A GPR and Mapping Study of the Evolution of an Active Parabolic Dune System, Napeague New York
B.S. Honors Thesis, James D. Girardi
Dept. of Geosciences, Stony Brook University, 2005

ABSTRACT

The growth histories of parabolic dunes in the Walking Dune Field, Napeague, NY, were studied in order to understand how these dunes have evolved in response to environmental and anthropogenic pressures. We are able to study the complex internal dune structure of these parabolic dunes using Ground Penetrating Radar (GPR), a non-invasive geophysical tool for imaging the shallow subsurface, which is ideal for studying this environmentally sensitive area. 2D GPR surveys were conducted using both 200 MHz and higher resolution 500 MHz antennas on the crest and windward slope of parabolic dunes in this dune field. These 2D surveys reveal characteristic parabolic internal dune structures such as high angle, downwind-dipping foreset beds. Unique to the Walking Dunes is a growth history, recorded in the internal dune structure, characterized by packages of changing orientations of reflectors corresponding to foreset bedding planes (former slipfaces). In order to better understand these changing reflector orientations and what they indicate about the nature of blowout deposition, a high resolution 500 MHz 3D GPR survey was conducted on the crest of an actively migrating dune. The extensive use of Geographic Information Systems (GIS) for georeferencing maps and aerial images has augmented our GPR studies. Maps which document the presence of stable dunes since 1848 and aerial images which document dune onset and development from 1930 - 2004 have aided in the study of the evolving morphology of the dunes, which is also documented in their GPR-imaged internal structure. From the maps and aerial images we can see decadal, and in some cases shorter time-scale, changes in the Walking Dunes that document the formation of blowouts and evolution of dunes.

From our GPR data and study of maps and aerial images, we have gained new insights to the history of the Walking Dunes, and how this dune field may have initiated. We have also gained important knowledge of how parabolic dunes grow and evolve in response to changing climate and anthropogenic pressures. From GPR data as well as aerial images it is clear that at least one of the Walking Dunes has had a growth history characterized by blowouts that have shifted through time with respect to the crest and dune axis. This is very different from the idealized model of parabolic dune growth in which there is a uniform deposition of sand over one slipface. We have documented in unprecedented detail how parabolic dunes can migrate as they grow incrementally by the migration of and formation of new blowouts on the dune crest, resulting in periods of deposition primarily on one side of the dune crest.
Ch. 1 An Introduction to Long Island Geology and Dune Studies

1.0 Introduction

The geologic features of Long Island are almost exclusively related to the most recent glaciation, which ended in this area approximately 20,000 years ago. The Long Island landscape (figure 1.0a) is dominated by two end moraines; the Harbor Hill Moraine which runs along the north shore, and the Ronkonkoma Moraine which is located further south. Many other glacial features, such as outwash plains, kettles, and tills are found across much of Long Island. A particularly interesting glacial feature of Long Island is a series of topographically prominent glaciotectonically folded hills preserved among the deposits of eastern Long Island at Hither Hills State Park on the south fork. The generation of such topography as a result of successive antiforms is unusual among the glacial features of northeastern North America. Although folded sediments are common throughout Long Island, rarely are they so well preserved as the main topographic feature - in this case a series of anticlinal folds. This series of parallel, regularly spaced hills at nearly the same height of about 10m is thought to reflect seasonal or possibly decadal scale climate changes resulting in the advance or retreat of glacial ice early in a period of overall retreat (Goetz, 2005). The study of these features has implications for our understanding of Long Island’s paleoclimate during the Pleistocene as well as the mechanics of pro-glacial deformation in semi-frozen stratified sediments.

However, there are other prominent geologic features - not glacial in origin - on Long Island which record both past and present climate conditions, and thus also have significance in the

![Figure 1.0a](image_url) Digital Elevation Model (DEM) of Long Island. Indicated by the dashed red boxes are the locations of Long Island's two parabolic dune fields.
understanding of Long Island’s climate history. These include Long Island’s two impressive parabolic dune fields (figure 1.0a), each of which is approximately 2 km$^2$ in area: the Grandifolia Dunes located on the north shore, and the Walking Dunes located on the south fork of eastern Long Island. The Grandifolia Dunes (figure 1.0b), located in Wading River, are completely stabilized and heavily vegetated by the rare *fagus grandifolia*, a dwarf beech tree; they are interpreted to be late Pleistocene in age (Englebright et. al., 2000). The Walking Dunes of Hither Hills State Park (figure 1.0c), located on the south fork of eastern Long Island are modern analogs to the Grandifolia Dunes and are composed of both stable and actively migrating dunes (Black, 1993,1996). It is known that actively migrating dunes reflect current climate conditions such as temperature, precipitation, wind strength and direction.

*Figure 1.0b*) Enlarged portion of DEM in Figure 1 showing the Grandifolia Dunes.

*Figure 1.0c*) Enlarged portion of the DEM in figure 1 showing the Walking Dune Field and adjacent dune fields across Napeague Bay.
and vegetation, all of which have an effect on the availability of sediment and its ability to be transported by eolian processes (Lancaster, 1994). Thus, a great deal can be learned about past climate conditions by studying the ancient Grandifolia Dunes. From the modern Walking Dune Field, we can study how climate changes have affected the growth histories of the dunes, as well as how these dunes respond to the well-documented climatic changes and anthropogenic pressures of the past century. Such a study is possible because the growth history of dunes is recorded in each dune advance by a deposition of sand over the dune crest. Successive depositions of sand over the dune crest results in stratified layers which record the growth of the dune as it migrates. The history of these climate changes and anthropogenic pressures is recorded in the buried stratigraphy or internal structure of the dunes, analogous to how tree rings record environmental conditions encountered by a tree.

