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

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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.

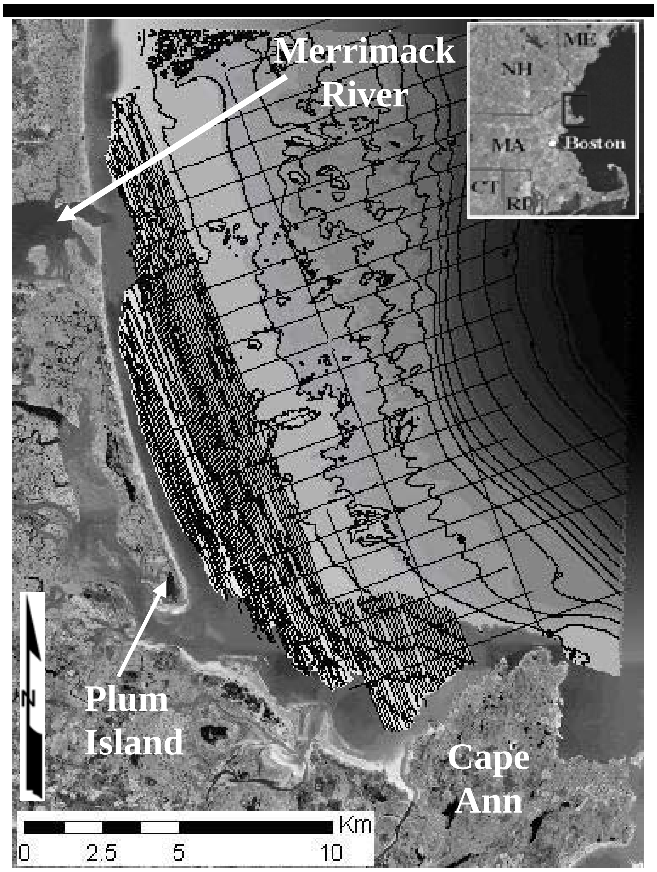

Figure 1. Study area in northern Massachusetts. Offshore study area shown in grayscale bathymetry with black isobath lines (contour interval = 5m). Parallel track lines (black) run NW-SE with shore-normal tie lines.

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.

