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Geological Signatures of Barrier Breaching and Overwash, Southern Massachusetts, USA

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ABSTRACT

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Historical documents, aerial photography, sediment cores, and 30 km of ground-penetrating radar (GPR) profiles were used to assess the history of barrier breaching and overwash at several sites in southern Massachusetts. Historical charts dating back to the 1700s show a number of openings along the barriers, some of which persisted for decades. On the shorelines affected by extratropical northeast storms (e.g., 1898, 1978, 1991) the geomorphological features include gaps in dune belts, deflected tidal channels, and low marsh-fringe ridges landward of the inlet sites. On the south-facing shorelines exposed to hurricanes (1630s, 1760s, 1815, 1860s, 1938, 1944, 1954-55, 1991) surficial indicators of breaching consist of small flood-tidal deltas and narrow segments of low elevation along the barriers. Most tidal channels owe their origin to storm surges overtopping and downcutting the foredune ridge and subsequent scouring of the overwash channels. The buildup of water in the bays often generates strong ebb-surge flow across the barrier that is capable of opening new channels. Even during a single tidal cycle, extreme storm surges (max. height > 4 m; wind speed >160 km/hr) are capable of substantial erosion. In places where complete breaching does not occur, extensive overwash fans have been deposited in backbarrier wetlands. Many washovers are attributed to intense storms dating back as early as A.D. 900. Where a freshwater lens is present in the shallow subsurface, GPR images confirmed many historical inlet positions and revealed a number of buried channels not present on the survey charts. Smaller features (width: 10-30 m; depth: 1-3 m) are likely ephemeral storm breachways or overwash channels, whereas historic inlets have greater cross-sectional areas (width: 100-600 m; depth: > 4 m). Although many ephemeral channels show no evidence of lateral migration, some appear to have moved tens of meters before closing. Geophysical surveys over the sites of largest inlets reveal complex patterns of channel migration and infilling. Historical and geological data suggest that channel-fill sequences may comprise up to 80% of the barrier lithosome. Given the widespread occurrence of breaching and overwash on retrograding barriers along the Massachusetts coast, identification and mapping of historic and pre-historic overwash and breaching sites along the barrier coasts should be an integral part of coastal hazard studies.

ADDITIONAL INDEX WORDS: *Storms, stratigraphy, ground-penetrating radar, Cape Cod.*

INTRODUCTION

In the past century, a number of large storms have impacted the shoreline of southern Massachusetts. The physiography of this region is dominated by proglacial landforms and the general shoreline orientation ranges from east to south (Figure 1), thus being exposed to local extratropical storms (northeasters, southeasters) and northward-tracking hurricanes (Figure 2; LUDLUM, 1963; NEUMANN *et al*., 1993; FITZGERALD *et al*., 1994; DONNELLY *et al*., 2001a; ZHANG *et al*., 2001). Coastal geomorphic features are often useful in locating and mapping the areas of the shorelines where barriers were overwashed or breached during these extreme events. On the shorelines affected by extratropical storms (e.g., 1898, 1978, 1991) surficial features include gaps in dune belts, deflected tidal channels, and low marsh-fringe ridges landward of the inlet sites. On the south-facing shorelines exposed to hurricanes (1630s, 1760s, 1815, 1860s, 1938, 1944, 1954-55, 1991) geomorphic indicators of breaching consist of small flood-tidal deltas and narrow segments of low elevation along the barriers.

Despite the fact that the geomorphic expressions of the most extreme events may persist for many decades, it is often difficult to identify and map their erosional and depositional signatures over large distances. Subsurface methods, such as sediment coring and high-resolution geophysical imaging provide a more complete picture of coastal responses to a variety of environmental forcing factors. However even when their sedimentological signatures have been identified, the unknown timing of pre-historic events makes it difficult to evaluate the recurrence intervals of large-magnitude events. Radiocarbon dating of organic sediments associated with storm-induced overwash or breaching events is beginning to address this question (LIU and FEARN, 2000; DONNELLY *et al*., 2001a,b), and new techniques, such as optically-stimulated luminescence dating of barrier sands (BRYANT *et al*., 1996) offer new opportunities for coastal scientists to date inorganic sediments. In this paper, we present examples of the geological records of barrier overwash, breaching, and inlet closure from southern Massachusetts and the approaches used to decipher the environmental histories at three coastal sites (Figure 1). We then use comparisons of sedimentological and geophysical data with historical charts and radiocarbon dates to determine the timing of large-magnitude erosional events.

