HOLOCENE SEDIMENTARY EVOLUTION OF THE MERRIMACK EMBAYMENT, WESTERN GULF OF MAINE

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OUTLINE

ABSTRACT

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A geophysical and sedimentological study of the Merrimack Embayment in northern Massachusetts has added to our understanding of sediment deposition during deglaciation and shed light on the formation of the region's barrier island system. Previous investigators have shown that the Merrimack lowstand delta was deposited in a series of lobes at approximately 12.0 kya in 45 m of water and further speculated that the onshore reworking of the delta surface during the Holocene transgression may have accounted for barrier construction (Oldale et al, 1983; Edwards, 1985). New shallow seismic, multi-beam, and backscatter data along with bottom photographs and sediment samples have revealed the presence of widespread channel cut and fill structures landward of the delta that suggest braided streams carried sediment to the lowstand delta.

Bottom sediments indicate that surficial sediment ranges from silty sand at the site of the submerged delta to coarse sand and fine gravel in the innermost shelf (5-25 m depth). Fine grained sand (phi: +3) comprises low backscatter, cuspate ripples (wavelength: ~20cm) and coarse grained sand (phi: 0.5) makes up high backscatter, two-dimensional sandwaves (wavelength: >1m). Additionally, mud (phi: +5) often drapes bedrock outcrops on the sea floor.

Bottom samples and backscatter images indicate an expansive medium- to coarse- grained sandsheet 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 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. The geometry and orientation of these positive bed features suggest that the sandsheet is being reworked in an offshore direction. One possible mechanism for this is water level set-up during northeast storms producing offshore currents and sediment transport.

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. Although the northern end of Plum Island, MA is presently stable, much of the region experienced extensive erosion in the past and numerous houses and infrastructure have been destroyed during the past 25 years.

5. 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.

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 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 paleo-delta and the glacio-fluvial sediment (braided streams?) landward of the delta. 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. Conducting a wave analysis of the study area to look at potential effects of wave focusing following sediment removal.

PHYSICAL SETTING

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. 1); 2) relatively shallow shelf depths; 3) variable basement relief (bedrock), and 4) diverse sediment sources.

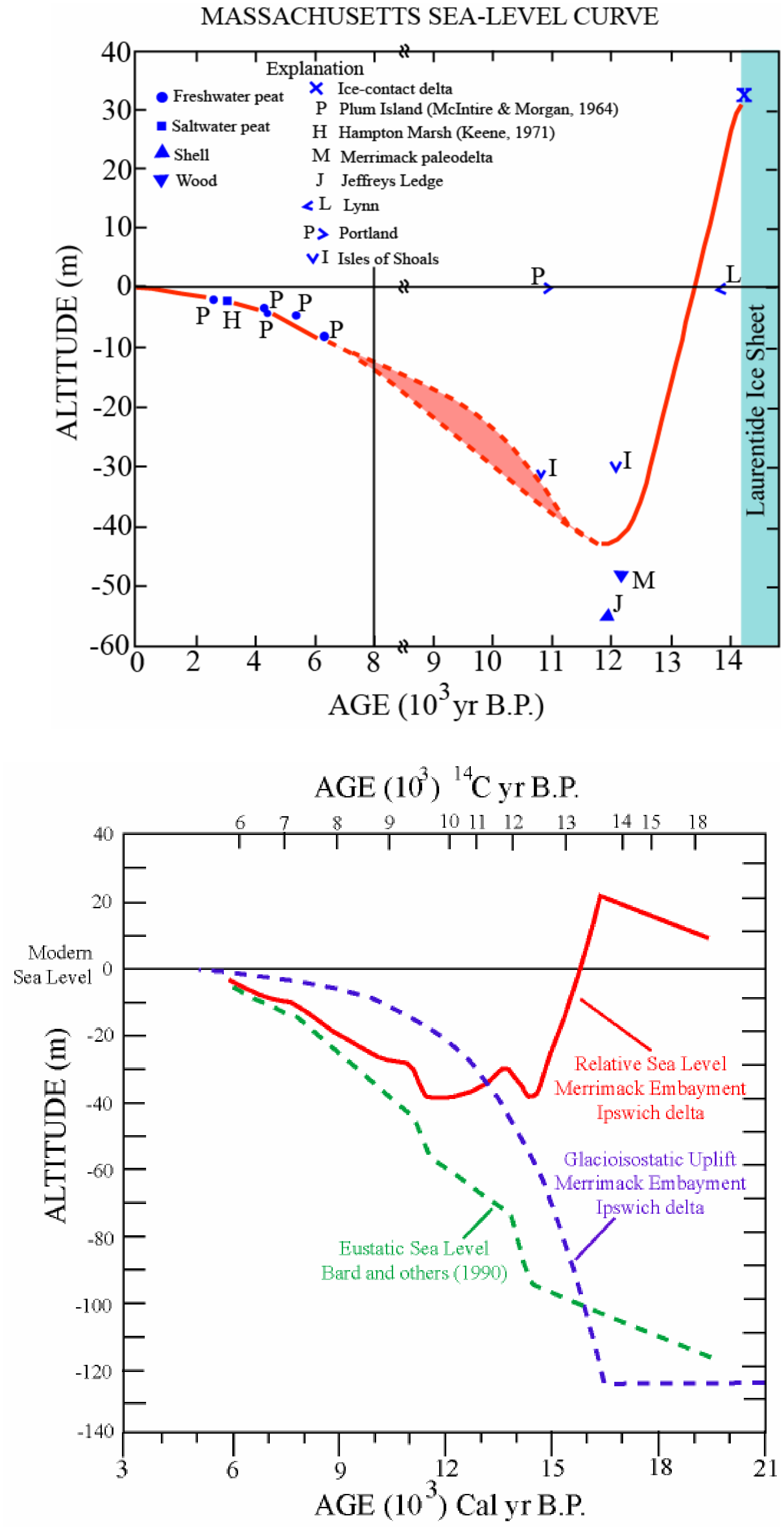


Figure 1: Relative sea level curves for northeastern Massachusetts and the adjacent inner continental shelf. The envelope (crossed line) in the first graph represents the range within which the actual curve may run. Note scale change at 8000 yr BP. (modified from Oldale et al, 1993 and Stone et al. 2004)

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. 2). 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. 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 (Figs. 3 & 4).

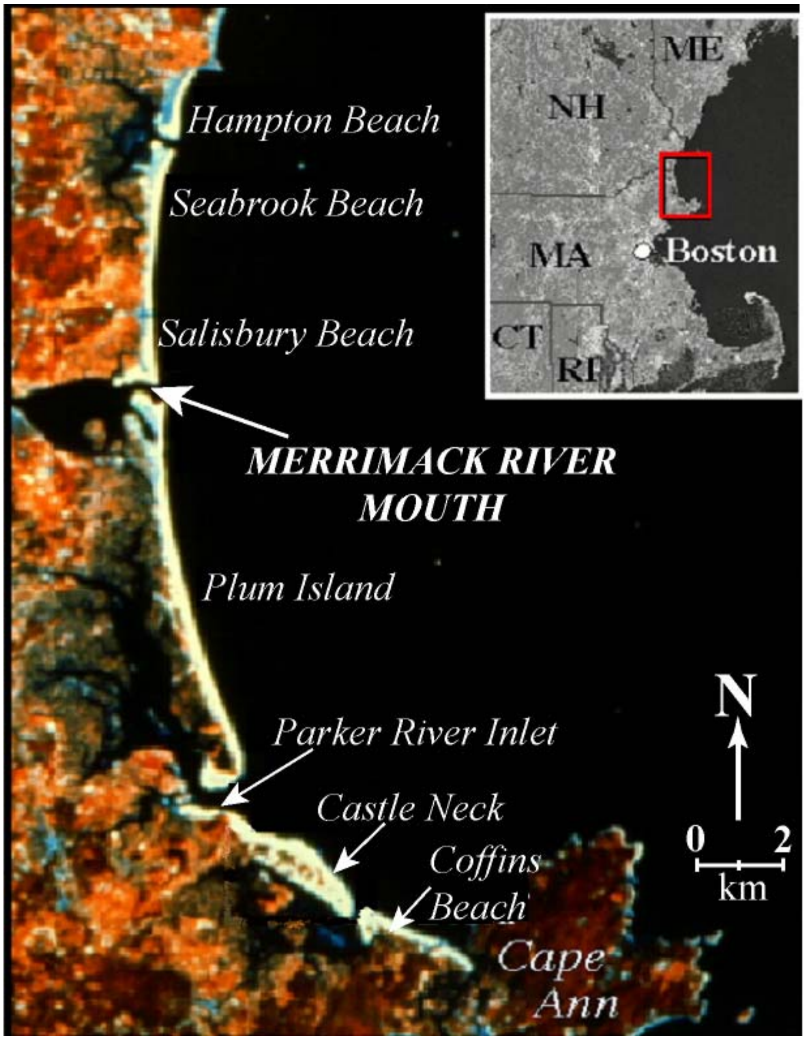


Figure 2: Satellite view Merrimack Embayment Study Area, northeastern Massachusetts

