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

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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).

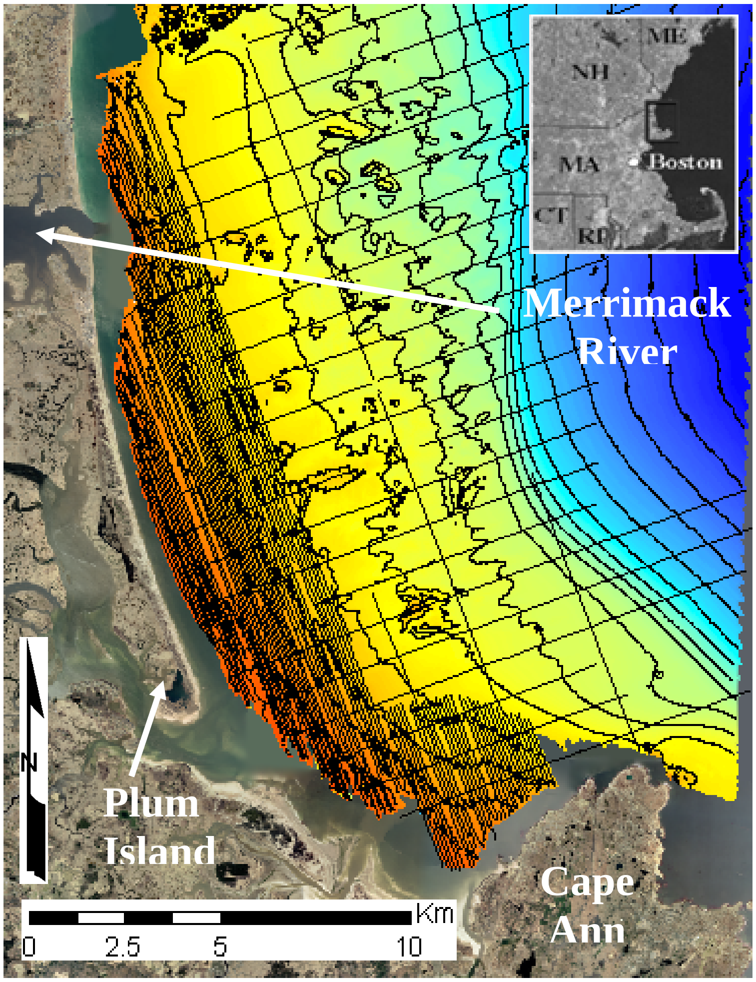

Fig. 1. Study area in northern Massachusetts. Offshore study area shown in grayscale bathymetry with black isobath lines (contour interval = 5m). Parallel track lines (black) run shore parallel with shore normal tie lines.

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).