Records of Barrier Overwash

Washovers occur when wave energy combined with high water levels (storm surge) overtop or breach coastal barriers and transport nearshore and barrier sediments into the backbarrier environment (SCHWARTZ, 1975). If the barrier is breached, a lobate fan at the terminus of the breach will form. If multiple breaches occur close together these lobes may coalesce. When the entire barrier is overtopped by storm surge, sheet washovers that extend the length of the barrier are deposited. Between overwash events, low-energy estuarine deposits are typically deposited over washovers. If these deposits are not reworked during subsequent storms, the washovers will be preserved as laterally continuous horizons of sand within backbarrier sediments and provide a record of past storm surge.

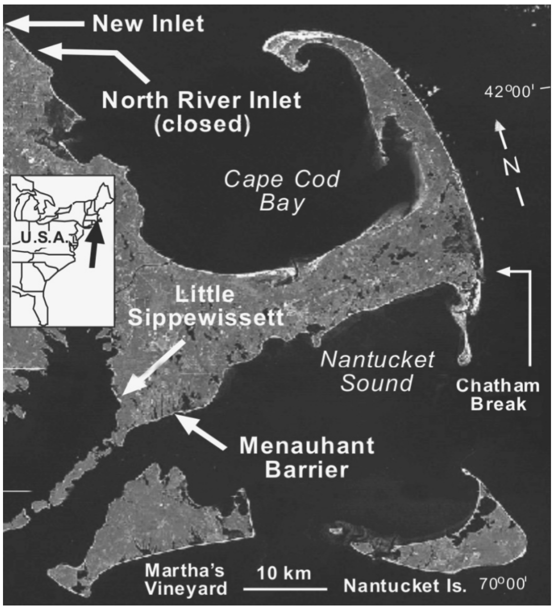

Figure 1. LANDSAT vertical aerial photograph of Cape Cod and Islands, Massachusetts showing locations of the study sites. Note the variable degrees of shoreline exposure spanning 360º and the relatively sheltered nature of the south shore of Cape Cod provided by the islands.

Washovers are composed of locally derived material from the foredune, beach and nearshore environments and are typically well-to poorly-sorted, fine-to-coarse sand. The mean grain-size within washovers generally decreases as a function of distance from the barrier (HENNESSY and ZARILLO, 1987). Washover sediments often exhibit horizontal stratification, and if the deposit terminates in a coastal pond or lagoon they can exhibit medium- to small-scale delta foreset stratification (SCHWARTZ, 1975). Overwash deposits can also lack stratification. Cores from backbarrier environments in southern Rhode Island contain overwash deposits with little or no horizontal stratification (DONNELLY *et al.*, 2001a; BOOTHROYD *et al.*, 1985).

Another characteristic of washovers preserved in backbarrier environments is the abrupt nature of the contact with the underlying peat or estuarine mud (DONNELLY et al., 2001a, b). Evidence of soft-sediment deformation is common where washovers are deposited over saturated, fine-grained sediments (KLEIN, 1986). In addition, rip-up clasts are frequently encountered at the basal contact of a washover and are indicative of high-velocity currents associated with overwash deposition.

Vibracores from Little Sippewissett Marsh in West Falmouth reveal a record of washovers within salt marsh peat (Figures 1 and 2). Radiocarbon dates of marsh macrofossils beneath the deepest two washovers in core 7 reveal that these storm-induced deposits were deposited prior to European settlement of the region and as early as AD 900. Three other washovers preserved in cores 6 and 7 were likely deposited during the historic interval and may correlate to intense hurricane strikes making landfall to the west (1938, 1869, 1815, and 1635; LUDLUM, 1963)(Figure 2).

Breaching and Inlet Processes

Barrier segments adjacent to active tidal inlets undergo rapid and dramatic changes that are often independent of long-term shoreline trends (LEATHERMAN, 1979; FITZGERALD, 1988; BUSH *et al.*, 1996; ZARILLO, 1999). The adverse impacts of barrier breaching and formation of ephemeral inlets may include a substantial changes in ambient wave and tidal conditions, sediment transport patterns, as well as damage to shorefront infrastructure (HEADLAND *et al.*, 1999). In some cases, breachways may rapidly evolve into large permanent inlets. For example, Shinnecock Inlet on Long Island, New York and the New Inlet (Chatham Break) on the outer Cape Cod (Figure 1) owe their existence to the 1938 Hurricane and a severe 1987 northeast storm, respectively. Barrier vulnerability to breaching and overwash is among the key factors to be considered by coastal scientists and managers, but despite a

