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Ground-Penetrating Radar Investigation of a Late Holocene Spit Complex: Cape Henlopen, Delaware

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ABSTRACT

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Understanding the development of coastal landforms is essential for evaluating and predicting the effect of sea-level change on shoreline evolution. Capes and spit complexes, as constructional features, are especially sensitive to changes in sea level, sediment supply, antecedent topography, and wind and wave environments. Cape Henlopen, on the southeastern margin of Delaware Bay, has evolved from a recurved spit complex, to a cuspate foreland, and finally to a simple spit. High-resolution digital ground-penetrating radar (GPR) surveys of this late Holocene cape complex reveal both similarities and differences in the internal stratigraphy of each shoreline morphology. Two radar facies identified in the recurved spit and cuspate foreland morphologies represent: (1) a subtidal spit-platform facies; and (2) an inter- to supratidal beach and dune facies. The interface between these two facies is distinct in GPR profiles, but is not always found at a depth predicted by models of spit evolution. In the Cape Henlopen system, the depth of this surface increases from 2 m below MSL in the older recurved spits to 4 m below MSL in the younger cuspate foreland. Local relative sea level has risen 2 m between 2000 yr BP, when the oldest relict spits developed, and the present. As predicted by a physical model of spit development (MEISTRELL, 1966), the depth of the boundary between the spit platform and intertidal facies would be expected to follow the trend of sea level. This discrepancy indicates that the spit-complex morphostratigraphy is responding to deepening bathymetry controlled by antecedent topography and changes in wave energy, as well as sea-level rise.

ADDITIONAL INDEX WORDS: *Spit, spit platform, cuspate foreland, stratigraphy, Holocene, sea level.*

INTRODUCTION

The response of a coastline to a general rise in sea level is complex and may reflect the effects of irregular antecedent topography, and changes in the rate of sea-level rise, sediment supply, and wave climate. Depositional coastal features such as spits and cape complexes preserve a record of this response that spans hundreds or thousands of years. The internal stratigraphy of the spit reflects these changes in depositional environment. A physical model of spit evolution (MEISTRELL, 1966) showed that a simple spit consists of a subtidal platform comprised of foresets overlain by the beach and dunes that form the spit ridge. The subtidal platform develops at a constant depth below mean low water. This implies that the boundary between the two units should be controlled by sea level. However, this model did not include changes in wave energy or changes in water level due to sea-level rise or tides.

The internal stratigraphy associated with the different morphologies as a cape complex evolves has not been well documented. The stratigraphy may provide clues to the controls on spit evolution and may include stratigraphic indicators of sea level that are valuable for interpreting Holocene coastal sequences or analogous ancient rock bodies. Ground-penetrating radar (GPR) provides high-resolution images of the subsurface features of the spit with much more continuity and detail than can be inferred from conventional methods such as coring. GPR has been used effectively in recent studies of other marine and lacustrine coastal environments (LEATHERMAN, 1987; FITZGERALD *et al.,* 1992; MEYERS *et al.,* 1994, 1996; JOL *et al.,* 1996; VAN HETEREN and VAN DE PLASSCHE, 1997). In this study, we use GPR to image the internal structures of three distinct shoreline morphologies associated with the evolution of Cape Henlopen, Delaware.

Goals of This Study

The primary goal of this study was to use ground-penetrating radar to produce continuous, high-resolution images of the internal stratigraphy associated with each of three different shoreline morphologies of Cape Henlopen. Specific questions that were addressed include:

- How do the internal structures compare among the different shoreline morphologies?
- Can the internal structures be used to infer the processes controlling evolution of the cape complex?
- Do different dominant processes control the formation of a

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simple spit versus a set of recurved spits or a cuspate foreland?

- Do the internal structures reflect changes in sea level? Can reliable stratigraphic indicators of sea level be identified in the GPR profiles?

Geologic Setting

Cape Henlopen has formed over the last 2000 years on the south shore of Delaware Bay at the bay mouth (Figure 1; KRAFT, 1971). Sands and gravels eroded from the shoreface along the Atlantic coast of Delaware south of the bay mouth are transported northward to supply the spit complex (KRAFT, 1971; MAURMEYER, 1974; KRAFT *et al.,* 1978). Recently, the spit has prograded rapidly to the northwest into Delaware Bay at nearly 20 m/year (KRAFT *et al.,* 1978). West of Cape Henlopen, littoral transport moves sediment eastward along the shore of Lewes Beach. Modern spit progradation is influenced by two breakwaters west and north of the spit. Breakwater Harbor, the area west of the spit, has shallowed dramatically as sediment accumulated in the lee of the inner breakwater (MAURMEYER, 1974; DEMAREST, 1978). Accretion at the spit tip and migration of sand waves across the back-spit tidal flat are the major processes of progradation at present (KRAFT and JOHN, 1976; HALSEY, 1978). The geomorphic elements of Cape Henlopen (Figure 1) include the Atlantic beach, coast-parallel dunes and a large coast-perpendicular dune (the Great Dune), relict recurved spits surrounded by salt marsh, a beach-accretion plain, a simple spit prograding to the northwest with an extensive intertidal flat on the bay side, and a large ebb-tidal shoal on the ocean side (Hen and Chickens Shoal) (KRAFT *et al.,* 1978).

The evolution of Cape Henlopen during the late Holocene has been reconstructed from the surface morphology, subsurface core information, a relative sea-level history for the area, and historical maps (KRAFT, 1971; MAURMEYER, 1974; KRAFT and JOHN, 1976; KRAFT *et al.,* 1976; HALSEY, 1978; KRAFT *et al.,* 1978; FLETCHER, 1987). The cape complex has three distinct shoreline morphologies: (1) a recurved spit complex; (2) a cuspate foreland with a beach-accretion plain; and (3) a simple spit (Figure 1) (KRAFT *et al.,* 1978). The recurved spit complex developed from 2000 to 500 years BP; the maximum age is constrained by radiocarbon dating of archeological material from the southernmost (oldest) relict spit (KRAFT, 1971; KRAFT *et al.,* 1978). At approximately 500 y BP, the recurved spits joined the Pleistocene headland to the west and formed a cuspate foreland. The actively prograding simple spit developed after construction of two breakwaters in the 1830s and 1870s that dramatically reduced wave energy on the bayward side of the cape (Figure 2) (MAURMEYER, 1974; KRAFT *et al.,* 1976; KRAFT *et al.,* 1978).

The general subsurface distribution of lithosomes beneath Cape Henlopen is known from power-auger holes and deep cores (Figure 3) (KRAFT, 1971; JOHN, 1977; KRAFT *et al.,* 1978). An irregular pre-transgressive surface at depth is unconformably overlain by a sandy unit interpreted to be an earlier Holocene bay-beach and spit complex (KRAFT *et al.,* 1978). These bay-shoreline sands are conformably overlain by shallow estuarine muds and muddy sands, which are in turn overlain by the beach and spit sands of the late Holocene cape complex (JOHN, 1977; KRAFT *et al.,* 1978). The sands and gravels beneath Cape Henlopen thicken to the north, reaching a maximum thickness of 20 m at the distal end (KRAFT *et al.,* 1978).

METHODS

Ground-penetrating radar data were collected at Cape Henlopen using the pulseEKKO IV digital GPR equipment, manufactured by Sensors and Software, Inc. Tests were conducted using the 50, 100, and 200 MHz frequency antennas. The 100 MHz antennas provided adequate depth of penetration and high-resolution profiles and were used for most data collection.

