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Records of Migration and Ebb-Delta Breaching at Historic and Ancient Tidal Inlets along a River-Fed Paraglacial Barrier Island

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ABSTRACT

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Tidal inlets link backbarrier environments to the coastal ocean and play a dominant role in both longshore and cross-shore sediment transport. Additionally, inlet-fill sequences comprise up to 50% of barrier lithosomes in wave-dominated settings. This study uses historic records to investigate centennial-scale cycles of inlet dynamics and barrier shoreline adjustment at Merrimack River Inlet (Plum Island, Gulf of Maine). Geophysical and sedimentological data reveal geometric and stratigraphic signatures of these recent changes, and allow for comparison to similar records preserved within a nearby 3600-year-old inlet-fill sequence. Driven by processes of longshore transport, spit elongation and ebb-delta breaching, the Merrimack River Inlet once actively migrated across a 2.5-km long section of Plum Island. An ebb-delta breaching event in the mid-1800s caused abandonment of the former inlet channel and the onshore welding of a large sand bar, which developed into the northern 1.5 km of the island. The inlet stabilized by jetties in the late 1800s. Ground-penetrating radar profiles and sediment cores across this former inlet channel capture the details of changes prior to breaching, including the seaward deflection of the otherwise southerly and landward-migrating channel, in response to onshore bar migration and welding. Similar details of inlet migration, bar welding, and ebb-delta breaching are observed stratigraphic records of an ancient inlet in central PI, located 7 km to the south. Comparison between the ancient and historical sequences provides clues to decipher the complex inlet dynamics preserved in the stratigraphic and sedimentologic record.

ADDITIONAL INDEX WORDS: *Tidal inlet, paraglacial coast, stratigraphy*

INTRODUCTION

Tidal inlets, channels maintained by tidal flow which hydraulically connect backbarrier environments (lagoons, marsh, tidal flats) with the coastal ocean, enable the exchange of water and nutrients, and provide access to sheltered harbors. They are also among the most dynamic and ephemeral features of barrier systems: along the ocean side of inlets, waves, tides, and currents interact across a complex bathymetry of ebb-tidal deltas, ebb and flood channels, and a series of bars and shoals, reworking and transporting sediment in both longshore and cross-shore directions. The sedimentological remnants of former inlets ("inlet-fill sequences") comprise up to 50% of barrier lithosomes in wave-dominated settings (Moslow and Tye, 1985) and have been identified in abundance along shallow continental shelves (*e.g.*, Sha, 1990; Foyle and Oertel, 1997), and in the rock record (FitzGerald *et al.*, 2012; Longhitano *et al.*, 2012).

FitzGerald *et al.* (2000) summarized nine models by which sand bypasses inlets, nearly all of which involve migration of the main ebb channel, ebb-delta or spit breaching, and sand bars. Recent high-resolution imaging of late-Holocene terrestrial inlet-fill sequences using ground-penetrating radar (GPR), ground-truthed with sediment cores, has demonstrated that the signatures of these processes can be preserved in the sedimentologic record (Mallinson *et al.*, 2010; Hein *et al.*, 2012; Seminack and Buynevich, 2013; Maio *et al.*, 2014). However, linking these inlet-fill sequences to the erosional-depositional processes responsible for their formation is largely inferential, based on observational studies at systems without direct relationships to the ancient inlet-fills.

We seek to address this knowledge gap through comparison of an ancient inlet-fill sequence with that produced by an active modern inlet. The focus of this study is Merrimack River Inlet (MRI) located at the northern end of Plum Island (PI) and a second ancient tidal inlet positioned midway along the length of Plum Island directly east of where the Parker River enters Plum Island Sound. This region is a paraglacial, mixed-energy, tide-dominated (range: 2.7 m), barrier coast located in the western Gulf of Maine, USA (Figure 1). Formation of PI was built from a variety of sediment sources, including glacial-fluvial sediment discharged by the Merrimack River and nearshore marine deposits. Its evolution was strongly influenced by a complex sea-level history that resulted from the combined forcings of global eustatic sea-level rise, and regional glacio- and hydro-isostatic adjustments (Hein *et al.*, 2012, 2014). Plum Island stabilized in its modern position about 3000–4000 years ago,

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following a slowing of relative sea-level rise to near modern rates and the rapid expansion of backbarrier marshes (Hein *et al.*, 2012). This timing coincided with the shoaling and closure of a tidal inlet in central Plum Island (Figure 1b). The resulting 2800 m^2 inlet-fill sequence (the paleo-Parker Inlet; PPI) captures events of channel migration, ebb-delta breaching, onshore bar migration, channel shoaling and infilling associated with the migration and closure of the inlet (Hein *et al.*, 2012). Following closure, PI has undergone 3000 years of aggradation, elongation, and progradation (Hein *et al.*, 2012).