In this study, both field observations of dune morphology and comparisons of aerial photographs were used to augment the findings of a geophysical study of internal dune structure. These diverse techniques were combined with the goal of understanding better the growth history and complex internal structure of the parabolic dunes in the Walking Dune Field, and gaining insights into processes likely to be found in other dune fields. The use of GIS (Geographic Information Systems) has allowed for the comparison of aerial photographs of the Walking Dune Field from 1930 to 2004 and maps dating to 1848, in order to see how these dunes have migrated and evolved over the past 150 years. The main focus of this study is the use of Ground Penetrating Radar (GPR), a non-invasive geophysical method to image the subsurface of these ecologically sensitive dunes. Both 2D and 3D GPR surveys were conducted in order to understand the growth history of these dunes, and to understand better the complex nature of blow-out deposition. In the following chapters, I discuss the dynamics of dune fields and parabolic dune forms. In addition, I address the use of GPR in studying internal dune structure, and the implications of this study for understanding the growth history of the Walking Dunes and their response to short and long term-climate variations. By studying Long Island’s two parabolic dune fields, much can be learned about this region’s climate history. The essential issue in this thesis is how internal dune structure reflects the growth history of the dunes.
1.1 Dune fields and related studies

A dune field is a very dynamic depositional environment where many factors affect the
development and migration of the dunes within it. Dunes, both modern and ancient, are interesting to
study because their development reflects a multitude of external forces. Studies classifying dune types,
their global distribution and mechanisms of formation have been carried out for decades (e.g., Bagnold,
1941; McKee, 1979) Areas of specific investigation have included the effects of dune morphology on
the near-surface air flow that in turn strongly influences dune evolution (e.g, Bagnold, 1941; Tsoar,
1985; Schenk, 1990; Hesp and Hyde, 1996), the role of climate in dune growth or stabilization (e.g,
Lancaster, 1994; Gaylord and Stetler, 1994; N. Catto et al., 2002; Hugenholtz, 2004), and the internal
structure of dunes, with cross-stratification indicating changes in wind patterns and dune growth (e.g.,
McKee, 1966,1979; Lancaster, 1995). The following discussion of the morphology and dynamics of
dunes is intended to distinguish parabolic dunes from other dune types and to discuss implications of the
dune types found in both the Grandifolia and Walking Dune Fields.

1.2 Dune Formation, Evolution and Classification

Dune formation and morphology are governed by the following conditions: sediment type and
availability, wind strength and direction(s), and moisture/vegetation (climate). There are certain
conditions under which dunes can form and migrate; if these conditions change the dunes could become
stabilized and preserved or they may become eroded away. It is important to consider these factors when
classifying dunes because their morphology is so representative of the environment in which they exist.
Although I will apply terminology applicable to, and reference previous work on dunes from many
different settings (from deserts to coastal environments), henceforth I will be referring to coastal dune
fields, the setting in which this study is focused. This demarcation is made because although the same
dune types may exist in different settings, the conditions of formation and growth may be completely
different. The very different examples of a coastal and desert dune field can be compared to illustrate
this point.
In the coastal setting, unlike in desert dune fields, dune growth is limited by sediment availability and controlled by a generally unimodal wind pattern, as opposed to variable patterns observed in deserts. Coastal dune fields typically have one main upwind sediment source, whereas in desert dune fields there is a sediment source available for any wind direction. Coastal dune fields are strongly influenced by vegetation and moisture, factors that are far less dominant in desert dune systems, where wind patterns (either unimodal, bimodal, or complex) are the primary factor controlling dune growth and morphology. In coastal dune systems moisture is important in controlling the growth of stabilizing vegetation. Moisture, from precipitation or water table, is also important in controlling the sand carrying capacity of winds by creating a cohesive force between grains which limits the ability of eolian processes to carry sediment (Chepil, 1956; Svendsen, 2003).

Dune morphologies reflect the conditions of the environment in which they form. For this reason we see certain dune types that are favored in and which are prevalent in specific environments. For example, the longitudinal, sief, and star dunes that often characterize desert dune fields would be unlikely or unable to form in other environments that have different climate, wind regime, and less sediment supply. The lack of barriers such as vegetation and moisture in the desert dune systems allow for the uninhibited transport of sand, which is reflected in these dune types. The role of vegetation and moisture as inhibiting or blocking sand transport has a great effect on the development and morphology of dunes. In settings where moisture and vegetation play a greater role in dune formation we see dune types, such as parabolic dunes, which reflect these conditions. Rarely observed in deserts is a dune morphology that is dependant on vegetation. One such desert dune is the nebkha dune which can be widely distributed in semi-arid areas and may also occur in hyper-arid areas, nebkhas develop where sand is trapped by vegetation clumps (Lancaster, 1995). Although some dunes may be characteristic of or more prevalent in a certain environment, there are dune types that are prevalent in several different environments, such as barchan dunes, dome dunes, and blow-outs. Just as we are able to characterize localities where we see dune fields based on climate, vegetation and sediment availability, there are characteristic features of dunes which we can use in the classification of different dune types found with in the dune field.
Dunes fall broadly into three types: basic (simple), compound and complex (McKee, 1979). A basic dune is one that is an isolated body not in contact with any other dunes. Compound dunes consist of two or more of the same dune type overlapping or being superimposed; complex dunes are composed of two different basic types that have coalesced or grown together (McKee, 1979). Basic dune types are most common in places with a single dominant wind direction; examples are parabolic, barchan, and transverse dunes. Examples of compound dunes include the coalescing of star dunes and the presence of small barchans superimposed on a large barchan (Figure 1.2a). The growth of blowouts on the crest of a transverse dune would be an example of a complex dune (Figure 1.2b).

Simple dunes are classified based on overall form as well as by the number of slipfaces (a slipface is the leeward slope over which sand is actively being deposited). The overall form (morphology) and number of slip faces reflect the depositional environment in which the dune formed, especially wind regime, sediment supply, climate (moisture and vegetation), as well as distance from source and the presence or absence of physical barriers such as vegetation and topography (McKee, 1979). From the number and orientation of slipfaces and limbs (also referred to as arms or horns),

Figure 1.2a) Compound dunes: Star (above) and Barchan (below), from McKee (1979).