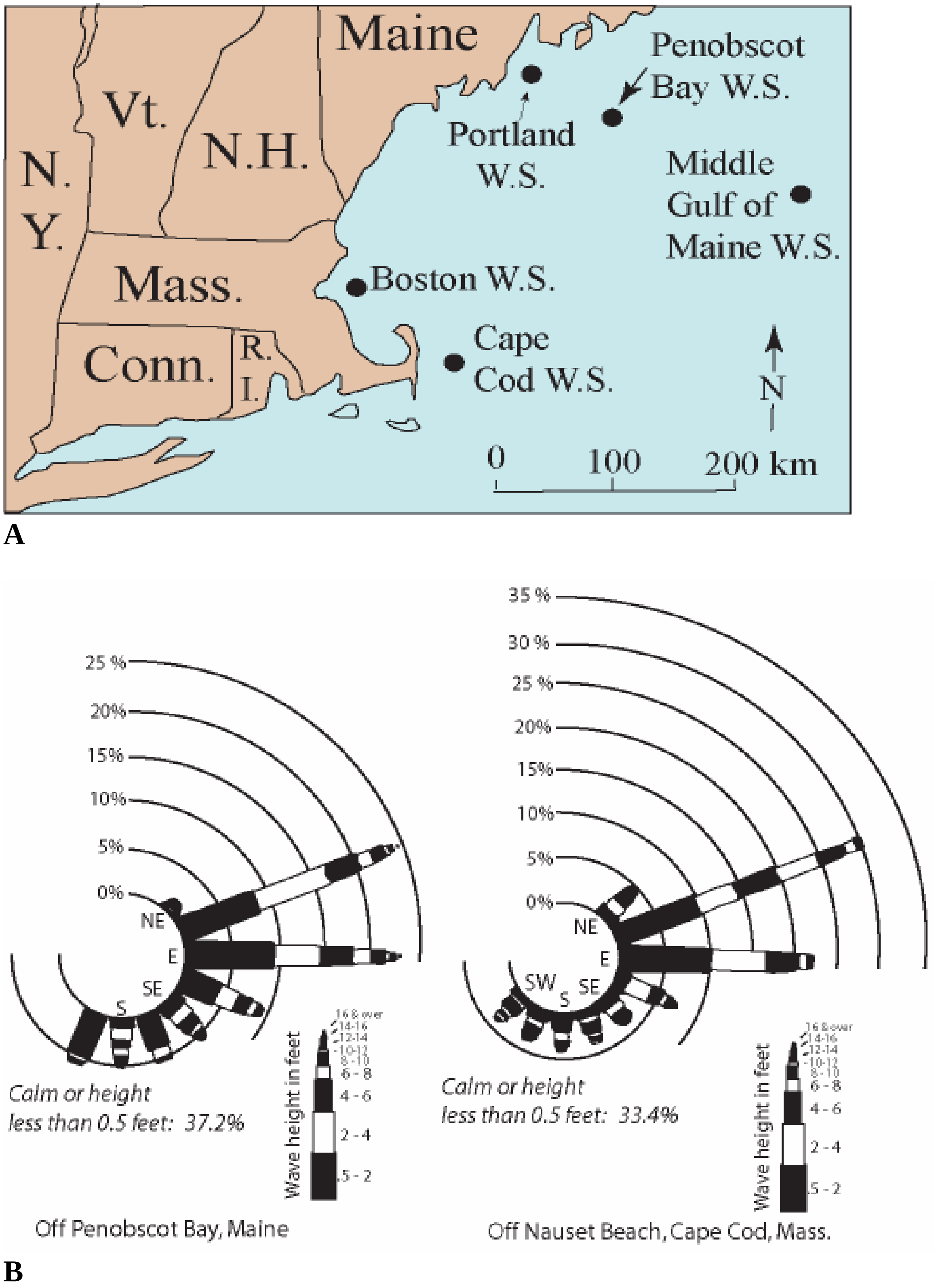


Figure 3: Wave data from areas near Merrimack Embayment (modified from FitzGerald et al, 1993).
A) Map of New England showing locations of wave stations.
B) Wave rose diagrams from Penobscot Bay, Maine and Cape Cod, Massachusetts.

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

Figure 4: Wave data from wave boys located in the Gulf of Maine, Portland, ME, and Boston, MA. Locations noted in Figure 3. (modified from FitzGerald et al, 1993)

The initial geophysical examination of the Merrimack paleo-delta (Oldale et al, 1983 and Edwards, 1988) revealed that the delta is located approximately 6 to 7 km offshore and trends parallel to the present coast (Fig. 5). The paleo-delta is 20 km long, 4 to 7 km wide, and 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 10.5 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 they 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). 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 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.

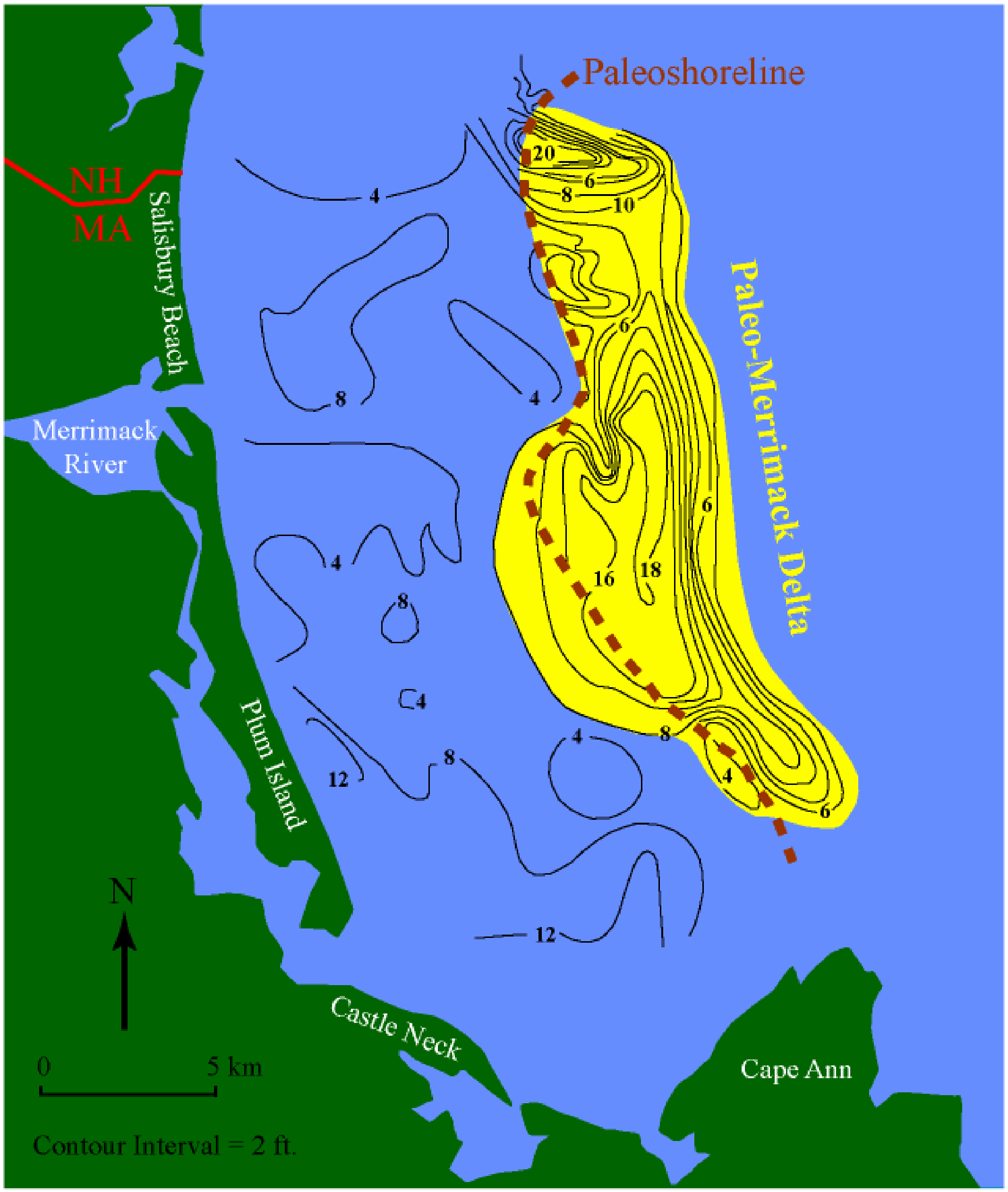


Figure 5: Inferred location of –45 m Paleo-Merrimack Delta (modified from Oldale et al., 1983)

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.

DATA ACQUISITION

To date, a variety of geophysical and sedimentological data has been collected in cooperation with the USGS in 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. This section will briefly describe these data sets and offer some preliminary observations.

A. Shallow Seismic Surveys

In September 2005, 3,857 km of shallow seismic track lines were taken in the study area using an Edgetech SB-512 CHIRP sub-bottom profiler. Track lines of the shallow seismic data and locations of two sample transects are given in Figures 6, 7, and 8.

