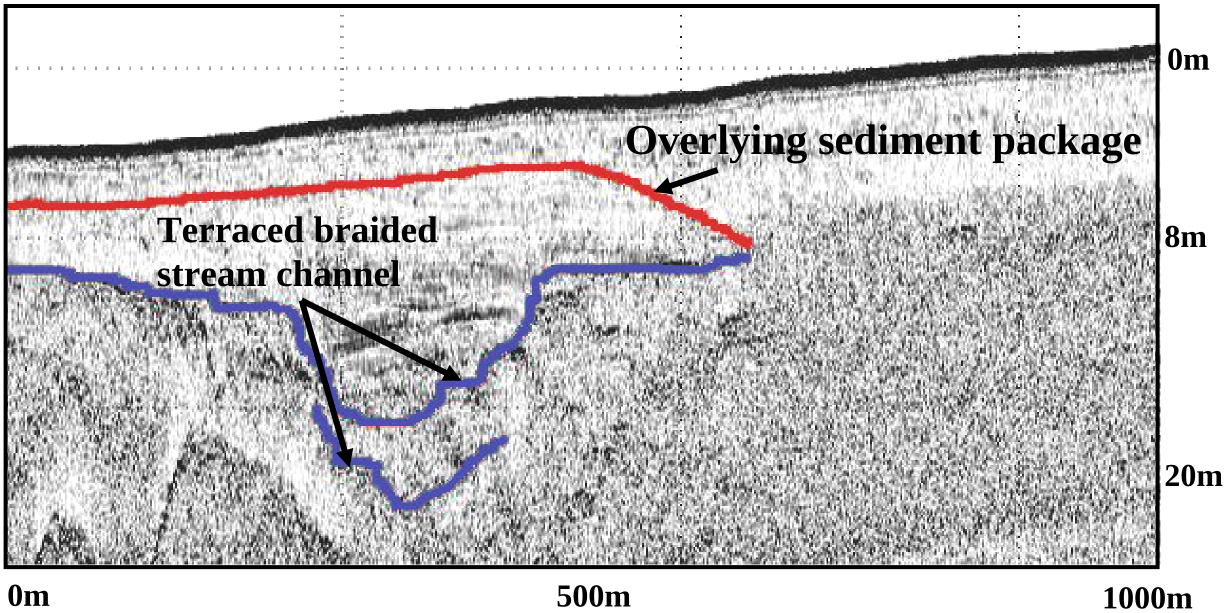

Fig. 5. Evidence of terracing in channel cut-and-fill structures (Seismic shot L106f1).

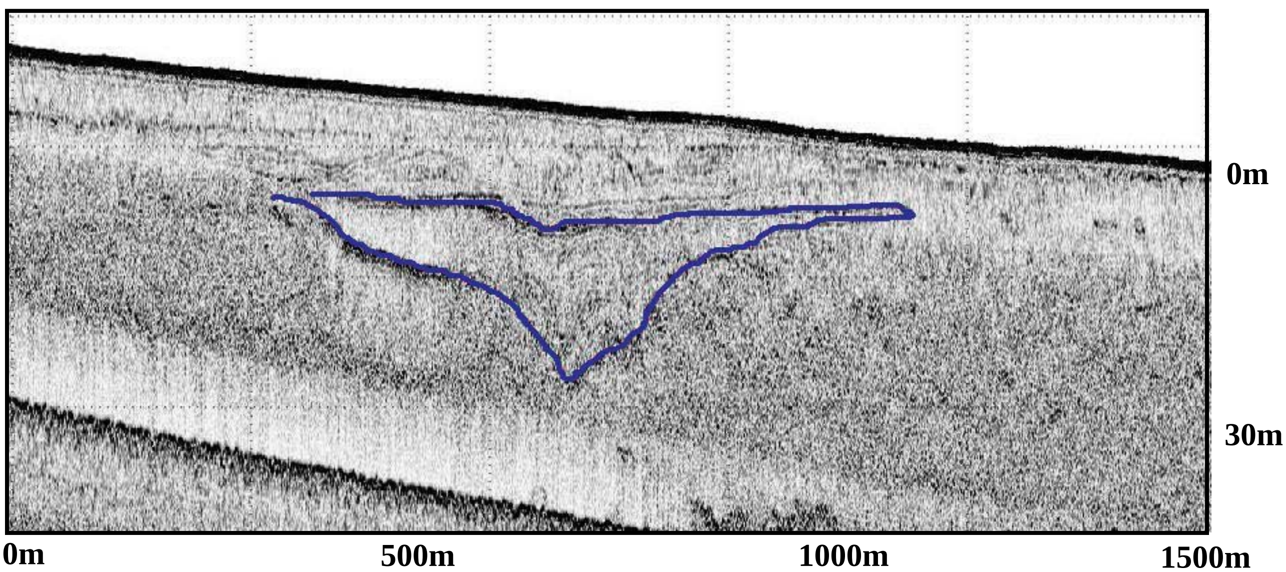

Fig. 6. Example of typical channel cut-and-fill feature mapped near Cape Ann. The form exhibited in this feature is easily traced across several parallel track lines (Seismic shot L97f5).