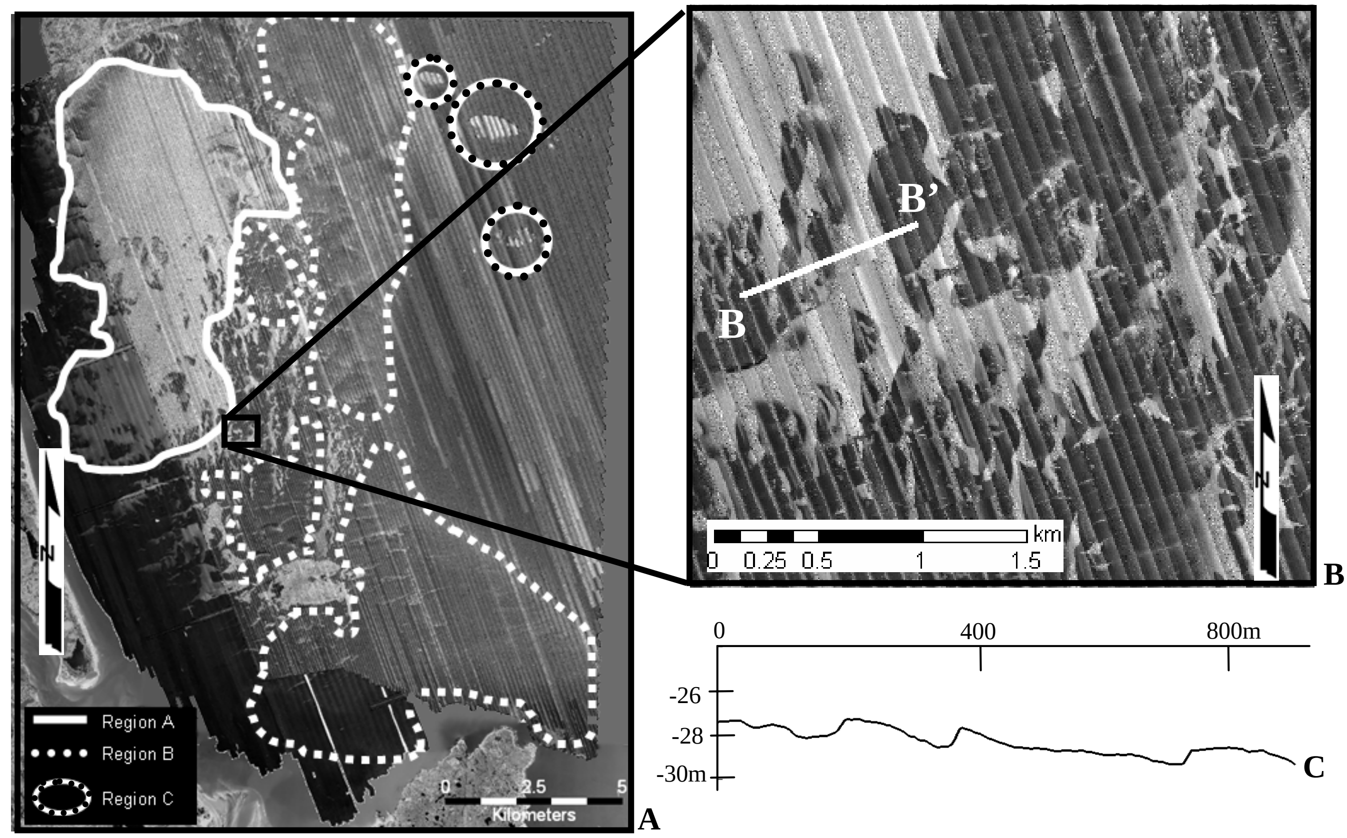

Figure 2. A) Backscatter map of Merrimack Embayment. Regions of the sea floor mapped based on the bathymetric, backscatter, and sedimentological data. Regions indicate the coarse-grained sand sheet (Reg. A), fine- to medium-grained sand (Reg. B), and offshore bedrock (Reg. C). B) Close up of coarse-grained 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.

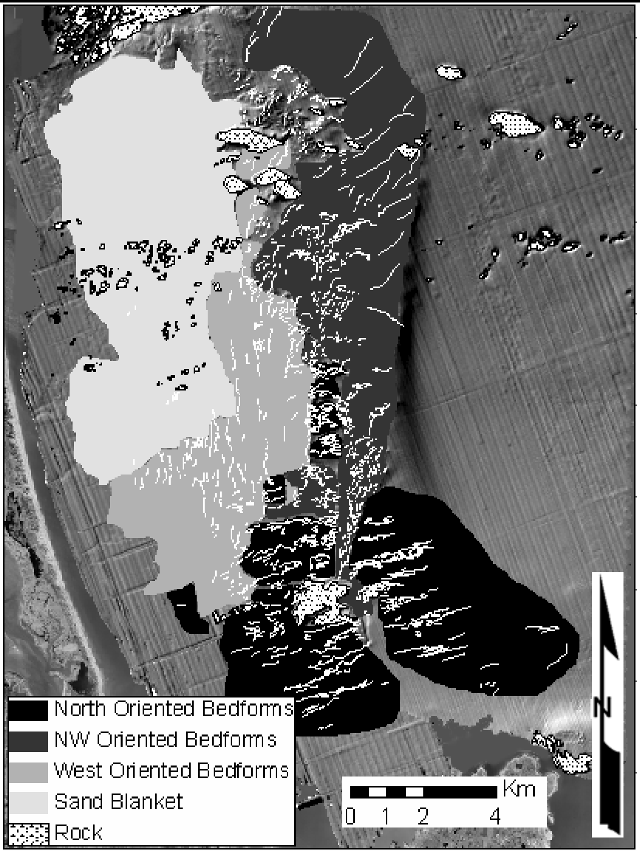

Figure 3. Map of bedform fields with crests traced in white lines.

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

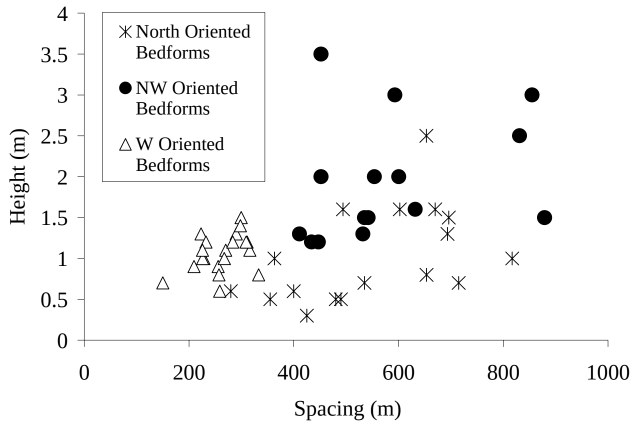

Figure 4. Height vs. Spacing graph of representative bedforms from each of 3 bedform orientation fields.

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.

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