The Evolution of a Cuspate Foreland; Cove Point, Maryland

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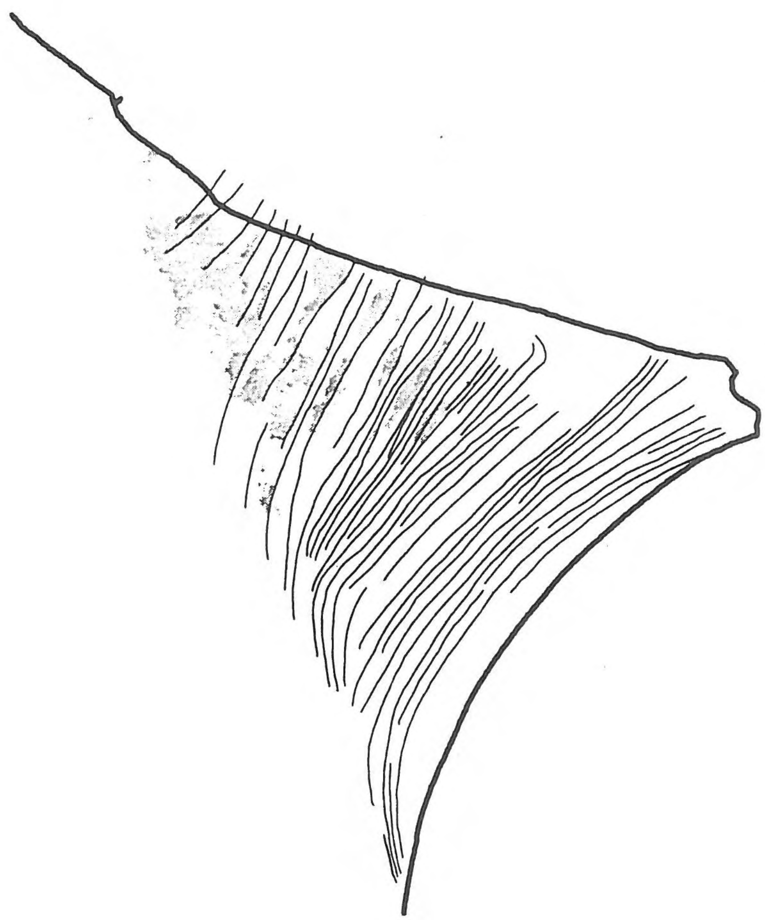

ABSTRACT

Title of Thesis: EVOLUTION OF A CUSPATE FORELAND;

COVE POINT, MARYLAND

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Cove Point, a coastal landform on the western shore of Calvert County, Maryland, is a classic truncated cuspate foreland. It is characterized by ridge and swale topography which is the result of relict beach ridges, representing former fronts of the foreland. Historical shoreline maps indicate that these ridges continue to grow southward while the northern flank of the foreland is eroded. Vibracores extracted from the beach ridge plain provide for a reconstruction of foreland development. Many of these cores penetrated the entire Holocene littoral beach ridge sequence; it was found that the cape rests upon a platform of Miocene aged sediments (the St. Mary's formation). The northern (oldest) portion of the beach ridge plain has been drowned by sea level rise, leading to the formation of a freshwater marsh. Radiocarbon dating of organic material reveals that the present

day cuspate foreland is approximately 1700 years old, and that its overall migration south has been relatively linear during this time span.

An analysis of historical and geomorphic evidence reveals that the present day rate of migration is 0.7 meters per year, while the Holocene migration rate has been 1.3 meters per year. This discrepancy can be explained by the conditions of local bathymetry and relative sea level rise in this region. Both of these factors have inhibited the present-day growth of the foreland. Shoreline engineering structures at the tip of Cove Point have also altered longshore sediment transport; these features may have a lasting impact on the continued evolution of Cove Point.

EVOLUTION OF A CUSPATE FORELAND;

COVE POINT, MARYLAND

by

Michael W. Beardslee

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Introduction

Background to research

The long-term morphology of coastal environments is often governed by large-scale changes in climate. Since the peak of the last glaciation (ca. 18,000 B.P.), sea level has risen as the great continental ice sheets melted. This process, which was largely finished by 8000 B.P., has caused a continual reshaping and landward displacement of the world's shorelines. Coastlines have migrated hundreds of kilometers in response to rising sea level, and ancient river valleys such as the Susquehanna have been drowned to create convoluted shorelines such as the Chesapeake Bay estuary (Leatherman, et al., 1995).

Relative sea level rise is therefore one of the primary agents of land loss as well as promoting coastal evolution. Contemporary sea level rises at an estimated global eustatic rate of 1.8 mm per year (Douglas, 1991), and indications are that it may accelerate in the future due to continued global warming.

The effects of sea level rise are compounded by other factors that must be considered. For example, antecedent geology plays a critical role in coastal morphology, as do sediment supply, wave climate, and existing shore protection structures. The highly variable nature of all these elements requires an understanding of the geomorphic principles that govern their relationships to each other and to the shorelines upon which they act. Particular combinations of these factors can create specific kinds of coastal features, such as tombolos, baymouth barriers, and recurved spits. Although most coastal formations are easily classified, understanding their origin and morphology is a much more difficult task.

The cuspate foreland is one such coastal landform. These features can be found all over the world. Some examples of cuspate forelands are Cape Canaveral in Florida, Cape Henry in Virginia, Cape Lookout in North Carolina, and Cape Henlopen in Delaware (now growing as a recurved spit). Cove Point, a truncated cuspate foreland on the western shore of Calvert County, Maryland (Figure 1), is similar in appearance to many cuspate forelands, but as with most such landforms, the conditions which cause its development are unique and require careful geomorphic analysis before an understanding of its evolution can be achieved.

Objectives of the study

The purpose of this study is to examine the geomorphic evolution of Cove Point, a cuspate foreland on the western shore of the Chesapeake Bay in Calvert County, Maryland. The specific objectives are to:

(1) examine historic shoreline behavior to understand recent patterns of change;

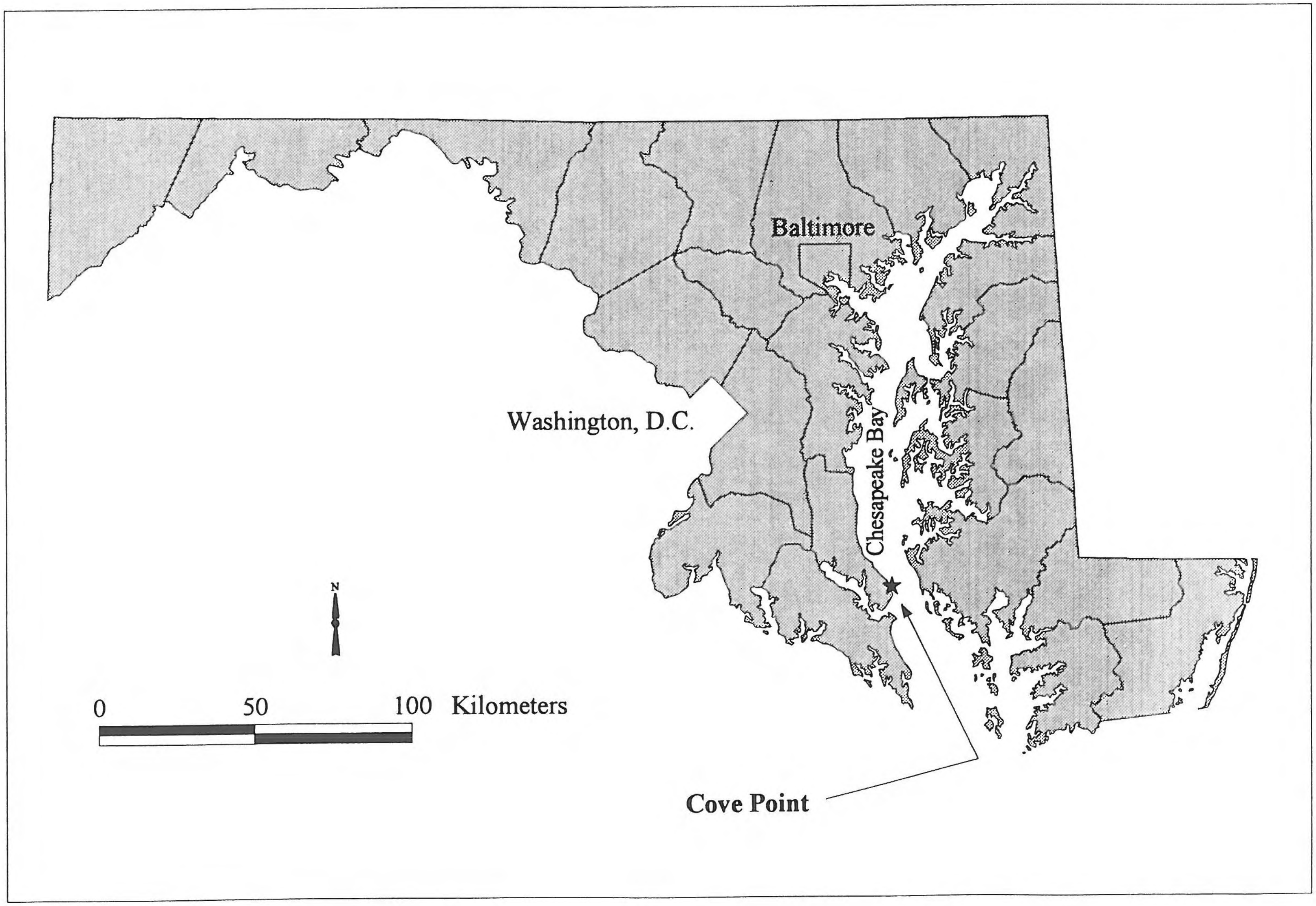


Figure 1. Location map of study area.

(2) examine stratigraphy of beach ridges and underlying units to derive models of beach ridge progradation and landform development;

(3) determine the rate of Holocene migration through radiocarbon dating;

(4) provide future scenarios of Cove Point evolution using shoreline data, vibracore data, radiocarbon dating, and geomorphic analysis.