GPR data were collected along several transects in three areas of the spit complex (Figure 1) to characterize the three distinct shoreline morphologies. Profiles were typically oriented both parallel and perpendicular to the trend of linear beach ridges or spits. The transects were surveyed using a Topcon Total Station and tied to Coastal and Geodetic Survey benchmarks in the area to determine elevation relative to mean sea level (MSL). All elevations are reported relative to modern mean sea level, except as specifically noted. Two-way travel times were converted to depth by calculating the average velocity of the subsurface material from common-mid-point profiles (CMPs) collected on the transect lines. In most areas, the water table was within 0.5 m of the ground surface, and the velocities calculated for the subsurface material are similar to those published for saturated sand. The GPR data are plotted using a constant gain and a two-trace and five-point (down-the-trace) averaging function. Facies or sediment packages identified in the GPR profiles were correlated with lithologies from core data from earlier studies (KRAFT, 1971; JOHN, 1977; KRAFT *et al.,* 1978).

RESULTS

The GPR profiles presented here show the internal sedimentary structures of each of the three spit morphologies (Figures 6–9). The images represent electromagnetic energy transmitted through the sediments that is reflected at boundaries between materials with contrasting electrical properties (DANIELS, 1989; DAVIS and ANNAN, 1989). A reflection could be produced by a change in lithology, grain size, packing, or water saturation (DAVIS and ANNAN, 1989). The line drawings beneath each plot of the digital GPR data are interpretations indicating the prominent reflections. The profiles are described in the chronological order of the evolving morphology, beginning with the recurved spits, which are the oldest features in the cape complex.

Radar Facies

Radar facies have been defined as “mappable, three-dimensional sedimentary units composed of reflections whose characteristics differ from adjacent units” (HUGGENBERGER, 1993). The radar facies of the Cape Henlopen shorelines are presented here as generalized line drawings based on the major characteristics of the features observed in the GPR profiles.

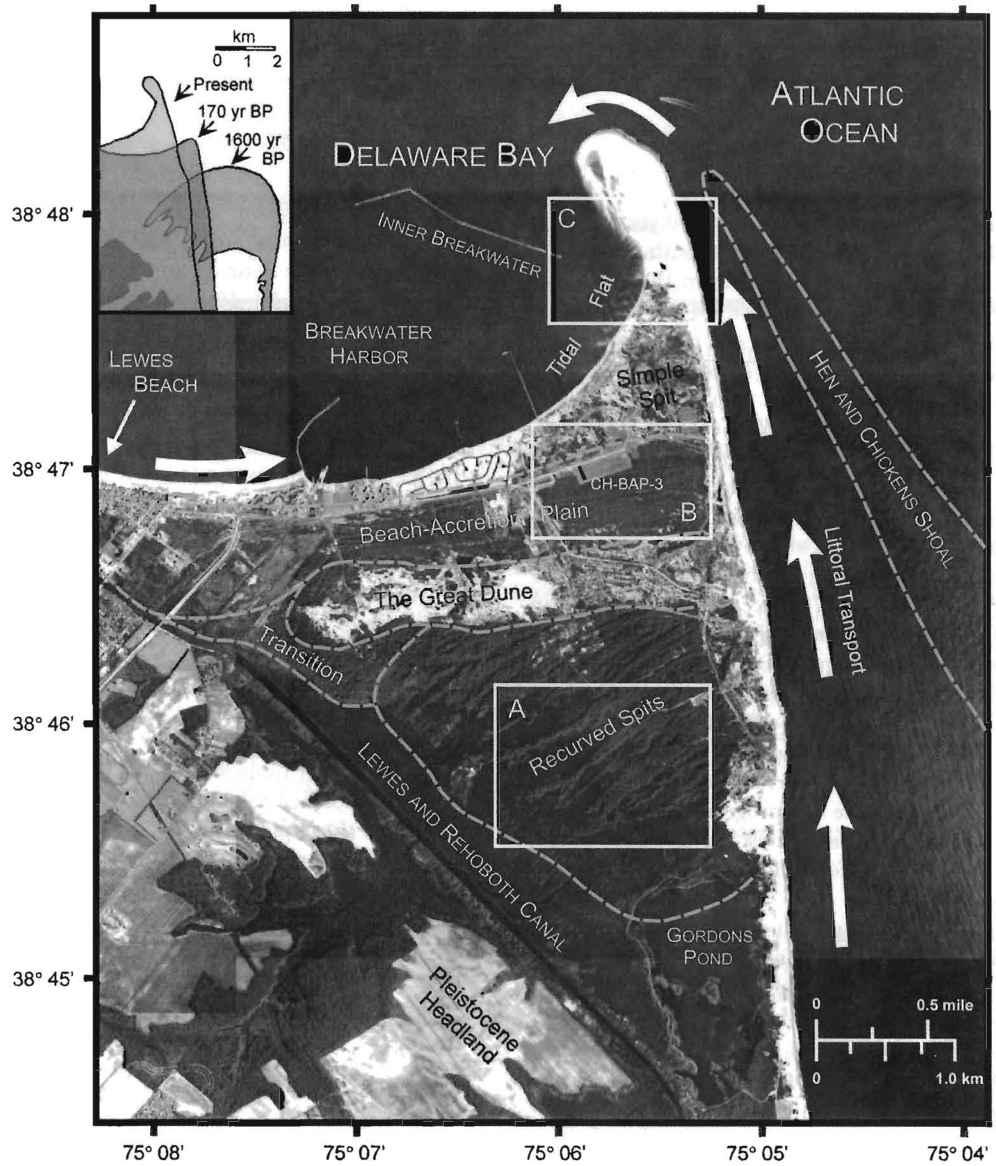

Figure 1. Major geomorphic elements of Cape Henlopen (following KRAFT *et al.,* 1978) and location of study areas. A,B, and C indicate study areas associated with the recurved spit, beach accretion plain, and simple spit morphologies, respectively. Large white arrows indicate littoral transport directions. Inset in the upper left shows the interpreted morphology of the cape complex at three times: present configuration (simple spit), 170 yr BP configuration (cuspate foreland), and 1600 yr BP configuration (recurved spit complex) (modified from KRAFT *et al.,* 1978). Dark unit at the lower left of inset is the Pleistocene headland, also identified on the larger map. The location of GPR profile CH-BAP-3 is indicated. Other profile locations are shown in Figures 2 and 5.

Defining characteristics include continuity, shape, and spatial context of the reflections, following established criteria (BERES and HAENI, 1991). These facies characterizations are based on two-dimensional subsurface data, and are related to the geomorphic context. Five radar facies are defined: (1) sigmoidal oblique; (2) tangential oblique; (3) even parallel; (4) hummocky; and (5) reflection free (Figure 4). Many of these facies are comparable to those described by VAN HETEREN *et al.* (1998) for a New England barrier.

Oblique Facies

Two oblique reflection configurations were identified on several GPR profiles collected at Cape Henlopen perpendicular to the trend of spit and beach ridges. Tangential-oblique and sigmoidal-oblique facies both occur at several locations. These configurations are characterized by downlap and toplap reflection terminations. Commonly, the reflections of these facies lap down onto a subhorizontal, continuous, high-