Channel cut-and-fill structures identified in sub bottom profiles were mapped onto a surficial bathymetric map of the Merrimack Embayment (Figure 7). Three sets of shore normal channel cut-and-fill structures are identified. The southern set continues towards the Parker River Inlet at the southern end of Plum Island (Set A, Figure 7). A central set tracks towards the northern end of a remnant drumlin at the southern end of Plum Island (Set B, Figure 7). The northern-most set trends toward the center of Plum Island near a low marshy region (Set C, Figure 7). Additionally, at the very southern end of the Merrimack Embayment there is some evidence of a forth set of cut-and-fill features that trend towards the present-day Ipswich River Inlet.

ANALYSIS AND DISCUSSION

Braided Stream Deposits

Seismic profiles of the region of the Merrimack Embayment inshore of the paleo-delta reveal an irregular basement overlain by channel cut-and-fills, flat lying reflectors, and acoustically transparent regions. Bedrock outcrops extending through the sediment surface increase in extent to the north. Our records and those collected by Oldale et al. (1983) suggest that glacial and bedrock topography strongly controlled the course of the river system while it was delivering sediment to the lowstand delta. Presently, bedrock outcrops continue to stabilize much of the lower river and estuary region.

The earlier studies of the Merrimack Embayment (Oldale et al. 1983; Edwards 1988; Oldale et al. 1993) did not report the pervasive channel cut-and-fill features characterizing the region landward of the delta. However, the channel cut-and-fill structures observed in our seismic profiles suggest that the delivery system conveying sediment to the delta consisted of a braided stream complex. Moreover, the size and morphology of the paleo-delta suggest that the delta was deposited in a series of lobes indicating significant river migration and/or avulsion (Figure 7). Present-day topographic evidence supports this conclusion. A ridge landward of the backbarrier marsh west of Plum Island may have controlled drainage landward edge of potential drainage (Figure 7).

Edwards (1988) postulated that distributary drainage through the paleo-Merrimack occurred at or near the present-day mouth of the Merrimack River. Sediment would have been deposited along northern end of paleo-delta and then reworked to the south to form the southern lobe. However, evidence from this study indicates that paleo-drainage of the Merrimack River was indeed to the south through various avulsion channels. Few cut-and-fill features are seen near the present-day mouth of Merrimack River; however thick (>20 m) layering of sediment overlying bedrock indicates a large input of sediment from the present-day Merrimack River.