The study area

The study area is a low-lying cape feature on the western shore of the Chesapeake Bay in Calvert County (Figure 2). It projects into the Bay approximately 1.4 km, and is 2.3 kilometers from the most northern tip to the most southern point (Figure 3). Historical shoreline records indicate that the northern side of Cove Point has been eroding for at least the last 90 years while the southern flank has been accreting (Downs, 1993). It is comprised primarily of unconsolidated sandy sediments which are the product of Holocene deposition. The foreland is backed to the west by bluffs which range in height from near sea level to approximately 33 meters high. These cliffs are oriented in a straight line, suggesting that wave attack once straightened this shoreline prior to foreland migration. The angle of these cliffs (approximately 25 to 35 degrees as determined from a topographic map) also implies that they were once undercut by wave activity. These relict cliffs continue to the north and south of the present day cape, where they merge with cliffs which currently are exposed and wave-cut

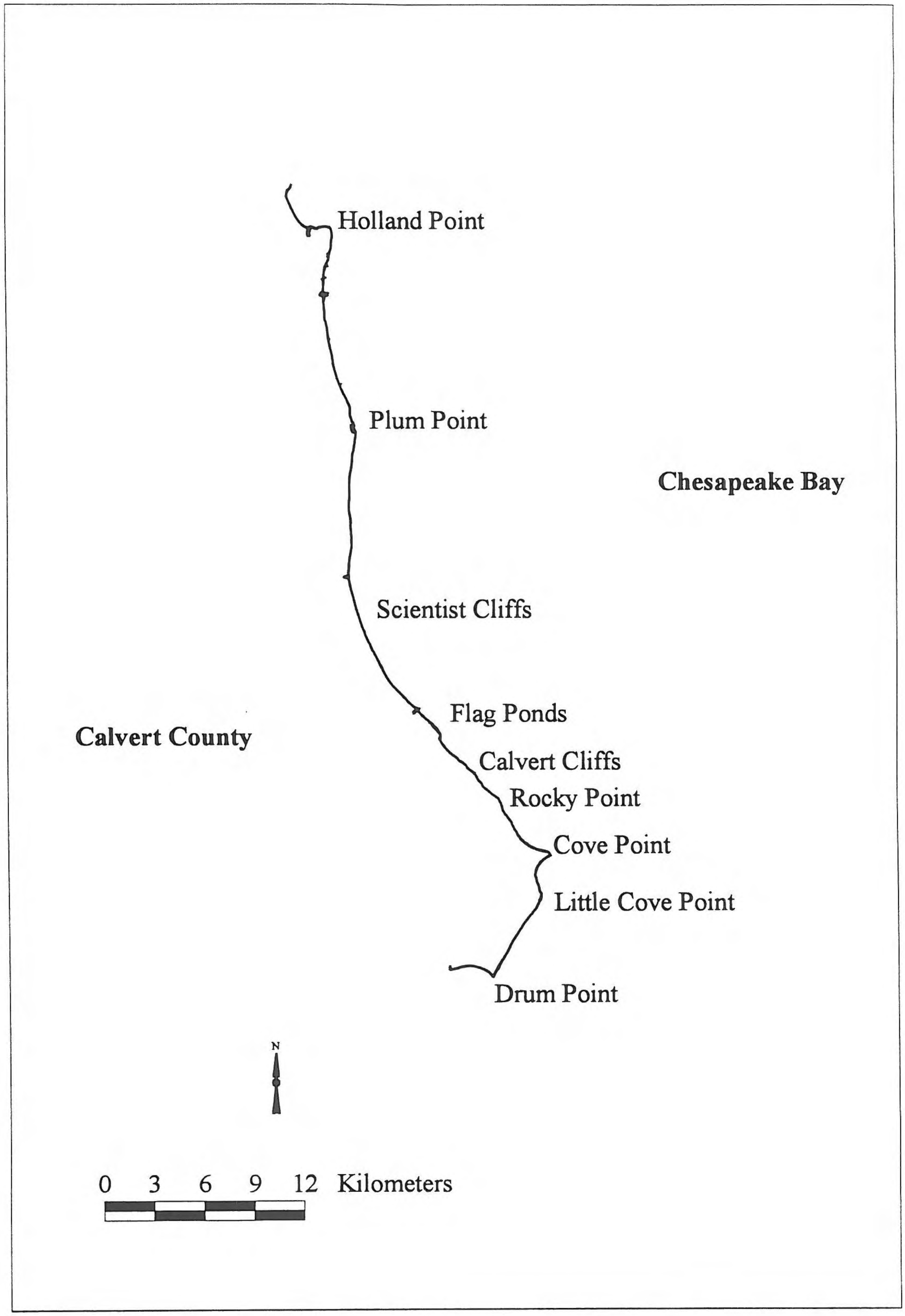


Figure 2. Calvert County coastal features and landmarks.

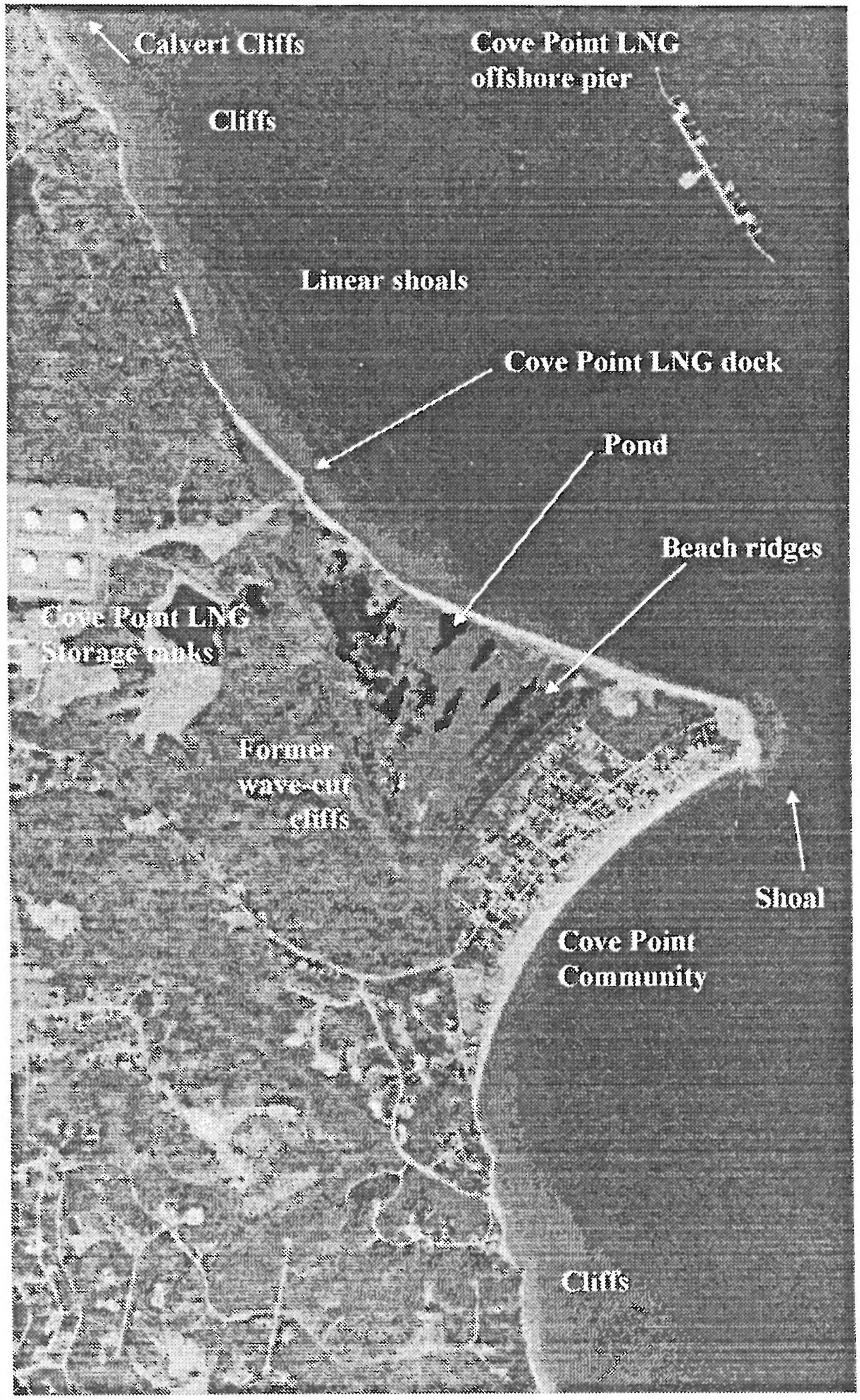


Figure 3. Photograph of Cove Point.

by the Chesapeake Bay along much of the Calvert County coastline. These freshly exposed cliffs are inclined at an angle of 35 to 45 degrees and higher.

The bluffs in the area immediately adjacent to Cove Point are composed of Miocene age marine silts which dip to the southwest at an average of 1.4 to 2.0 meters per kilometer (Kidwell, 1997). These strata also contain smaller portions of sand in variable quantities. Because there are no active local riverine sediment sources, these sandy sections supply essentially all of the material to the longshore sediment transport system. Miocene sediments were also found beneath Cove Point; these silts and clays are part of the St. Mary's formation of the Chesapeake Group, a unit which averages approximately 15 meters in thickness (Kidwell, 1997). These lithofacies were deposited in a shallow marine environment between eight and twelve million years ago during the last major transgression of the sea into the Susquehanna River basin (Glaser, 1968). The St. Mary's is composed of an interbedded, dense, bluish-gray clay and a similarly colored fine argillacious sandy silt or silty sand (Glaser, 1968), and rests unconformably on top of the older Miocene-aged Choptank formation. The St. Mary's can be divided into seven separate facies based on exposed outcrops along the Calvert County coastline (Kidwell, 1997); no attempt was made in this research to distinguish between these subunits. These earlier studies indicate that the St. Mary's formation can be variable in composition; sometimes it is a hard, dewatered clay (almost lithified), while in other instances it is an unconsolidated sandy silt.

However, it is fairly uniform in color (bluish-gray or greenish-gray), and easily distinguished from modern deposits.

The Chesapeake Bay is fairly shallow and slopes gently offshore of the northern flank of Cove Point. A multiple bar system common to much of Calvert County can be readily observed on this flank of the foreland, and these bars are apparent east of the tip of the spit (Kindle, 1936). However, there is a steep slope to an average depth of about 3.5 meters off the southern flank of the foreland, and no bars can be observed on this accretionary side.

The Bay itself is characterized by a low tidal range (0.3 meters) and a low average wave height of approximately 0.15 meters (Wang, et al., 1982). Because of the limited fetch, the Bay also lacks long period swell waves which dominate the accretionary processes of open oceanic coasts. Predominant wave attack for this area is from the north and northeast. Storm conditions can greatly alter this typically low-energy environment. The Bay is impacted by two types of storms: northeasters and hurricanes. Both produce a dominant wave attack from the northeast, normal to the erosional flank of Cove Point. Because of the limited wave energy, the depth of closure for much of the Chesapeake Bay is usually no more than 3.0 meters (Downs, 1993). The sediment supply along the Calvert County coastline is controlled by a number of littoral cells (Downs, 1993; Figure 4). It is these cells which have governed the genesis of the cuspate foreland.