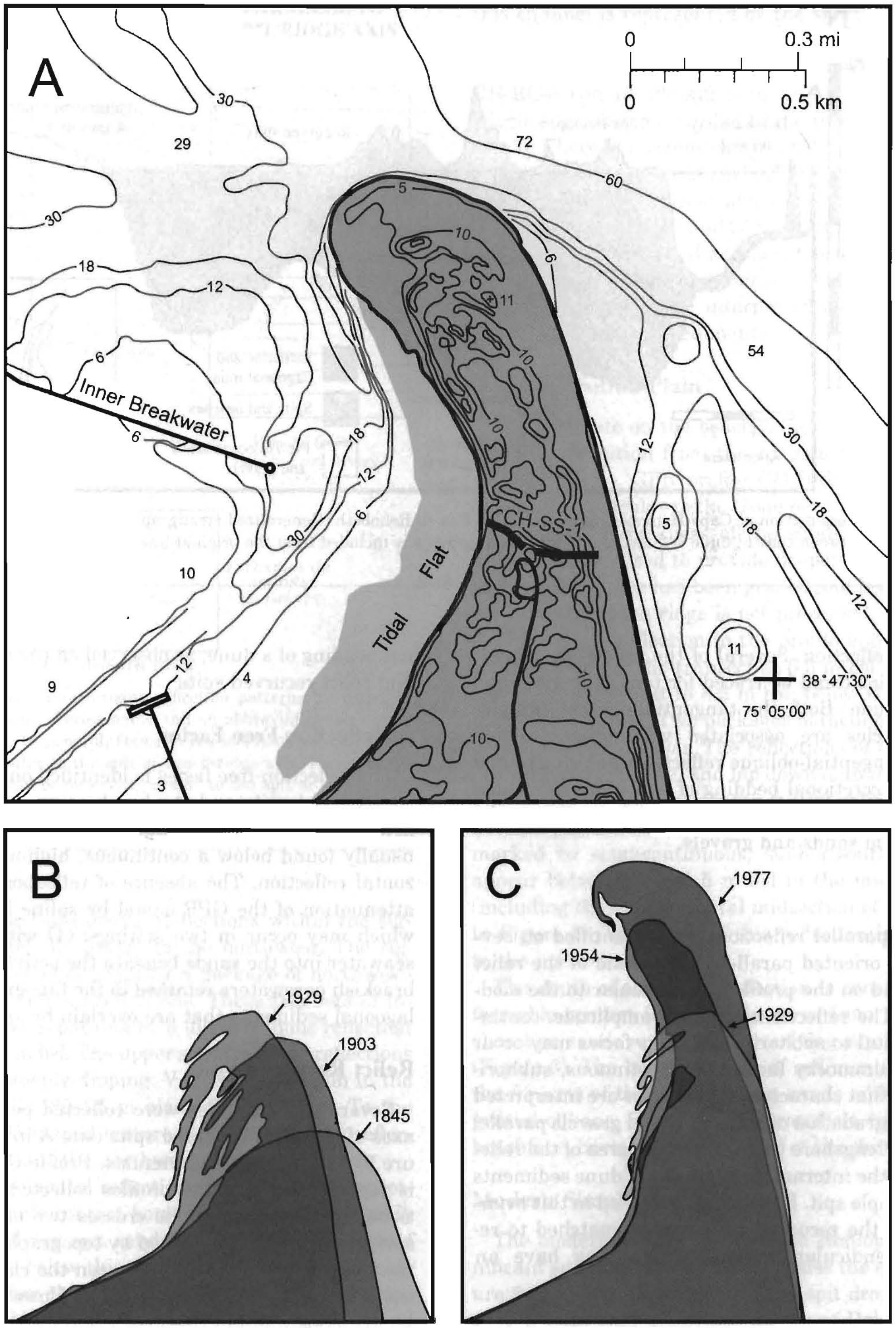

Figure 2. (a) Topography of the modern simple spit and bathymetry of surrounding waters in 1991, showing the location of GPR transect CH-SS-1. The Outer Breakwater is 1 km north of the spit. Bathymetric contours are 6 feet; topographic contours are 5 feet; from Cape Henlopen 1:24,000 topographic quadrangle. (b) Evolution of the cape from 1845 to 1929, after construction of the Inner Breakwater. Position of transect CH-SS-1 is shown. Shoreline positions from GALGANO (1989); see also MAURMEYER (1974) and KRAFT *et al.*, (1976). (c) Extension of simple spit from 1929 to 1977.

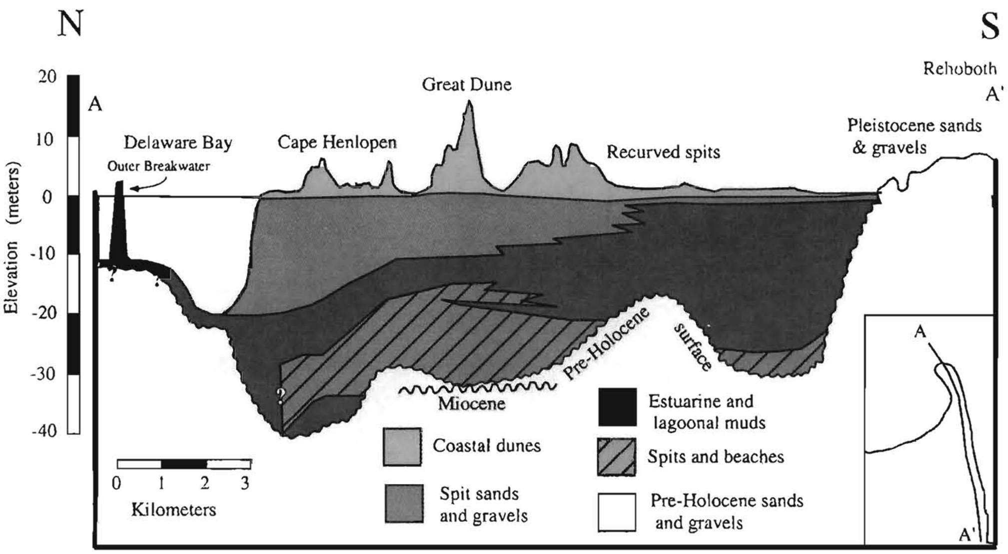

Figure 3. North-south cross section of Cape Henlopen, from Delaware Bay to Rehoboth. Generalized stratigraphy of major lithosomes and surfaces is shown. The distinction between coastal dune sediments and spit sands/gravels is included from the original interpretation (modified from KRAFT *et al.*, 1978).

amplitude basal reflection. Several of the reflections associated with this facies could be traced for tens of meters, and were high amplitude. Both the tangential-oblique and sigmoidal-oblique facies are associated with progradational landforms. The tangential-oblique reflections are interpreted to represent the accretional bedding of beachface sediments or dune sands. The sigmoidal-oblique facies is interpreted to be the spit-platform sands and gravels.

Parallel Facies

Evenly spaced parallel reflections were identified on several GPR profiles oriented parallel to the trend of the relict recurved spits, and on the profile perpendicular to the modern simple spit. The reflections are high-amplitude, continuous, and horizontal to subhorizontal. This facies may occur adjacent to the hummocky facies. The continuous, subhorizontal reflections that characterize this facies are interpreted as showing the aggradation of spit sands and gravels parallel to the direction of longshore transport in the area of the relict recurved spits, or the internal stratigraphy of dune sediments on the modern simple spit. Reflections identified in this even-parallel facies on the recurved spits can be matched to reflections in perpendicular profiles, where they have an oblique geometry.

Hummocky Facies

The hummocky facies is less common than the other facies at Cape Henlopen, but can be identified in profiles from the modern simple spit and the relict recurved spit tips. The reflections are continuous, but limited in extent. In most cases, this facies is only one mound-shaped structure with limited internal reflections. This facies is interpreted to be the internal bedding of a dune, as observed on the modern simple spit and relict recurved spits.

Reflection-Free Facies

The reflection-free facies is identified on profiles of the relict recurved spits and the beach-accretion plain. It is characterized by a nearly complete absence of reflections. It is usually found below a continuous, high-amplitude, subhorizontal reflection. The absence of reflections is attributed to attenuation of the GPR signal by saline interstitial waters, which may occur in two settings: (1) with the intrusion of seawater into the sands beneath the active beach; or (2) with brackish porewaters retained in the fine-grained estuarine or lagoonal sediments that are overlain by spit sands.