Figure 1.2b) Example of a complex dune, from McKee (1979).
dune types can be uniquely identified. Although the classification of dunes may seem straightforward, it is important to realize that each dune’s morphology is representative of the specific conditions under which it formed. Since dune morphology within a dune field is very sensitive to changes in wind, vegetation, and sand supply, it is commonly observed that dune morphology changes or evolves throughout the dune field. These changes occur as the dunes migrate farther from sediment source and also by the alteration of wind patterns by other dunes in the dune field (McKee, 1966, 1979).

Dune fields are dynamic environments which often change rapidly through time. Eolian dune field systems are so sensitive that they evolve on their own as they migrate farther downwind, even when climate conditions remain the same. Changes in dune morphology are the result of how the dunes upwind affect wind flow and sediment availability for the dunes farther downwind, causing a well documented evolution of the morphology (type) of the dunes as they migrate downwind. Genetic relationships between these forms are recognized in a sequence of dune types which evolve under conditions of diminishing sand supply and downwind migration in the dune field (McKee, 1966, 1979).

The dune types, in order of diminishing sand supply, are transverse, compound ridge, and simple. Under conditions of high winds and sediment supply with little or no vegetation, transverse dunes are formed as features on a previously flat land surface. As a transverse dune migrates and grows larger downwind, wind speeds may not be equal across the dune, and places that have slightly higher wind speeds will migrate faster. These locations on the dune continue to migrate faster because vegetation is unable to take root on a surface where there is constant erosion, any existing vegetation often dies off as their roots become exposed from erosion. Conversely, wind speeds may be decreased downwind, with the result that vegetation may partially cover the dune because it can take root on a surface where there is minimal erosion. In these places dune advance is retarded. As the transverse dune continues to advance at different rates across strike, the dune becomes segmented into smaller dunes which are still in contact with adjacent dune segments (compound) and in a nearly linear alignment of the transverse dune front. This linear alignment of compound dunes is commonly referred to as a ridge of dunes. Such a compound dune ridge is then named for the dune type which forms as a result of the different rates of advance
across the transverse dune. For example, a transverse dune that has evolved into a linear trending ridge of compound barchan dunes is known as a barchanoid ridge (Figure 1.2c). As the compound ridge dune migrates, eventually the compound dune forms will separate into isolated or simple dune forms which are not in contact with other dunes (McKee, 1979). The growth of a flat land surface into a dune has been studied, and it has been shown that transverse ridges are the first to form under a unidirectional wind and an abundance of sediment; they subsequently evolve as they move downwind or with changing wind regimes (Bagnold, 1941).

It is important to note that I am not implying that dunes initiate only as transverse dunes and then evolve exclusively under conditions of decreasing sediment supply. In fact any change in sediment supply, wind regime, or climate may result in dune formation and migration, changes in dune morphology, or dune stabilization; again I emphasize the sensitivity of eolian systems to external conditions. It is often observed that under high wind strength and abundant sediment supply, transverse dunes form from a flat land surface and it is these transverse dunes that have been observed in many dune fields to evolve as the dune migrates downwind (Bagnold, 1941; McKee, 1979). As dunes move downwind, the upwind sediment source of the dune field no longer contributes sand to the growth of the downwind dunes, but rather to younger dunes forming closer to the upwind sediment source. In this way, there are specific types of dunes that characterize a field of migrating dunes. Transverse, star and dome dunes are typically found upwind. Transverse dunes form as mentioned above, under conditions
of high winds and sediment supply, resulting in a prominent linear dune oriented perpendicular to
direction of the sand-transporting wind. Dome dunes are a common upwind dune type in many dune
fields; these dunes have a dome shape because the wind speeds are high enough that there is no
formation of slip-faces; sand is carried far past the dune crest due to high wind velocity, unlike other
dune forms where sand just makes it to the crest and falls down a slip face. For this reason, dome dunes
do not typically build to great vertical heights, though they may be laterally extensive. Star dunes are
sometimes observed in the unprotected upwind portions of a dune field, where the sand is subject to
varying wind patterns that do not significantly affect more protected dunes elsewhere in dune field. As a
compound ridge dune migrates farther downwind, barchan dune types commonly evolve from the
segmented transverse dune under conditions of unidirectional winds and no vegetation. In the case of
unidirectional winds and a partial vegetation cover, the compound ridge will likely form parabolic dunes
(blowouts): this relationship was described by McKee (1979) for barchan dunes but is applicable to
other dune types. The barchan dune which is not dependant on vegetation can migrate for many
kilometers even without a sediment supply due to their aerodynamic shape (crescentic with “horns”
pointing downwind) which allows for the easy transport of sand from the windward slope to the leeward
slope as the dune migrates, retaining its same size and shape. Parabolic dunes, with their dependence on
vegetation do not commonly migrate as far as barchans due to their inevitable stabilization as vegetation
becomes denser farther downwind.

A dune may also initiate as a blowout, a local sediment advance relative to a pre-existing dune or
sand deposit. A blowout is a dune advance caused by a locally-focused more intense wind. The
advancing blowout deposits sand ahead of it as depositional lobes, each of which may be the result of
differing wind patterns as wind is steered through the blowout. Blowouts may have several different
morphologies; the most common are saucer- and trough-shaped blowouts. Like transverse dunes, blow-
outs often evolve as they move downwind (Hesp and Hyde, 1996). As blowouts are supplied with more
sand and persistent uni-directional winds, they commonly evolve into parabolic dunes if there is
vegetation present to partially stabilize portions of the blowout, and provide a means to preserve dune
form. If vegetation is not present, blowouts can be purely an erosional feature acting to focus and intensify winds locally creating a rapid erosion of pre-existing sediments.

