Evidence for storm-dominated early progradation of Castle Neck barrier, Massachusetts, USA

Amy J. Dougherty*, Duncan M. FitzGerald1, Ilya V. Buynevich2

Department of Earth Sciences, Boston University, 685 Commonwealth Ave., Boston, MA 02215, USA

Received 7 June 2002; received in revised form 20 October 2002; accepted 3 May 2004

Abstract

Washovers, dune scarps and flattened beach profiles with concentrations of coarse-grained sediment or heavy minerals are the diagnostic geological signatures of large storms on barriers today. It is clear that storms are a major force driving transgressive barriers onshore, but what is not as well understood is the role these powerful erosive events play in the evolution of prograding barriers. Application of ground-penetrating radar (GPR) and a combination of coring techniques have significantly improved our ability to image barrier architecture. Results of these studies reveal a more complex evolution than previously recognized. It is now possible to precisely locate and map storm deposits within prograded barrier lithosomes.

A comprehensive study of northern Castle Neck, Massachusetts was performed using 15 km of GPR surveys, a 120-m-long seismic line, 11 cores, and several radiocarbon dates. Storm-related layers are the most prominent horizons contained in the barrier stratigraphy. The geometry and sedimentology of these layers closely resembles those of a present-day post-storm beach. Twenty closely spaced, curvilinear heavy mineral layers imaged in the landward portion of the barrier suggest that the Castle Neck barrier was heavily influenced by storms during its initial phase of progradation beginning ~ 4000 years BP. Approximately 1800 years BP, two intense storms impacted the coast depositing two extensive coarse-grained units. These layers mimic the flat-lying sand and gravel deposits that occur in front of a nearby eroding till outcrop following major storms. The great number of storm deposits in the early history of Castle Neck is related to either a period of greater storm activity and/or a slow rate of barrier progradation. The occurrence and preservation of these earlier storm layers are likely a product of the exposure of nearby drumlins resulting in greater availability of iron oxide and ferromagnesian sands. The supply of heavy-mineral sands has gradually diminished as the barrier prograded and the proximal drumlin source was buried by beach and dune sands.

© 2004 Elsevier B.V. All rights reserved.

Keywords: ground-penetrating radar; heavy minerals; prograding barrier; stratigraphy; Nor’easter

1. Introduction

The stratigraphy of a barrier contains a sedimentological record of the processes that produced and modified it. Until recently, deciphering barrier evolution was primarily accomplished through the interpretation of sediment cores and geochronometric techniques (Bernard et al., 1962). Problems arose...
when dateable material is lacking or the organic material that is present consists of shells, most of which are not in situ. Moreover, if shells exist, they are commonly contained within lagoonal or shelf sediments and are not part of the barrier lithosome. In light of these obstacles, it is apparent and understandable that models of prograded barriers are somewhat simplistic. For example, early models of regressive barriers based on Galveston Island, Texas (Bernard et al., 1962), Sapelo Island, Georgia (Hoyt, 1967) and Kiawah Island, South Carolina (Moslow and Colquhoun, 1981) present the barrier as having developed through the addition of sigmoidally shaped accretionary wedges. The advent of ground-penetrating radar (GPR) has provided a much clearer picture of the facies architecture of barriers and most importantly their complex evolution (FitzGerald et al., 1992; Jol et al., 1996; Van Heteren et al., 1998; FitzGerald and van Heteren, 1999; Bristow et al., 2000; Neal and Roberts, 2000; Buynevich and FitzGerald, 2001). Similarly, being able to date sand grains using optical luminescence techniques has improved our ability to determine the chronology of barrier development (Bryant et al., 1996).

The main parameters that distinguish prograding, retrograding, and aggrading barriers, are sediment supply and sea-level history (Curray, 1964). Antecedent geology (Belknap and Kraft, 1981), tidal inlets, storms, climatic trends, and other factors also influence the evolution of a barrier. During the past decade, scientists have assessed the relative importance of these factors and some studies have attempted to quantify their effects on barrier development (Riggs et al., 1995; Van Heteren et al., 1998; FitzGerald and van Heteren, 1999; FitzGerald et al., 2001; Buynevich and FitzGerald, 2001). Storms have the most obvious and lasting effect on barrier morphology. In the lithosomes of retrograding barriers, storm events are recorded in stacked washovers commonly separated by peat layers. Scientists have used these back-barrier deposits to provide a storm chronology (Liu and Fearn, 2000; Donnelly et al., 2001). The role of storms in modifying beaches and barriers through the formation of dune scarp, flattened beach profile, breaches and washovers are well known (Hayes, 1967; Hayes and Boothroyd, 1969). Likewise, the stratification that is produced when a beach and foredune ridge rebuild following a high-magnitude erosional event is also well documented (Hine et al., 1979). In spite of this body of knowledge, the manifestation of storms within the lithosomes of prograding barriers is poorly understood. To date, few studies have related heavy mineral deposits as evidence of erosional episodes in a long-term record of barrier progradation (Meyers et al., 1996; Buynevich and FitzGerald, 2001, Buynevich et al., 2004).