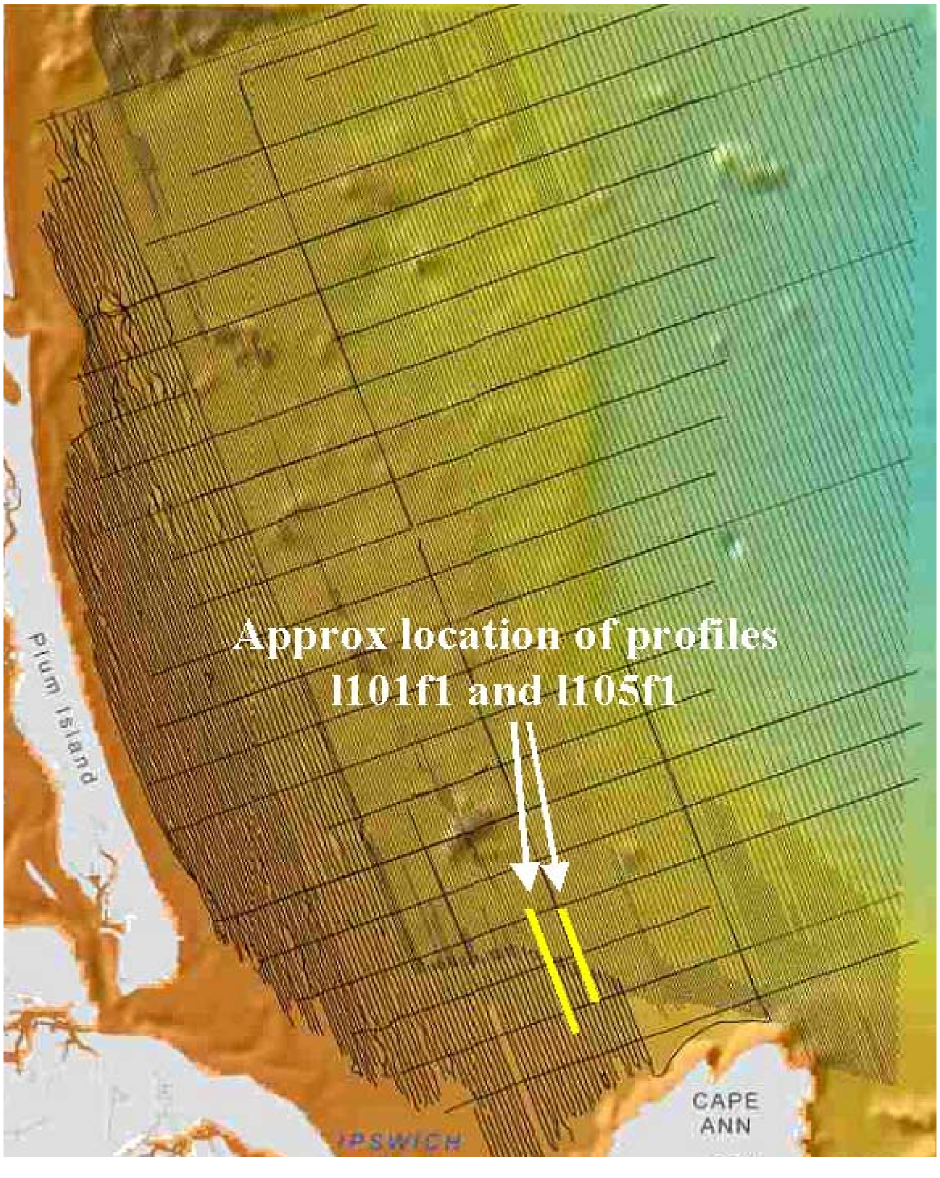


Figure 6: Map of study area showing track lines of shallow seismic profiles taken during September USGS cruise

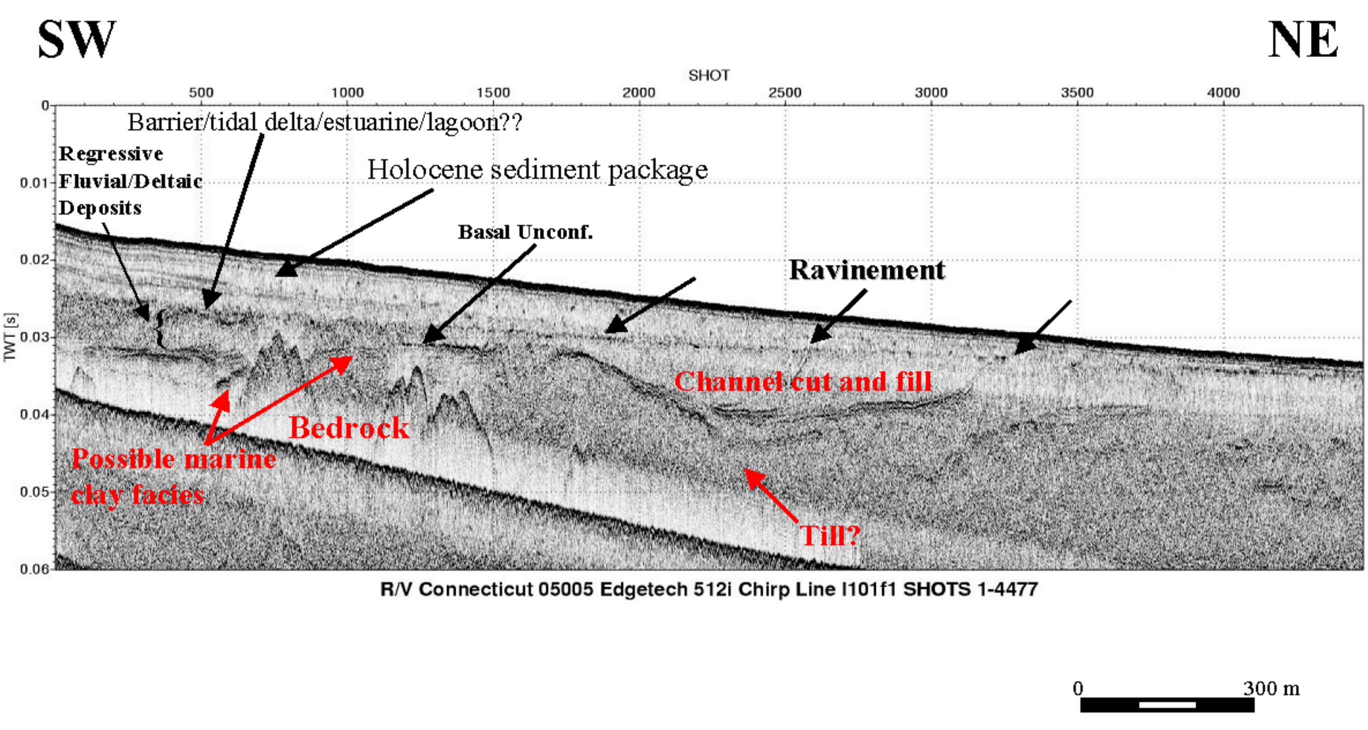


Figure 7: Sample shallow seismic profile line #L101F1

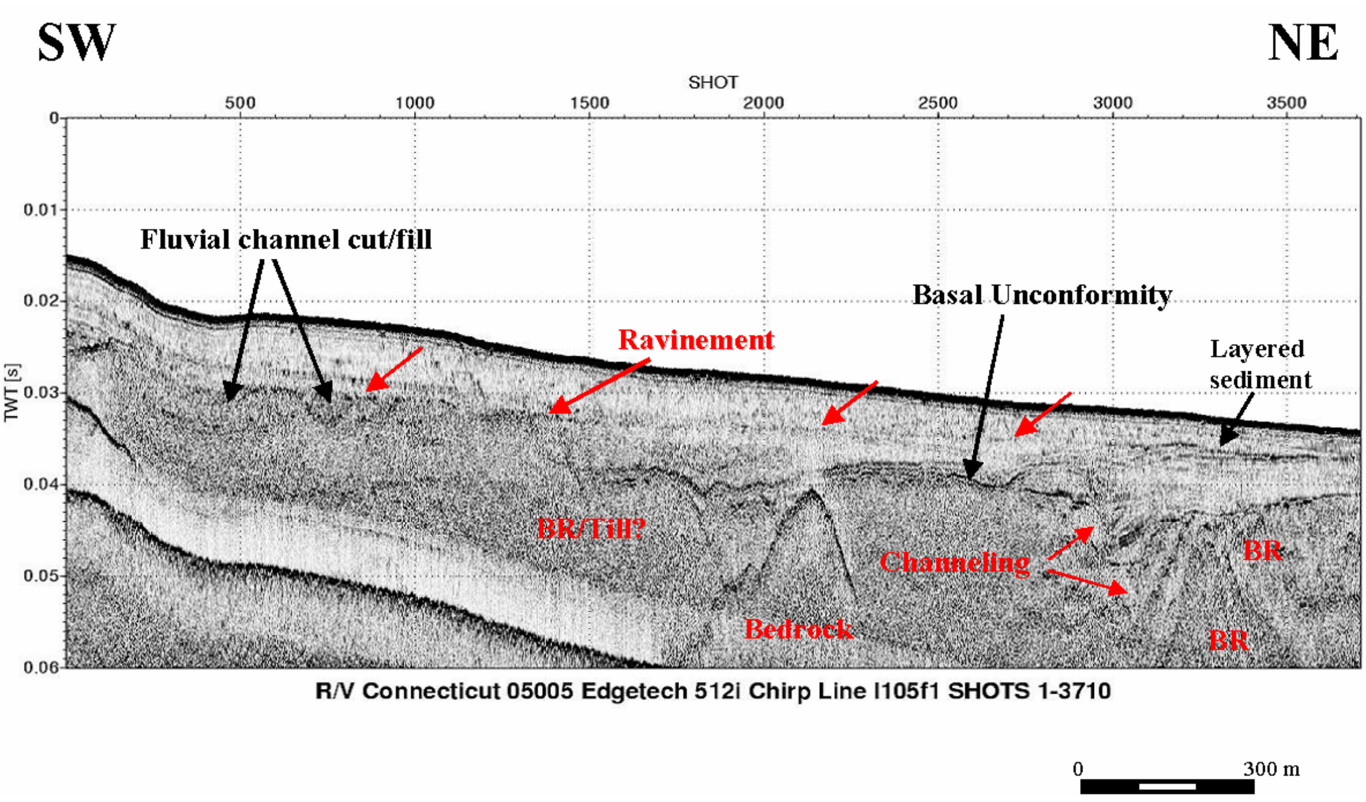


Figure 8: Sample shallow seismic profile line #L105F1

These data sets build and expand upon previous work done by Edwards and Oldale (1986) and increases our understanding of the Merrimack paleo-delta. 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.