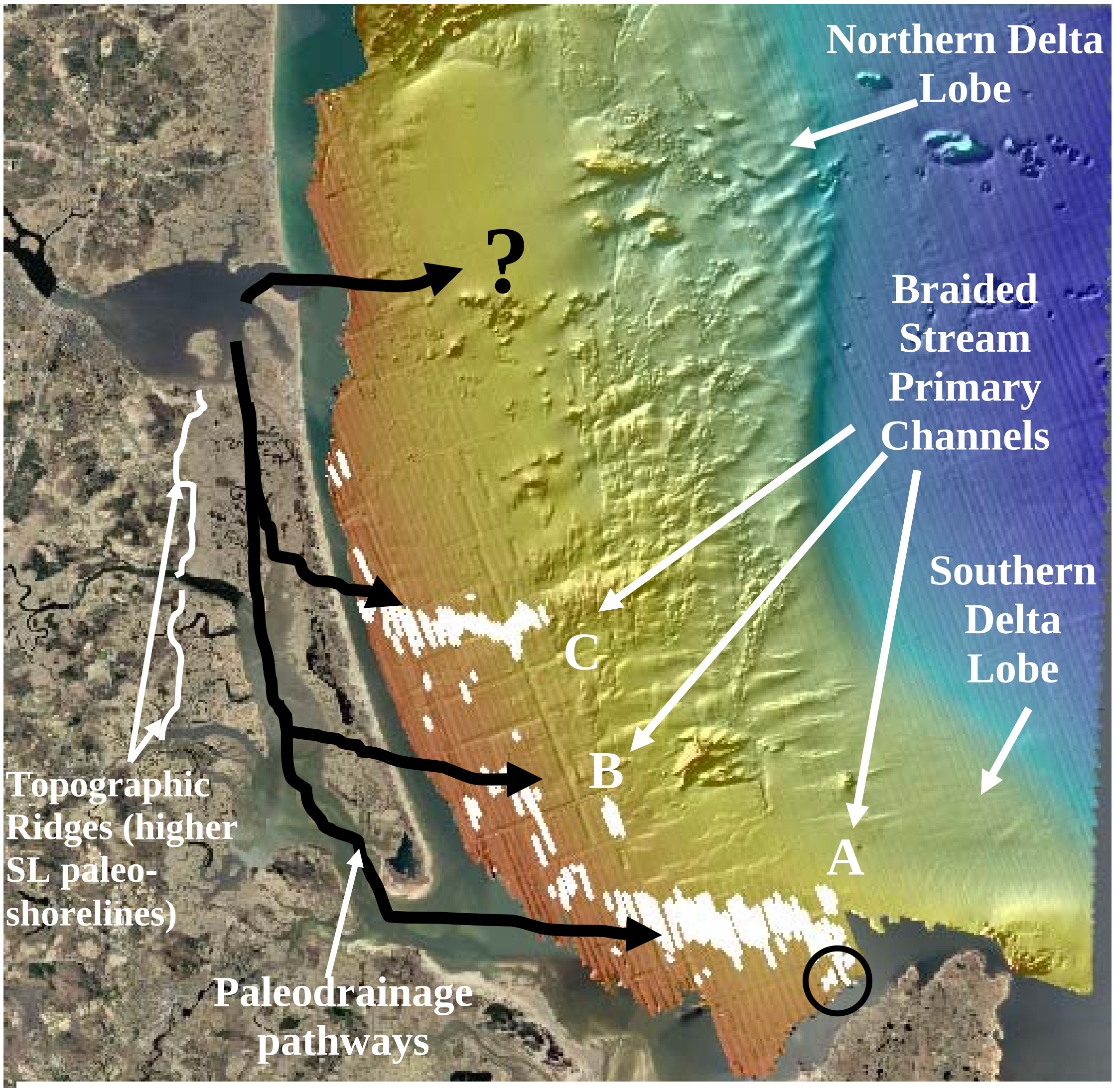

Fig. 7. Map showing locations of subsurface channel cut-and-fill features. Note the 3 distinct sets of features denoting possible locations of braided streams, labeled A-C. The possible forth set of features is circled just north of Cape Ann. Edwards (1988) identified a braided stream complex directly offshore of the present-day mouth of the Merrimack River, however, no channel cut-and-fill features were mapped in that location from data in this study.

Formation of the Merrimack Embayment Barriers and Subaqueous Sand Sheet

Surficial sediments in the Merrimack Embayment have been substantially reworked during the Holocene, as indicated by the existence of a broad sand sheet (18 km x 7 km) extending from approximately 2 km north of Cape Ann to 4 km north of the mouth of the Merrimack River and from the nearshore (-10 m) to the paleo-delta front (-45 m). This sand sheet consists of silty sand in the outer reaches near the delta and coarse-grained sand further inshore. An expansive (32 km^2), featureless coarse-grained sand deposit is centered off the Merrimack River. Fine-grained sand overlies this deposit in many locations, although it is not continuous, and forms asymmetrical bedforms (Hein et al. 2007).

Notably in shoreward regions, channel cut-and-fill features are truncated suggesting that the braided stream deposits themselves were reworked during the Holocene marine transgression. Shallow seismic profiles show a basal unconformity located immediately below a set of regressive fluvial / deltaic deposits. Capping these deposits is a pronounced ravinement surface, which extends from the delta to the nearshore of the Merrimack Embayment, indicating extensive reworking of the fluvial-deltaic lithosome during the Holocene transgression.

Granularmetric analyses indicate that the delta sediments are bimodal containing poorly sorted silt and fine sand components, which is characteristic of fluvio-deltaic sediments (Giosan and Bhattacharya 2005). Cores through the paleo-delta generally show intercalated silty clays and fine to medium silty sands. The upper 20 to 30 cm of the cores consists of medium sand with coarse pebbles and shell fragments (Edwards 1988). The cores that extend between 3 and 8m confirm that the delta is composed largely of fine-grained sediments, unlike the sediments that comprise the sand sheet.

The sediments composing the broad Merrimack Embayment sand sheet are likely sourced from the braided stream deposits that were reworked during the Holocene transgression and not from the delta itself. Furthermore, though FitzGerald et al. (1994) postulate that the reworking of paleo-delta sediments contributed to the formation of Plum Island and the other barriers in the Merrimack Embayment, it is likely that these coarser braided stream deposits were the true offshore source for any barrier sediments. The sand sheet and barriers were likely generated during the Holocene transgression when shoreface processes reworked both delta and braided stream deposits. Additional sand may have been derived from the Merrimack River (FitzGerald et al. 1994).

CONCLUSIONS

1. New shallow seismic data indicate a widespread system of channel cut-and-fill structures inshore of the Merrimack paleo-delta having a depth of 5-10 m and an apparent width of 25 – 300 m.

2. The channel geometry and spatial extent of the cut-and-fill features are consistent with those of braided streams. Several distinct sets of channel cut-and-fill features represent avulsion of the primary distributary channel of the paleo-Merrimack River.

3. This braid plain system was responsible for delivering a large volume of sediment (1.3 billion cubic meters) to a multi-lobate lowstand delta during late Pleistocene (12 kya, at -45 m, Oldale et al. 1983).

4. Sediment comprising this braid plain was reworked during the Holocene transgression and likely contributed sediment to the present day barrier system in the Merrimack Embayment.

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