Using the northern portion of Castle Neck barrier, Massachusetts as an example, it is the aim of this paper to: (1) identify the surficial and subsurface signatures of storm activity, (2) assess the extent to which storm erosion and deposition influenced the sedimentary regime in the initial phase of barrier progradation, and (3) demonstrate that storms leave a recognizable signature along prograding barriers in the form of buried erosional scarps that are preserved due to the net accretionary trend of the sedimentary sequence. In order to accomplish these goals, a detailed geophysical and coring study was performed concentrating along the northern portion of the island. This region was chosen after studying the entire barrier system and finding little subsurface evidence of storms elsewhere on the island. It is important to note that even though this paper focuses on the investigation of storm signatures in the northern portion of the island, it is done within the context and greater understanding of the overall barrier evolution (Dougherty, 2002).

2. Study area

2.1. Geomorphic setting

Castle Neck is one of five coastal barriers located within Merrimack Embayment, Massachusetts (Fig. 1). The barriers and intervening inlets span a 34-km length of coast making it the longest barrier chain in New England. Extensive salt marsh, tidal creeks, and lesser areas of tidal flats back these islands. Tidal inlets are situated in drowned river valleys and maintain well-developed ebb-tidal deltas (FitzGerald et al., 2002). The mean tidal range in this area is 2.6 m and the average significant wave height is 1.0 m (Abele, 1977; Smith and FitzGerald, 1994). These values place this formerly glaciated coastline in a mixed-energy, tide-dominated setting (Hayes, 1979).
Castle Neck is a 6.7-km-long, 0.8-km-wide sand-rich barrier whose history of progradation is preserved beneath a dune system that reflects little of the original beach ridge construction. Present dune morphology is a product of past episodes of devegetation and sand mobilization, during which time prevailing winds formed parabolic dunes and irregular sand sheets (Dougherty, 2002). The rear of the barrier is low in profile and abuts the supratidal back-barrier marsh. The barrier gains relief in a seaward direction with parabolic and irregular dunes separated by ephemeral freshwater ponds. A well-developed foredune ridge and beach characterize the seaward side of the barrier. The width of the beach (10–50 m) is partially controlled by periodic migrations of the Parker River inlet main ebb channel. When the channel impinges against the shore, the beach erodes and the foredune may be scarped (FitzGerald and Hayes, 1980). In the northern portion of the barrier at least one former dune scarp is present. This scarp is 800-m-long and is located ~250 m landward of the ocean (Fig. 2). No other obvious storm related features are evident throughout the barrier (Dougherty, 2002).

A seismic profile taken across the northern portion of the barrier records an 11- to 15-m-thick Quaternary sequence (Dougherty, 2002) that sits atop Cape Ann Granite (Zen, 1983). Deep wash-bore cores taken throughout Castle Neck and adjacent Plum Island suggest that a layer of till was deposited directly on top of the bedrock during the last glaciation (McIntire and Morgan, 1964; Rhodes, 1973). In some cases, the ice sheet molded the till into drumlin forms, several of which underlie the barrier sands while others are exposed in the back-barrier region. The till-covered bedrock provided anchor points for sand accumulation in the initial phases of barrier development.

2.2. Sediment supply and transport patterns

Early studies of this region led researchers to conclude that sand comprising the Merrimack barrier chain was derived from the large offshore paleodelta of the Merrimack River (Edwards, 1988; FitzGerald, 1993). These investigators concluded that during the Holocene transgression the surface of the delta was reworked and sediment was moved onshore in the form of low retrogradational barriers and sand sheets. Recent investigations of bedform data, grain-size trends (FitzGerald et al., 2002) and 40Ar/39Ar provenance information (Dougherty, 2002) indicate that most of the sand comprising the southern portion of the barrier chain came directly from the Merrimack River. Sediment supplied to the mouth of the river has been reworked by wave action and transported alongshore. The dominant east–northeast storm wave approach in the Gulf of Maine produces a net movement of sand from north to south in the Merrimack Embayment. The longshore transport direction is corroborated by: (1) decreasing grain size southward from the Merrimack River mouth, (2) seaward displacement of offshore bathymetric contours, (3) existence of spits at the southern end of Plum Island and Crane Beach, and (4) wave data collected at Plum Island showing dominant southerly longshore currents (Abele, 1977).