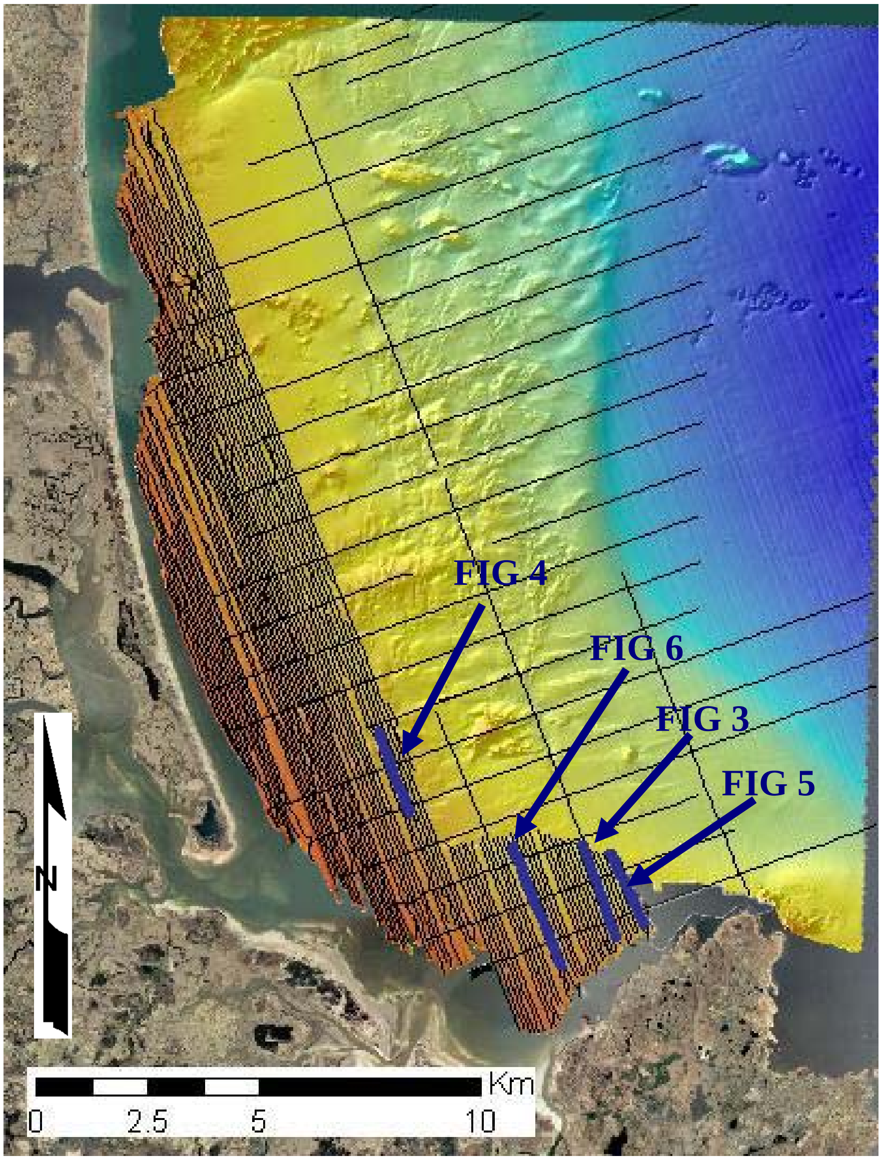

Fig. 2. Locations of tracklines shown in Figures 3-6

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.

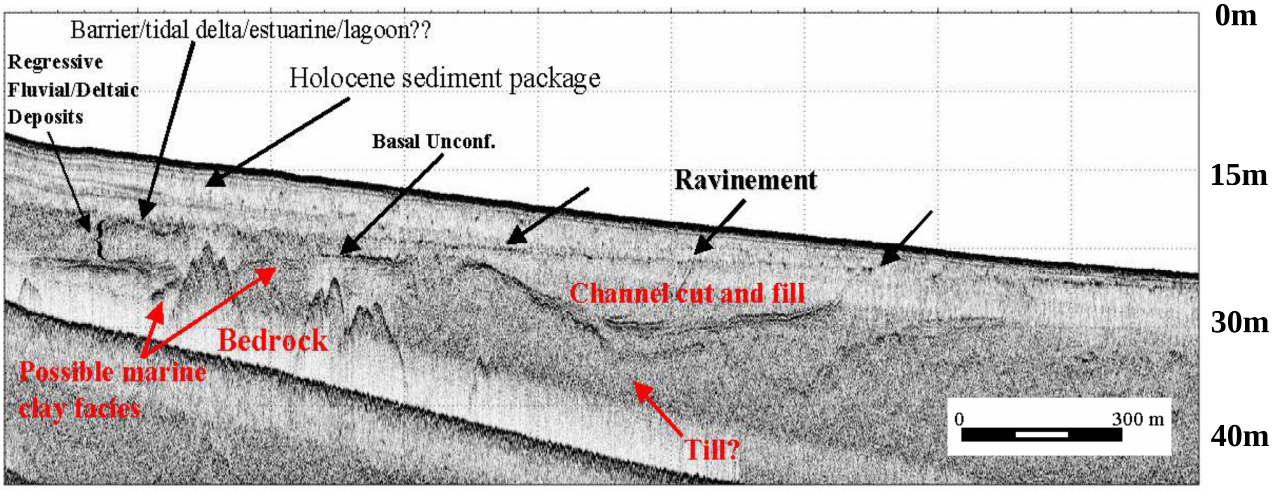

Fig. 3. Sample shallow seismic line indicating general features seen in both shore normal and shore parallel transects (Seismic shot L101f1).