Relative sea level rise also plays a role in the evolution of coastal landforms in the Bay. Sea level has been rising at a rate of approximately 2.0 +/-

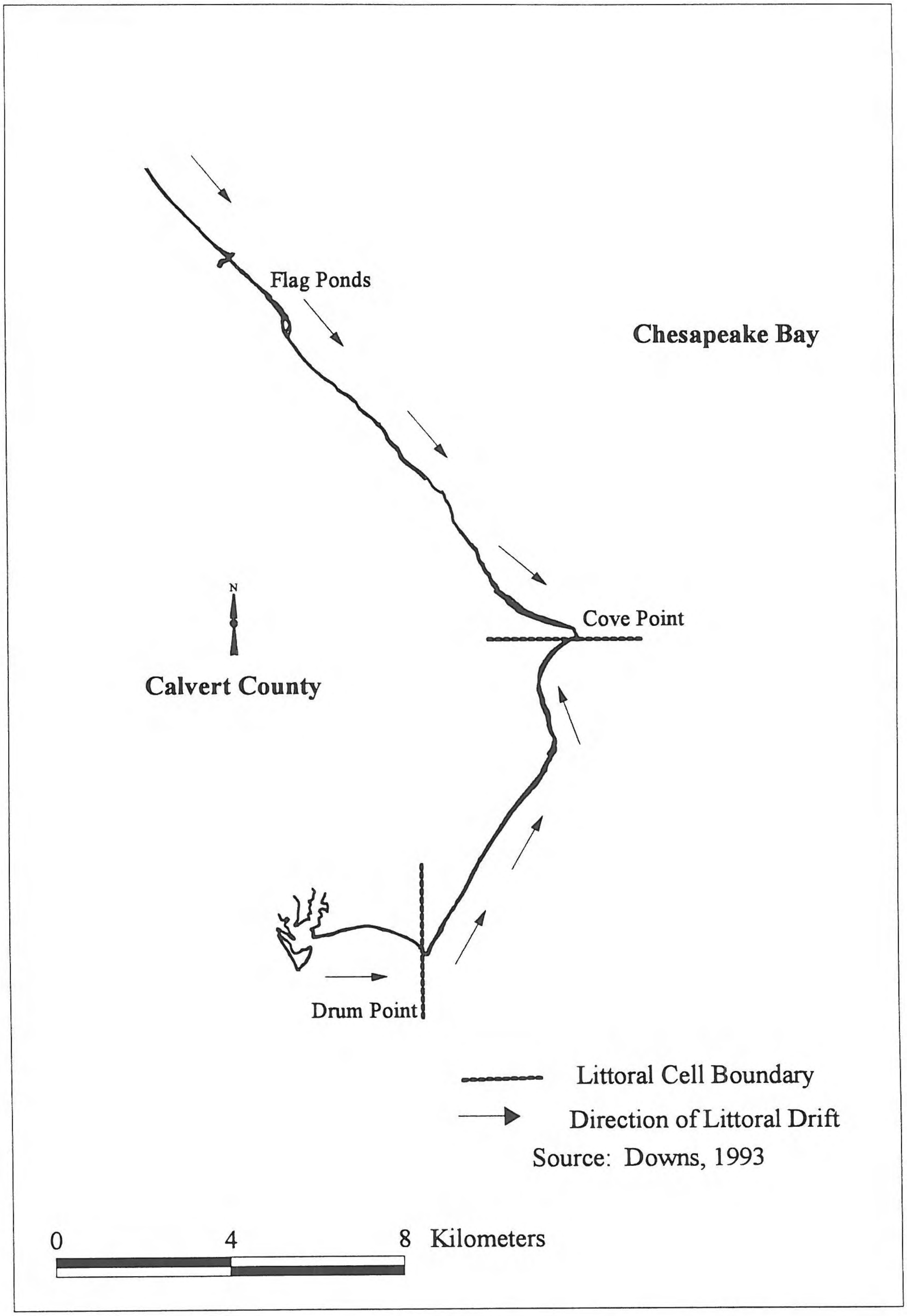


Figure 4. Directions of littoral drift in southern Calvert County.

0.6 meters per 1000 years for the last several thousand years in the Chesapeake Bay (Peltier and Jiang, 1997). This rate of rise can be attributed almost entirely to the effects of glacial isostatic adjustment (forebulge collapse in this region); (Douglas, 1997; Peltier and Jiang, 1997). This rate of rise has increased to an average of approximately 3.6 mm per year over the last 150 years for the Chesapeake Bay region (Douglas, 1991; based on the average long-term trend of local tide gauge records). This higher rate of sea level rise is due to the global eustatic rise of 1.8 mm per year coupled with continued glacial isostatic adjustment (Douglas, 1991).

Cove Point itself is a low-relief feature, with the highest elevations found on the present day dune line (nowhere above 1.5 meters). Ridges trend southwest to northeast in the southern portion of the foreland at an average spacing of 25 meters (Figure 5). In the northern part of the foreland a freshwater marsh has developed and accreted vertically through the accumulation of peat as a result of sea level rise. This has caused a partial submergence of the beach ridge plain, eliminating the subaerial evidence of ridge and swale topography.

There are several anthropogenic developments at Cove Point which should be noted. First, there is the existence of the Cove Point LNG (liquid natural gas) offshore loading platform. This pier is approximately 1 km northeast of Cove Point (about 1.5 km offshore), and is connected with the Cove Point LNG facility by an underground tunnel. The construction of this tunnel disturbed local sediments.

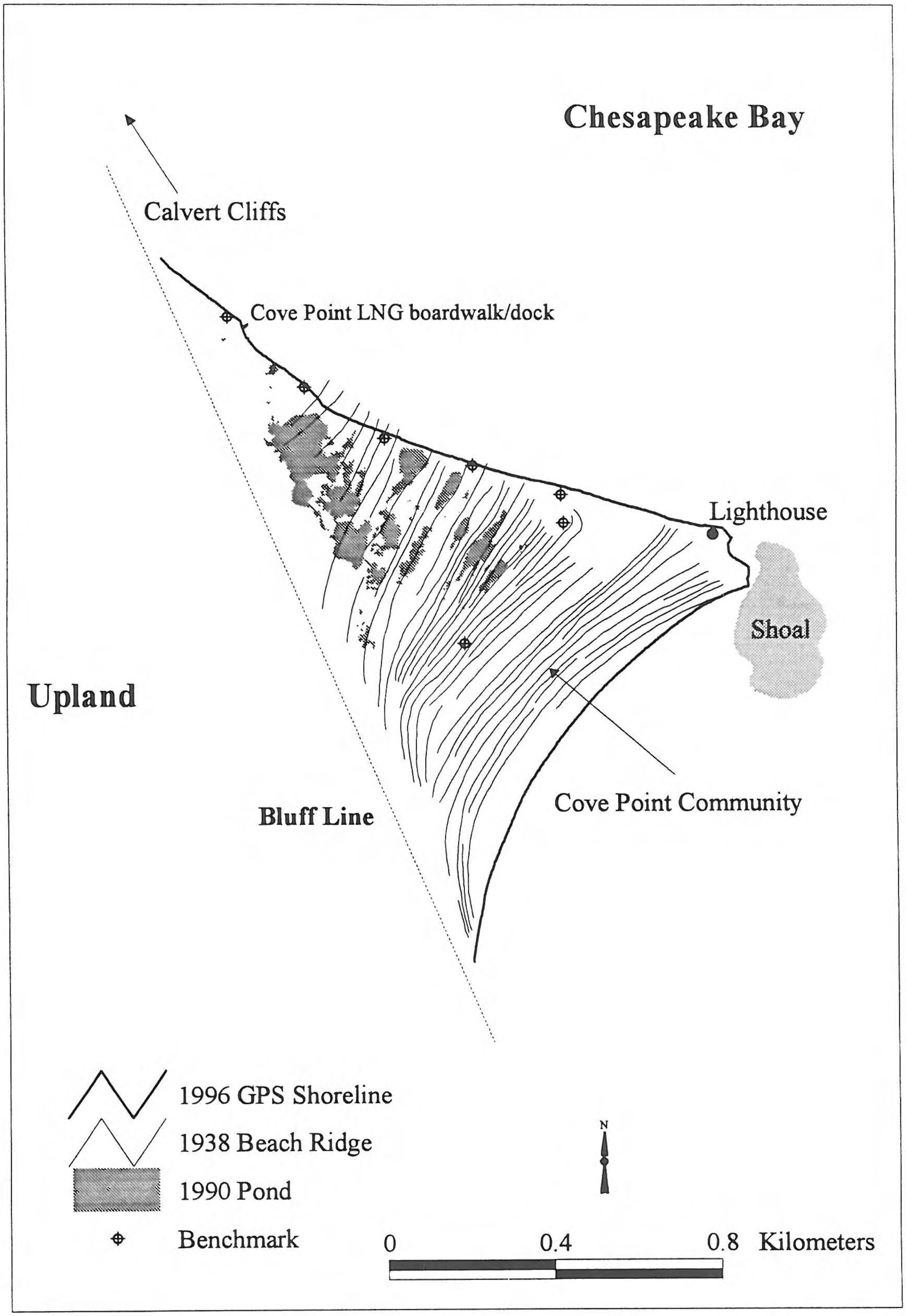


Figure 5. Local physiography of Cove Point.

A disruption of natural sediment transport processes is likely occurring at the tip of Cove Point. Here a lighthouse was constructed in 1828. A concrete seawall was constructed in 1929 to protect this lighthouse, and several small groins were added between 1963 and 1971 (Figure 6). There is evidence that these shoreline engineering structures may have disturbed the natural system. The operation of a titanium mine in the 1970's near the tip of the spit has also disturbed local geomorphic evidence. In addition, a sizable community has developed on the southern flank of Cove Point (the portion of the cape highest above sea level). Those inhabitants closer to the freshwater marsh have noted increased incidents of flooding, an indication of rising sea level. Anthropogenic activity here has also erased much of the evidence of foreland development. An attempt was made to avoid these areas during the collection of geomorphic data for the Cove Point study (Figure 7).

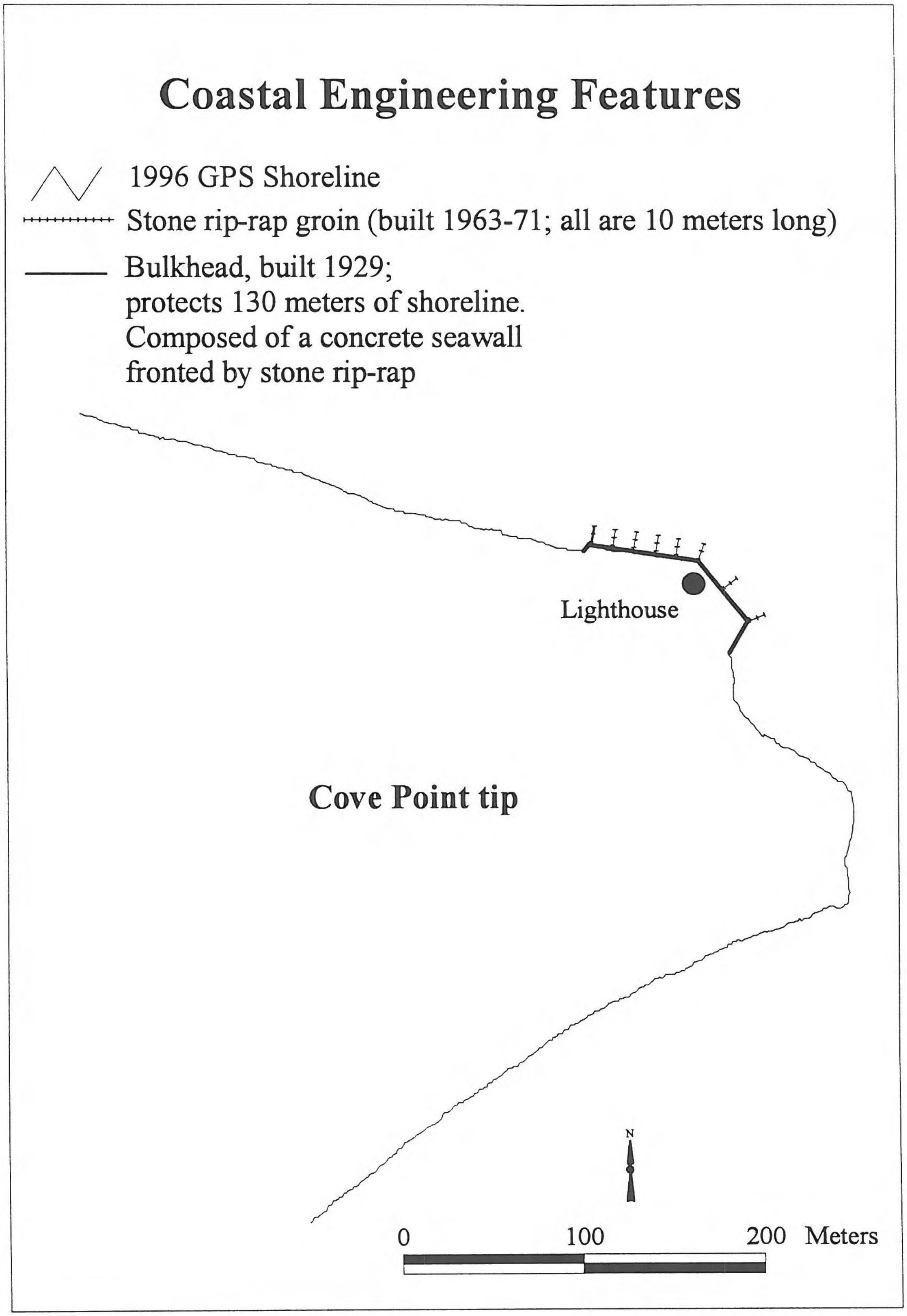


Figure 6. Shore protection structures of Cove Point.