2.3. Storms

Extratropical storms, known locally as Nor’easters, are the dominant storm type in New England. These
low-pressure systems that form above the tropics, commonly travel northward along the Atlantic coast (Dolan et al., 1988; Zhang et al., 2001). As the storm center moves east of New England, their strong northeasterly winds produce storm surges of 0.2 to 1.2 m and nearshore wave heights of 3 to 4 m (Dolan and Davis, 1992; FitzGerald et al., 1994). Large magnitude storms coinciding with spring high tide result in severe beach erosion, dune scarping, and extensive overwash activity. Tropical storms occur less frequently in this region because their energy usually dissipates by the time it travels this far north.

The 6–7 February Blizzard of 1978 is the largest storm on record along the northern New England coast. This storm coincided with the highest astronomical tides of the year and caused a storm surge that corresponded to the 100-year coastal flood in this region (1.72 m in Boston Harbor; FitzGerald, 1981).

3. Database

A total of 27 km of ground-penetrating radar records and 49 cores, yielding 375 sediment samples,
have been collected throughout Castle Neck barrier (Fig. 3A). The database reveals a complicated barrier stratigraphy and sedimentation history. This complexity is most evident in the northern portion of the island, where the arrangement of GPR reflectors and core data suggest barrier construction involved numerous erosional and depositional phases related to storm and tidal inlet processes (Dougherty, 2002).

Three kilometers of analog GPR were collected throughout northern Castle Neck using the SIR System-3 unit and a 120-MHz antenna with the two-way travel time set at 300 ns, for penetration of up to 10 m (Fig. 3B). A second detailed grid of 138 shore-perpendicular transects was taken in a large parking area. The grid lines, having a total length of 12 km, were run at 2-m intervals using an SIR 2000 high-resolution, digital GPR system set at 300 ns with a 200-MHz antenna for penetration of up to 12 m. All GPR transect positions and elevations were surveyed using Pentax PCS-300 series Electronic Total Station. A 120-m-long seismic line was run in the parking lot using a Geometrics Geode 12 channel seismic module with 14 Hz geophones (Fig. 3B). Single Geode Operating Software (SGOS) was used for seismic data collection and processing to determine the depth to bedrock in this region. Description of the GPR facies in this paper follows the terminology of Van Heteren et al. (1998). The nature of the reflectors in the GPR record was determined from 11 sediment cores obtained using both the pulse auger coring system and the 2000 Geoprobe Advance 66DT with a maximum penetration depth of 10.5 m (Fig. 3B). The cores were georeferenced using a handheld Magellan 4000XL Geopositioning System (GPS). Grain-size statistics were

Fig. 3. (A) Aerial photo of Castle Neck showing location of ground-penetrating radar transects and sediment cores. (B) Close-up picture of the study area in the northern portion of Castle Neck barrier, showing the location of the GPR transects, seismic line and cores.
determined for 51 sediment samples using a standard settling tube and student version of MATLAB. One radiocarbon date was acquired from a peat deposit cored below the parking lot (analyzed at Geochron Laboratories in Cambridge, MA) and used in conjunction with preexisting dates of the back-barrier marsh from Som (1990). All $^{14}$C dates are reported as $\delta^{13}$C-corrected, uncalibrated ages.

4. Results

The detailed geophysical and coring studies provide a basis for reconstructing the stratigraphy of the barrier and determining the influence of storms during its progradational history. GPR transects across the northern portion of the barrier (Fig. 3) exhibit relatively consistent stratigraphy with variability in the geometry of individual units. A representative GPR transect extending from the edge of the marsh across one third of the barrier exhibits several distinct reflector configurations (Figs. 4–6). Six cores along this profile aid in the interpretation of the stratigraphy. The gross pattern of GPR reflectors in the northern barrier sector consists of broad seaward-dipping reflectors. However, within this framework there are numerous landward-dipping reflectors in addition to cut and fill structures. The most prominent images along the profile include a group of strong curvilinear, tangential-oblique reflectors in the landward portion of the transect (Figs. 4 and 5) and a sharp reflector that extends across the entire seaward section of the transect (Fig. 6). Descriptions of all the GPR facies are presented below in order to provide stratigraphic context of the principal reflections which bear on the storm-induced erosion within an overall prograding sequence. Because this paper focuses on the storm deposits, a detailed treatment of adjacent barrier facies is the subject of other papers (Dougherty et al., 2003; Dougherty et al., 2002).