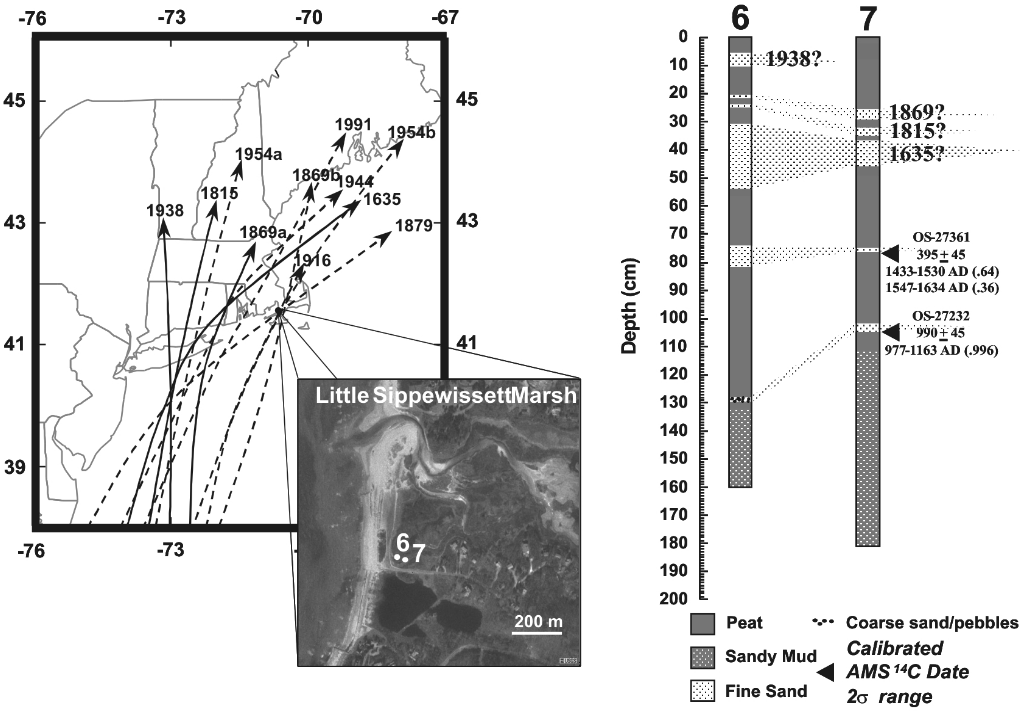

Figure 2. Tracks of hurricanes impacting southeastern Massachusetts in the last 400 years (from Neumann et al., 1993; Ludlum, 1963; Donnelly et al., 2001a). Solid tracks denote intense hurricane strikes (≥ cat 3; winds >50 m s^{-1}). Dashed tracks denote category 1 or 2 hurricane strikes (winds <50 m s^{-1}). Aerial photograph of Little Sippewissett Marsh in West Falmouth, Massachusetts (Core locations are noted by white dots). Stratigraphic cross-section of cores 6 and 7 from Little Sippewissett Marsh show sand layers of variable texture interbedded within the overall sequence of marsh peats.. Radiocarbon dates have been calibrated to calendar years using method B of the Calib 4.1 program (STUIVER *et al.*, 1998)

number of qualitative studies and observations of barrier breaching, there is a paucity of research on breaching processes and the geological legacy of former inlets (KRAUS *et al*., 2002).

Conventionally, geological signatures of coastal erosion have been identified through geomorphic evidence, extensive coring efforts, or historical documents (FISHER, 1962; MOSLOW and HERON, 1978; MOSLOW and TYE, 1985; FINKELSTEIN, 1988; BUSH *et al*., 1996; MCBRIDE, 1999). However, surficial signatures of erosional shorelines and inlet channels may be drastically modified or obliterated by natural or human-induced processes. In many cases, sediment cores are expensive to obtain and offer point data that often miss subsurface features of limited spatial extent, such as concentrations of heavy minerals diagnostic of buried storm scarps (LEATHERMAN, 1985; BUYNEVICH and FITZGERALD, 2001).