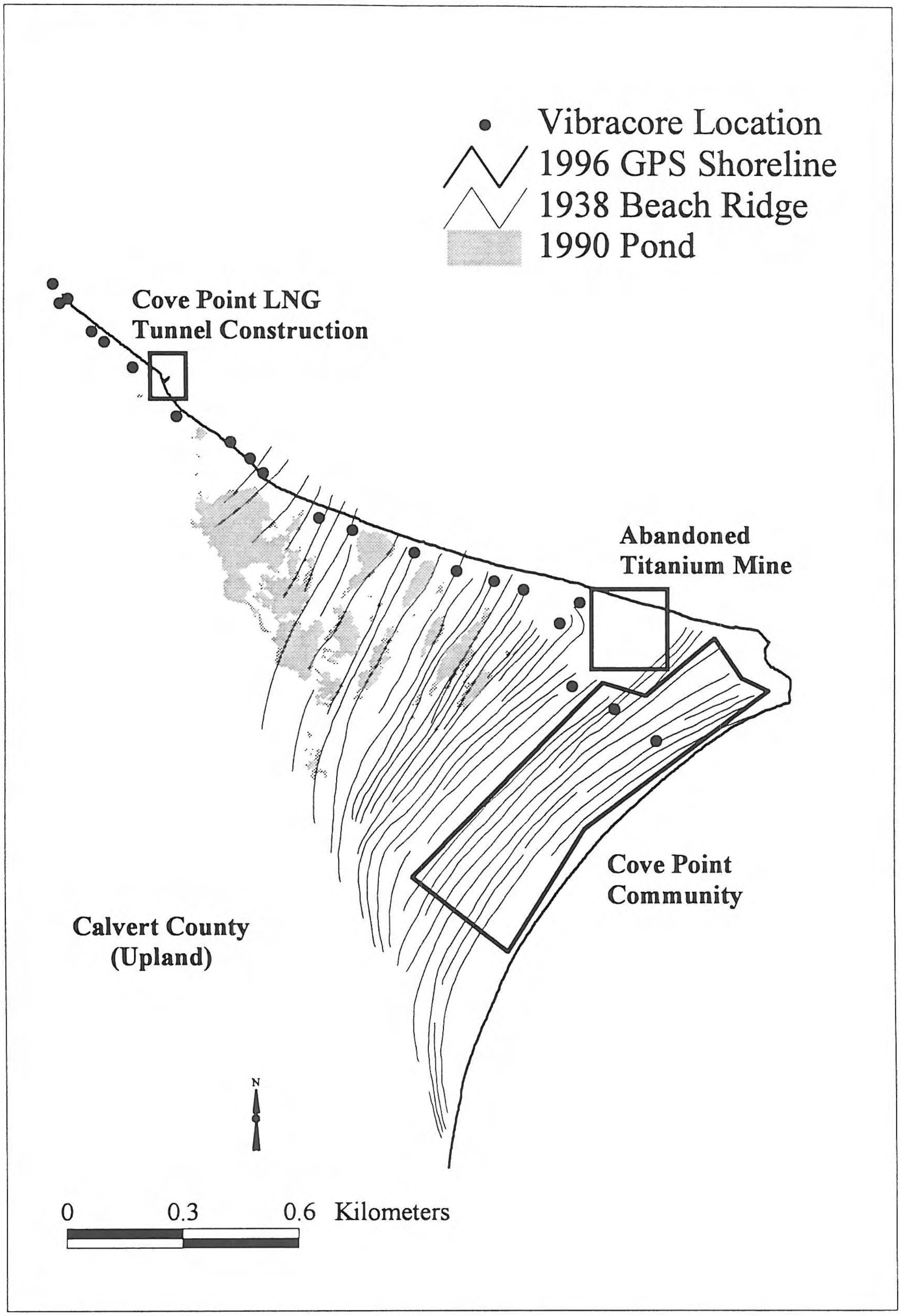


Figure 7. Cove Point disturbed areas.

Chapter 2

Review of Related Literature

Introduction

The variety and scale of cuspate forelands requires an understanding of the geomorphic principles which govern their development. Factors such as sediment supply, tidal range, sea level change, wave climate, antecedent geology, anthropogenic activity, and storms all have an impact on the morphology of these landforms, and can produce features which are similar in appearance but have very different constructional mechanisms (Davies, 1977). The spatial and temporal scale at which the formation is examined is also critical when determining evolution.

To assess the geomorphology of a particular cuspate foreland it is necessary to examine all of these factors within the context of the coastal environment which produces the landform. It is also important to differentiate cuspate forelands from other types of crescentic coastal landforms such as beach cusps and sand waves.

Crescentic landforms

There are several types of crescentic coastal landforms, each of which is formed by a particular set of physical processes. These features can be divided into three classes, ranging in geographic size from smallest to largest: (1) cusplets and cusps; (2) sand waves; and (3) cuspate forelands, including capes and secondary capes. Although this classification is not based on the morphogenesis of these features, it does provide a broad overview. Komar (1976) adopted a genetic classification, separating rhythmic topography (sand waves, giant cusps) from beach cusps. Both of these are distinct from cuspate forelands, the former existing on shorter temporal and spatial scales.

The smallest of these, cusplets and beach cusps, are typically on the order of 1 to 30 meters in spacing, and form within the swash zone of the beach. They are characterized by a series of topographical low, concave-seaward bays separated at equal intervals by more steeply sloped horns which project normal to the shoreline. The destruction and subsequent reformation and migration of beach cusps has been observed to occur within a matter of hours at Duck, North Carolina (Miller, et al., 1989). It has been speculated that these cuspate features are formed by edge waves (Guza and Inman, 1975), or by incident waves from two different directions (Branner, 1900). Although the genesis of beach cusps has not been fully determined, it is understood that they are ephemeral features, limited in spatial and temporal scale to the present-day morphology of the active beach.

Sand waves are larger features, ranging in size from 100 to 3000 meters (Dolan, 1974). Komar (1976) recognizes that sand waves and giant cusps are typically controlled by the positioning of offshore bars which may be either crescentic, oriented parallel to the shoreline, or a combination of both. Such formations along the barrier coast near Cape Hatteras, North Carolina have been shown to migrate at rates of up to 180 meters per month (Dolan, 1970). These sand waves in North Carolina average about 23 meters in amplitude with a maximum observed amplitude of 38 meters (distance between innermost part of the embayment and the maximum extent of the horn or projection). Because these features are often a reflection of local bathymetric conditions, which are subject to alteration on a seasonal basis (primarily due to storms and summer/winter profile fluctuations), they are relatively short-lived and limited in spatial development.

Cuspate Forelands

Cuspate forelands are the largest type of crescentic coastal formations. They can vary widely in geographic extent, ranging from only a few hectares to many square kilometers. Some examples include: Cape Hatteras and Cape Lookout of the Outer Banks of North Carolina, Cape Canaveral in Florida, and Cape Henlopen, Delaware. The term cuspate foreland was first used by Gulliver (1896) in describing the Dungeness Foreland in the UK. Johnson (1919, p. 319) defined the foreland as a feature for which "the shoreline is systematically prograded by wave and current action, and an appreciable area of more or less continuous dry land added to that previously existing." Forelands are typically triangular in shape, with the apex projecting seaward. Forelands have also been called beach ridge plains (Johnson, 1919) and wave-built terraces (Gilbert, 1890), the latter a term which is more properly applied to relict, uplifted shorelines. Johnson (1919, pp. 324-326) classifies forelands into 3 types: (1). Simple Cuspate Foreland—characterized by equal beach ridge progradation on both sides of the foreland; (2). Truncated Cuspate Foreland—characterized by erosion removal of material from one side of the foreland, producing a shoreline which is oblique to the lines of beach ridge growth; (3). Complex Cuspate Foreland—identified by repeated variations in the orientation of the beach ridges as they are alternately truncated and prograded during different time periods (Figures 8 and 9). These alterations may be evidence of shifts in sediment supply and/or fluctuations of sea level (Stapor, 1975). Johnson (1919) also identified the cuspate bar as a possible precursor to a cuspate foreland, and found that there is no sharp division between compound cuspate bars (bars with several ridges) and cuspate forelands.

Escoffier (1954) focused on the truncated cuspate foreland or "traveling" cuspate foreland. He concluded that material is removed from one side of the foreland and deposited on the other side, producing a migration and enlargement of the cape feature. This process is driven by the direction of dominant wave action, frequent wave action, and occasional wave action (Figure 10). The direction of dominant wave action corresponds to the zone of erosion, while the side with frequent wave action is progradational. Occasional wave action impinges the cape directly offshore due to limited fetch or lack of prevailing winds.

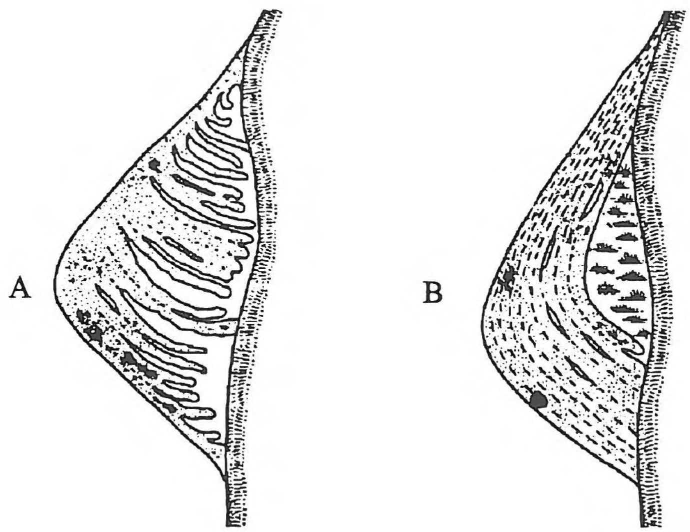


Figure 8. Two types of cuspate foreland (from Johnson, 1919).
A. Truncated cuspate foreland, B. Simple cuspate foreland.