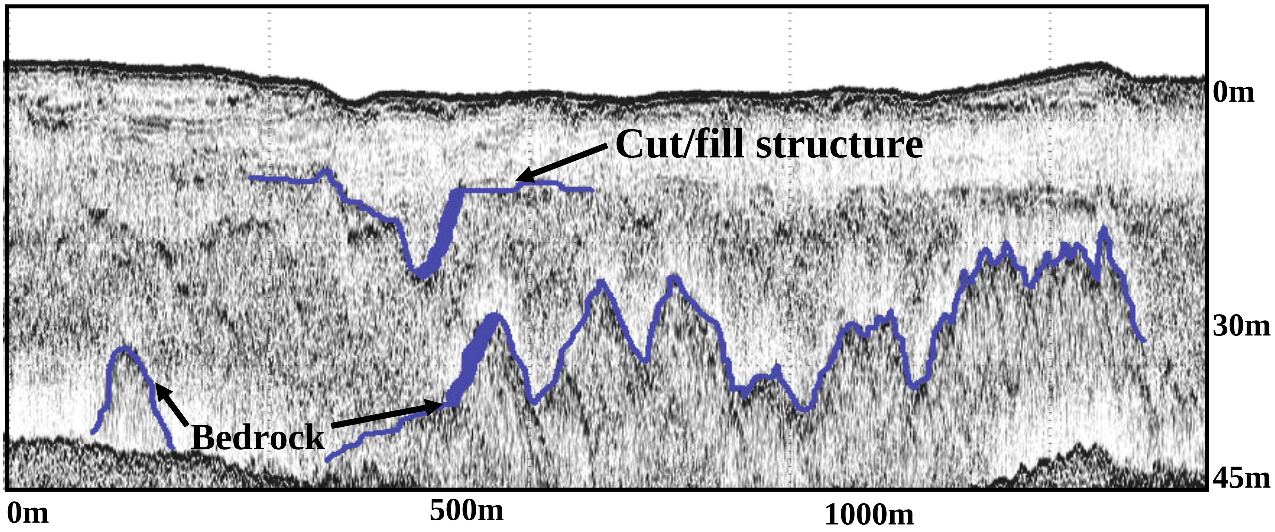

Fig. 4. Sample shallow seismic line indicating a channel cut-and-fill structure overlying bedrock. The bolded lines highlight the close correlation between the geometry of the bedrock and the side of the channel (Seismic shot L5f2).