Relict Recurved Spits

Several GPR profiles were collected perpendicular to the axes of the relict recurved spits (site A in Figure 1, and Figure 5) using 100 MHz antennas. Profile CH-RC-8 (Figure 6) is representative of the profiles collected from this depositional setting. This profile crosses two emergent spits; the spit ridges are distinguished by topographic relief and a distinct vegetation difference between the ridges (forested) and the intervening swale (salt marsh). However, the GPR transect is along a level gravel road that cuts across the two spit ridges. Consequently, the upper 1 to 1.5 m of the section is truncated and the uppermost part of the spit ridges was not imaged with the GPR at this location.

Profile CH-RC-8 (Figure 6) shows several prominent reflective surfaces and radar facies. A strong, continuous subhorizontal reflection at an elevation of 5 m below sea level (bsl) separates the reflection-free facies below from the sig-

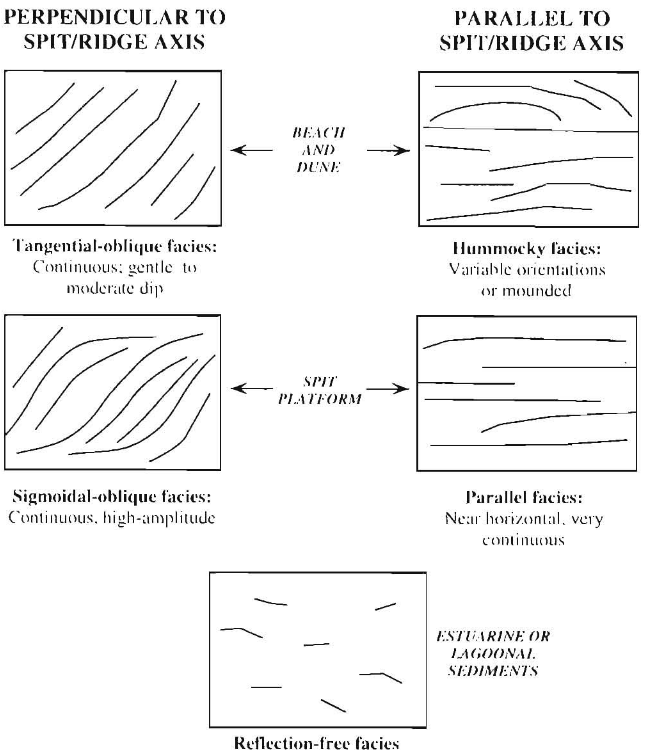

Figure 4. Radar facies characterizing reflection patterns identified in data from Cape Henlopen. Facies name and an abbreviated description are below each sketch. In general, facies in the left-hand column would be observed perpendicular to the spit or beach-ridge axis. Facies in the right-hand column would be observed parallel to the spit or beach ridge axis. Italicized labels indicate interpreted environments of deposition usually associated with these radar facies at Cape Henlopen.

moidal-oblique reflections above. Reflections within the sigmoidal-oblique facies dip gently to the northwest. The sigmoidal-oblique facies is overlain by a package of northwest-dipping tangential-oblique reflections. These two sets of inclined reflections are separated by a discontinuous reflection at approximately 2 m bsl. The upper set of inclined reflections is truncated by a steeply dipping, V-shaped reflection in the middle of the profile (80–95 m along the transect). To the northwest of this V-shaped feature (130–150 m), the reflections dip gently toward the northwest to nearly 4 m bsl.

The strong subhorizontal reflection at 5 m bsl is interpreted as the conformable contact between the estuarine sandy muds and the overlying spit sands and gravels. The lack of coherent reflections below this subhorizontal reflection is attributed to the higher electrical conductivity of the estuarine muds, which probably retain saline porewaters, and the rapid attenuation of the electromagnetic signal. The sigmoidal-oblique reflections in the package below the discontinuity at 2 m bsl are interpreted as the foresets in the spit-platform sands. The tangential-oblique reflections in the upper package are linear to slightly concave-up; these are interpreted as the bedding in the beach and dune sands. The V-shaped reflection that truncates the upper package of inclined reflections is interpreted as a channel, possibly of a small tidal creek that formed between the two spit ridges. The infill of this channel is represented by the short subhorizontal draping reflections within the feature.

Many of the same internal features identified in profile CH-RC-8 can be identified in profile CH-RC-2 (Figure 7), which was collected parallel to the trend of a ridge axis (Figure 5). There is a strong, horizontal basal reflection at ~120 ns (~4 m below ground surface). There are several continuous, horizontal reflections above this surface, and hummocky reflections between 15 and 25 m along the transect. The basal reflection is interpreted as the conformable contact between estuarine sediments and spit sands and gravels. The even-parallel reflections are interpreted as showing the vertical accretion of the spit sediments.

Beach-Accretion Plain

The GPR site on the beach-accretion plain lies on the geomorphic transition from the cuspate foreland to the simple spit (Figure 1). GPR profile CH-BAP-3 (Figure 8) was collected perpendicular to the trend of the beach ridges. Because of the greater thickness of the sands at this site, 50 MHz antennas were used to provide deeper penetration. The land surface at the site has been graded and leveled, so the upper ~1 m of the beach ridge is not preserved.

The deepest reflection in the profile appears at the south-southeast end of the transect at 6.5 m bsl and dips gently to the north-northwest to 8.5 m bsl; below this surface is a reflection-free facies. Two packages of inclined reflections overlie the basal reflection. The reflections of the lower package are sigmoidal-oblique, and lap down onto the basal reflection. The upper package has a tangential-oblique geometry. The boundary between the two sets of inclined reflections is demarked by semi-continuous, subhorizontal reflections that appear between 4 and 5 m bsl in the middle of the profile (including the subhorizontal midsection of reflection event A in Figure 8). The depth of this reflection increases bayward to the north-northwest.

The depth of the basal reflection is consistent with a conformable contact identified in cores from the area between shoreline sands and gravels overlying estuarine sandy muds (Figure 3). The lower package of sediments is interpreted as the foresets of the spit-platform sands and gravels. The tangential-oblique facies is interpreted as the bedding of the beachface, berm, and lower part of the dunes.

Modern Simple Spit

The modern simple spit of Cape Henlopen includes a significant submerged sand body besides the subaerial spit (Figure 2a). The northern edge of the spit drops off sharply into a deep tidal channel at the mouth of Delaware Bay. Sands transported around the end of the spit have created a shoal on the northern side of the Inner Breakwater. This shoal is separated from the back-spit tidal flat by a moderately deep, but narrow, tidal channel. The entire tidal flat is approximately 400 m wide and the surface slopes gradually from the low-tide mark to about 3 m depth. The outer edge of the tidal flat drops off steeply into the tidal channel. With a 1.5-m