1.3 Parabolic Dunes

Parabolic dunes are a special dune form, because unlike other migrating dunes, their form is completely dependant on vegetation and moisture. These dunes migrate downwind, and are usually found in uni-modal wind regimes. Parabolic dunes are characterized by partially stabilized limbs which point upwind, and a blowout at the center of the dune which migrates faster than the limbs. On the limbs of the dune where wind velocities are lower, there is less erosion of sand, which allows for vegetation to take root. This partial vegetation cover, usually composed of grasses or small shrubs, retards the advance of vegetated dune limbs with respect to the blowout. A parabolic dune is essentially a blowout, but it has a pair of partially vegetated limbs which grow in length as the central blowout advances. The parabolic dune crest is the blowout, with the slipface being composed of its depositional lobes. It is characteristic of parabolic dunes that wind blows up a concave windward slope. As it does so, it is accelerated to higher wind velocities increasing its ability to carry sediments, so the blowout is characterized by having highest wind velocity and no vegetation. As the blowout advances ahead of the partially stabilized limbs, the dune takes on a parabolic shape as a result of the slower advance of the limbs.

The parabolic form that a blowout may take is a result of its dependance on the role of vegetation or moisture partially stabilizing parts of the dune. Because of their extreme sensitivity to climate, which is much less well constrained than wind patterns (which are the most significant factor in determining other dune morphologies), parabolic dunes are relatively poorly understood.

Figure 7) Parabolic Dunes, note the presence of a partial vegetation cover, arrow indicates wind direction. From McKee (1979).
Parabolic dunes have been studied in many environments, from semi-arid to arid deserts (McKee, 1966; Lancaster, 1995) to lake fronts (Arbogast et. al, 2002), to coastal environments (Inman et. al, 1966), to subarctic environments (Dijkmans and Koster, 1990) and even evaporite settings (Svendsen, 2003) with varying sediment compositions and varying degrees of vegetation and moisture. Although dunes (parabolic or otherwise) are typically dominated by quartz sands (due to their hardness and resistance to weathering) there is some variety in dune sediments. For example, the parabolic dunes of the White Sands Dune Field, New Mexico are composed of semi-cemented gypsum grains (McKee, 1966). Parabolic halite dunes have also been studied in the most unlikely place to find any dune type - in the evaporite environment of The Salar de Uyuni, Bolivia, which is the largest salt flat in the world (Svendsen, 2003). These small scale parabolic dunes form in the absence of vegetation by the partial stabilization of eolian transported halite crystals by moisture resulting from fluctuating brine levels (Svendsen, 2003). The parabolic dunes of the Walking Dune Field are composed of approximately 90% quartz sands, with the remaining 10% being composed of minerals such as magnetite, illmentite, and garnet. The presence of the iron oxide minerals, especially magnetite is significant in our ability to image fine scale internal dune structure in high resolution using GPR at the Walking Dunes.

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Ch. 2 The Walking Dune Field

2.1 Description of Study Area

The Walking Dune Field of Hither Hills State Park is a coastal parabolic dune field located in Napeague, NY. This dune field is bounded by Napeague Bay to the west, Gardiners Bay to the north, and the Atlantic Ocean to the south, and is comprised of five parabolic dunes ranging from 8.5 to 16 meters in height. Dune 1 (figure 2.1a) appears as high as 18 meters but this is due to the superposition of this dune over glacial deposits. Coastal dune fields are different in many ways from the desert dune fields with which many people often associate dunes. In the coastal environment, moisture and/or vegetation play significant roles in the development of dunes, unlike desert environments where these factors are minimal or absent. Coastal dune fields can be very large, but they are not usually as large as the mega-dune fields found in some of the largest and most arid deserts, where there is no shortage of sediment supply. The approximately 2 km² area of the Walking Dune Field is very large by Long Island standards but is rather small in comparison to other coastal dune fields, for example the 40 km² area of the coastal sand dunes of Guerrero Negro, Baja California, Mexico (Inman et al, 1966). The main dune field of the Badain Jaran desert, Inner Mongolia, China, is much larger at 50,000 km² (Yang et. al, 2003).

The predominant sand-transporting winds of the Walking Dune Field are from the NW, and as a result all of the dunes in the Walking Dune Field trend roughly NW-SE. Sediments eroded from the adjacent headlands which eventually come to comprise the dunes are first carried into the Napeague Harbor by coastal currents and are deposited as a series of offshore ridges, which are then transported to the beach by wave action. Eolian processes move the sediments from the beach face landward where ultimately the dunes are formed (Black, 1996). As the dunes grow they migrate landward in a southeasterly direction, a result of the prevailing winds from the northwest which carry the sediments and shape the parabolic dunes. Dune migration continues at a rapid rate, until new dunes are formed. Newer dunes alter the wind flow, and countervailing winds from the Atlantic Ocean slow the rate of migration of dunes farther downwind in the dune field, and eventually the dunes become stabilized by the growth of vegetation (Black, 1996).
From the 2001 aerial photograph (Figure 2.1a) it is clear that the Walking Dunes are characterized by decreasing dune size toward the north (up-wind). This indicates that this dune field has had only a limited supply of new sediment and has been progressively starved of sediments added to the system, possibly the result of the development of sand spits over the past 100 years which have obstructed tidal flow into and out of Napeague Bay. From aerial photographs during the period 1930 – 2004 and coastal survey maps from 1848 and 1891, it is clear that the southernmost dunes

Figure 2.1a) 2001 aerial photograph of the Walking Dune Field. Note the decreasing size of dunes in the upwind (NW) direction. Dune 1 and 2 are stable indicated by heavy vegetation, while dunes 3, 4 and 5 are actively migrating at rates of up to 6.5 m/y. Linear trends in the northwest area of the dune field are cobble pavements which have been exposed by eolian processes. In recent decades the inlet to Napeague Bay has rapidly been closed by the development of sand spits shown in the northwest portion of the figure.
(Dunes 1 and 2) of this dune field have been stable (not depositing sand over the slipface and migrating) for the last 150 years - how they formed and how old they are will be a topic of speculation later in this paper. The actively migrating dunes, Dunes 3, 4, and 5, are currently moving at rates of 0.5 – 6.5 m/yr (during the period 2001 - 2004).