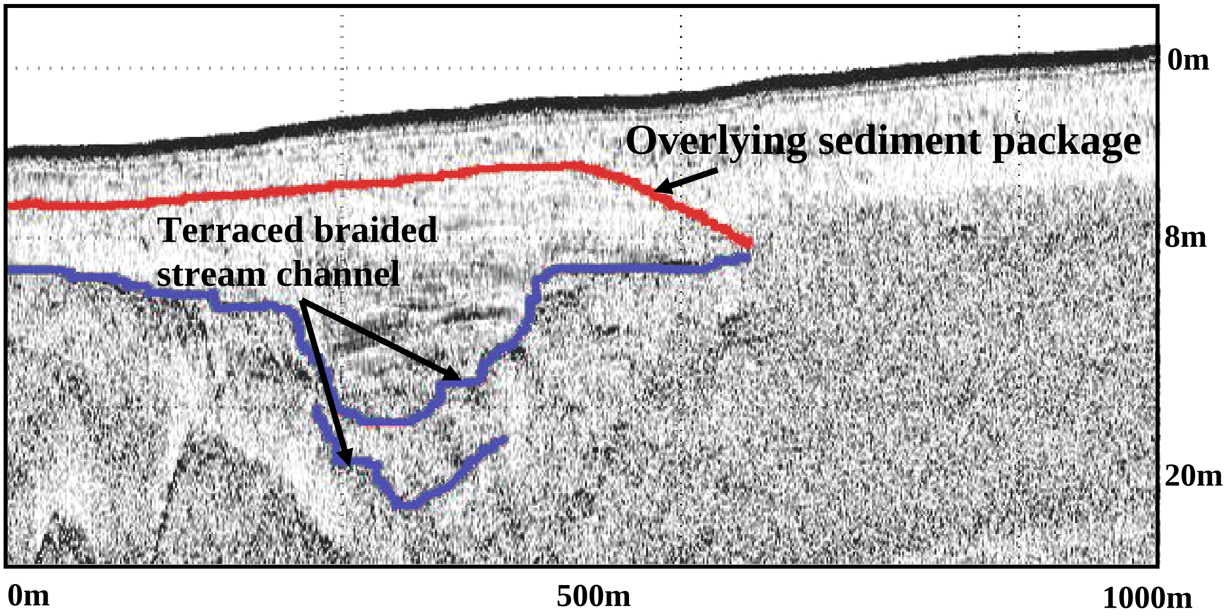

Fig. 5. Evidence of terracing in channel cut-and-fill structures (Seismic shot L106f1).

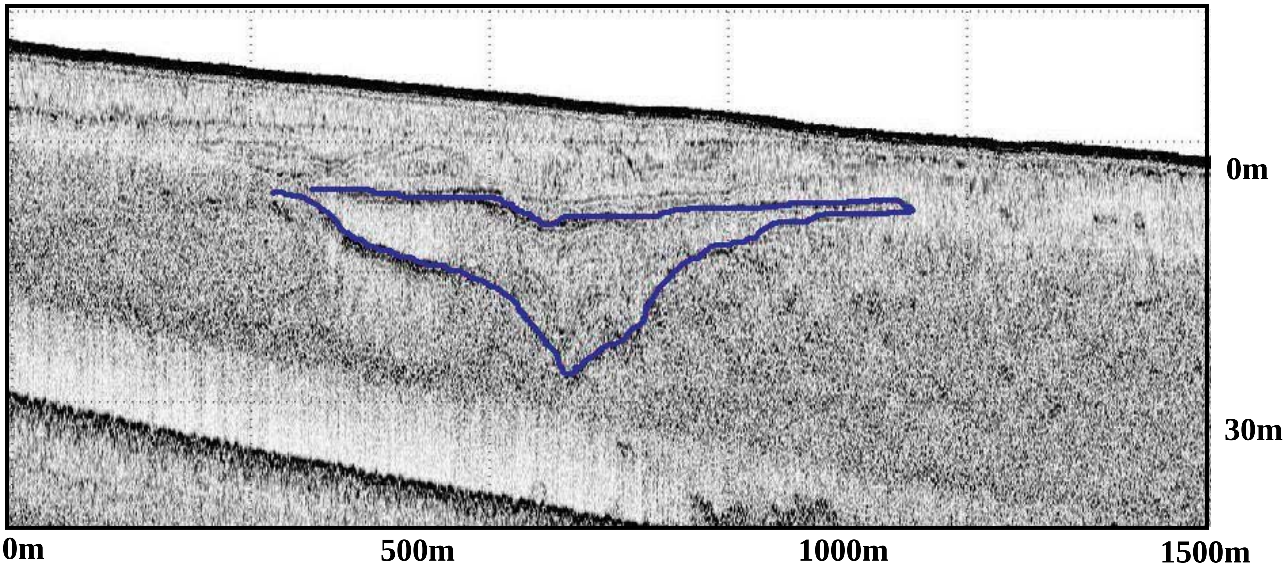

Fig. 6. Example of typical channel cut-and-fill feature mapped near Cape Ann. The form exhibited in this feature is easily traced across several parallel track lines (Seismic shot L97f5).

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.