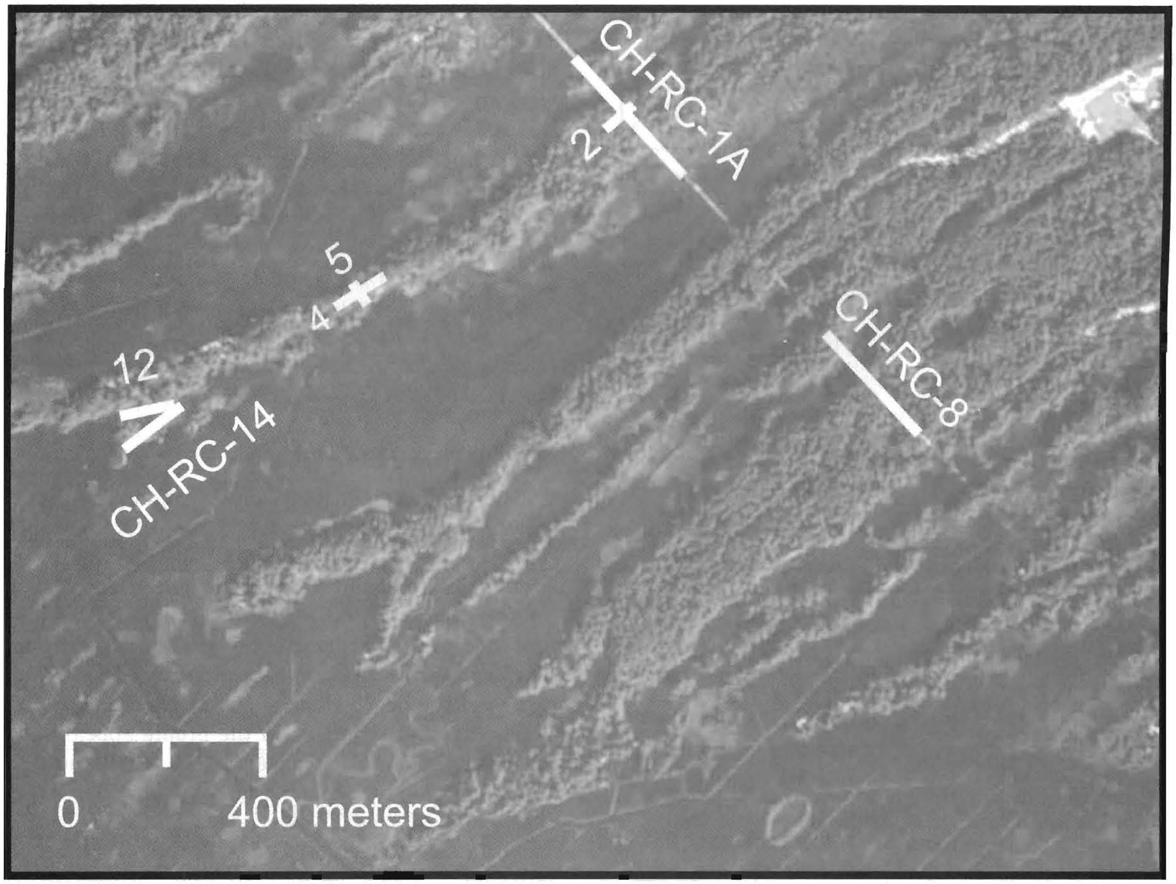

Figure 5. Detailed map of the relict recurved spits (area A in Figure 1), indicating location of GPR profiles collected. Note the vegetation difference between the forested relict recurved spits and the surrounding salt marsh. Profiles CH-RC-12 and CH-RC-14 were collected for another study.

spring tidal range, approximately 100 to 150 m of the tidal flat is exposed at perigean spring low tides. Before the distal end of the simple spit turned to prograde to the northwest, sand waves were transported around the tip and migrated across the tidal flat. These sand waves are exposed at low tide and can be seen in the aerial photograph of Figure 1.

The internal structure of the modern simple spit is different from that of the recurved spits and the beach-accretion plain. The 100 MHz antennas do not have sufficient depth of penetration to image the base of the spit sands at this location, but show the internal structure of the upper sediments in detail (Figure 9). The base of the spit sands is at approximately 20 m bsl in cores from this area (Figure 3) (JOHN, 1977; KRAFT *et al.,* 1978). No crossing lines were collected due to restricted access in this area of Cape Henlopen State Park. Data collected at the distal (northern) end of the spit were of low quality due to the intrusion of saltwater into the sediments. A 40 m hiatus in the profile includes a parking area. Steeply dipping reflections on either side of the profile hiatus are interpreted to result from power lines, cars, and other anthropogenic objects. Strong hyperbolic reflections at ~45 m were produced by the passage of the antenna by the battery and other electronic equipment.

Several different facies and four prominent surfaces (events A through D) are identified in profile CH-SS-1. The reflection-free facies at the bayward and seaward ends of the profile are interpreted as the attenuation of the radar signal by saltwater that lies beneath a shallow freshwater lens. The sequence imaged in the profile can be subdivided into four sediment packets (units I through IV) that are bounded by prominent reflections and have distinct internal bedding structures. These sediment units are the preserved record of the progradation of the simple spit.

The stratigraphically lowest reflections in profile CH-SS-1 (Figure 9) occur in the eastern third of the transect. A prominent horizontal reflection, designated event A, appears at 1 m above sea level from 20 to 120 m along the transect. West of 120 m, event A becomes tangential- to sigmoidal-oblique with a steeper dip to the west. The oldest sediment packet, designated unit I, is bounded on the top by event A from 20 to 180 m along the transect. The reflections within unit I are nearly horizontal and parallel with event A between 20 and 100 m along the transect, and become sigmoidal-oblique with a westward dip west of 100 m. East of 20 m, steeply east-dipping parallel reflections may not represent real geologic structures, but may be anthropogenically related.

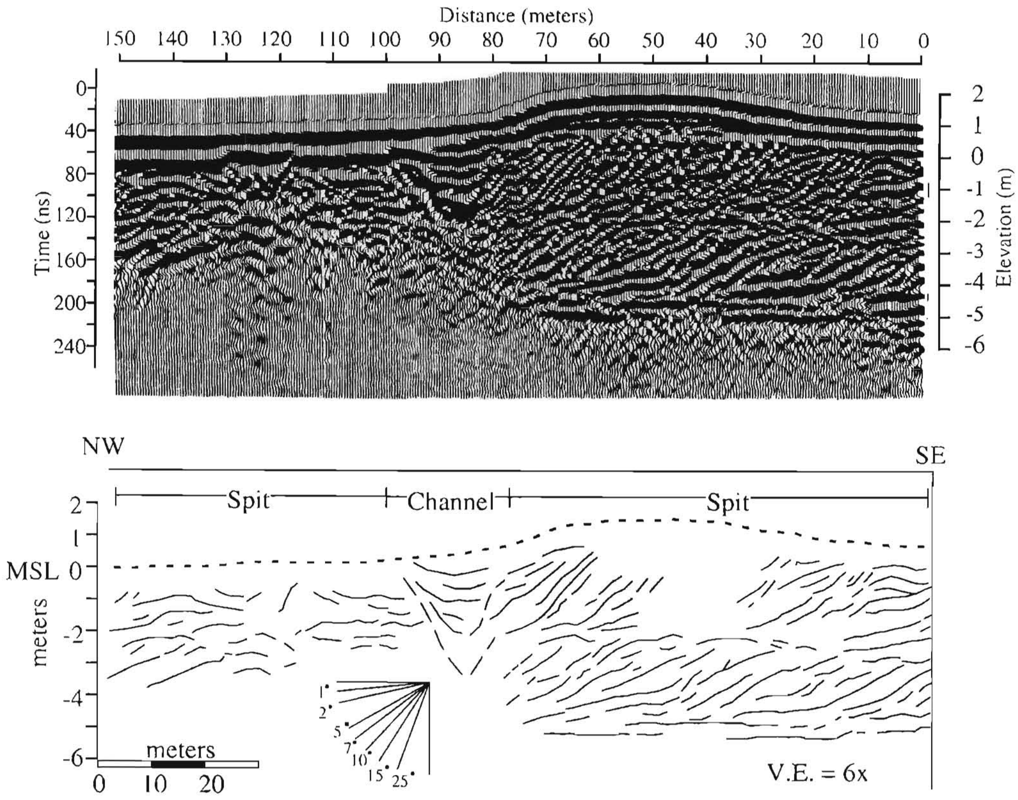

Figure 6. 100 MHz GPR data and line drawing interpretation of profile CH-RC-8, collected perpendicular to the axes of two recurved spits. Location of CH-RC-8 is shown in Figure 5. Dashed line indicates approximate ground surface. Three major radar facies are identified at this location: 1) sigmoidal-oblique reflections from 0 to 80 m at an elevation of −2 to −5 m, overlain by 2) tangential-oblique reflections, both truncated by 3) channel fill.