B. Side Scan Sonar Backscatter

Side scan sonar was used to map the sea floor over a 323 km^2 area from the nearshore zone to about 17 km offshore (Fig. 9). The resulting high-resolution backscatter image (Barnhardt et al, 1998) shows distinct patterns of high and low backscatter regions (Fig. 10). 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.

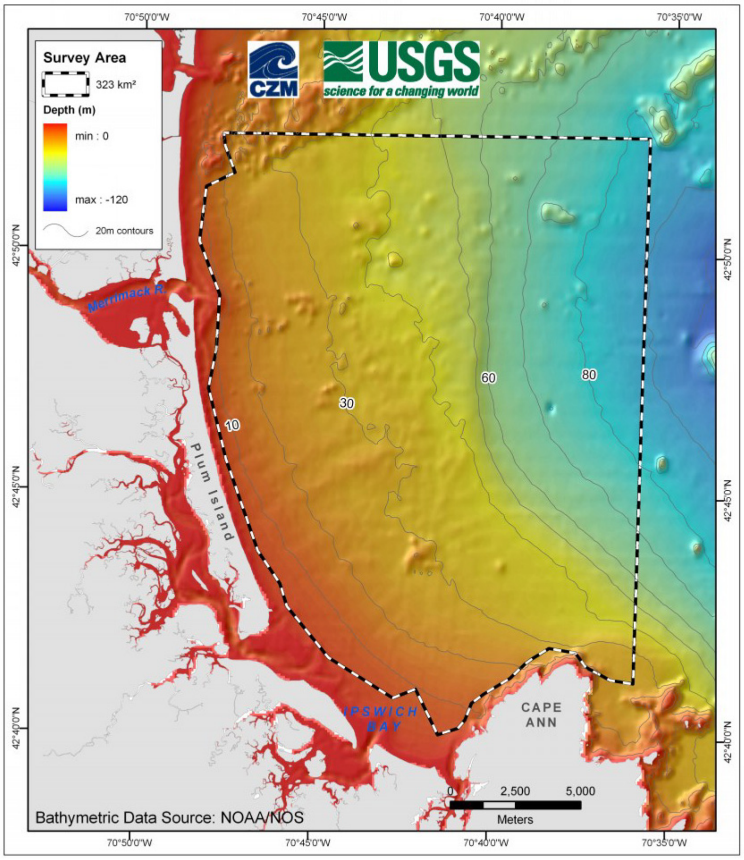


Figure9: Bathymetric map of Merrimack Embayment. Black and white dotted line surrounds the 323 km^2 study area.

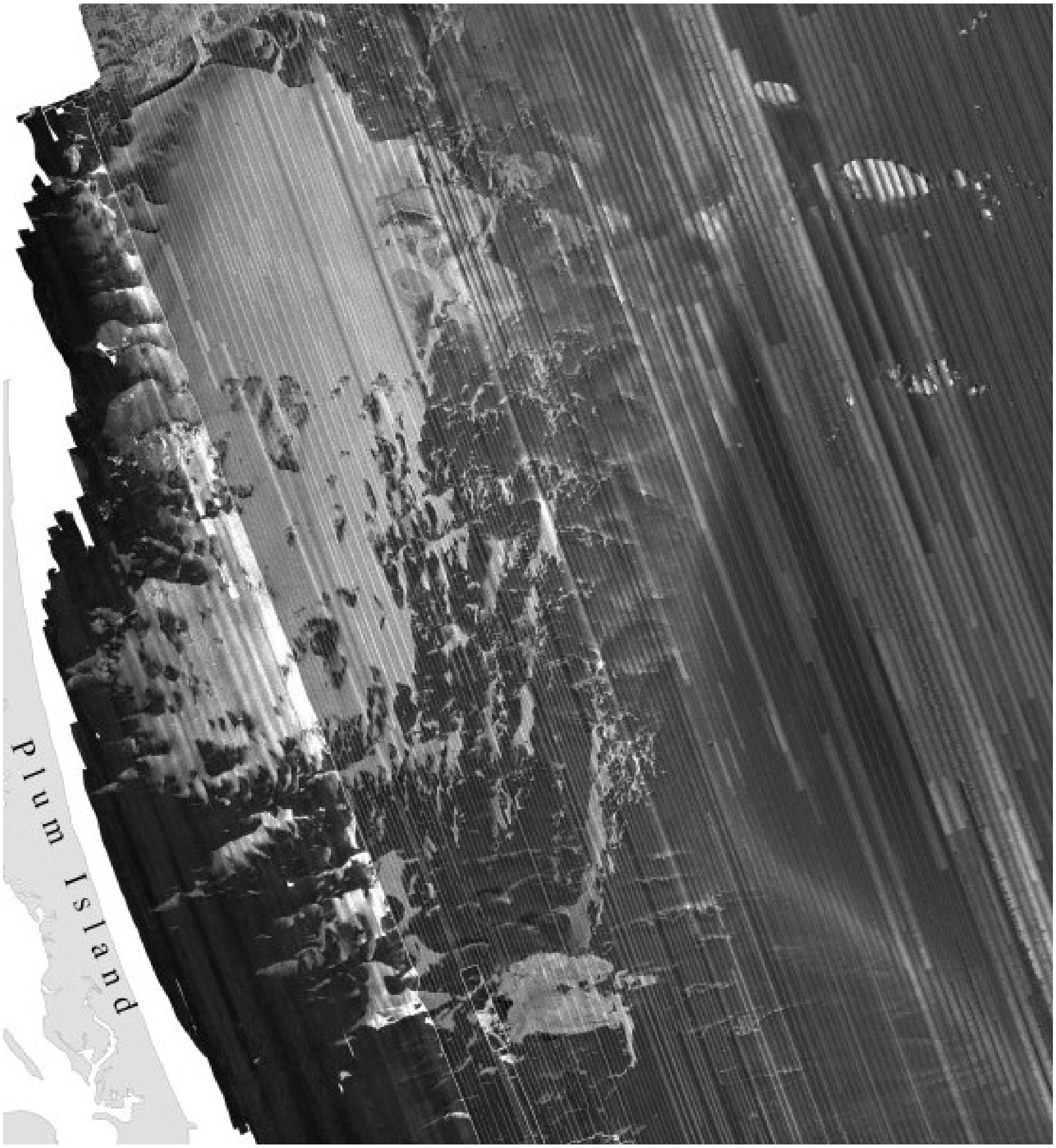


Figure 10: Backscatter map of sea floor taken using side scan sonar. Lighter colors represent high backscatter and darker colors represent low backscatter. The Holocene shelf surficial sand sheet, linear and cuspate ridges, and the delta front are all visible as high backscatter features in this image.

The high backscatter features visible in Figure 9 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 18km (N-S) x 7km (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.

C. Offshore Sampling

Bottom videos and sediment samples were taken at nearly 100 locations within the study area, both inshore and offshore of the paleodelta. Sample sites were chosen based on the backscatter data. The sampling device was held several feet above the sea floor as the research vessel coasted over the zone of study for 5-10 minutes. Bottom video and still photos were taken. The primary study locations were the zones of transition between regions of high backscatter and low backscatter. This method was also used to ground truth other areas of the backscatter image, such as the sand sheet and areas in the vicinity of bedrock outcrops. The results of this sampling reveal much about the nature of the sand sheet and processes of reworking. Approximate locations and general categorizations of the 12 bottom sites sampled during the University of New Hampshire cruise in August 2005 are shown in Figure 11 and a map showing the locations of the 85 bottom sites sampled during the September USGS cruise are shown in Figure 12.

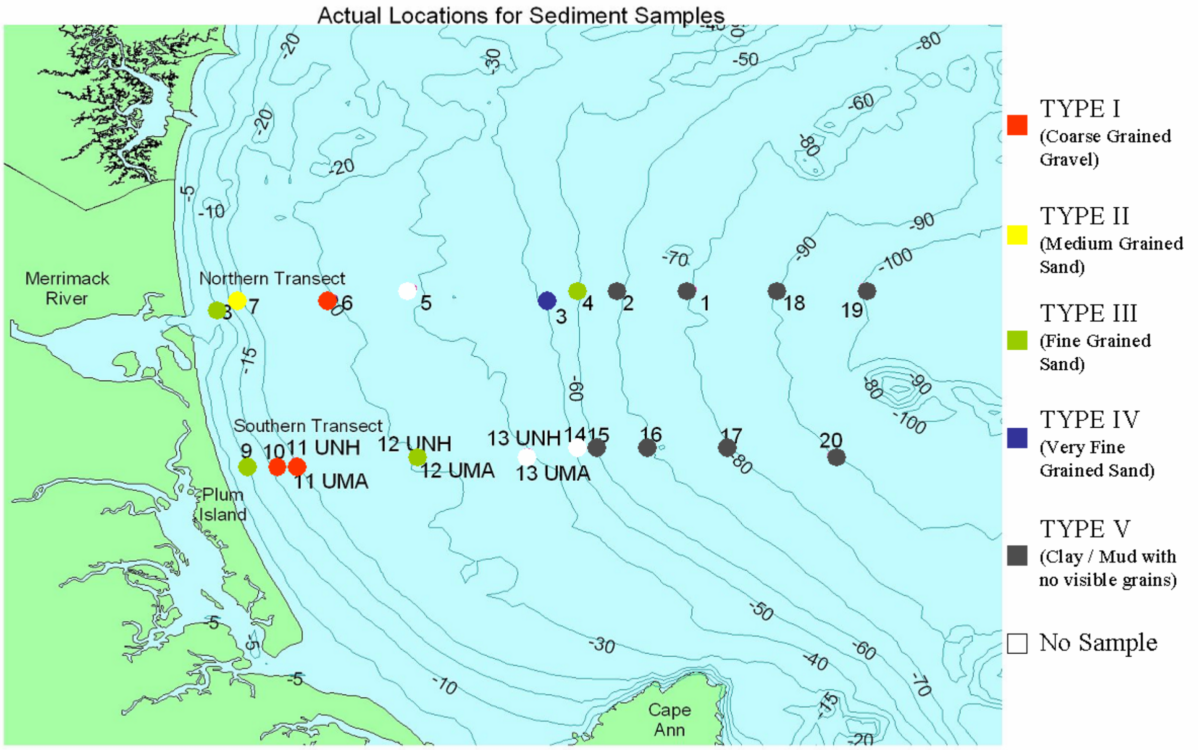


Figure 11: Locations and preliminary analysis of bottom sediment samples taken by L. Ward (University of New Hampshire), August 2005