At the northern end of PI the MRI once freely migrated across a 2.5-km long section of the coast through spit elongation, inlet migration, and ebb-delta breaching (FitzGerald, 1993). These processes alternately built and eroded the northeast sector of the island and created a significant navigational hazard. In response, the US Army Corps of Engineers (USACE) initiated a series of public works projects at the mouth of the river in the 1880s, including the construction of the South and North jetties, completed in 1905 and 1914, respectively.

Here, we combine historic maps of northern PI with new geophysical and sedimentologic data collected to document MRI dynamics immediately prior to the final pre-stabilization ebb-delta breaching event. We then compare the resulting stratigraphic signatures to those from the ancient PPI to better elucidate the nature of events captured in inlet-fill sequences.

METHODS

Historic maps and documents describing changes in northern PI are derived from a series of sources, including the Boston Public Library, the USACE, and the NOAA digital library. A total of 27 maps from between 1739 and 1940 were analyzed.

Ground-penetrating radar data were collected along shore-parallel and shore-normal transects (Figures 1b,c) using a Mala Pro-Ex with a 100 MHz antenna (Figure 3) and a Geophysical Survey Systems Inc SIR-2000 with a 200 MHz antenna (Figure 4). These data were post-processed and time-depth converted using relative dielectric permittivities, hyperbola fitting, and depth-to-reflector ground-truthing. Radar profiles were ground-truthed using vibracores, auger drill cores, and direct-push sediment cores in central PI (see Hein *et al.*, 2012 for details) and a 10.5-m long Geoprobe direct-push core in northern PI. The latter was logged, photographed, x-rayed, and sampled in detail. Grain sizes were determined by visually comparing samples under 10x magnification to known standards.

RESULTS

The MRI has undergone a series of complex changes over the past 300 years (Figure 2). Earliest maps of this area (1741) depict the MRI as bounded by thin, elongate bodies of sand connected to Salisbury Beach to the north and PI to the south. By the late 1700s, the southern bar had grown wider and migrated landward, forming a northeast fork of PI ("Old Point") bounded to the west by a narrow subtidal region, not dissimilar to the northeast (NE) fork and Basin of today (see Figure 1b). In the latest 18th century and early 19th century, the MRI migrated 500–1000 m south, eroding northern PI. The NE fork had been completely removed by 1826 and by 1830 the MRI was located >1200 m south of its present location. At some time between 1830 and 1851, the inlet re-oriented to the north, abandoning its former channel. Following the growth of a narrow, northward-elongating arcuate bar ("New Point") to its east, the abandoned inlet channel became the shallow wetlands and tidal flats of the Basin. The eastern fork would later prograde and, following completion of the south jetty, form the modern NE fork of PI.

GPR profiles and sediment cores collected ***ca.*** 50 m south of the modern Basin reveal three distinct radar and sedimentologic units. At the base of sediment core PIG26 is coarse sand, overlain by a 1.1-m thick set of silt- and clay- rich fine sand. These sediment types are indistinguishable in GPR profiles, in which they have a weak radar signature and semi-horizontal to gently landward- and seaward-dipping reflections (Unit I in Figure 3). Together, these deposits are interpreted as estuarine and fluvial sands related to an earlier (pre-1700s) southerly migration of the MRI, followed by abandonment due to ebb-delta breaching and formation of the earlier incarnation of the Basin. Sitting atop this unit is a 4–6-m thick sequence of oblique-tangential, eastward-dipping (slopes: 7–9^o) reflections (Unit II in Figure 3). This unit is at least 150 m long in a cross-shore direction and composed of interbedded medium, coarse, and very coarse rounded sand; the bottom of this unit is composed of ~50 cm of bedded medium-coarse to very coarse sand. This unit is interpreted as fluvial deposits associated with the migration of the MRI channel. It is topped with 2.5 m of medium to coarse beach and dune sand (Unit III).