Event B is a prominent convex-up, west-dipping reflection that is the upper bounding surface of a sigmoidal packet from 130 to 200 m on the profile. One lower-amplitude reflection that immediately overlies event B is the first of a series of convex-up to sigmoidal-oblique reflections west of 150 m that have upper bounds that approach horizontal between 0 and 1 m elevation. The tops of these sigmoidal reflections define toplap surface C, which is stratigraphically above event A but nearly coincident in elevation. Sediment unit II is defined as the set of west-dipping tangential-oblique to sigmoidal-oblique reflections from 130 to 340 m along the transect that are below toplap surface C and west of and above the dipping section of event A from 120 to 170 m. The individual sets of reflections in unit II are similar to those seen in profile CH-RC-8 (Figure 6). Reflections in unit II at the west end of the transect (from 270 to 340 m) dip at ~5 to ~7 degrees.

Event D is the undulating, nearly horizontal reflection at 3 m above sea level that extends laterally the entire width of the transect. Event D overlies one sediment packet, unit III, that is comprised of parallel and hummocky reflections. In turn, event D is overlain by a second hummocky facies, unit IV.

Sediment unit I in profile CH-SS-1 is interpreted as representing the aggradation of sand and gravel as the modern simple spit began to develop. Sediment unit II is interpreted as representing the progradation and aggradation of sand waves moving landward from the the back-spit flat. Toplap surface C represents the upper boundaries of the sigmoidal packets of sand at approximately 1 m above MSL, locating this surface within the intertidal zone defined by a 1.2 to 1.5 m tidal range. Event D may be interpreted as the wind-scoured surface over which the dunes are migrating. An alternative interpretation for event D is that this reflection represents the water table; however, there is not clear evidence that event D crosscuts the more steeply dipping reflections of unit IV. The even-parallel and hummocky reflections of unit III, below event D and above event A and toplap surface C, are interpreted as the structure of a buried dune field. The tangential-oblique reflections of unit IV lap down onto event D and are interpreted as the internal structure of the active dunes.

The dunes that cap the simple spit seem to have developed in two stages, based on the GPR data. The lower hummocky facies of unit III is interpreted as a low-elevation dune field that was the first subaerial section of the developing simple spit. This initial dune field would have developed on the welded beach ridges of a spit configuration similar to that of the 1929 shoreline, which prograded north and west past the 1903 shoreline (Figure 2b) (Maurmeyer, 1974; Kraft *et al.*, 1976). The thicker and higher-elevation dune field of sedi-

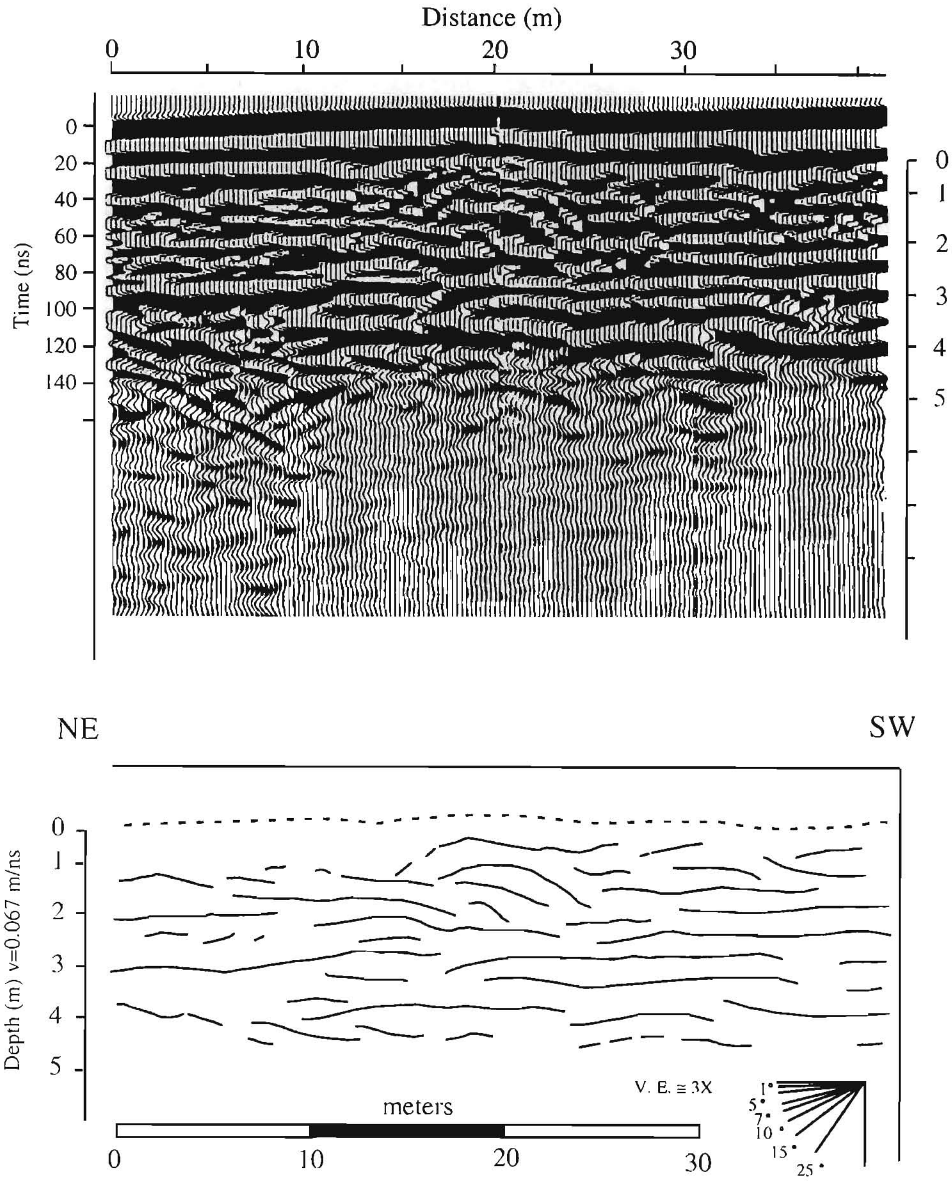

Figure 7. 100 MHz GPR data and line drawing interpretation of profile CH-RC-2, collected parallel to the axis of a recurved spit. Location of CH-RC-2 is shown in Figure 5. Dashed line indicates approximate ground surface. Only depth below surface is shown; data are not related to MSL. Both parallel and hummocky radar facies are identified in this profile.

ment unit IV, which caps the CH-SS-1 sequence, would have formed as the rapid extension of the spit to the north-northwest supplied a large volume of sand exposed subaerially.

DISCUSSION

Identifying the internal structures associated with the different shoreline morphologies of Cape Henlopen allows us to evaluate models of spit evolution and the relative influences of depositional environment and rising sea level on spit development. The reflections in the GPR profiles from each of the three geomorphic settings, the recurved spits, beach-accretion plain, and simple spit, are defined by characteristic radar facies.