With the advent of new subsurface imaging technology, such as ground-penetrating radar (GPR), high-resolution continuous records of subsurface barrier architecture can be imaged, with penetration depths of 5-15 m common for coastal regions (JOL *et al*., 1996; Van HETEREN *et al*., 1998; BUYNEVICH *et al*., 2003). Although the electromagnetic radar signal is attenuated by salt water, relatively high permeability and width of many barrier systems allow for freshwater conditions to dominate the shallow subsurface, making GPR a viable imaging tool for these settings (for background information on the GPR technique, see REYNOLDS, 1997). In formerly glaciated settings, such as New England region, the mixed-sediment composition of many coastal sequences ensures the lithological contrast necessary for creating a variety of subsurface reflections. In recent years, ground-penetrating radar technology, complemented with sediment cores, has been used successfully in coastal-stratigraphic research in New England and the Mid-Atlantic States. For example, in a recent study along the south shore of Falmouth, Massachusetts, GPR surveys revealed a number of breaches not present on historical charts with up to 60-80% of barrier lithosome represented by channel-fill deposits (BUYNEVICH and EVANS, 2003). The ability to locate former inlet sites in other coastal areas and image their sedimentary fill, as well as to identify the inlet-related features along the nearby barrier segments should provide new insights into barrier dynamics and become part of coastal vulnerability studies. Below, we present examples of the geophysical records of a simple and a complex inlet fills from southern Massachusetts.

Breach at Menauhant Barrier

Menauhant Beach is a short mixed-sediment baymouth barrier fronting Bournes Pond along a sheltered, microtidal (TR=0.6m) outwash coastline of Falmouth Harbor (Figure 1). Based on historical charts, a tidal inlet existed through the westernmost part of the barrier for most of its recent history at least since 1846, with and the relocation of the channel to its present mid-barrier position in the early 1990s (Figure 3). Also present on all charts and photos is a lobate deposit behind the eastern part of the barrier (relict feature labeled as RF in Fig. 3 a, b). Today it is mostly a dissected intertidal feature, which partially maintains its supratidal elevation due to saltmarsh growth (Figure 3). The context of this relict feature, as well as the nature of recent washover deposits (Hurricane Bob, 1991) overlying its eastern flank (Figure 3b), suggest that it most likely formed as a result of storm deposition sometime prior to 1846. The inability to penetrate the barrier seaward of this feature due to extensive development required an alternative field approach.

Recent high-resolution geophysical survey using a mobile SIR-2000 GPR system revealed a channel structure in this segment of the barrier (BUYNEVICH, 2003). Based on the record in Figure 3c, depth calculations using electromagnetic signal velocities in saturated and unsaturated gravelly sands (VAN