From the maps and aerial photographs we have also been able to study the migration and evolution of these actively migrating dunes; beginning with Dune 3 which is first mapped as a distinct parabolic dune in an 1891 coastal survey (Figure 2.2f), and continuing with the subsequent development of dunes 4 and 5 as successive blow-outs on the limbs of pre-existing dunes. The Walking Dune field is

![Figure 2.1b](image-url) The “phantom forest,” was exposed as dunes migrating over this area revealed the buried trees they once enveloped. This is a major attraction for tourists who unfortunately have torn down parts of the trees as souveniers.
distinct in several ways from many other coastal dune fields. One feature of this dune field not commonly observed elsewhere is that many of the dunes in this dune field have been migrating across a forested area. In some places, tops of trees can be seen protruding through the dune crests and in others the dunes have migrated past the forest leaving behind dead, but still standing trees (figure 2.1b). There are also large areas of exposed cobble pavements, presumed to be glacial in origin, but reworked by marine processes so that they are now in parallel orientation to the current shore line. The alignment of these pavements is thought to be related to the growth of this land body by marine processes (Black, 1993, 1996; Dubecky and Maher, 1994). These pavements may also play an important role in the formation of both the linear beach dunes along Napeague Bay, as well as the parabolic dunes of the Walking Dune Field (Black, 1993, 1996).

The Walking Dune Field is composed mainly of parabolic dunes, a special dune form which is completely dependant on the role of vegetation and moisture for its morphology. For this reason parabolic dunes are very sensitive to climate and anthropogenic pressures which may affect the amount of vegetation. As mentioned earlier, changes in vegetation can lead to the stabilization or erosion of these dunes. Unfortunately, due to irresponsible hikers not keeping to marked trails, two large blowouts have formed upwind in the Walking Dune Field, along the western limb of Dune 5 (Figure 2.1c). As vegetation was killed from being trampled by hikers, winds were able to erode sands along the hiking trail; this exposed patch of sand rapidly developed into large blowout as winds became focused through such a narrow breach in the vegetated linear dune ridge. These blowouts will draw sediments from the

Figure 2.1c) Note the two blowouts to the left (west) of Dune 5. In each, a case hiking trail can be seen leading up to the blowout.
migrating parabolic dunes in this already sediment starved system, leaving the fate of the Walking Dunes unknown. Many other trails are in locations that are prone to develop blowouts which jeopardize the preservation of this unique geologic land form.

The ecologically fragile setting of the Walking Dunes makes GPR an ideal method for studying the internal structure of these dunes. Not only is GPR non-intrusive, preserving the dunes, but it is also a powerful tool which can provide very clear resolution at shallow depths as well as deep within and below the dune, aiding our study of internal structure and understanding of the growth history of these dunes.

2.2 Classification of the Walking Dunes

The Walking Dunes of Napeague (figure 2.1a) consist of both stable and actively migrating parabolic dunes. These dunes trend NW–SE, in the direction of the prevailing winds in the region. The winds, which are effective in transporting sand for the actively migrating dunes, may be channeled by a wind funnel created by the headland to the west of Napeague Bay and Gardner’s Island (figure 2.2a). The Walking Dunes can be characterized as parabolic dune forms based on the morphology they have adopted due to the complex interactions between wind, sediment availability, moisture, and importantly vegetation (McKee, 1966, 1979). These dunes have one curved slip face, a concave windward slope, and two limbs which point up wind, characterizing them as parabolic dunes.
Parabolic dunes of the Walking Dune field exhibit both compound and complex dune morphologies. Compound parabolic dune morphologies characterize this dune field as all of the dunes are either overlapping or superimposed upon one another; this relation is obvious from a DEM image (figure 1.1c) or an aerial photograph (figure 2.1a). Dune 1, the southernmost and stabilized parabolic dune is composed of three main V-shaped blowouts. The close orientation of these blowouts – parabolic in form, suggests that this dune may have possibly initiated as a transverse dune under conditions of strong winds, high sediment supply, and low vegetation. It has been observed that as dunes move farther downwind they tend to evolve from transverse to compound to simple form (McKee, 1979). Therefore, the close proximity of the blowouts, which presumably have migrated at nearly the same rate, suggests that they did not move far enough down wind to evolve into simple dune forms before becoming stabilized. The parabolic ridge formed by these dunes collectively creates the largest parabolic dune in the Walking Dune Field, at a height of 16m, width of 600m, and length of 700m. The elevation of this dune is due largely in part to the reactivation and superposition of dunes above glacial deposits. Episodes of dune re-advance and re-activation are clearly recognized in GPR data from Dune 1. From a DEM (figure 1.1c) as well as from GPR data it appears as if the parabolic ridge is superimposed upon a much older glacial deposit. These findings will be discussed to a greater detail, along with other GPR findings later on in this paper.

To the north, Dune 2 (figure 2.1a) is a U-shaped parabolic dune. The wide U-shaped form of this dune indicates different conditions during its migration which resulted in the near parallelism of its limbs. The parallelism of the opposing limbs of this dune indicates that this dune was migrating under conditions where the limbs were heavily vegetated. Therefore the heavily vegetated limbs had a limited ability to migrate, resulting in a nearly parallel orientation. Parallel limbs do not necessarily indicate a high rate of advance, only that they were well stabilized by vegetation, indicating that either the climate was slightly different at that time (allowing for this vegetation), or that the winds were very focused through the blowout and weaker at the limbs, enabling vegetation to grow. The orientation of these limbs and very wide dune crest suggest that there was a wide wind flow focused through this blowout.
Clearly this dune had an abundant sediment supply; it is very wide in comparison to other blowouts of this dune field. The winds effective in transporting sand must have been focused over a wide area by the heavily stabilized limbs, allowing the movement of such a large volume of sand in what appears to be essentially one large blowout. The origin and ages of Dunes 1 and 2 remain a mystery; future studies aimed at dating these dunes are needed to confirm our interpretation that these dunes are significantly older than the actively migrating dunes, and may have formed under very different conditions. From our study of maps and aerial photographs, as well as GPR study of internal structure, we can strongly speculate on the origin and evolution of these dunes, which will be discussed in detail later in this paper.