Fig. 4. (A) Raw GPR data from a representative transect. (B) Interpretation of the GPR image, with major facies reflectors highlighted and labeled corresponding to their description text. See Fig. 3 for GPR transect and core locations.
4.1. Landward segment

The landward segment of the profile is dominated by over 20 sharp, tangential-oblique reflectors (c.f. Van Heteren et al., 1998) that extend for 150 m from the marsh across the parking lot (Fig. 4, Facies A). Dunes in this region were bulldozed so that the tops of the reflectors are truncated. These concave-up, seaward-dipping reflectors begin approximately 1.5 m below present mean high water level and continue to a
depth of 6–8 m. Cores #4 and #5 taken through these units demonstrate that the prominent reflectors coincide with fine-grained, very well-sorted heavy-mineral sand. The heavy-mineral layers consist of greater than 20% “rose” quartz, garnet, ilmenite and magnetite. The intervening transparent part of the image corresponds to a sequence of fine-grained, well-sorted, quartz-rich sand, layered in beds ranging from 0.5 to 0.8 m thick. (Fig. 4, Facies A). The heavy mineral layers are 2–5 cm thick. The central portion of the GPR record shows a sequence of uniformly spaced sigmoidal-oblique reflectors.

The alternating sequence of heavy minerals and quartz-rich sand is bounded below by high-frequency chaotic GPR reflectors (Fig. 4, Facies B). The cores did not penetrate deep into this layer due to its indurated nature. Sediment recovered from this layer consisted of orange, oxidized, sandy silt, typical of till matrix in this region. The uppermost unit in this area is a fine-grained, well-sorted, quartz-rich sand, which characterizes the dune facies of the barrier (Fig. 4, Facies C) (Dougherty, 2002).

4.2. Seaward segment

Although the seaward segment is a continuation of the landward GPR profile, the reflectors within this section exhibit greater complexity indicating a more dynamic constructional history than the early progradational phase (Fig. 6). A pronounced reflector stretches across the entire record beginning at depth of 3 m and extending seaward to a depth of about 7 m. This reflector is actually a combination of two sharp reflectors, the seaward one (Fig. 4, Facies D) cutting across the landward one (Fig. 4, Facies E). The western portion of each of these
segments rises at a relatively steep angle toward the surface. The two cores taken in the landward segment of this profile extended to a depth of 3 m (Fig. 4). Core 7 bottomed in an impenetrable layer and Core 8 terminated in a layer with sand and subangular gravel. A layer of peat about 38 cm in thickness was found in Core 7 just above the flat-lying gravel deposit (Fig. 4, Facies F). Radiocarbon analysis of this peat gave a $\delta^{13}C$ of $-24.8\%$ and an age of 1790 ± 130 years BP (Geochron Laboratories). The facies above the peat includes organic sand containing abundant granules and a well-sorted, medium sand near the surface. There was no peat layer above the sandy-gravel in Core 8; rather the overlying section is characterized by a series of well-sorted, medium sand units separated by numerous heavy-mineral horizons (10–30% garnet). Differences in facies above the gravel layer in the two cores correspond to distinct GPR signatures. Core 7 penetrated several landward-dipping reflectors (Fig. 4, Facies G), whereas Core 8 went through seaward-dipping reflectors (Fig. 4, Facies H). The heavy-mineral layers in Core 8 are similar to those in Cores 4 and 5.

The seaward segment of the GPR profile was interpreted from sediment Cores 9 and 10. Both cores contain a gravelly sand layer composed of rounded to subangular gravel in a matrix of sand and granules. Core 9 bottomed in cobble-sized material, which was penetrated in Core 10 and reached fine, gray sand. This same sand facies ubiquitously underlie the barrier lithosome and have been interpreted as an estuarine deposit (Dougherty, 2002). Above the prominent seaward dipping reflector in this section are several GPR facies that have been interpreted as channel-fill, landward-migrating bar, and beach face deposits (Fig. 4, Facies J) (Dougherty, 2002). This stratigraphy is testament to the complexity of barrier progradation (FitzGerald and van Heteren, 1999).