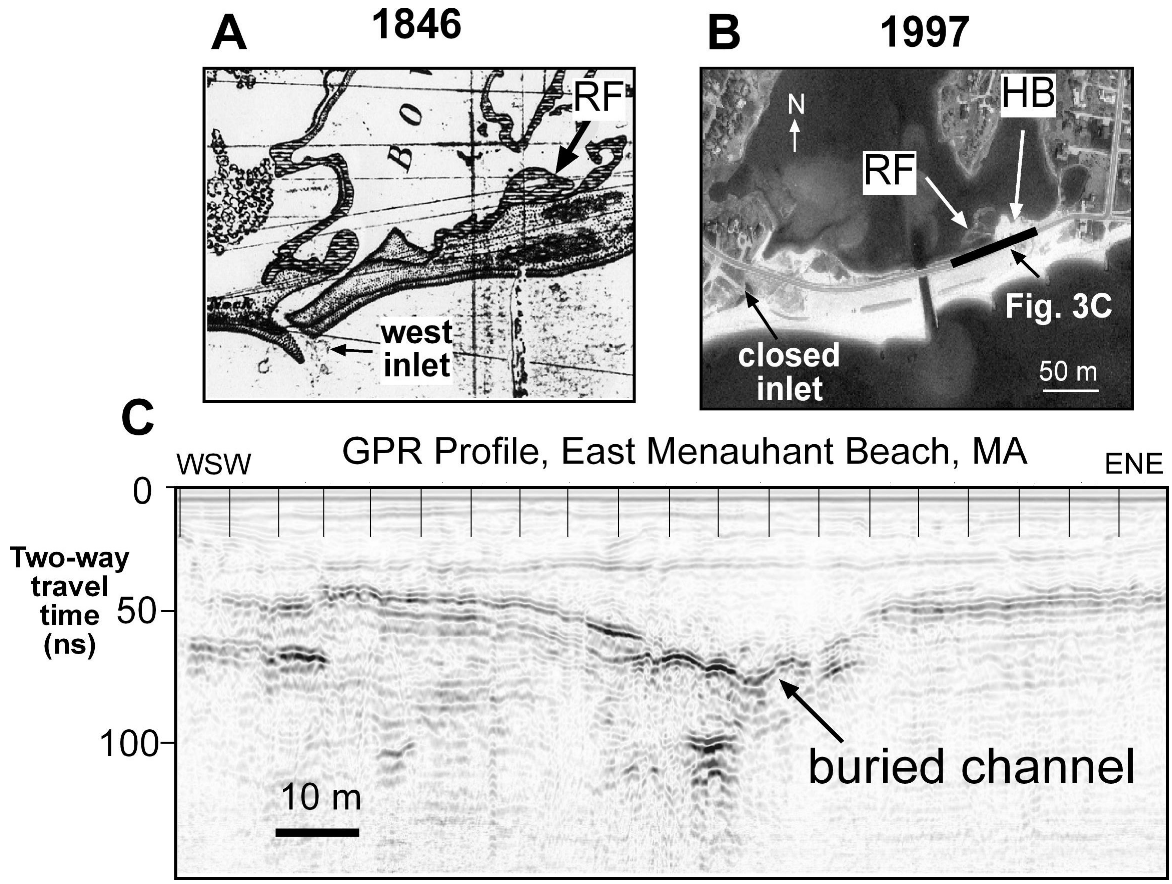

Figure 3. A) Historical chart showing an inlet at the western end of Menauhant barrier, Falmouth, Massachusetts. A relict, lobate, marsh-covered backbarrier feature (RF) can be seen behind the eastern part of the barrier (see Fig. 1 for location). B) 1997 vertical aerial photograph with the inlet relocated to the center of the barrier. The 1991 washover from Hurricane Bob (HB) partially covers the eastern portion of the relic feature. C) Shore-parallel ground-penetrating radar profile reveals a channel structure, with its deepest part approximately 3.3 m below the ground surface (see BUYNEVICH, 2003 for a detailed discussion).

HETEREN *et al*., 1998), and accounting for sea-level rise since early 1880s, the channel across the east Menauhant barrier was likely scoured to subtidal elevation. The relict backbarrier feature was the overwash fan that may have temporarily become a flood-tidal delta prior to inlet closure by 1846. BUYNEVICH (2003) suggested that the Great September Gale of 1815 (see Figure 2) is likely the high-magnitude erosional event responsible for the breaching of the barrier.

Old Mouth of the North River

Similar geophysical investigation of the old location of the North River inlet in Marshfield, known locally as the Old North River Mouth, suggests a complex history of inlet migration and closure (Figures 1 and 4). According to historical charts, the North River emptied into the Atlantic Ocean at its confluence with the South River. During the Portland Gale of 1898, the barrier was breached and the New Inlet was formed approximately 5.6 km to the north (Figure 1; JOHNSON, 1925). This new channel captured the tidal prism of the North and South Rivers resulting in subsequent closure of the old inlet (FITZGERALD, 1993). A similar history of inlet closure due to a reduced tidal prism has been described along the northern Outer Banks of North Carolina where the Old Currituck inlet has filled shortly after the formation of the New Currituck Inlet (MCBRIDE and ROBINSON, 2003).

Aside from the historical documentation of the inlet closure, several geomorphic signatures of the former active channel are present. A broad indentation along the backside of the Rexhame barrier preserves the shape of the inlet prior to closure (Figure 4 inset). Immediately landward, there is a vegetated ridge along the edge of the saltmarsh. These geomorphic features have been described along the North Carolina coast by CLEARY *et al*., (1979), where their genesis is the result of storm reworking of inlet and flood-tidal delta sand and subsequent deposition of sediment along the fringe of the marsh. Similar ridges have been identified along the mixed-energy coast of southern Maine (BUYNEVICH *et al*., in press). The ridge associated with the former North River inlet is probably of similar origin.

Presently, a large dunefield dominates the topography at the former channel location (Figure 4). In order to examine the geometry of the channel fill, a series of ground-penetrating radar profiles were taken along the rear portion of the barrier. Despite saltwater attenuation along the edge of the marsh, two shore-parallel GPR segments show a complex, inlet fill dominated by sigmoidal-oblique reflection geometry. The width of the fill is over 5 m deep and at least 600 m, far greater than the 100m-wide remnant of the channel seen in the vertical aerial photograph (Figure 4). The post-1898 inlet fill is partially imaged on both GPR profiles directly seaward of that remnant. A small, 40m-wide channel structure imaged in the northernmost portion of profile 2 truncates the barrier-inlet sequence (Figure 4) and seems to be separated spatially and temporally from the most recent position of the Old North River Mouth.