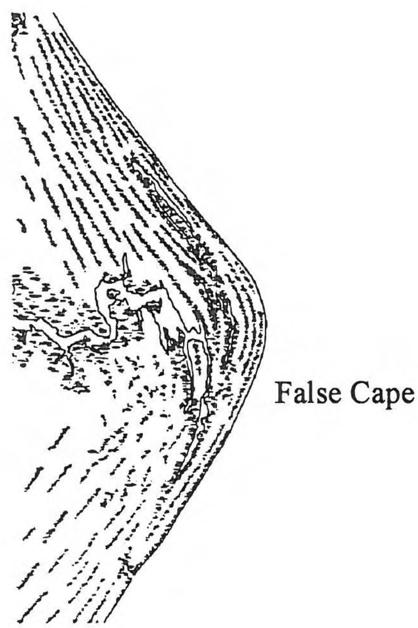
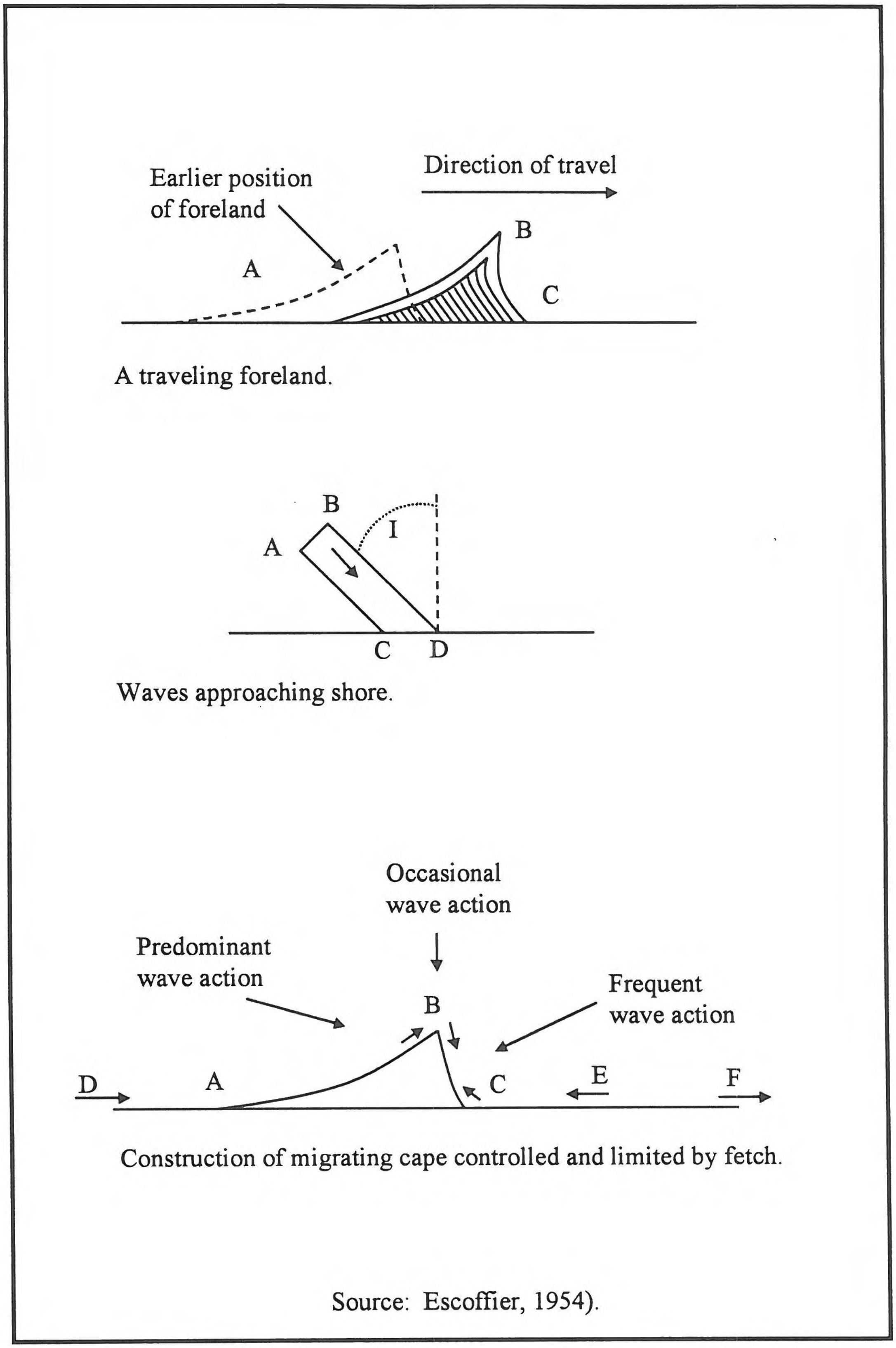


Figure 9. Cape Canaveral, a large simple cuspate foreland (from Johnson, 1919).

Figure 8-9. Types of cuspate forelands.



A traveling foreland.

Waves approaching shore.

Construction of migrating cape controlled and limited by fetch.

Source: Escoffier, 1954).

Figure 10. Construction of a migrating cape.

The construction of cuspate forelands may be controlled by a number of factors. Sanderson (1997) found that cuspate forelands of the south coast of western Australia are typically formed by wave refraction around headlands and islands. Other shoreline salients may also occur where longshore currents converge. By contrast, landforms similar in appearance along the central west and Ningaloo coasts of western Australia have formed leeward of offshore reefs. These reefs are restricting wave attack and hence controlling sediment movement. Sanderson (1997) described one such cuspate foreland (Turquoise Bay) as a traveling foreland similar to Cove Point. However, a reef is controlling the wave climate at Turquoise Bay and restricting further development of the foreland; there are no reefs in the Chesapeake Bay.

Other cuspate forelands differ in composition from the finer grained sediments found at Cove Point. The Dungeness foreland in the UK is composed of sets of beach ridges, but they are constructed from shingle deposits, and are representative of a different depositional environment. However, some work in this area suggests that the growth of the Dungeness foreland is at least partially controlled by limited fetch offshore of the point (Komar, 1976). Escoffier (1954) and Sanderson (1997) also implied that an offshore control of wave climate resulting in restricted angles of wave attack can play an important role in the development of cuspate forelands. This observation may be applied to Cove Point; fetch is limited to the east by the width of the Chesapeake Bay, while fetch lengths from northerly and southerly directions are much greater.

Beach ridges

Cuspate forelands are constructed by the successive progradation of beach ridges. Beach ridges are constructed by marine (wave) processes, and hence each ridge is a function of tidal range, wave energy, and the sea level conditions present during the construction period (Taylor and Stone, 1996). They are morphogenetically distinct from dune ridges, which are eolian in construction, and chenier ridges. Chenier ridges are storm deposits, usually composed of shells, which are separated by swales made up of muddy littoral units (Otvos and Price, 1979). A chenier ridge is built upon this platform of fine clays and silts, which are typically river delta sediments. The muddy unit progrades seawards during quiescent periods until a storm comes and rapidly winnows out the finer material, leaving an erosional shell lag. This erosional lag is deposited by the storm surge as a new ridge on top of earlier muddy units. Each ridge is thus perched on a basement of finer grained sediments. After the storm, the progradation of muddy littoral sequences is renewed (Komar, 1976). The finer deposits of the platform are the dominant feature of a chenier plain. By contrast, a beach ridge plain is composed of closely spaced ridges with less well-defined swales.

There are a number of theories which have been suggested for beach ridge construction (Figures 11 to 13). Davies (1957) proposed the cut and fill model. In this process, a berm is formed under normal swash conditions, and is capped by eolian activity. This capping places the first berm above the limit of swash; hence, a new berm begins to form in front of the first. It too is capped; in this

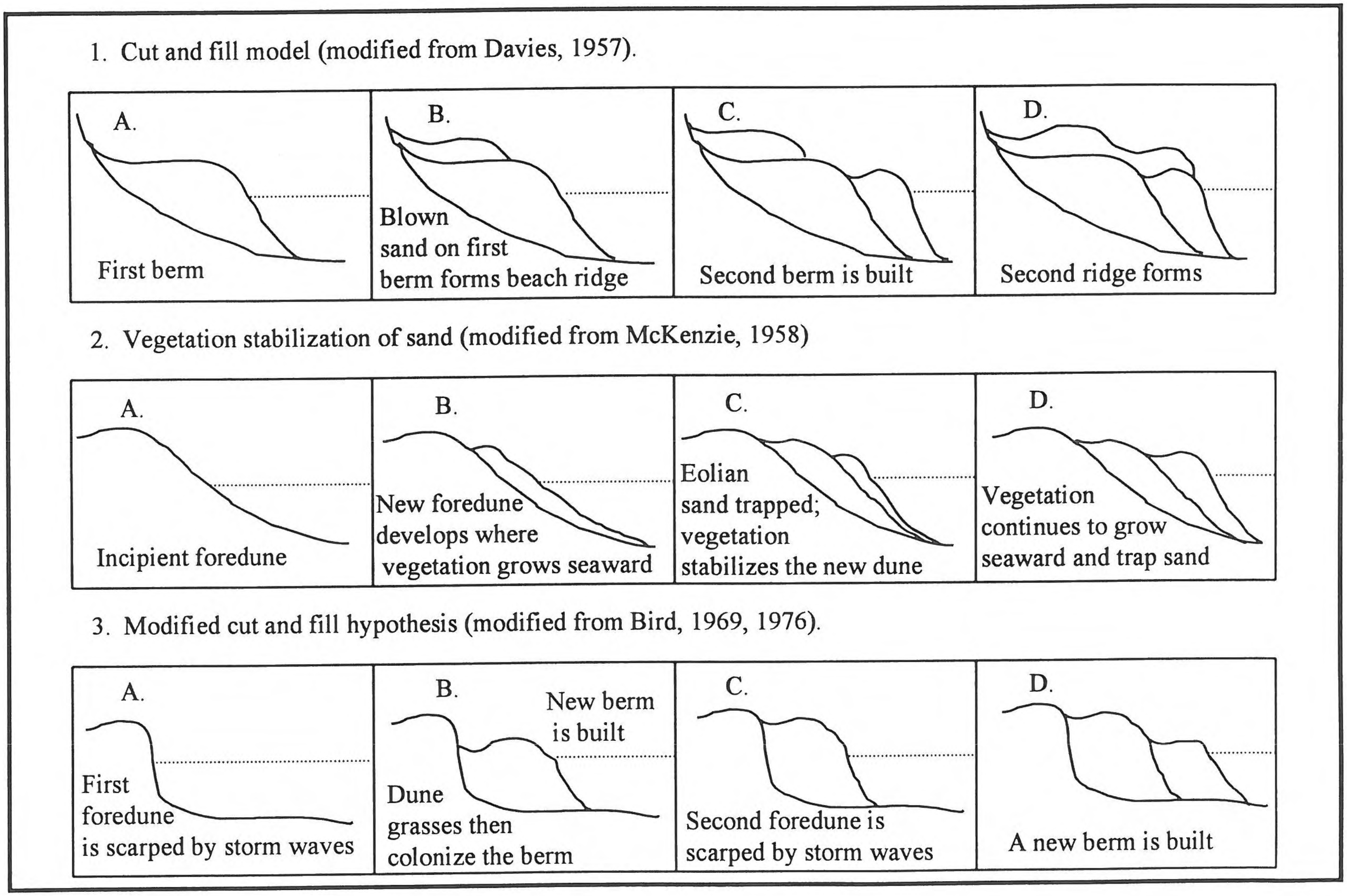


Figure 11. Theories of beach ridge formation (1).