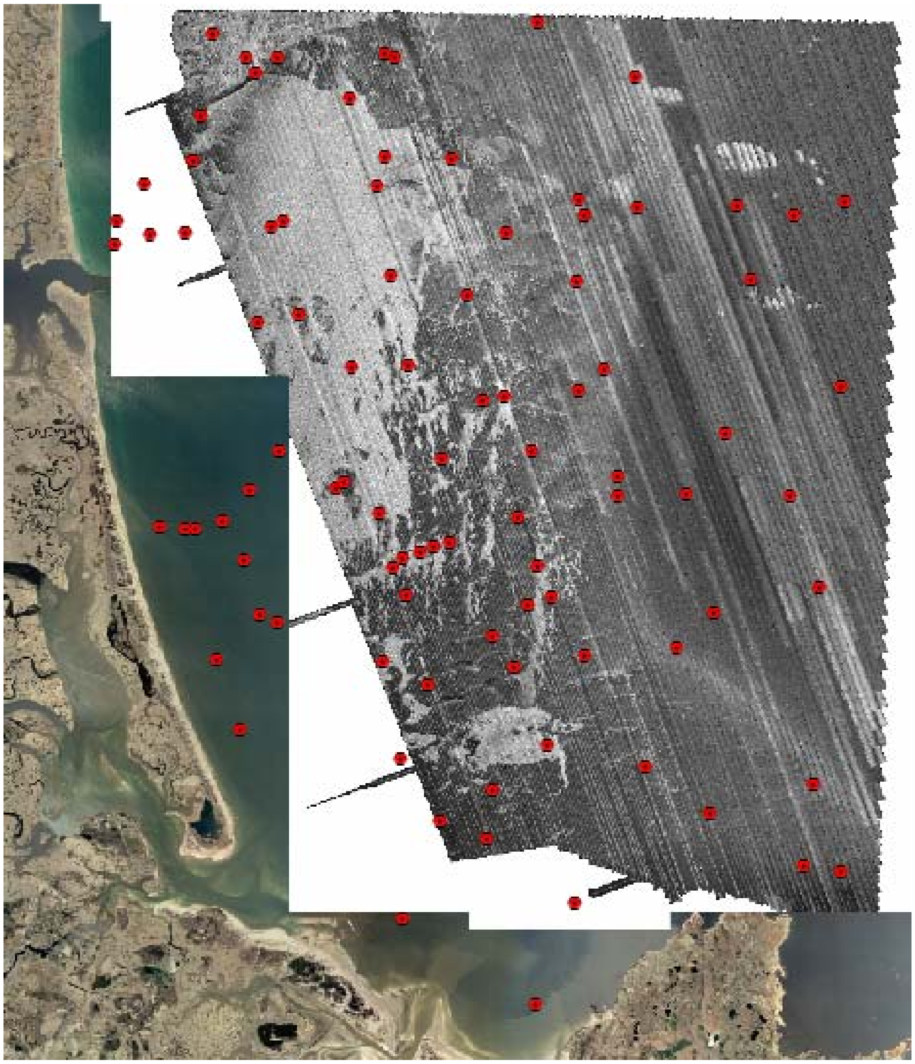
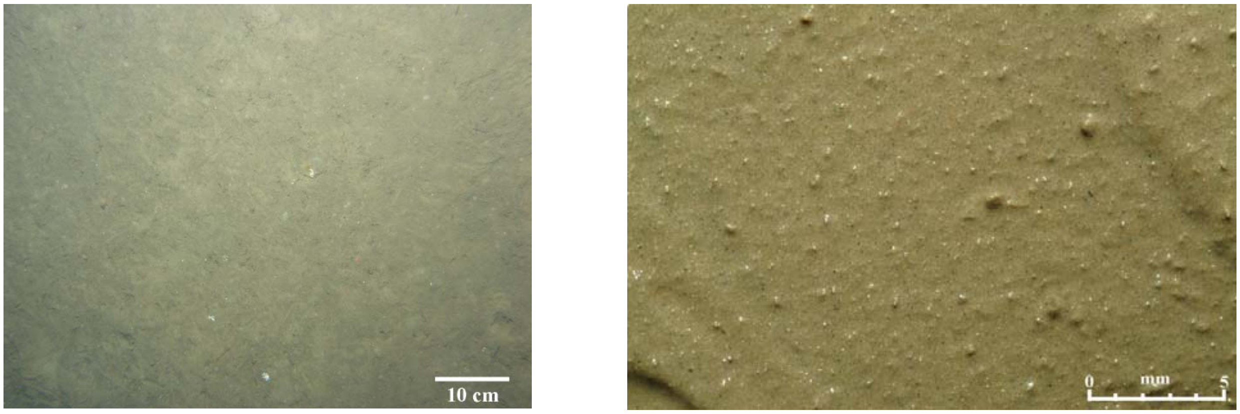
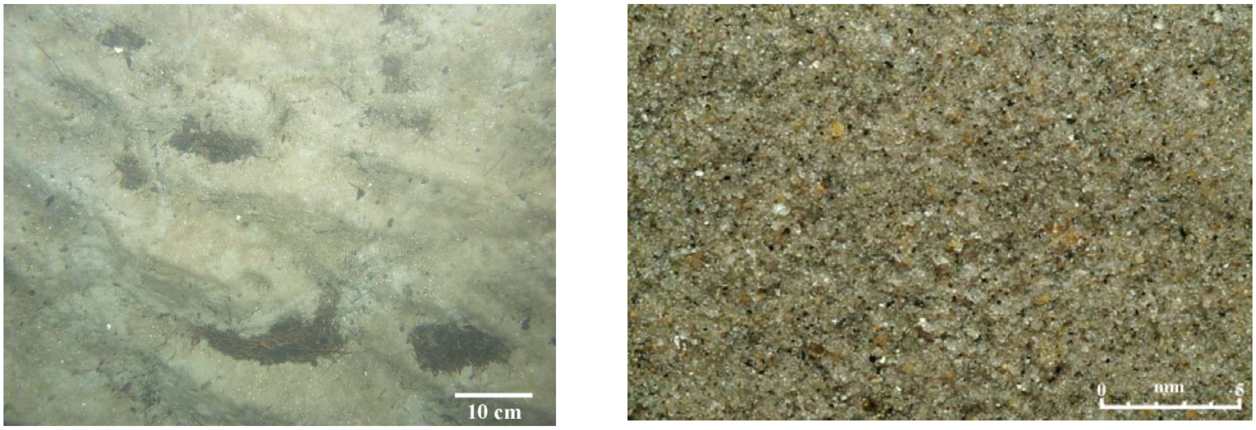


Figure 12: Backscatter map and color orthophotos showing locations of 85 bottom sites sampled during the September USGS cruise and the 12 samples taken during the University of New Hampshire cruise in August 2005.

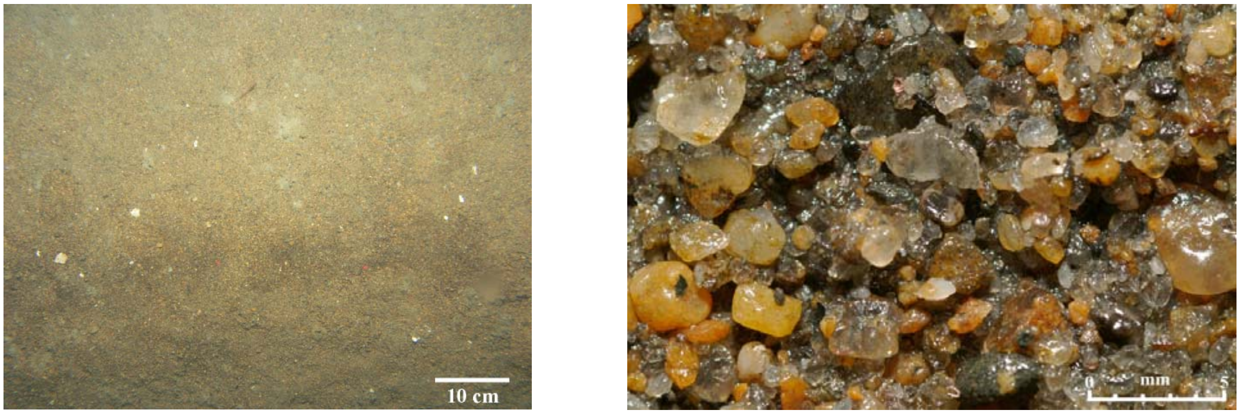
Bottom sediment samples were grouped according to the backscatter region from where they were retrieved. Sediments in regions of high backscatter are composed of coarse-grained sands to fine gravels (mean φ is 0.61; mode φ is 0.53). These regions are dominated by two dimensional megaripples with wavelengths of about 1m. 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. Sample sediment and bottom photos and a sedimentological analysis of the bottom samples are presented in Figure 13 and Appendix II, respectively.