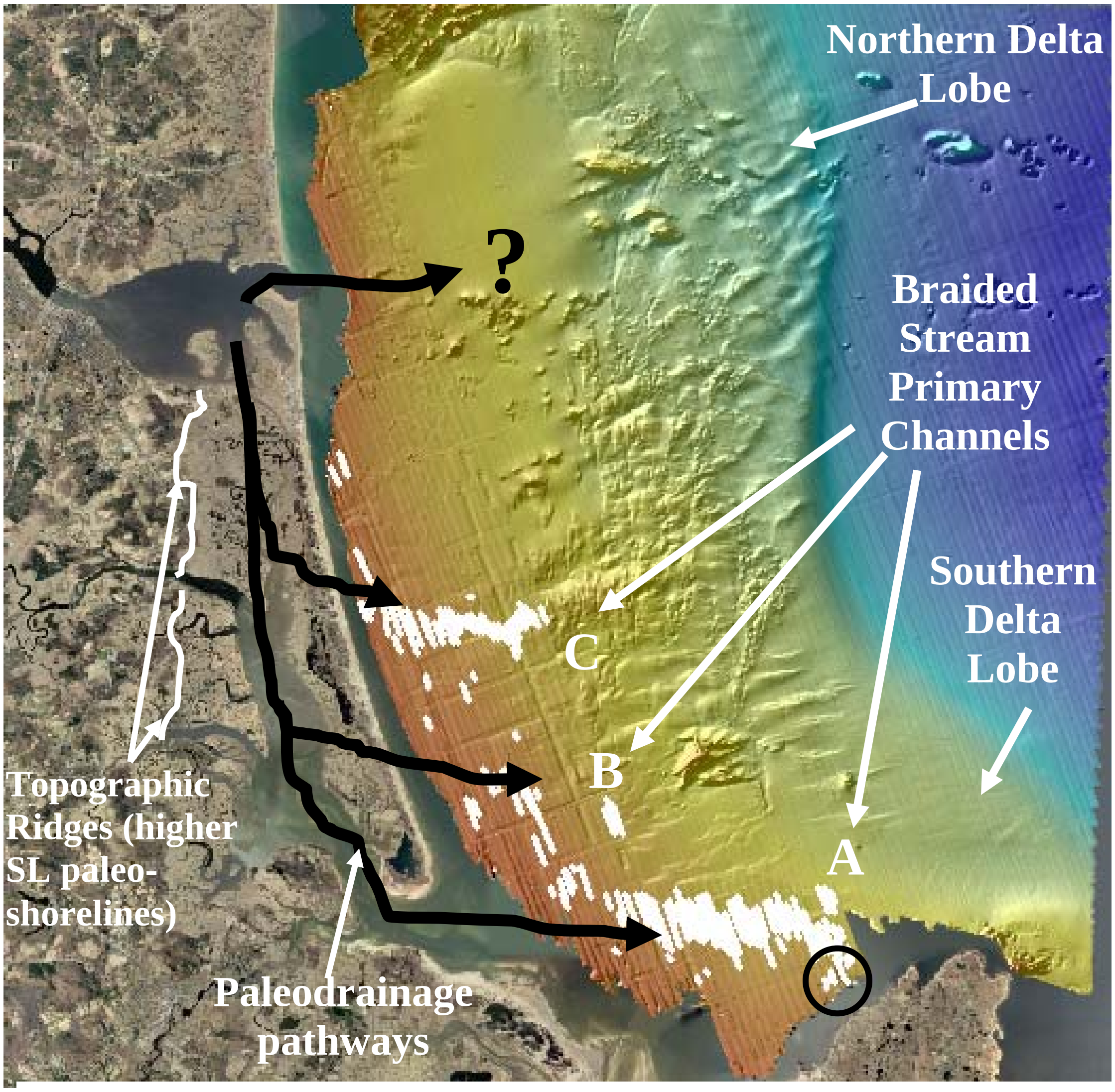

Fig. 7. Map showing locations of subsurface channel cut-and-fill features. Note the 3 distinct sets of features denoting possible locations of braided streams, labeled A-C. The possible forth set of features is circled just north of Cape Ann. Edwards (1988) identified a braided stream complex directly 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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