Radar facies have been defined to describe the internal stratigraphy of each geomorphic setting from GPR transects both parallel and perpendicular to the trend of the spit or beach ridge (Figure 4). Along transects oriented perpendicular to the trend of the spit or shoreline, reflections are oblique, with a seaward (or bayward) dip. Reflections in transects parallel to the ridge trend are typically parallel or hum-

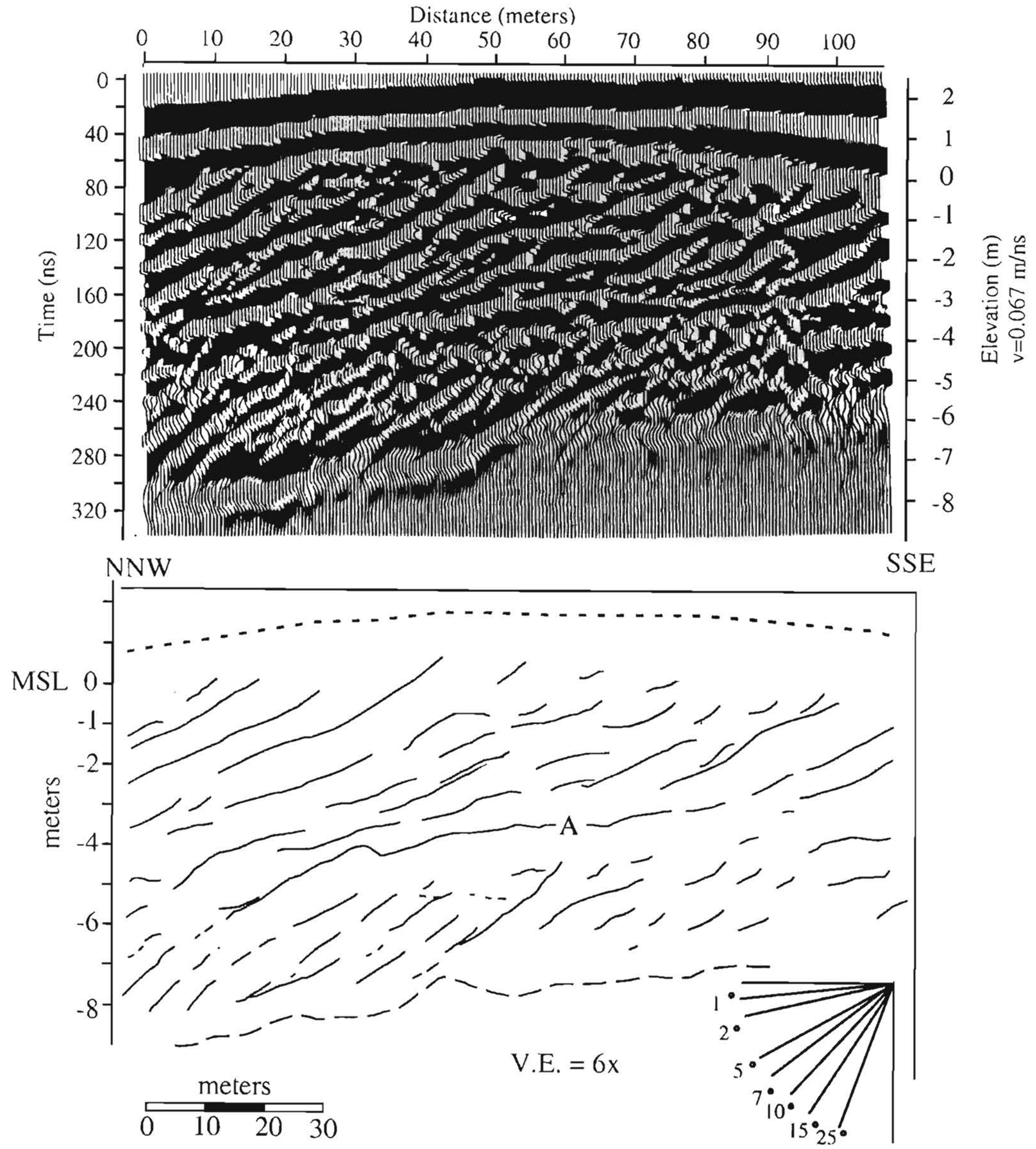

Figure 8. 50 MHz GPR data and line drawing interpretation of profile CH-BAP-3, collected perpendicular to the trend of the beach accretion ridges. Location of the profile is shown in Figure 1. Dashed line indicates approximate ground surface. Event A indicates the separation between the spit platform facies below, and the beach and dune sediments above.

mocky, or sigmoidal in a few cases. The estuarine-lagoonal muds that underlie the spit sands produce a reflection-free facies due to attenuation of the radar signal by saline porewaters retained in the muds. Subaerial upper-beach and dune sands may have variable dip directions because of eolian transport.

Spit Morphologies and Evolution

Comparison of GPR data for the three spit morphologies allows us to infer changes in depositional mode associated with each morphology. For the recurved spits, the tangential-and sigmoidal-oblique facies indicate that the spit platform and ridge prograded to the north-northwest into Delaware Bay. The basal reflection, interpreted as the boundary between the platform sands and underlying estuarine sediments, occurs at 5 m bsl. At the time that the recurved spits developed, the platform prograded across a relatively shallow, low-energy embayment. The evenly spaced, nearly horizontal, parallel reflections seen in profiles parallel to the trend of the spit ridges indicate vertical accretion of the beachface (Figure 7). The development of these recurved spits is analogous to the model of barrier development described

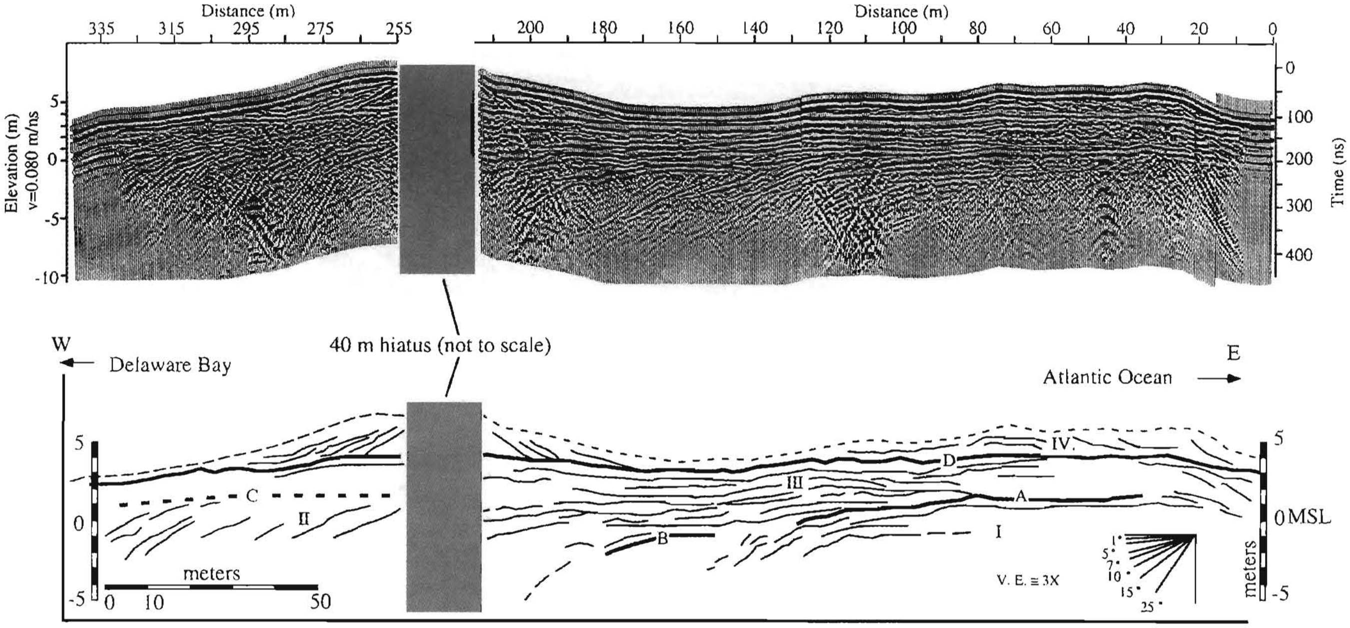

Figure 9. 100 MHz GPR data and line drawing interpretations of profile CH-SS-1, collected across the modern simple spit. Dashed line indicates approximate ground surface. The break in section is not to scale. Events A,B, C, and D are major surfaces. Surface A represents the top of sediment package I, the oldest sediments imaged. Event B is a convex-up surface interpreted to be the top of a progradational feature. Surface C is a toplap surface interpreted to delineate the tops of accreting swash bars (sediment package II). Event D is interpreted to indicate the surface above which dunes are actively migrating. Alternatively, it may be interpreted as the water table. Sediment package III is interepreted to be inactive dune sediments, and sediment package IV is interpreted to show the stratigraphy of active dunes.

by HOYT (1967, 1968). Both aggradation and progradation are important processes in barrier development according to the HOYT (1967) model; however, the model did not include a spit platform or analogous feature. GPR data from this recurved-spit setting indicate that the platform is a separate, distinguishable feature.