Moving farther north in the dune field (figure 2.1a), we encounter the actively migrating parabolic dunes - Dune 3, Dune 4 and Dune 5, which are migrating at rates of about 0.5 m – 6.5 m per year (average rate from 2001-2004). These dunes are progressively younger to the north, and we have studied their migration using coastal survey maps from 1848 and 1891, and aerial images from 1930 to 2001 which have been georeferenced using GIS – ArcMap software. The use of ArcMap has allowed for the accurate comparison of aerial photographs and maps enabling us to observe noticeable changes in the dune field on a decadal time scale and in some cases over only a few years. What is unique about the history of this dune field, recorded by the aerial photographs, is that we can actually see dune initiations as blowouts, and their development into parabolic dunes documented by successive aerial photographs. GIS has also made it possible to accurately measure rates of advance for all of the actively migrating dunes. Comparison of aerial photographs and maps has allowed us to gain a better understanding of how this dune field, and specifically the actively migrating dunes, has evolved over the past 150 years.

From the maps and aerial images it is clear that Dune 3 is the oldest actively migrating dune. As early as the 1848 Coastal Survey map, there was a prominent dune feature that we infer to be Dune 3 (figure 2.2b). It is not clear, however, whether its linear form on the map represents a truly linear dune or possibly the mapping of only one limb (the one closer to the shore) of a parabolic dune. Not until 1891 was this area mapped in sufficient detail to show parabolic dune forms. Dune 3 is currently migrating at a rate of about 0.5 m/y, although during the period 1891 - 1930 it was migrating at 5.6 m/y;
the slower rates at present reflect the significant amount of vegetation on the dune which slows its advance. From the 1930 aerial image (figure 2.2c), the oldest available of the study area, we can see Dune 3 as an active simple dune, mostly base of vegetation and with what appears to be a developing blowout on its western limb. If starved of sediment, such a blowout would become stabilized rapidly as the limbs grew; without adding sand to the main blowout it would fail to develop into a full-fledged dune. The blowout could also erode the limb away if there were no vegetation holding it in place, especially if no new sands were being transported. However, this blowout formed at a time when there was sufficient available sediment as well as some vegetation to allow it to develop into a distinct parabolic dune (Dune 4). The development of Dune 4 as a blowout on the limb of dune 3 is documented in a series of subsequent aerial images from 1930 - 1959. Note that in the 1930 aerial photograph (above) Dune 4 is a developing blowout, and by 1955 (figure 2.2d) it is a well formed parabolic dune. During this period of rapid growth (1930-1955) Dune 4 migrated at a rate of 8.8 m/y, after this time period migration rates decreased steadily to the current rate of 1.67 m per year (average rate from 2001-2004) as vegetation progressively anchored the dune. Similarly, later aerial images (Figs. 2.2e) show the development of Dune 5 from a blowout on a limb of Dune 4. Note, however, that the younger Dunes 4 and 5 are progressively smaller; suggesting that limited supply of sand has constrained dune development.

Dune 3 is a large U-shaped parabolic dune, currently migrating at a rate of about 0.5 m per year (average rate from 2001-2004), but during the period 1891- 1930 migration was 5.6 m/y and from 1930 -
2001 the rate was 1.25 m/y. The slowing of migration rates corresponds to increased amounts of vegetation on the dune and also a decreasing sediment supply. Dune 3 shares a limb with Dune 4, the most rapidly migrating dune of the walking dune field. Dune 4 is a compound parabolic dune, with an actively migrating parabolic blowout on its western limb. Aerial images show that at one time the northeastern limb of Dune 3 was a continuous ridge, extending down to what, based on field observations, have been identified as star dunes. This complex morphology of Dune 3 suggests that the

Figure 2.2c) 1930 aerial photograph georeferenced to 2001 aerial image (in color). Note the absence of vegetation on Dune 3 and the re-activation of Dunes 1 and 2, which have areas of free sand, although the dunes have been stable since at least 1848.
wind patterns in to the north end of the dune field are slightly more variable than farther to the south east, possibly as a result of winds coming off Gardner’s Bay.

Dune 4 is unique because it is actively overrunning a forested area: tree branches can be seen protruding from its crest as it migrates over the trees. A “phantom forest” of dead trees (figure 2.1b) was once enveloped by the dune (killing them) and subsequently became exposed as the dune continued to migrate. This dune is currently migrating at a rate of 1.67 m/y, but similarly to Dune 3 this rate was much greater in the past at 8.8 m/y during the period 1930-1955. The rapid rate of migration corresponds to a time early in this dunes growth history when it was first developing into a parabolic dune from a blowout on the limb of Dune 3. The main blowout of this dune has responded to varying amounts of vegetation (due to climate variations) on the dune crest over time as well as different size and numbers of trees in the migration path, the result being a migration of the blowout in response to barriers which impede sand transport.

In figure 2.2e, aerial images clearly show blowout migration from the SW to the SE portion of the dune crest. GPR data from this dune indicate that throughout this dune’s growth history it was characterized by a migrating blowout. In 1966 the crest of Dune 4 was irregular due to the extent of buried trees supporting the dune in that location, as a result it appears as if the main blowout is on the SW side of the blowout. In the 1976 a new blowout appears to have formed in the center of the dune and subsequently migrated to the SW, as indicated in the 1988 aerial image. Some time between 1988 and 2001 a new blowout formed on the SE side of the dune crest as vegetation stabilized the older blowout to the SW, this is apparent from the 2001 aerial image. It appears that Dune 4 was being

![Figure 2.2d) A close up of Dune 4 in a 1955 aerial photograph, note how it has clearly evolved into a parabolic dune since its onset in 1930.](image-url)
supplied with sediments by a large trough blowout during this period, as indicated by the characteristic “rims” (figure 2.2e). Also from this figure note the onset of Dune 5 in 1976 indicated by a small blowout located on the limb of Dune 4. The development of Dune 5 has likely caused a disturbance in the near surface wind flow, creating a wind shadow to the western side of Dune 4; this may explain the migration of Dune 4’s blowout to the southeast area of the dune crest where winds are now locally more intense.