5. Discussion

The results of this geophysical and sedimentary study were used to reconstruct the development of northern Castle Neck barrier and the role of storms throughout its evolution. In Som's (1990) study of the back-barrier region of Castle Neck, basal peat and shells yielded radiocarbon ages of 3905 ± 90, 3955 ± 190, and 3690 ± 90$^{14}$C years. Since this basal peat began developing in a sheltered area behind a coastal barrier, these dates can be used to infer the approximate time of barrier inception. The incipient barrier formed as sand moving alongshore became anchored to the till-covered bedrock ridge, followed by a progradation of the shoreline (Boothroyd et al., 1978). Our findings indicate that multiple storm events punctuated the early constructional phase. A series of prominent GPR reflectors exhibiting a tangential-oblique, concave-up geometry are evidence of these storms (Fig. 5A) in that their morphology is practically identical to present-day post-storm beach profiles in this region (Hayes and Boothroyd, 1969; Fig. 5B). Cores taken through these reflectors penetrated multiple horizons of sand with abundant heavy minerals including ilmenite, magnetite, and garnet (Fig. 5C). The concentration of heavy minerals is a common response to storms on beaches today (Brenninkmeyer, 1978; Hayes and Boothroyd, 1969; Meyers et al., 1996; Hamilton and Collins, 1998; see Fig. 5D). Modern and buried storm scarps in Maine display similar heavy mineral concentrations (Buynevich and FitzGerald, 2001; Buynevich et al., 2004).

Our geophysical and sedimentological data indicate that early progradation of the Castle Neck barrier was punctuated by numerous storms leaving behind a heavy-mineral lag. The number and close spacing of the heavy mineral layers, in addition to their similarity to those on present erosional beach surfaces, may be explained by one or a combination of the following factors: (1) storms were more frequent and/or intense in the past; (2) early barrier progradation occurred very slowly; (3) there is a higher proportion of these mineralogical components in the local glacial sources (drumlins) than in the sands supplied from the updrift fluvial source (Merrimack River); (4) the preservation of heavy-mineral deposits was more favorable in the past, and (5) our ability to recognize these deposits in the sedimentary record is limited in the younger part of the sequence. The second and third factors seem to be more plausible. It is unlikely that the frequency or magnitude of storms would dramatically decrease through time. The abrupt decrease in the preservation potential of heavy-mineral concentrates is difficult to
explain. Also, if these deposits were present in comparable amounts in the seaward segment of the profile, they would have left recognizable signature in the geophysical record. Alternatively, slow accretion rate of the shoreline may be due to a less abundant sand supply. Thus, the eroded paleo-beach surfaces seem over-represented in the landward barrier segment. The abundance of heavy minerals is likely due to their greater availability from nearby eroding drumlins. Garnet and ilmenite occur in the drumlins defining the northern end of Castle Neck as well as the southern end of adjacent Plum Island (Dougherty, 2002). Through time, the addition of sand caused the barrier to prograde, gradually separating much of the eroding drumlin shoreline from storm erosion and thereby reducing the supply of heavy minerals to adjacent beaches, a trend which is reflected by the absence of prominent tangential-oblique reflectors in the seaward part of the sequence (Fig. 4). Rather, nearly evenly spaced, relatively weak reflectors in this part of the record suggest a more uniform progradation, most likely through the addition of sand supplied alongshore from the Merrimack River (Buynevich and FitzGerald, 2001; FitzGerald et al., 2002).

The two prominent storm reflectors in the seaward segment of the GPR transect are likely the subsurface images of major storm layers of more recent origin (Figs. 4 and 6). This interpretation is based on the fact that these reflectors correspond to coarse sand and gravel layers and their geometry is similar to present-day erosional beach profiles. In addition to heavy minerals, nearby drumlins may have also supplied gravel to the adjacent beaches under extreme conditions. In the northern end of Castle Neck, a small section of drumlin is unvegetated and erodes during high-energy wave events. Following major storms, the beach adjacent to this drumlin is strewn with coarse sediment including pebbles and cobbles. FitzGerald et al. (1992) have described a similar gravel-lined storm beach face at Horseneck Beach, Massachusetts. If the northern drumlin complex was indeed the source of the gravel, then the storm must have been strong enough to erode significant amounts of gravel from the drumlins and deliver this material to the northern portion of the barrier. A peat layer overlies the lower gravel layer in the seaward segment. The peat has a $\delta^{13}\text{C}$ of $-24.8\%$ indicating a freshwater origin. The nature and location of the peat suggests that it formed as rainwater pooled in an interdunal swale producing a small wetland/pond. Radiocarbon dating yielded an age of $1790 \pm 130 \text{^{14}C}$ years BP as the onset of peat accumulation. Some time after $1800 \text{^{14}C}$ years BP, a second large storm truncated the first major sequence of the storm gravel layer, beach sands, peat and dunes. The cross-cutting relationship of the two prominent reflectors suggests that the earlier storm must have been at least of the same magnitude or greater than the first storm. No other gravel layers have been located within the subsurface of the barrier, suggesting that either no other storms of comparable magnitude have impacted this region or the impact was not preserved. The only evidence that another major erosional event has affected this part of the coast is the existence of the prominent dune scarp left by the Blizzard of 1978 (Dougherty, 2002).