Hein ***et al.*** (2012) describe the ancient PPI in central PI in detail. It is 5–6-m thick, 700-m wide, and was active 3.4–3.6 ka. It was connected to the Parker River, which currently discharges into PI Sound and to the Parker Inlet at the southern end of PI (see locations, Figure 1). It is divided into two complexes: a 3.5-m thick northern section dominated by southerly dipping reflections; and a southern section of variable thickness (Figure 4). Both contain complex internal reflections interpreted as evidence of high-energy depositional events associated with spit accretion and southerly inlet migration, ebb-delta breaching, onshore bar migration, and inlet shoaling and closure in response to and decreasing tidal prism (Hein *et al.*, 2012).

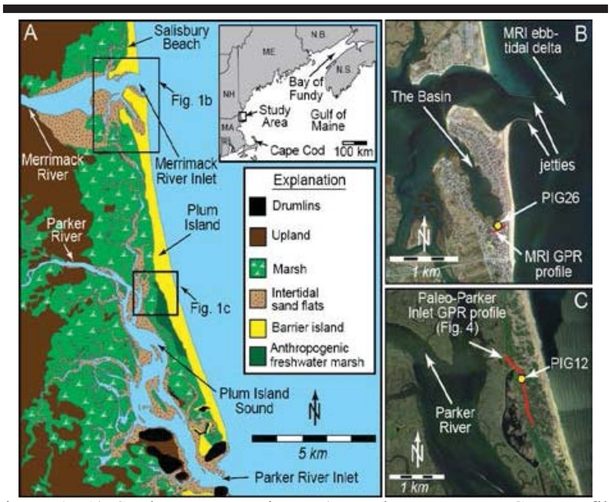

Figure 1. A) Study area overview. B) Northern PI; note GPR profile (Figure 3) C) Central PI and Parker River; note GPR profile (Figure 4).

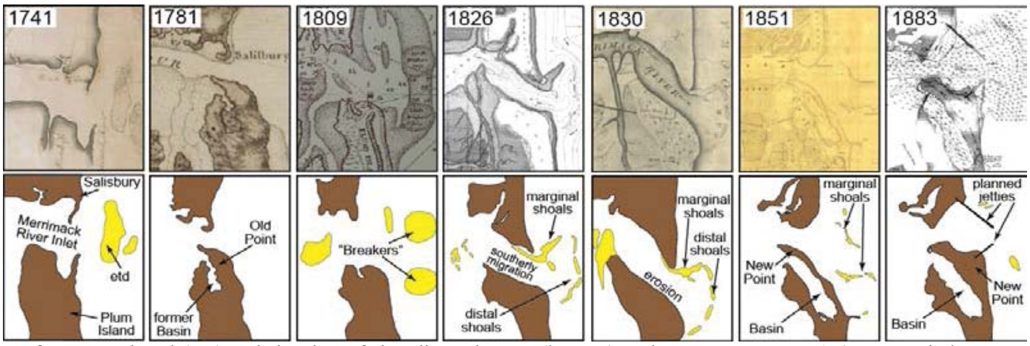

Figure 2. Sub-set of maps analyzed (top) and sketches of shorelines changes (bottom) at the MRI over a *ca.* 150-year period. Data sources: Mitchell (1741); Desbarres (1741); Blunt (1809); Anderson (1826); Anderson (1830); US Coast Survey (1851); USACE (1883). "etd" – ebb-tidal delta.

DISCUSSION

Historic, geophysical, and sedimentologic data provide insight into the complex cyclical inlet processes associated with breaching events which are captured in the stratigraphic record.

Multiple Phases of Ebb-Delta Breaching

Nichols (1942) and Watts and Zarillo (2013) documented changes in the position and morphology of the MRI prior to, and after, construction of the jetties. FitzGerald (1993) attributed these changes, and the development of the Basin and the NE fork, to ebb-delta breaching in response to the development of a hydraulically inefficient southerly deflection of the main ebb channel caused by the longshore transport driven by dominant northeast storms. The sand, which once comprised the channel-margin linear bars and swash bars of the inlet channel, migrated onshore, eventually welded to PI. By 1851, the remnant ebb-delta sand shoals formed a narrow, north-ward-elongating arcuate bar ("New Point"), which enclosed the former river/inlet channel, forming the Basin (Figure 5). New Point has since elongated and prograded, largely in response to artificial stabilization of the inlet mouth, and enhanced sediment delivery through a local reversal of longshore transport immediately downdrift of the inlet (Hubbard, 1976).