A) Bottom Photo **A) Sediment Sample Photo**



B) Bottom Photo **B) Sediment Sample Photo**



C) Bottom Photo **C) Sediment Sample Photo**

Figure 13: 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 assoctaed 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)

DISCUSSION

A. Formation of the –45m Paleo-delta

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. 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. The seismic 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.

B. Early Holocene Reworking of Paleo-delta 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). 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.

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 8m 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 the high backscatter regions of the Embayment, forming an extensive sand sheet

(18km x 7km). This feature is composed of coarse-grained sand which has been molded into 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

The vertical and lateral extent of the sand sheet and processes governing its reworking are being investigated. Preliminary analysis of surface sediment samples show that the fine- to medium-grained sands (mean φ: 2.42) that comprise the majority of the inner shelf surface sediments (the medium to low backscatter) are significantly coarser than the delta front mean grain size (φ: 3.62) or beyond (mean φ: 5.84). The sand sheet and associated features occupy approximately 130km^2 of the study area and are separated (by what) from the landward sandy barrier island system. The sand sheet is thin (20-30cm) 5 km offshore of northern Plum Island (Edwards, 1988). Additional coring is needed to obtain a more complete record of the thickness, volume and variability in extent of the sand sheet.

The large scale linear to cuspate features comprising the periphery of the sand sheet (give their dimensions) exhibit variety of orientations (Fig. 13). 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 (<1m) than nearby fine-grained sediments. The sand sheet may currently being reworked by modern processes and moving sand in mostly an offshore direction. However, this generalized observation does not fully account for the variety of forms comprising the sand sheet and associated linear to cuspate features. Nor does it account for the variety of orientations of these features, though most have sharper edge with the surrounding fine-grained regions on their offshore side. 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, a more detailed study of the nearshore dynamics of the region will be necessary to determine the feasibility of this theory.

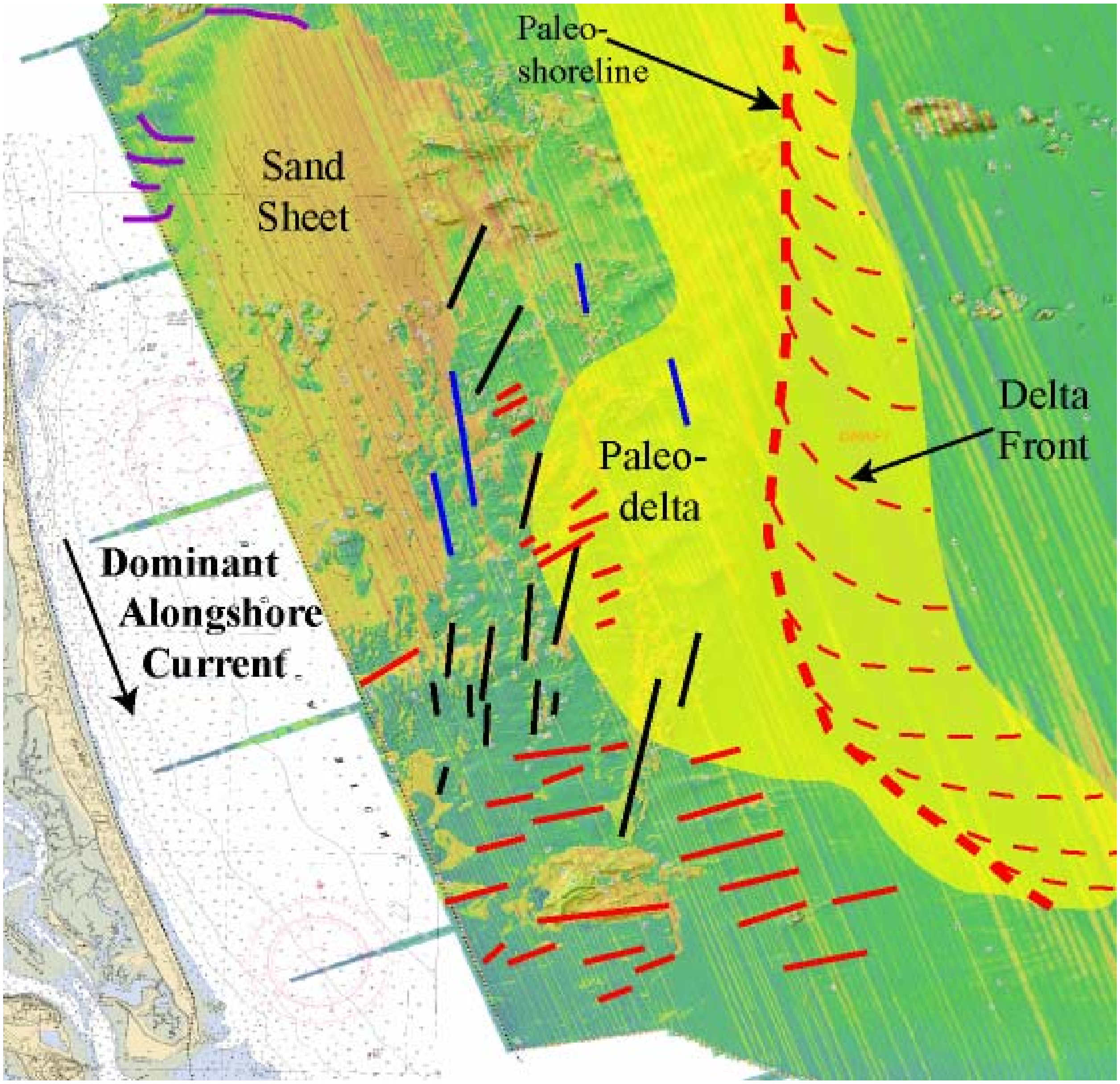


Figure 15: Backscatter image of study area showing the sand sheet and linear / cuspate high backscatter features. Different colored lines represent the orientations of these features. Inferred locations of the Merrimack paleo-delta, delta front, and paleo-shoreline are noted. Orange / yellow colors represent higher backscatter sediments and green colors indicate lower backscatter sediments.

D. Future Work

Over the next several months the USGS in Woods Hole, MA will complete data processing of the September USGS cruise. This will allow a more comprehensive study of the bathymetry, backscatter map and shallow seismic reflection profiles. Ultimately, we will produce a detailed analysis of the sea floor using bottom videos, bottom samples, and backscatter maps with the goal of classifying surface sediments and determining the overall sand sheet dynamics of the study area.

Analysis of shallow seismic profiles will provide a basis for identifying coring targets. The cores will be used to ground-truth our stratigraphic interpretations and hopefully will supply organic material for radiocarbon dating the various sedimentary units comprising the inner shelf lithosome. A detailed stratigraphy and chronology of the region will allow us to create an evolutionary model for the emplacement of the Merrimack paleo-delta and associated deposits. Hydrodynamic and sediment transport modeling will assist in determing present day nearshore processes and their effect on the reworking of paleo-delta, braided stream, and sand sheet sediments during the late Pleistocene and Holocene transgression through the present time. Modeling will provide additional information concerning the potential effects of wave focusing following sediment removal in the area.

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APPENDIX I.

This section contains some of the raw data from granularmetric analyses of the bottom sediment samples retrieved during the September USGS cruise and the University of New Hampshire cruise in August 2005. 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.

LAT-ITUDE	LONG-ITUDE	FIELD ID	BS LOCATION	VERBAL EQUIVALENT (SHEPARD 1954)	MEDIAN	Ave Median	MEAN (MOM)	Ave Mean
42.74281	-70.64921	STA39	DELTA FRONT	SAND	2.49	3.62	2.65	4.00333
42.77770	-70.66510	STA60	DELTA FRONT	SAND	3.49		3.96	
42.83178	-70.6588	AV861	DELTA FRONT	SILTY SAND	4.88		5.4	

42.77718	-70.73974	STA3	HIGH	GRAVEL > 10%	-1.21	0.526552	-0.99	0.60931
42.81478	-70.70549	STA8	HIGH	GRAVEL > 10%	-0.93		-0.93	
42.86356	-70.72763	STA16B	HIGH	GRAVEL > 10%	-0.79		-0.8	
42.80034	-70.72185	STA5	HIGH	GRAVEL > 10%	-0.7		-0.71	
42.72348	-70.68493	STA36	HIGH	GRAVEL > 10%	-0.42		-0.24	
42.76153	-70.72375	STA55	HIGH	GRAVEL > 10%	-0.36		-0.2	
42.79316	-70.70145	STA6	HIGH	GRAVEL > 10%	-0.35		-0.19	
42.86284	-70.75705	STA18	HIGH	SAND	-0.27		0	
42.84257	-70.72749	STA73	HIGH	SAND	-0.25		-0.12	
42.75031	-70.76313	STA30	HIGH	GRAVEL > 10%	-0.24		0.09	
42.75971	-70.72655	STA54	HIGH	GRAVEL > 10%	-0.16		0.12	
42.76947	-70.7731	AV869	HIGH	GRAVEL > 10%	-0.06		0.02	
42.78334	-70.75723	STA81	HIGH	GRAVEL > 10%	-0.02		0.05	
42.82995	-70.75557	STA25	HIGH	GRAVEL > 10%	0.07		0.02	
42.74131	-70.77474	STA83	HIGH	SAND	0.1		0.12	
42.74879	-70.75808	STA31	HIGH	GRAVEL > 10%	0.14		0.28	
42.80929	-70.76303	STA27	HIGH	SAND	0.45		0.47	
42.76773	-70.78320	STA82	HIGH	SAND	0.48		0.6	
42.77567	-70.76520	STA28	HIGH	SAND	0.51		0.56	
42.85984	-70.76250	STA19	HIGH	SAND	0.61		0.63	
42.74564	-70.69962	STA49	HIGH	SAND	0.63		0.76	
42.83743	-70.79351	STA77	HIGH	SAND	0.65		0.72	
42.84222	-70.78028	STA24	HIGH	SAND	0.84		0.96	
42.71449	-70.70010	STA35	HIGH	SAND	0.97		1.03	
42.81086	-70.75168	STA26	HIGH	SAND	1.73		1.85	
42.80022	-70.73726	STA4	HIGH	SAND	2.33		2.28	
42.85833	-70.65876	STA14A	HIGH	GRAVEL > 10%	2.37		2.68	
42.74064	-70.72941	STA32	HIGH	SAND	2.84		2.65	
42.86952	-70.68556	STA15	HIGH	SAN SIL CLAY	6.31		5.96	