Figure 2.2e) Aerial images from 1966 - 2001 reveal evolution of Dune 4 and the onset of Dune 5. For each year blowout positions are indicated by arrows. Note the large trough blowout indicated by parallel dashed lines along its “rims” in the 1966 photo. Shown by the red box is the development of a blowout which formed as a result of erosion from a hiking trail. The naturally formed large trough blowout is interpreted to be a main sediment source to these dunes, while the smaller trough blowout is starving the dunes of sand, inhibiting their growth.
Dune 5, the smallest parabolic dune has also migrated over a once forested area which has been observed in aerial photographs. This dune is currently migrating at 6.5 m/y (during 2001 - 2004), the highest rate among the active dunes is likely due to its upwind position where it receives a direct wind flow that is not altered by other dunes. Dune 5 is starving Dune 4 of sand, inhibiting its growth, just as Dune 4 starved Dune 3 of sands. However, Dune 4 formed at a time when there was a higher availability of sediments and was able to develop into a large parabolic dune. As expected from a limited sand supply, the aerial photographs indicate that Dune 5 does not appear to significantly increase in size, even though it is migrating at a high rate. The U-shaped morphology of Dune 4 and the narrow V-shaped morphology of Dune 5 represent different amounts of sand supply and vegetation during their formation. Previous studies have referred to Dunes 3, 4 and 5 as one main compound dune (Black, 1996), but in this study they are recognized as individual dunes. The basis for the identification of these dunes as such is that from aerial photographs we have been able to study the genesis and growth of Dune 4 and Dune 5, showing that they formed at different times, and under different conditions. Dune 3, which precedes both Dune 4 and Dune 5, is believed to be much older than subsequent dune developments. It is recognized in this study that Dunes 3, 4, and 5 form a compound parabolic dune with Dune 3 and Dune 4 sharing a limb, and Dune 5 superimposed on the stable limb of Dune 4. However, since we are able to prove the time transgressive nature in the formation of each parabolic blowout, we have chosen to identify the individual dune forms which collectively compose the compound dune. This identification also makes it easier to identify the specific parabolic dune of the large compound dune from which we have been collecting data.

Inter-dune areas are relatively flat, and in many areas, cobble pavements have been exposed by eolian processes that remove sand and transport it to the southeast portion of the dune field. This deflation plain is characterized by exposed pavements in a linear trend believed to be the result of the growth of the peninsula (Black, 1993, 1996; Dubecy, 1994). A large dome dune to the north of Dune 3 (figure 2.2a) may have been formed in several different ways. This dune appears in the same location in an 1891 map of this region (figure2.2f), indicating that it has been stable for at least 115 years.
The close proximity of this dome dune to Dune 3 (windward side) in the 1891 map suggests that it may represent a stabilized portion of Dune 3 which was left behind as it migrated. Unique conditions of vegetation and moisture may have played a significant role in stabilizing part of Dune 3 resulting in what eventually became a dome dune being left behind. Since winds were likely focused and intense this close to the blowout of Dune 3 (during a time of faster dune migration, 5.6 m/y), this dome dune
was likely eroded to near its present height not long after Dune 3 advanced past its location. The possibility of this dune representing the beginning stages of what could have become a parabolic dune, as suggested by Black (1993) does not seem likely given its close proximity to Dune 3 in the 1891 map. Dome dunes, typically upwind features, are not likely to form with in the blowout of a parabolic dune where the sands would more likely be transported to the migrating parabolic dune, rather than forming a dome dune. GPR investigations are needed in order to determine the origins of this dune. If slip surfaces are imaged then this may be a remnant of Dune 3, any other internal structure imaged may indicate either that this is part of a primary dune (possibly from a paleo-shore line), or the unlikely possibility that it is in fact a dome dune. I believe that this dune is probably a remnant of Dune 3 which became stabilized by vegetation or moisture (from inland tidal water) as the parabolic dune advanced. It left behind what eventually took on a dome morphology, but likely has internal structure characteristic of parabolic dunes.

Another possible genetic model for the formation of the parabolic dunes is the mobilization of a blowout from the linear primary dune close to the shore, where substantial wind blowing from the northwest was steered through a trough blowout making it possible to have depositional lobes of sand being deposited to the east, where it could have been remobilized by the prevailing winds. The “snow fence” effect has been proposed by others who have studied these dunes, where the linear trending pavements trap sand by both topographic barriers and moisture (Black, 1993, 1996; Dubecky and Maher, 1994). It appears that the sediment source of the actively migration Dunes 4 and 5 has been a large trough blowout, distinguished by its parallel rim features in aerial photographs (figure 2.2e) in which forms a gap between the linear primary dunes. Sediments transported from the Napeague Bay shore as well as eroded from the primary dune have been contributing to the growth parabolic Dune 4 and Dune 5. It does not appear that this trough blowout was a main sediment source for Dune 3, which suggests that this dune formed farther to the north, possibly fed by a similar blowout in the primary dunes. As Dune 3 migrated to the south east the distance from its main sediment source and the
development of Dune 4 (which took most of the sand from the recent trough blowout) contributed to the decreased sediment supply to Dune 3 and its slow stabilization as vegetation began to take root.