The most recent breaching event and associated morphologic changes were not unique. Rather, prior to stabilization, the MRI likely underwent a series of major ebb-delta breaching events on an approximate centennial timescale: the modern NE fork of PI and the Basin are the latest in a series of similar features, the prior of which date to the late 1700s (Figure 2). Under natural conditions, the NE fork was routinely driven onshore by the southward migrating MRI, filling the former river channels. It was eventually removed, but reformed through onshore migration and welding of the remnant ebb-tidal delta after breaching (Figure 2). Coarse sand at the base of core PIG26 is interpreted to have been deposited during this earlier phase of MRI migration and ebb-delta breaching, followed by occupation of the site by a quiet water environment of the 1700s "Paleo-Basin", during which time the fine sediments at the top of Unit I were deposited. The subsequent southerly MRI migration likely partially eroded these deposits. This natural cycle of growth and destruction of the ephemeral NE fork and the Basin would likely have continued unabated had it not been interrupted by the stabilization of the MRI, allowing for the development of PI, and initiating the development of a 25–40-year cycle of erosion and accretion along the northern PI beach (Fallon *et al.*, 2015).

Complex Inlet-Breaching Processes

The process of inlet ebb-delta breaching at natural inlets is well documented from a variety of case studies (*e.g.*, Balouin *et al.*, 2001; FitzGerald, 1982, 1988; Kana *et al.*, 2014). It is most common at inlets with stable throat positions, but whose main ebb channels cyclically migrate downdrift, occasionally impinging the downdrift shoreline and eroding into the adjacent beach (FitzGerald *et al.*, 2000). Our data elucidate some of the details of the final stages of channel migration prior to ebb-delta beaching. Here, following erosion of Old Point by the southerly and landward migrating channel, the MRI shifted several hundred meters eastward (seaward) (Unit II, Figure 3) prior to breaching and partial filling of the southern section of the channel with reworked ebb-delta sands (Unit III, Figure 3). This eastward reorientation of the channel is interpreted to be a response to deflection by outermost ebb-tidal delta breaching (Figure 6). As the channel re-orientates, sand comprising the downdrift side is more influenced by waves and sand moves onshore in the form of a bar. The main channel deflects off this protruding shoreline and migrates updrift as it straightens. The bulge in the downdrift shoreline is ephemeral and is rapidly flattened through longshore reworking by wave action (Figure 6) as ebb-delta breaching proceeds.

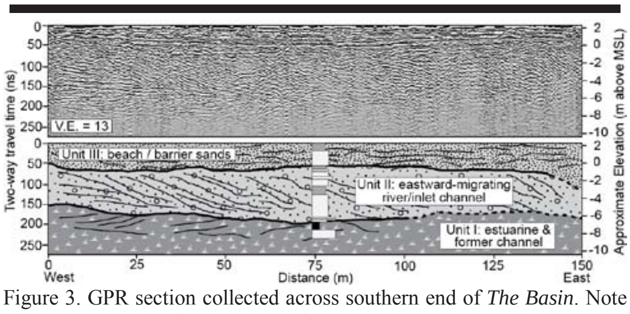

Figure 3. GPR section collected across southern end of *The Basin*. Note eastward-dipping reflections signifying eastward migration of the MRI prior to ebb-delta breaching. See figure 4 for core log explanation.

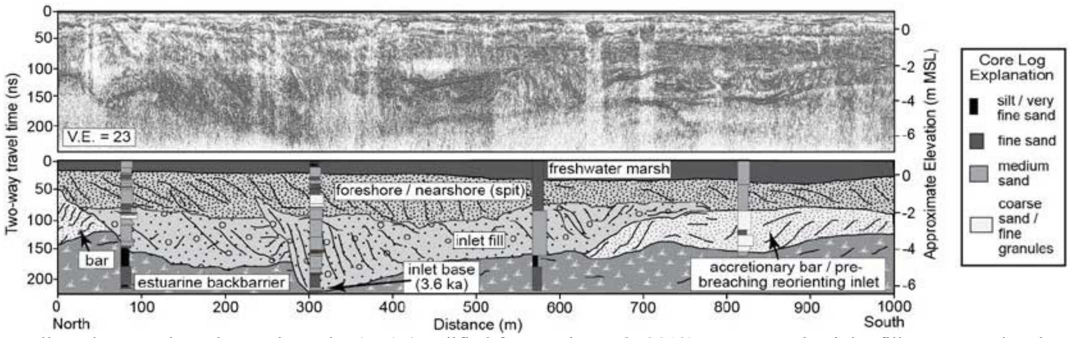

Figure 4. GPR collected across the Paleo-Parker Inlet (PPI) (modified from Hein *et al.*, 2013). Note complex inlet-fill sequence showing with multiple former channels. To the south is a northward-migrating sequence interpreted as originating from re-orientation of PPIprior to ebb-delta breaching.