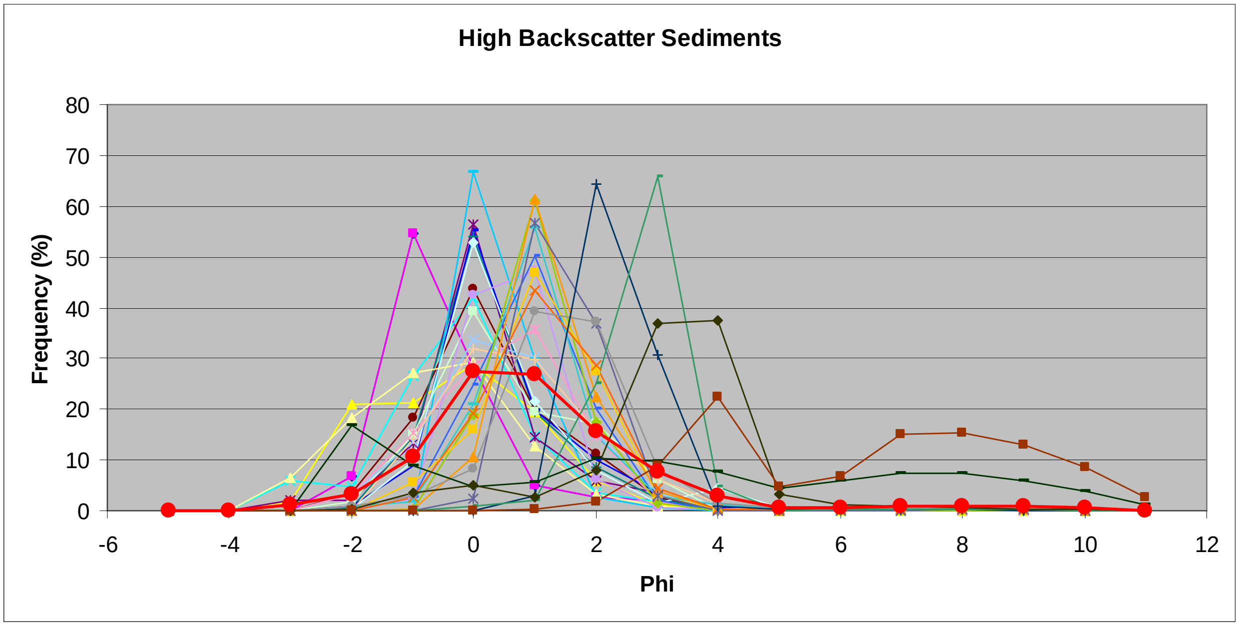
42.86769	-70.77420	STA21	INTER	GRAVEL > 10%	-0.99	1.565	-0.92	1.626
42.82787	-70.78228	STA79	INTER	GRAVEL > 10%	0.37		0.34	
42.76386	-70.71510	STA57	INTER	SAND	0.72		0.81	
42.85146	-70.77761	STA23	INTER	SAND	1.25		1.23	
42.74135	-70.67418	STA38	INTER	SAND	1.96		1.98	
42.78280	-70.68808	STA66	INTER	SAND	2.35		2.29	
42.70459	-70.70142	STA88	INTER	SAND	2.38		2.39	
42.81717	-70.67575	STA9	INTER	SAND	2.48		2.69	
42.79513	-70.67513	STA65	INTER	SAND	2.5		2.6	
42.82711	-70.69493	STA70	INTER	SAND	2.63		2.85	

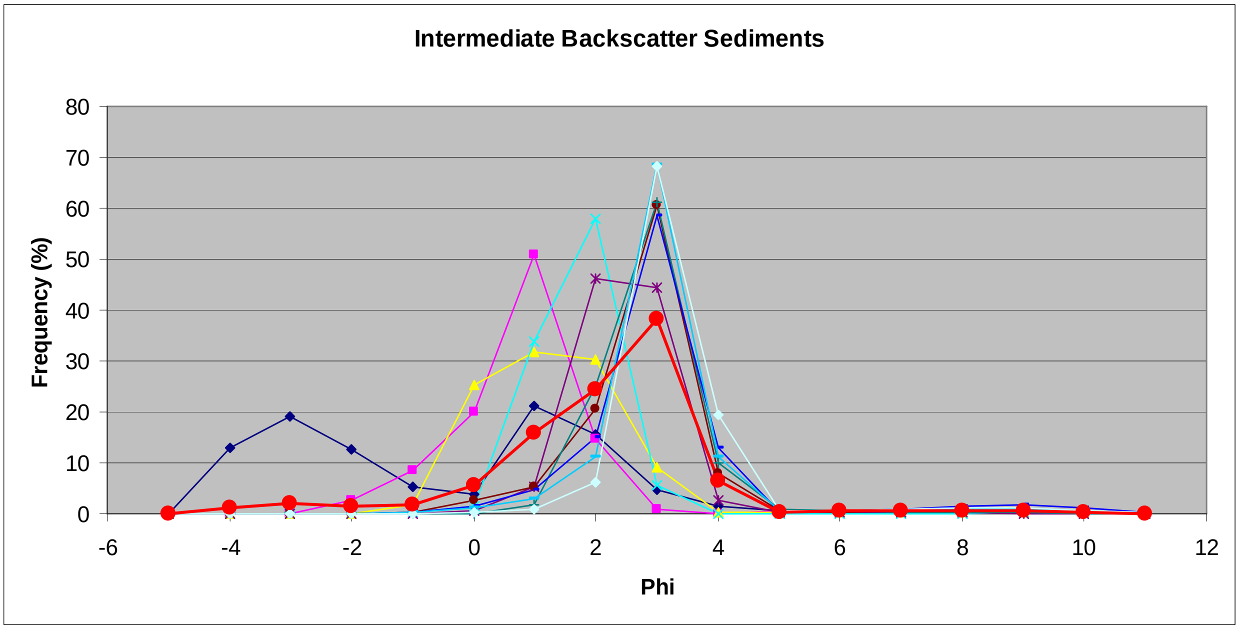
42.86311	-70.76557	STA20	LOW	SAND	1.49	2.602	1.59	2.68133
42.76141	-70.76691	STA29	LOW	SAND	1.91		2.14	
42.72117	-70.72477	STA86	LOW	SAND	2.03		2.09	
42.79399	-70.69578	STA7	LOW	SAND	2.07		2.09	
42.71907	-70.65821	STA37	LOW	SAND	2.19		2.25	
42.76282	-70.71897	STA56	LOW	SAND	2.21		2.16	
42.78166	-70.71300	STA67	LOW	SAND	2.25		2.18	
42.75985	-70.68675	STA52	LOW	SAND	2.31		2.1	
42.77603	-70.74176	STA2	LOW	SAND	2.31		2.26	
42.76462	-70.71071	STA58	LOW	SAND	2.36		2.31	
42.75174	-70.68993	STA50	LOW	SAND	2.37		2.34	
42.71521	-70.61223	STA42	LOW	SAND	2.39		2.42	
42.75409	-70.72270	STA53	LOW	SAND	2.39		2.34	
42.83675	-70.72996	STA74	LOW	SAND	2.4		2.62	
42.73947	-70.69354	STA48	LOW	SAND	2.41		2.42	
42.75337	-70.68346	STA51	LOW	SAND	2.52		2.58	
42.84209	-70.70937	STA72	LOW	SAND	2.56		2.64	
42.68882	-70.72472	STA91	LOW	SAND	2.59		2.67	
42.83033	-70.80124	STA78	LOW	SAND	2.72		2.73	
42.86284	-70.72467	STA16A	LOW	SAND	2.72		3.02	
42.70931	-70.64089	STA46	LOW	SAND	2.78		3.06	
42.85465	-70.73718	STA17	LOW	SAND	2.79		3.01	
42.81875	-70.72613	STA68	LOW	SAND	2.82		2.99	
42.67126	-70.68853	STA90	LOW	SAND	2.85		2.93	
42.72707	-70.76881	STA84	LOW	SAND	2.99		3.01	
42.69845	-70.61518	STA45	LOW	SAND	3.42		3.39	
42.69156	-70.67797	STA89	LOW	SAND	3.44		3.43	
42.69734	-70.60499	STA43	LOW	SAND	3.44		3.46	
42.70853	-70.71415	STA87	LOW	SAND	3.54		3.72	
42.73608	-70.71741	STA33	LOW	SILTY SAND	3.79		4.49	