The internal stratigraphy of the beach-accretion plain represented by the GPR reflections indicates that progradation to the north-northwest continued as the beach ridges developed. The basal reflection is at a greater depth than below the recurved spits, and dips toward the north-northwest, indicating that the spit platform was prograding into deeper water. The shoreline of the cuspate foreland associated with the beach-accretion plain was oriented nearly east-west and was exposed to high-energy waves generated by northeaster storms. Consequently, the beachface of this shoreline should be steeper and deeper than those of the recurved spits or the bayward side of the simple spit imaged in profile CH-SS-1. The GPR data for this morphology are consistent with this hypothesis.

Two packages of reflections can be distinguished within both the recurved-spit and beach-accretion plain morphologies. The lower package is characterized by the sigmoidal-oblique or tangential-oblique facies. The similarity between these two facies in the lower spit stratigraphy suggests that some type of subtidal platform was present and prograding proximally to both the recurved-spit ridges and beach-accretion-plain ridges. There is less similarity between the upper packages of the two morphologies. The upper package of the beach-accretion plain is characterized by the tangential-oblique facies and indicates progradation in a uniform direction. However, the upper package of the recurved spit morphology is more heterogeneous, and is comprised of many different radar facies. Many of the reflections in this package indicate progradation to the north-northwest, similar to the beach-accretion plain, but several facies are evidence for washover or eolian processes.

HOYT (1967) described seaward progradation of the beachface and upper shoreface as a barrier-building process. Seaward progradation was important for construction of the recurved spits and beach-accretion plain, but is not currently active on Cape Henlopen. Cape Henlopen is oriented relative to the dominant northeast wave attack such that the seaward side is eroding and migrating westward at a significant rate (MAURMEYER, 1974; KRAFT *et al.*, 1976). The process of back-spit accretion was significant in the formation of the modern simple spit, but was not described by MEISTRELL (1966) or HOYT (1967). The entire width of the simple spit (at transect CH-SS-1) is underlain by packets of sigmoidal reflections at depth that indicate bayward progradation and aggradation of the back-spit tidal flat. However, MEISTRELL's (1966) physical model of spit development did not predict this process or the effects of tides on spit formation.

Internal Stratigraphy and Local Relative Sea-Level Change

A physical model for spit development predicts that a spit platform will prograde ahead of a spit ridge, and that the boundary between the spit-platform and spit-ridge sediments will develop at a constant depth below mean low water (MEISTRELL, 1966). This implies that this boundary will occur at a constant depth below mean sea level within recent spit ridges, and that it may track sea-level change within spits or spit complexes that have developed over a longer period of time. A spit platform has been interpreted to track Holocene sea-level change (NOVAK and PEDERSON, 2000), and a similar relationship has been described for another stratigraphic boundary within a spit (VAN HETEREN and VAN DE PLASSCHE, 1997). However, the GPR data from the three morphologies at Cape Henlopen indicate that this boundary is not present in all morphologies. Within the recurved spits, the oldest morphology, the boundary between the platform and the ridge is 2 m below present mean sea level. This roughly corresponds to the sea level at the time this morphology developed (PIZZUTO and SCHWENDT, 1997). This crude correlation indicates that, for this morphology, the boundary may serve as a stratigraphic indicator of sea level at the time of spit development.

The internal stratigraphy is similar for the recurved spits and the beach-accretion plain, especially for the lower package of sediments. A spit platform is interpreted from the sigmoidal-oblique facies in the lower part of the GPR records from each setting. The surface defining the top of the spit platform decreases in elevation from 3 m bsl to 5 m bsl, dipping toward the north. Although this surface can be traced in the internal structure of the beach-accretion plain, the top of the spit platform does not appear to track sea level in this environment. Sea-level histories for this area indicate that sea level has risen steadily from 2 m below to present mean sea level during the past 2000 years (BELKNAP and KRAFT, 1978; PIZZUTO and SCHWENDT, 1997). The beach-accretion plain developed between about 500 and 200 years BP, and the model would predict that the top of the spit platform would be shallower than 2 m below present sea level. The boundary can be identified several meters deeper than paleo-sea level at the time that the beach-accretion plain developed. Additionally, the depth of the surface increases in the direction of deposition, although sea level rose. The depth and geometry of this surface varies and was controlled primarily by wave energy; consequently, it does not serve as a valid indicator of paleo-sea level for this setting.

One surface associated with the progradation and back-spit accretion of the modern simple spit occurs within 1 m of modern sea level (event A and toplap surface C in profile CH-SS-1). These are interpreted as representing the upper boundaries of prograding sand packets deposited on the leeward side of the simple spit within the 1.5-m intertidal zone. Tentatively, the elevation of this surface may be strongly related to sea level. Further work defining the geometry of the simple spit in three dimensions may determine the relationship between the surface and sea level.

SUMMARY

Ground-penetrating radar is a valuable tool for investigating the internal structure of Holocene coastal features. In this study, GPR was used to image the internal structure of three distinct shoreline morphologies associated with the evolution of Cape Henlopen, Delaware. This cape complex at the mouth of Delaware Bay evolved over the past 2000 years from a set of recurved spits prograding into a protected shallow lagoon, to a cuspate foreland with a well-developed beach-accretion plain, and finally to the modern simple spit. Changes in shoreline morphology during the evolution of Cape Henlopen are reflected by changes in the internal stratigraphy. Although similar features may be identified in more than one shoreline morphology, the orientation and depth of these features relative to contemporaneous sea level varies. The internal geometry reflects rising sea level, deepening depositional environment, and changing wave energy during the evolution of the cape.

The stratigraphic record from Cape Henlopen is complex, and identifying reliable stratigraphic indicators of sea level is not always possible. The GPR profiles show subsurface reflections created by a variety of processes, including progradation of the spit platform, beach-ridge accretion, and back-spit accretion of a tidal flat. Deposition in the relatively lower-energy setting of the recurved spits produced a transition between the top of the spit platform and the base of the beachface that occurs consistently 2 m below the contemporaneous sea level. No reliable sea-level indicator was identified for the cuspate foreland morphology, although the internal stratigraphy of the morphology is similar to that of the relict recurved spits. The orientation of this shoreline toward high-energy waves from northeaster storms produced a steeper and deeper beachface than in the other settings. Two surfaces in the simple-spit section seem to be associated with the upper bounds of spit progradation and back-spit accretion, respectively, within the intertidal zone. Additional field study is needed to better characterize these surfaces and demonstrate their utility as sea-level indicators. The upper elevation limit of steeply seaward-dipping, linear reflections that are interpreted as the accretion of a prograding beachface are within 1 m of sea level; however, the tops of these reflections may be controlled more by storm waves than by mean water level.

This characterization of the internal structures of the Cape Henlopen spits and shorelines may be useful in evaluating the Holocene sea-level history of other coasts or for predicting the response to future sea-level rise. Further, the radar facies may be used to develop depositional models for analogous Pleistocene coastal landforms and to estimate paleo-sea levels.

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