CONCLUSIONS

Historical and geological data from the southern coast of Massachusetts suggest that backbarrier salt marsh sediments preserve records of major Atlantic storms dating as far back as A.D. 900. In addition to partial scour and overwash, responses to severe storms may include localized breaching of vulnerable barrier segments or a wholesale closure of large inlets due to tidal prism diversion to newly established channels. Even along relatively sheltered coastlines, breaching and overwash are an integral part of the long-term coastal behavior, with channel-fill sequences comprising up to 80% of the barrier lithosome. A combination of traditional barrier-stratigraphic research with high-resolution subsurface imaging, and the continuous improvements in age-dating techniques for Quaternary sediments are contributing to new approaches for exploring coastal behavior on a variety of temporal and spatial scales. Future integrated research that focuses on identification and mapping of historic and pre-historic overwash and breaching sites along the barrier coasts should be an essential element of coastal hazard studies.

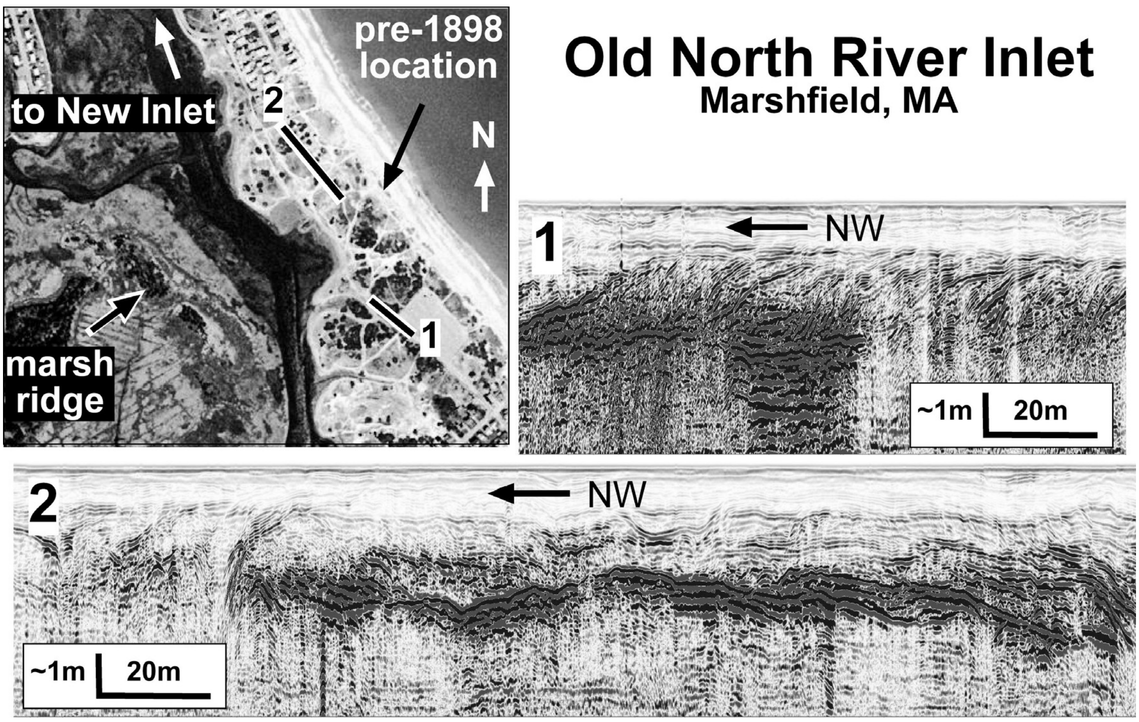

Figure 4. Vertical aerial photograph of Rexhame Beach, Massachusetts, showing the former position of the North River inlet. Part of the channel is still visible as the indentation on the landward side of the barrier. Note a vegetated sand ridge along the edge of the marsh directly landward of the former inlet location. Shore-parallel ground-penetrating radar profile 1 and 2 show a series of sigmoidal-oblique reflectors that represent the migration and final infilling of the inlet channel. On the left side of profile 2, a small channel-fill structure truncates the overall sequence.

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