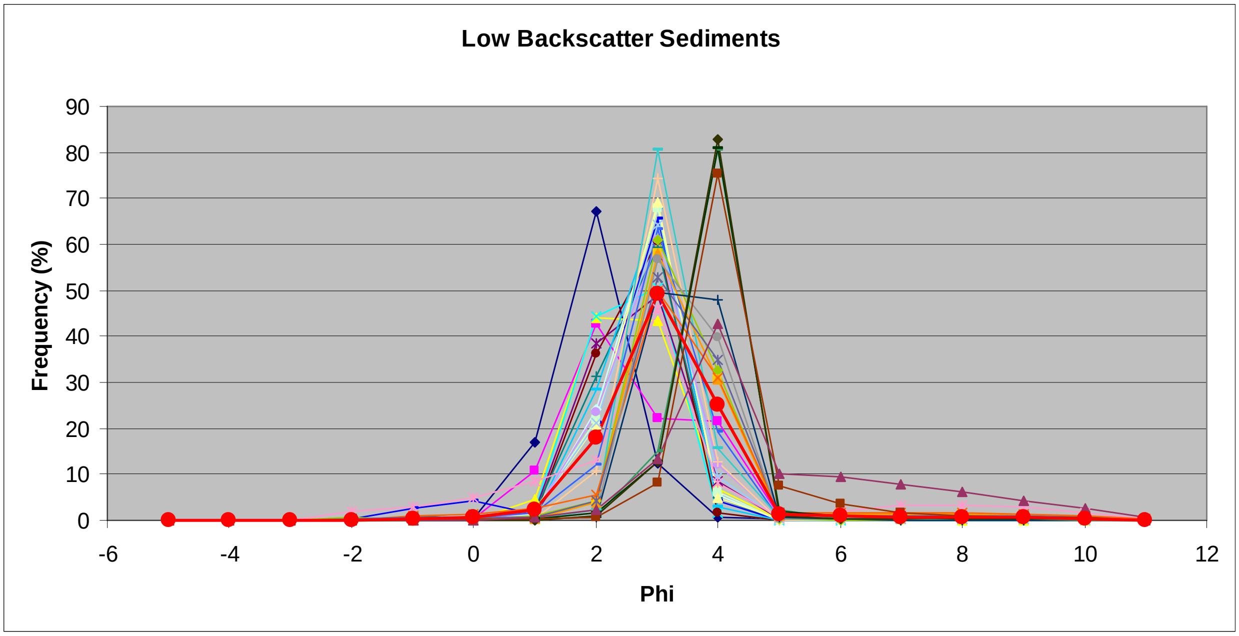
42.83383	-70.67475	STA71	OFFSHORE	SAND	2.44	5.706923	2.64	5.84154
42.74999	-70.63920	STA40	OFFSHORE	SAND	3.41		3.82	
42.79921	-70.66852	STA64	OFFSHORE	SAND	3.42		3.91	
42.77405	-70.6463	AV872	OFFSHORE	SILTY SAND	4.43		5.32	
42.832	-70.6313	AV860	OFFSHORE	CLAYEY SILT	5.09		5.64	
42.77348	-70.6176	AV873	OFFSHORE	SAN SIL CLAY	6.09		6.07	
42.75477	-70.61010	STA41	OFFSHORE	SAN SIL CLAY	6.21		5.92	
42.78610	-70.63543	STA62	OFFSHORE	SAN SIL CLAY	6.26		6.26	
42.83282	-70.6021	AV874	OFFSHORE	CLAYEY SILT	6.97		6.92	
42.77188	-70.582	AV876	OFFSHORE	CLAYEY SILT	7.44		7.31	
42.83295	-70.5706	AV875	OFFSHORE	CLAYEY SILT	7.45		7.4	
42.79540	-70.60388	STA63	OFFSHORE	CLAYEY SILT	7.46		7.28	
42.83020	-70.61573	STA11	OFFSHORE	CLAYEY SILT	7.52		7.45	

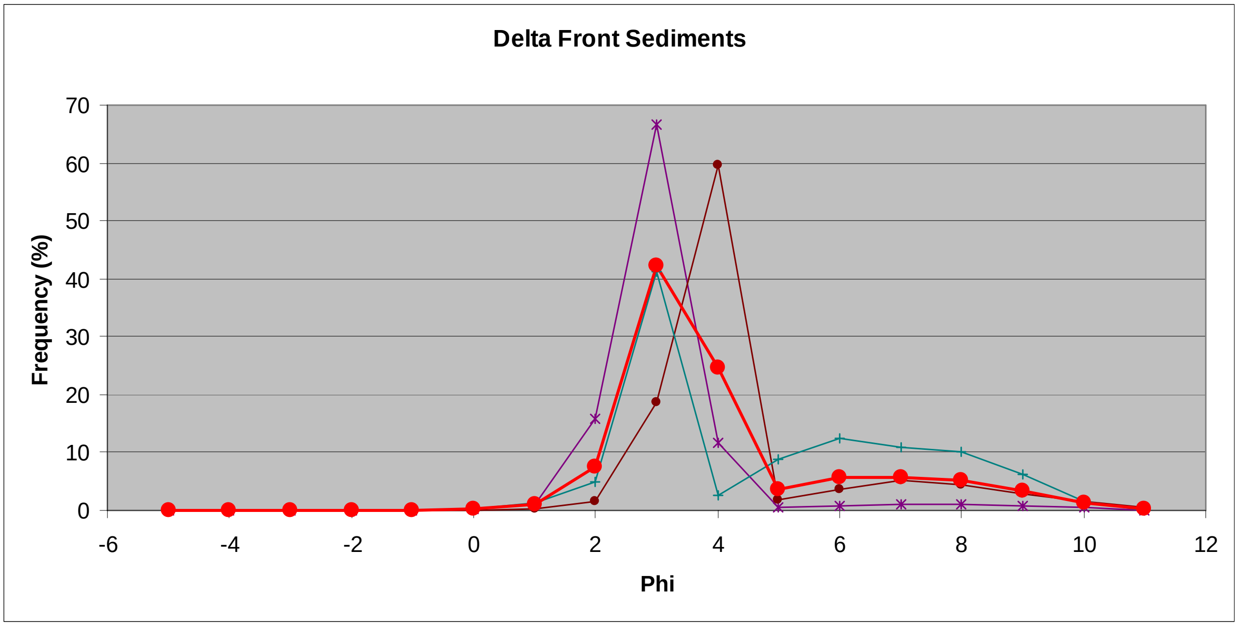
APPENDIX II.

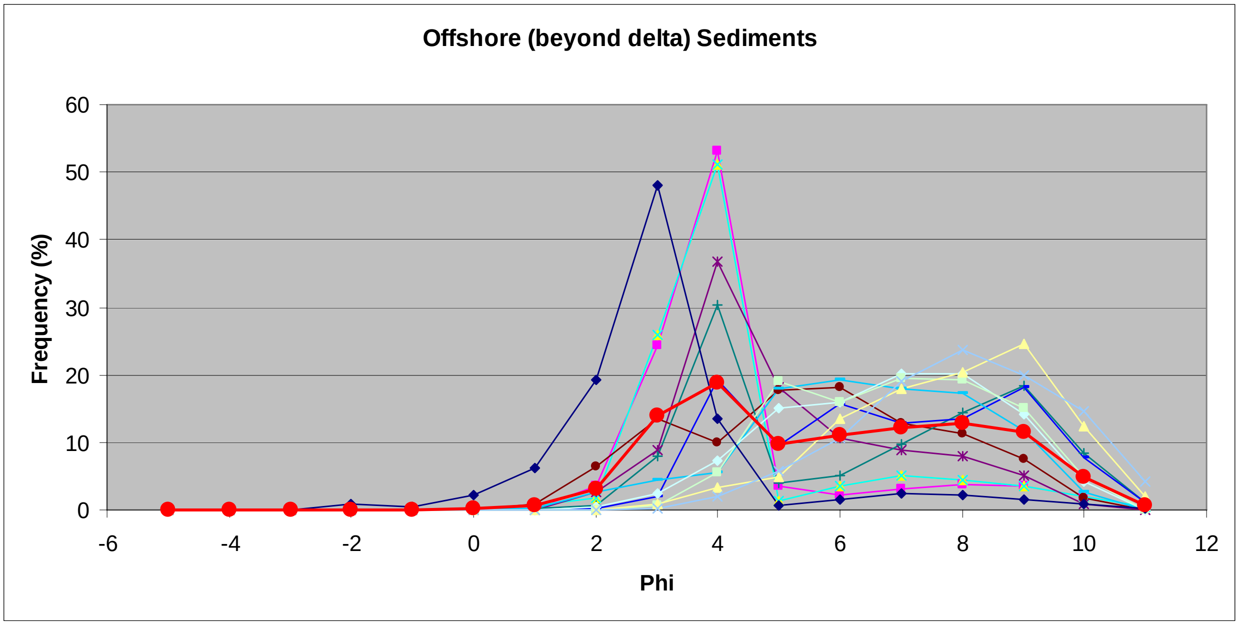
This section contains graphs showing grain size distributions (by percent of phi size) for each bottom sample retrieved during the September USGS cruise and the University of New Hampshire cruise in August 2005. Samples have been grouped according to the backscatter region from where they were retrieved and graphed accordingly. Each graph contains an additional thicker red line representing the mean grain size distribution for each sediment group.


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


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


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