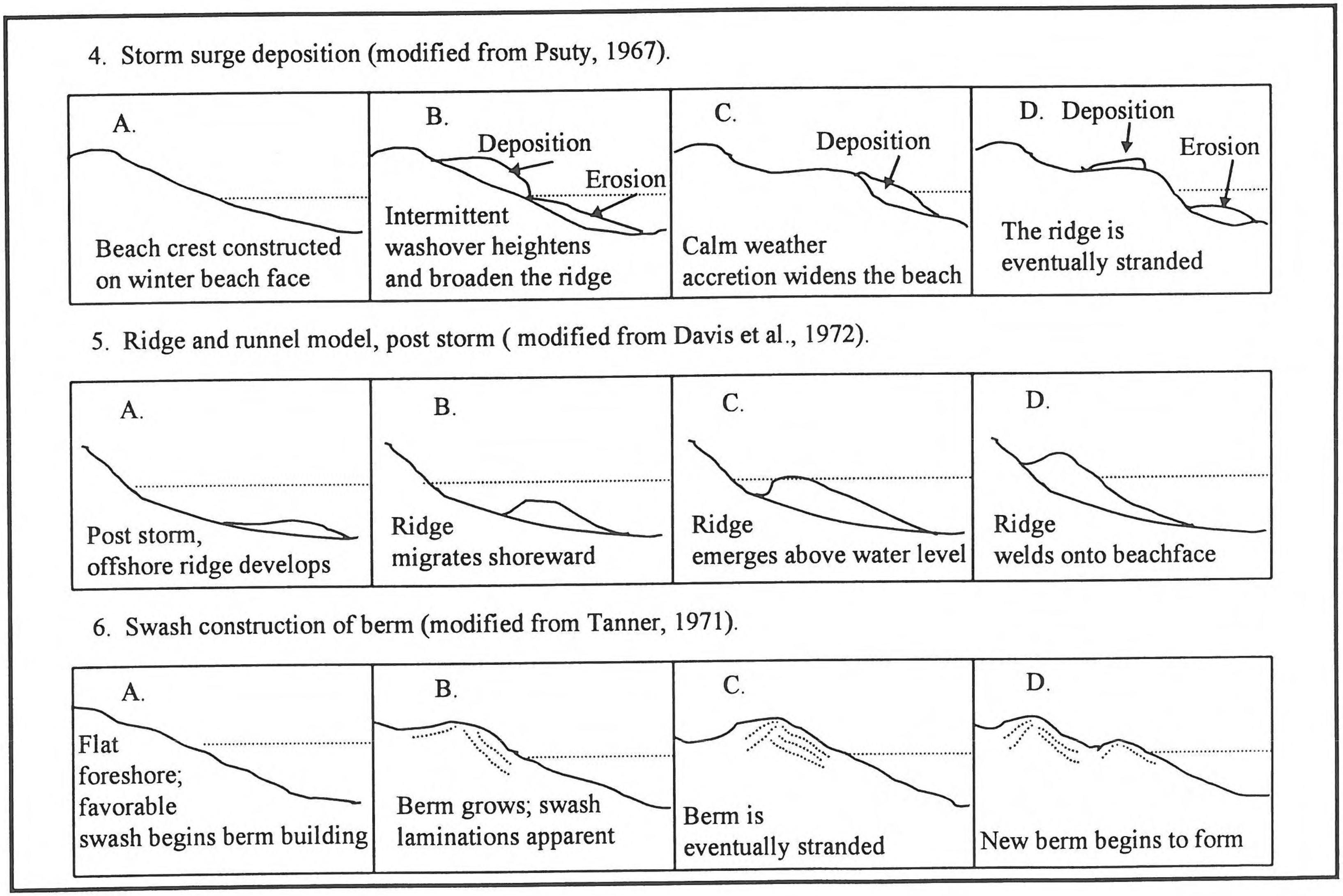


Figure 12. Theories of beach ridge formation (2).

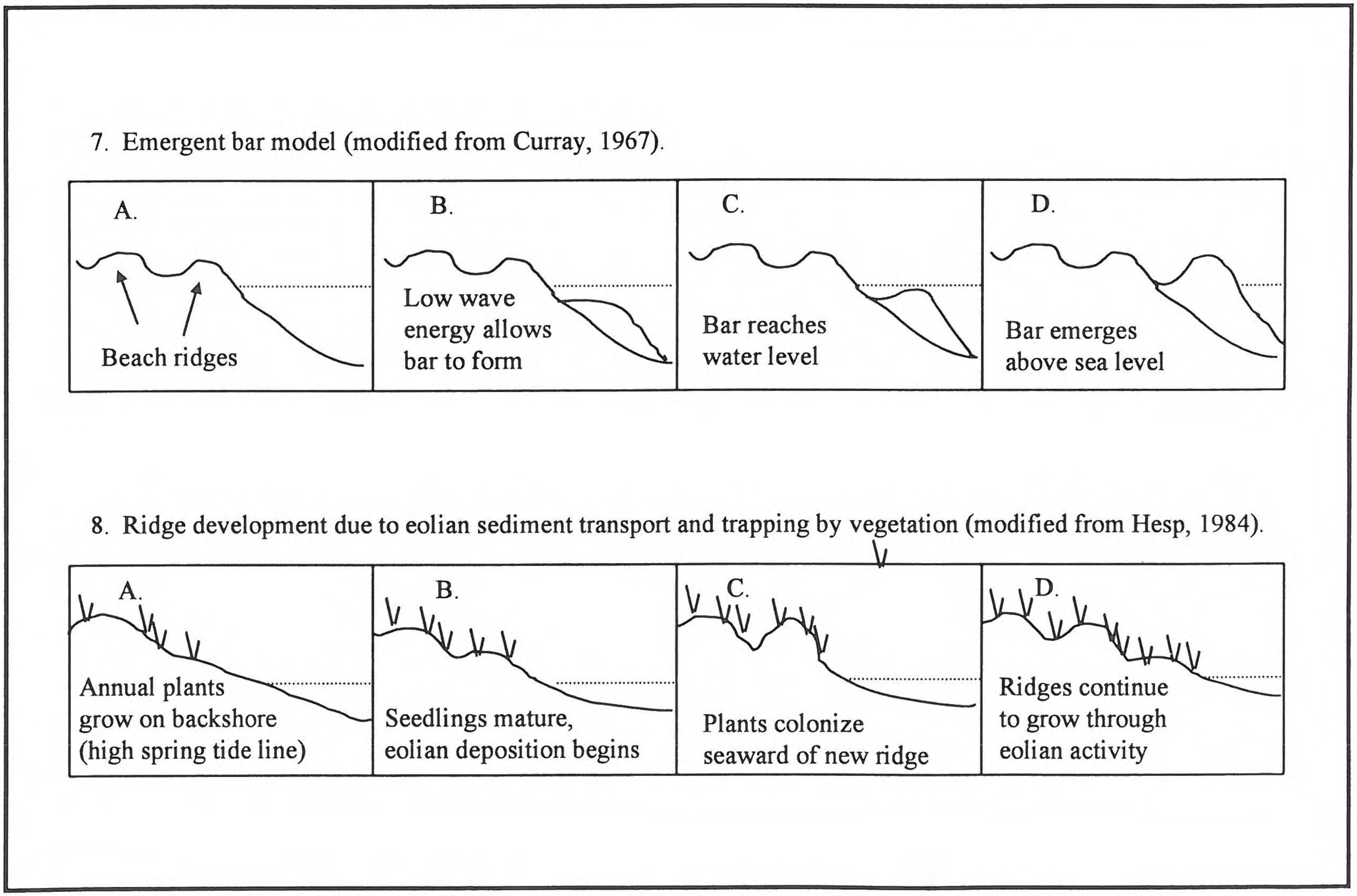


Figure 13. Theories of beach ridge formation (3).

fashion ridges are built seaward through a combination of swash and eolian processes. This requires a large enough subaerial beach for eolian transport and a continued sediment supply.

McKenzie (1958) proposed that ridges are build through stabilization by vegetation. This process again requires a sediment surfeit. More importantly, this process is closely associated with dune rather than beach ridge construction, which is primarily driven by marine processes.

Bird (1969 and 1976) proposed a modified cut and fill model. Here storms play a role by scarping the foredune, leaving a ridge or topographic high. A berm builds in front of this foredune and is eventually stabilized by beach grasses and vegetation. Storms then scarp this newly constructed dune, and a new berm begins to form once again. This again is similar to dune construction rather than true marine ridge construction. However, it may be possible to apply this model to a well developed berm rather than a foredune which has been stabilized by deposition and capped by eolian deposition. It is important to note that this model is event driven; other models typically require fair weather conditions or at least do not rely on high-energy events.

Psuty (1967) proposed beach plain construction through storm surge deposition. In this model, a crest is constructed on the winter beach. Washover causes the ridge to widen while erosion takes place in front of the ridge. Fair weather accretion widens the beach, eventually stranding the ridge. This model is more applicable to those areas which experience true summer/winter beach profile changes and ample sand supply, such as at a river delta. This is not really the case at Cove Point, Maryland. In addition, Psuty confuses swash deposition with washover events. Swash processes operate in the foreshore and are capable of building a berm; washover events are typically caused by storms and tend to flatten the beach profile. In addition, washover occurs on a larger scale, and breaches the dune.

Davis (1972) proposed a model of ridge construction through ridge and runnel topography. Davis observed that offshore ridges develop in mesotidal and small microtidal conditions after storm events (northern Massachusetts and Lake Michigan, respectively). These bars would assume a definite ridge profile and march into the nearshore over a period of several days. Usually ridge and runnel topography is considered to be intertidal; however, these ridges would eventually weld to the beachface to produce ridges. This process may be applicable to Cove Point, provided that several such ridge and runnel, storm-driven events act to eventually construct one ridge.

Tanner and Stapor (1971) found that ridges are complex features and are constructed by swash, not governed by storm events. Each ridge begins by run-up deposition which acts to form a berm. This berm grows upward and seaward with adequate sediment supply with almost all the internal bedding dipping in a seaward direction. More energetic waves are required to build the berm higher, and eventually it is stranded and a new berm builds in front of the first berm. Although this work was done on the northwest coast of Mexico and hence has a different sediment source and wave climate, Tanner's model of swash construction seems the most appropriate towards explaining the genesis of Cove Point's most recent beach ridges; Curray's model and the process of distal spit extension may account for the older ridges.

Curray (1967) proposed the emergent bar model. This implies a sediment surplus and favorable wave conditions for bar construction. This bar elevates above water level under these conditions, and may or may not weld directly onto the beachface. This model is appropriate to some of the ridges constructed at Cove Point (those ridges which emerged in deeper water without welding onto the beachface).

Chapter 3

Methodology

Introduction

Several methods and data sources were used to examine the geomorphic evolution of Cove Point. The data may be divided into two primary classes of historic and prehistoric. The historic evidence is comprised primarily of a database of historic shoreline positions for both Cove Point and Flag Ponds. Bathymetry and wind data are used to supplement these records and provide geomorphic evidence of local conditions. In addition, the interior ponds of Cove Point were mapped from aerial photographs for two different years. Sediment samples were also taken from the active beach on the prograding flank of the foreland to compare with paleodepositional environments as interpreted from the vibracore facies.