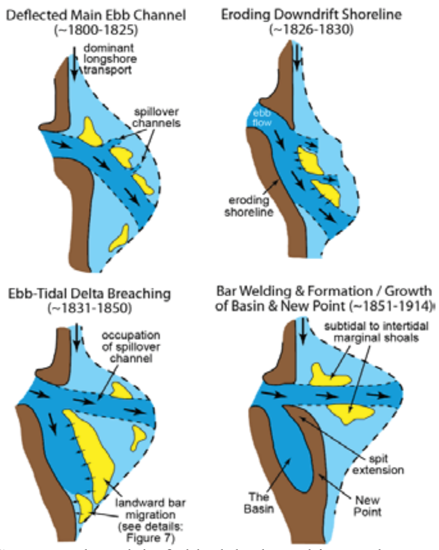

Figure 5. Conceptual model of ebb-delta breaching at the MRI. Modified from FitzGerald (1993).

Comparison of Ancient and Historic Inlets: Implications For Interpretation of Inlet-Fill Sequences

The historic MRI inlet-fill sequence captures a short phase of the latest ebb-delta breaching event. By contrast, the PPI sequence contains evidence of multiple phases of southerly inlet migration separated by ebb-delta breaching events. Moreover, this PPI sequence was formed by an inlet associated with the Parker River, a substantially smaller system than the Merrimack River. Thus, it would be expected that these two sequences would record different patterns of inlet dynamics. These differences are most dramatically reflected in the sediment types composing the inlet-fill sequences: largely medium to coarse sand in the PPI as compared to fluvial, coarse sand and granules in the MRI. These latter sediments are similar to those observed in the modern lower Merrimack River by FitzGerald *et al.* (2002), whereas the sediments within the PPI more closely approximate those observed along the modern beach.

Nonetheless, there are notable similarities between the ancient and historic inlets. Shore-perpendicular crossing lines at the PPI indicate periods of eastward (seaward) inlet channel migration (Hein *et al.*, 2012) not dissimilar to that captured at the historic MRI. Moreover, south of the PPI are three packets of sigmoidal, northward-dipping reflections (Figure 4) stretching across 500 m in a shore-parallel direction. These may originate from re-orientations of the hydraulically inefficient PPI prior to ebb-delta breaching events (Figure 4). Alternatively, these features may be the incompletely eroded remnants of landward-migrating bars responsible for deflection of the main ebb channel immediately prior to breaching. Regardless, the presence of these bed sets dipping counter to the expected longshore migration direction of the PPI indicate the complexity of processes captured within inlet-fill sequences which may be preserved in inlet-fill sequences elsewhere.

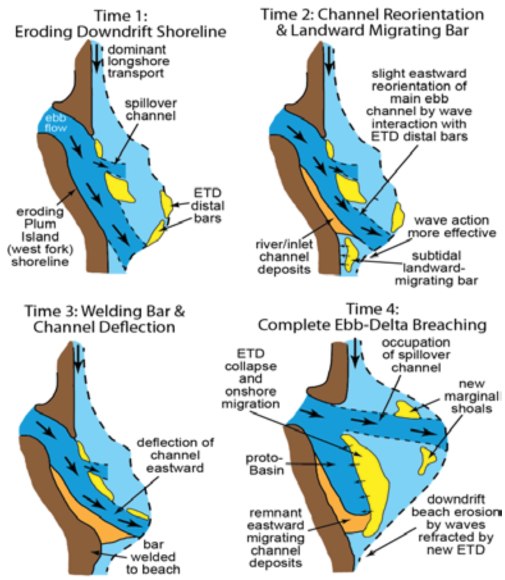

Figure 6. Model of eastward deflection of the MRI main ebb channel, creating eastward-dipping river inlet channel deposits in GPR profile.

CONCLUSIONS

New GPR, sedimentologic, and historic data from PI reveal complex inlet-migration patterns preserved within a historic inlet-fill sequence. Southerly and landward-migrating MRI reoriented seaward in response to deflection by a protruding shoreline formed from the onshore welding of downdrift ebb-delta sediment. This study provides new insight into the details of ebb-delta breaching and the utility of the historic record in deciphering recent stratigraphies. Moreover, comparison of the historic inlet sequence with that associated with an ancient inlet in central PI reveals evidence of a similar set of dynamics and underscores the need to carefully document complex inlet processes recorded in inlet-fill sequences in close comparison with those preserved by modern analogs.

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