6. Conclusions

1. Through a combination of high-resolution geophysical imaging and sedimentological analyses of the northern Castle Neck barrier, Massachusetts, our study illustrates the favorable preservation of storm-related features in coastal systems that have experienced net progradation during the mid-late Holocene. Prior to this investigation, the only evidence of past storms along this barrier included a geomorphic feature—a single dune scarp along the northern part of the beach. No evidence of prehistoric storm events was reported from the area.

2. Our study reveals two types of subsurface signatures most likely related to impacts of intense storms: (1) concave-up, tangential-oblique subsurface reflections corresponding to heavy mineral deposits that commonly cover eroded beach and dune base, and (2) prominent subhorizontal reflections that represent eroded beach face with an anomalous proportion of coarse-grained fraction.

3. The stratigraphy of northern Castle Neck indicates that storms had a prominent influence during the beginning stages of barrier progradation between
4000 and 1800 $^{14}$C years before present. A sequence of heavy-mineral-lined paleo-beach surfaces in the landward portion of the sequence give way to nearly evenly spaced surfaces of uniformly prograding barrier, which are subsequently truncated by two gravel-lag surfaces.

4. The availability of heavy-mineral sands, likely due to the initial exposure of nearby drumlins, is a major factor in the manifestation of storm layers. The preservation of these mineralogically distinct deposits in the stratigraphic record is due largely to the net accretionary mode of the barrier. The apparent high frequency of these storm layers early in the progradation history is probably related to a combination of heavy-mineral availability (drumlin vs. fluvial/nearshore source) and a slow rate of the initial barrier progradation.

5. The two gravel and coarse sand horizons in the seaward part of the sequence are likely a result of two intense storms dating to approximately 1800 $^{14}$C years BP. The only other evidence of a major storm impact along this barrier is an extensive dune scarp formed during the Blizzard of 1978. Further research along this coastline will utilize the integrated geophysical, sedimentological, and chronostratigraphic approach to locate and map regionally correlative paleo-storm deposits.

Acknowledgements

This work was partially funded through a Student Grant from the Geological Society of America awarded to A. Dougherty. Geochron Laboratories supplied the $^{14}$C analyses, a division of Krueger Enterprises, Cambridge, MA, through a grant to A. Dougherty. We thank Elizabeth Pendleton, Mark Rits, Anna Tary, Emily Himmelstoss, Peter Reynolds and Jessica Dockendorff for their assistance in the field and Aaron Ferris and Josh Stachnik for seismic data acquisition and analysis. We would also like to thank the Massachusetts Trustees of Reservation for unlimited access to Castle Neck, especially Peter Pinciero, Wayne Castenguay and the park rangers who helped with the field logistics. The comments by two anonymous reviewers helped improve the manuscript.

References


FitzGerald, D.M., Baldwin, C.T., Ibrahim, N.A., Humphries, S.M., 1992. Sedimentologic and morphologic evolution of a beachridge barrier along an indented coast: Buzzards Bay, Massachu-


ries, vol. 8. LSU Press, Baton Rouge, FL.


Neal, A., Roberts, C.L., 2000. Applications of ground-penetrating radar (GPR) to sedimentological, geomorphological, and ar-


Rhodes, E.G., 1973. Pleistocene–Holocene sediments interpreted by seismic refraction and wash-bore sampling, Plum Island-Cas-


Som, M., 1990. Stratigraphy and the evolution of a backbarrier region along a glaciated coast of New England: Castle Neck-

Essex Bay, MA. Masters Thesis, Department of Earth Sciences, Boston University, Boston.


Zen E., 1983. Bedrock Geologic Map of Massachusetts. Depart-
ment of Public Works, Commonwealth Massachusetts, Boston, MA.