Prehistoric evidence was derived through the use of vibracores to examine stratigraphy and radiocarbon dating to determine a rate of evolution. Loss-on-ignition organic content testing was also performed on core sediments to aid in interpretation. Beach ridges which were apparent in aerial photographs were also mapped and incorporated into a GIS.

The stratigraphic evidence is used to develop a long term picture of the evolution of Cove Point. Vibracoring and radiocarbon dating are methods commonly used to examine the depositional histories of similar landforms. The historic evidence provides for a more temporally dense reconstruction of Cove Point's recent development. A comparative shoreline analysis of Flag Ponds is also discussed. Flag Ponds is an incipient cuspate foreland found on the coast of the Chesapeake Bay, just north of Cove Point in Calvert County. The present day morphology of Flag Ponds is believed to be analogous to the early geomorphic development of Cove Point.

Historical Shoreline Analysis

The geomorphic analysis of a coastal region through the use of historical shoreline change requires a length of record spanning many decades. Such a database was compiled by Downs (1993) and incorporated into a computer mapping program called Metric Mapping (Leatherman and Clow, 1983). Shorelines were analyzed for both Cove Point and Flag Ponds (Tables 1 and 2).

Cove Point shoreline data

Year	Source (datum is High Water Line)
1847	NOS T-sheet
1908	NOS-T sheet
1944	Aerial photograph
1952	Aerial photograph
1971	Aerial photograph
1996	GPS survey (this study)
1997	GPS survey (this study)

Table 1. Year and source for each shoreline recorded for Cove Point.

Flag Ponds shoreline data

Year	Source (datum is High Water Line)
1847	NOS T-sheet
1908	NOS T-sheet
1944	Aerial photograph
1952	Aerial photograph
1971	Aerial photograph

Table 2. Year and source for each shoreline recorded for Flag Ponds.

Several of the shorelines for the Calvert County coastline were taken from National Ocean Service topographic sheets (NOS T-sheets). These are accurate maps of the coast dating as far back as the 1840's. The datum used to represent the shoreline is the high water line (HWL). These maps were examined for media distortion by Downs (1993); those T-sheets which were in good condition were digitized and translated to North American Datum of 1927.

Many of the shorelines used by Downs (1993) were derived from vertical aerial photographs of the Calvert County coastline. The position of the HWL was interpreted from these photographs and digitized. Aerial photographs have a number of inherent errors associated with camera distortion, orientation of the aircraft from which the photograph is taken, and relief or topography of the land surface. All of these errors must be corrected prior to overlay and mapping of the individual shorelines. Metric Mapping is a program designed to emulate standard photogrammetric techniques, and it removes the effects of aircraft tilt, yaw, and relief distortion by using the Space Resection module and ground control points (locations on the aerial photograph which can accurately be spatially referenced). The use of these spatially referenced points allows real world coordinates to be assigned to the digitized shoreline data. Details on the Metric Mapping procedure can be found in Leatherman and Clow (1983); details on the construction of the Calvert County data set can be found in Downs (1993).

The final shoreline incorporated in the Metric Mapping data set (June 1996) is based on the global positioning system (GPS). This method is more accurate than digitizing and correcting NOS T-sheets and aerial photographs. In addition, interpretation of the high water line is performed in the field, further reducing error. This GPS shoreline was taken using pseudo-range measurements on a 6 channel Trimble GPS receiver. It was differentially corrected using data taken from the Gaithersburg Continuously Operating Reference Station (CORS).

The 1997 shoreline was not utilized because the April survey was strongly affected by the erosion caused by Hurricane Fran in September of 1996. Cove Point may have experienced limited beach recovery, making this shoreline an outlier in the data set. However, an qualitative evaluation of the changes between 1996 and 1997 is given as part of the analysis.

Worst case error estimates for NOS-T sheets predating 1880 is 8.9 meters; those surveyed after 1880 have a worst case error of 8.4 meters (Crowell, et al., 1991). Estimates for aerial photographs are 7.7 meters. To minimize the effects of this error, the longest time intervals possible are used to quantify shoreline change. In this way, the actual shift in shoreline position is much larger than the error range so that a true signal is measured rather than errors in plotted shoreline positions. Using longer-term records also reduces the chances that short-term variability will be measured. For example, a section of coastline may undergo alternating periods of accretion and erosion, but the overall trend may be erosional.

Quantitative analysis of shoreline change was undertaken using Arcview 3.0. This required exporting the Calvert County data set to Arc/Info 7.0.4 and importing it to Arcview 3.0 for Windows NT. An Avenue script for Arcview written by Keqi Zhang allows for the construction of transects at regularly spaced intervals perpendicular to the shoreline. These transects are used to measure distances between shorelines of different years, allowing rates of change to be generated. All rates of change indicated in this study are derived through linear regression. This method uses all of the shoreline positions for each transect to derive a single number which is indicative of the long-term shoreline movement. Transects generated for Cove Point and Flag Ponds are spaced at 20 meter intervals.

There are several distinct morphological units which comprise Cove Point. Rates of shoreline erosion or accretion are calculated for each distinct unit to allow for a statistical comparison of the different geomorphological behaviors. There are four basic zones or units which are shown in Figure 14; their extent and

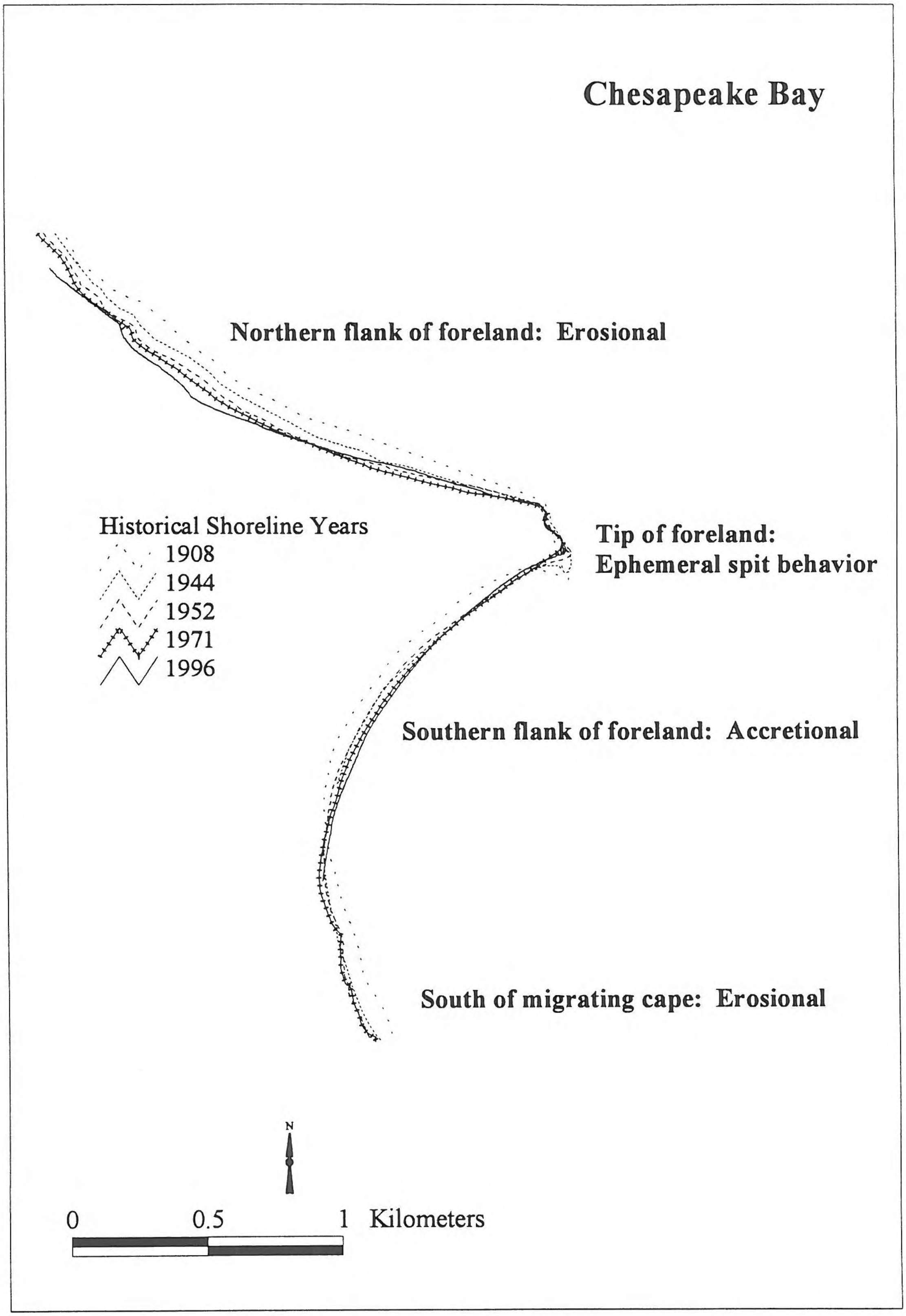


Figure 14. Geomorphic boundaries of shoreline behavior.

the reason for the delineation are shown in Table 3. Flag Ponds is similarly divided into morphological compartments (Table 4).

Cove Point compartments

Zone #	Length	Location	Reason for Delineation
1	2.32 km	Northern flank	Continuous record of erosion.
2	0.38 km	Spit tip	Bulkhead and groins affect historical shoreline trend.
3	1.24 km	Southern flank	Continuous record of accretion.
4	0.90 km	South of foreland	Reversal from accretional trend to erosional trend.

Table 3. Geomorphic delineations for Cove Point.

Flag Ponds compartments

Zone #	Length	Location	Reason for Delineation
1	1.06 km	Northern flank	Continuous record of erosion.
2	0.90 km	Southern flank	Continuous record of accretion.
3	0.18 km	South of foreland	Reversal from accretional trend to erosional trend.

Table 4. Geomorphic delineations for Flag Ponds.

Bathymetry

Bathymetry data was used to obtain a general overview of the offshore conditions at Cove Point. The Chesapeake Bay navigational chart, published by ADC in 1996, has a resolution that does not allow for interpretation of nearshore bars. It provides only a generalized overview of the nearshore slope conditions of Cove Point.

Pond Mapping

The interior marsh of Cove Point is characterized by a number of ponds. Many of these ponds are linear in shape, an orientation which suggests their formation is geomorphically controlled by the placement of the underlying beach ridges. These ponds appear to have been expanding over the last 52 years according to aerial photography, probably as a result of sea level rise. Although this marsh is not tidal, over the long term its water table is controlled by the sea level of the adjacent Chesapeake Bay. These ponds were mapped from vertical aerial photographs for 1938 and 1990 using Arc/Info 7.0.4 and PhotoGIS (Salamanaca Software). The ridges were digitized and orthorectification was performed by the PhotoGIS software. This program is similar to Metric Mapping except that it employs a digital elevation model (DEM) to correct for relief displacement (although there is essentially no local relief). Once mapped, the number of interior ponds and the total area of the ponds were tabulated. This mapping provides for an analysis of pond expansion as a result of sea level rise.

Wind data

Wind climate data are derived from a summary of recorded wind and wave conditions at Patuxent Naval Air Station from 1945 to 1980 (USACE, 1985).

This site is located a few kilometers south of Cove Point. These data were not used to hindcast wave climate; instead they provide only a generalized overview of the prevailing wind climate which is associated with the Cove Point region. These data were used to create the wind rose displayed in the Results chapter.

Stratigraphic analysis

The sedimentology of Cove Point was examined by obtaining 21 vibracores along the shoreline, oriented perpendicular to the beach ridge plain. This sampling design was chosen so that the entire history of Cove Point would be sampled from oldest (in the northwest) to youngest (in the southeast). Where possible, these cores were taken in the swales between the beach ridges. In some cases, these swales could be seen on the ground. In other cases, the location of the swales was inferred by probing the peat layer. This was not always successful; some of the vibracores taken this way provided samples of beach ridges rather than swales. In addition, one core (#20) was discarded due to poor sediment recovery.

Analysis of vibracores is one of the primary ways by which sedimentary histories (stratigraphy) are developed. Cores can allow a direct, detailed examination of the layering and sequences of the subsurface sediments, and thus are valuable for determining the depositional history of coastal landforms. Vibracores are relatively cheap, easy to extract and have the advantage of providing a relatively undisturbed sample when compared with other methods such as rotary drilling (USACOE, 1994). Recovery of stratigraphic samples has been shown to be between 80% to 100% complete in homogenous sand and sandy muds (Lanesky et al., 1979).

The vibracorer is a small-horsepower gasoline motor which drives a concrete vibrator head. This head is clamped to the vibracore tube (for Cove Point, a thin walled aluminum irrigation pipe with an internal diameter of 3 ½ inches (8.9 cm) was used). The tubing is then elevated so that it is perpendicular to the ground. The vibration of the head is translated to the tubing, creating a low-amplitude standing wave. This rapid vibration fluidizes the sediment in contact with the core barrel, allowing it to slip past the particles with little resistance. This results in minimal distortion of the sediment even along the core tube walls, and fine laminations within the stratigraphic column are preserved (Lanesky et al., 1979). Once the tube has been driven to the desired depth, usually until refusal, the top is plugged and the core is winched out using a tripod and come-alongs. The plug at the top of the core creates a vacuum, preventing sediments from slipping out from the bottom of the core. One of the primary problems with vibracoring is compaction during the sampling process. To account for this, the depth to the sediment is measured inside the tube and outside the tube prior to extraction. The difference between these two measurements represents the amount of compaction which has occurred during vibracoring.

Not all sediments compact at the same rate. Sands tend to compact very little, and the silty clays encountered at Cove Point were usually fairly dense and dewatered. Hence, most of the compaction observed in the vibracoring process tended to occur in the upper meter or so of sediment; typically the marsh peat. This was verified by probing the vibracoring sites with a thin metal rod and recording the depth at which the first sand contact was reached. This depth was compared with the depth of sand observed in the compacted vibracore taken at that site. The difference between these two measurements represents the amount of compaction which occurred within this upper layer of peat. In every instance sampled, the compaction of the peat layer represented approximately 90% of the overall compaction observed for the vibracore. This was applied to the core logs which are displayed in Appendix A, and all depths cited in this research reflect this correction for compaction.

Once removed the sample tube is cut into meter sections and labeled. Each core was numbered according to the order in which it was taken (1 through 21), and individual sections of the core were labeled starting with number 1 as the uppermost meter of the sample. These meter sections are then sliced longitudinally to reveal the stratigraphic sequence of the core. Each of the sections were carefully examined and logged according to sediment composition, grain size, color, and organic content. Sediment size was estimated using a comparison card which had representative grain sizes incremented in 0.5 phi (∅). Sizes ranged from 2.0 ∅ (0.25 mm) to -1.0 ∅ (2.00 mm). A qualitative estimate of color is given (e.g., a Munson color chart was not used). Particular attention was paid to changes in the littoral deposits from gray to orangish or reddish tint as this color change is likely representative of the boundary between subaerial and subaqueous deposition. Sediment composition (e.g. quartz, feldspar, peat, clay) was derived through a visual inspection of the facies, aided by the use of a hand lens when necessary.

These core logs were then used to interpret the depositional history of the cuspate foreland. This history is examined on two scales. First the overall development of the foreland is examined, with particular attention toward defining the underlying basement or platform upon which Cove Point rests. An examination of the typical characteristics of beach ridge and marsh deposition is given. The individual depositional history of each core location is also explored. It was not possible to construct a detailed diagram of Cove Point's entire stratigraphy because of the extreme variability between individual cores. This is due to the construction process of the beach ridges which compose the foreland; each core location is sampling a unique facies pattern so that often generalization to a larger model was not possible. Mr. Randy Kerhin, an expert on Chesapeake Bay geology and coastal depositional processes, aided in the interpretation and analysis of the sedimentary sequences.

Precise location of the vibracore sample is critical to an accurate interpretation of the geomorphology. Several vibracore positions were fixed using standard surveying techniques (a theodolite and an rod). These surveys were tied to benchmarks located along the shore of Cove Point. Horizontal positions of these cores is on the order of about a meter. Vertical positions of the conventionally surveyed cores were fixed using an autolevel and a rod. These elevations are accurate to within 3.0 cm. Most of the cores were surveyed using differential GPS. Ashtech 12-channel geodetic receivers were employed to geoposition the vibracores using long occupation times and short baselines. This yielded accuracies on the order of 2 cm horizontally and vertically.

These two methods derived ellipsoidal elevations. To correct to mean sea level, it was necessary to use a geoidal model of the earth's surface. Geoid93 was employed in the translation of the ellipsoidal elevations to orthometric heights (height above mean sea level). Once the height of the geoid for each vibracore was known, orthometric height was calculated based on the equation: $H = h - N$, where H = orthometric height, h = ellipsoidal height as observed by GPS, and N = the geoidal height.

Sediment samples from the accretionary beach

In order to aid in the interpretation of the vibracores, a number of samples were taken along a transect of the beach profile. The crest of the dune was sampled, as were the berm crest, parts of the foreshore, and the step environment. These samples are from the prograding section of the Cove Point shoreline, and are thus representative of the depositional environments which might be associated with a developing ridge. These present day samples thus provide a key to interpreting the paleodepositional environment as observed in the vibracore stratigraphy. Each sample was classified according to sediment grain size, composition, and color for this comparison.

Radiocarbon dating

Tracing the evolution of Cove Point requires the dating of carbon-based material, which is associated with the depositional development of the coastal landform. As the foreland grew, organic material was deposited within the beach ridges and in the swales of the beach ridge plain. This peat material has accreted vertically to keep pace with sea level rise. The bottom of this peat sequence represents the earliest development of vegetation for that part of the foreland, and hence is a good indicator of the age at which that beach ridge or swale was constructed.

Radiocarbon dating is a widely used method for deriving the age of Holocene and late Pleistocene organic materials (USACOE, 1994). This dating method measures the ratio of Carbon-14 (^{14}C) to Carbon-12 (^{12}C) and Carbon-13 (^{13}C) present in the organic matter. All plant and animal organisms continually take in the unstable ^{14}C isotope during their lifespan. Upon death, this uptake ceases, and the ^{14}C isotopes begin to decay to more stable forms of carbon (^{12}C and ^{13}C). The half-life presently used is 5560 years. Typically organic substances must be between 30,000 years and 300 years old to be accurately dated. More recent dates are reported as modern, while older dates are unreliable because they are not as easily calibrated to calendar years, and after several half-lives the ratio of isotopes is difficult to measure. Other dating methods were not appropriate for this study. Lead-210 (^{210}Pb) has a half-life of about 22 years, making it unsuitable for prehistoric materials. Other dating methods such as Potassium-Argon-40 dating and Thorium230/Uranium-234 have half-lives of millions of years, making them imprecise and of limited use for more recent materials.

Two basic methods exist by which organic materials can be radiocarbon dated. The first, radiometric dating, requires a minimum sample size of 7.0 grams for most materials. The second technique is Accelerator Mass Spectrometry (AMS), a method which can accurately date a few milligrams of organic material. A total of seven organic samples were sent to Beta Analytic Inc., a company located in Miami, Florida which provides radiocarbon dating services. The type of sample sent, the second sigma error, the age Before Present (1950), and the dating method used are shown.

Radiocarbon dates

Sample #	Material	Age B. P.	2nd Sigma	Method
1	Charcoal	1710	168	Radiometric
2	Wood	1270	50	AMS
3	Wood	1175	83	Radiometric
4	Phragmites stalk	modern		AMS
5	Wood	700	38	Radiometric
6	Organic sediment	500	25	AMS
7	Phragmites rhizomes	modern		Radiometric

Table 5. Results of radiocarbon sampling.

The original study design was to use only basal peat for radiocarbon dating. However, datable peat samples were not found in sufficient amounts to make this possible. The use of basal peat allows for a close correlation with the construction of the beach ridges, as this peat would likely form shortly after the construction of the ridge and swale topography. Basal peat is also not subject to autocompaction because it rests on sands and dewatered silty clays which are essentially noncompressible. The use of wood and Phragmites introduces potential errors. These materials can float in during a high wave energy event which is subsequent to ridge construction. This means they are not always directly correlated with the foreland's evolution, and the organic material dated may have died some time before deposition. These organic materials are also more subject to contamination from the surrounding environment. However, confidence can be placed in the individual dates in light of the results.

It is customary to use radiocarbon dates such as these to generate local sea level rise curves. However, most of the dates are derived from material which may not have been deposited at sea level. In addition, the Cove Point marsh is freshwater, not a Spartina patens saltmarsh. Over the long-term, the water level is controlled by sea level, but the marsh is elevated above sea level, making organic materials from the marsh poorly suited to tracking sea level rise.

Beach ridge mapping

Cove Point is constructed of beach ridges which are apparent from vertical aerial photography. An attempt was made to survey a transect across these ridges to define ridge spacing and height, but heavy vegetation made this impossible. Instead, vertical aerial photographs were used to map the positions of all the visible beach ridges.

Ridges were mapped from a 1938 vertical aerial photograph using Arc/Info 7.0.4 and PhotoGIS (Salamanaca Software). The ridges were digitized, and orthorectification was performed by the PhotoGIS software. This program is similar to Metric Mapping except that it employs a digital elevation model (DEM) to correct for relief displacement. Once mapped, the number of ridges and spacing between ridges was tabulated. When added to the radiocarbon dating data, the ridge mapping provides for an analysis of beach ridge construction periods.

Organic testing

The vibracores extracted at Cove Point contained a variety of sediment types. To aid in the categorization of these sediments, tests were performed which measured the amount of organic material present in the sample by weight. Only samples which obviously contained organics were tested. In addition, sampling was only performed where there appeared to be an obvious change in the composition of the sediment within the stratigraphic column. This gives the appearance of the irregular sampling design as shown in the core logs.

Organic content studies employed loss-on-ignition tests. Each sediment sample was dried in a convection oven at 100 Celsius for 4 hours, weighed, and placed in a induction-type furnace for 4 hours at 550 Celsius. After this ignition phase, the sample was weighed again. The difference between these two measurements represented the loss in organic material which was burned off. The crucibles used during these tests were weighed before and after each trial to eliminate the small effects of crucible vaporization. All samples were weighed on an analytic balance accurate to 0.10 of a milligram.