Compared to the actively migrating dunes, Dune 1 and Dune 2 may have formed by different mechanisms and potentially under vastly different conditions during their migration. Similarly, the dome dune to the north of Dune 3 presents many questions as to its origin and conditions of its formation. Fortunately aerial photographs and maps can be used to study the past 157 years of changes in this dune field, allowing for the complete study of the formation and migration of Dune 4 and Dune 5, as well as the migration and stabilization of Dune 3. Although the aerial photographs and maps do not yield significant information on Dune 1 and Dune 2 aside from a minimum age of stabilization, there is a feature of these dunes and of the actively migrating dunes, not observable in aerial photographs or maps, which can be used to learn about their growth history and even conditions under which they migrated. As the dunes migrate they compile many layers of stratified sand. These stratified deposits can be studied wherever they have been exposed by erosion or by subsurface GPR imaging, to reveal a recorded history of their growth. From these stratified sands and other features preserved among the dune stratigraphy it is possible to compare the growth conditions of the older stabilized dunes with the modern actively migrating dunes in order to learn more about how parabolic dunes of the Walking Dune Field have evolved, and to gain insight to the development of parabolic dunes elsewhere.

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Ch. 3 Internal Structure and Growth History

3.1 Internal Structure - Significance

The internal structures within dunes result from the history of dune development, which reflects the complex interactions of wind regimes, sediment size and availability, and degrees of vegetation and moisture (barriers to transport) in the dune field. It is possible to infer the types and orientations of internal structures in a dune based on its morphology and the wind regimes in which it forms (McKee, 1979). For example, in a uni-directional wind regime one would expect slipface (bedding plane) orientations to dip downwind, and strike roughly perpendicular to the direction of the sediment-transporting winds. This may be true for a transverse ridge, or other linear dune form, but dunes with curved or multiple slip face orientations such parabolic (blowout) dunes typically have complex internal structures at multiple orientations with respect to wind and direction of dune advance. Other dune forms such as star and sief dunes have complex internal structure and growth histories due to multi-directional wind regimes.

Parabolic dunes such as the Walking Dunes have complex internal structures which reflect the dependence of this dune morphology on a partial vegetation cover. A unique feature of the Walking Dune field is the fact that these dunes are actively overrunning (or have over run) a forest which also affects dune morphology and internal structure. As the dunes encounter forested areas their growth pattern may be changed when trees begin to be overrun. The trees can provide partial stabilization or possibly a barrier to migration. The result of this interaction is that the dunes are constantly being subjected to barriers to their migration which alter the pattern of deposition and wind flow at the crest. These changes take the dune out of steady state, so the dune must change morphology to maintain a profile which requires the least amount of energy to transport sand as it advances. The work of Tsoar (1985) has detailed how dunes in a steady state are able to migrate retaining the same shape, profile and size; subsequent changes in wind, sediment supply, or vegetation may result in taking the dune out of steady state where it must change is morphology in order to maximize energy efficiency. A dune will naturally respond by trying to return to the state it was in, changing the pattern of deposition, or it may
completely change its morphology in response to the changes in deposition and wind flow which also may strongly affect the amount to vegetation present. Any change in deposition or morphology in response to changes which take a dune out of steady state will be recorded in the internal dune structure. The study of internal dune structure lends insight into how dunes initiate and evolve through time, and is important in attaining a better understanding of the dynamics of eolian systems.

3.2 Previous studies of internal dune structure, GPR background

In the past, studies of internal dune structure required extensive excavation of dune sands to reveal buried stratigraphy (e.g., McKee, 1966, 1979; Fryberger, 1990; Lancaster, 1995). Often these studies were focused in less environmentally sensitive environments such as in large “sand seas” or deserts. Excavations in various dune forms were typically shallow, only a meter or two, or limited to erosional surfaces which revealed bedding planes. In more comprehensive studies, large trenches were dug using bulldozers in order to yield full cross sections in which to study internal structure (figure 3.2a). Exposed cross sections along trench walls (figure 3.2b) beautifully revealed large-scale structures such as bedding planes and avalanche surfaces, as well as fine scale internal structures such as laminations between bedding planes. Trenches were a great aid in the study of internal dune structure, but this was a time-consuming method. After trenches were dug or bulldozed, the walls then had to be smoothed by hand so that structure could be observed. The collapse of excavation walls was also a concern: for this reason many such studies are ideally conducted in partially cemented dunes (McKee,
By excavating trenches, each wall of the trench could be used to study the exposed bedding planes, and internal sedimentary structures.

The limitation of a single trench is that only apparent dips and orientations can be measured. In order to determine true orientations of beds, intersecting trenches roughly perpendicular to each other must be cut: From the apparent dips along the two wall orientations it is then possible to determine the true orientations of bedding planes. Even with intersecting trenches, only the orientation of beds located at the intersection of the two trenches can be studied. To better understand the 3D stratigraphy, many trenches would have to be dug, in essence completely destroying the dune, even if it were large enough to allow for the time-consuming task of excavating multiple trenches.

The benefit of digging multiple trenches would be to understand better the morphological changes in the dune’s growth history, and how these may reflect various controls on dune morphology such as climate, winds, sediments, and vegetation. Such trenches, however, are poorly suited to the task of understanding the complex stratigraphy associated with dunes which exist in dynamic environments that have differing effects on dune growth history throughout time. Therefore, the dunes best suited for this type of study have only one effective wind direction, and have relatively simple internal structure that is easy to interpret using trenches. More complex dune morphologies often lead to a poor understanding of morphology and evolution when studied using trenches, unless past/present climate history and wind regimes are well constrained.
Technological advances have recently allowed for the noninvasive study of internal dune structure using a geophysical tool known as Ground Penetrating Radar (GPR). GPR is a method of subsurface imaging in which electromagnetic waves are sent through the ground via transmitting antenna, and the reflected signal is recorded by a receiving antenna. In dunes, these reflectors commonly correlate to bedding planes, or groups of bedding planes, depending on the resolution of the antenna being used. GPR allows for rapid data collection without the need for excavating trenches, which makes it possible to study more environmentally sensitive areas. GPR data can be used to create both 2D and 3D radargrams; a 2D radargram would be the equivalent of a trench wall, and a 3D radargram would be the equivalent of an infinite number of intersecting trenches!

3.3 Internal Structure - Methods Used in This Study

The ecologically fragile setting of the Walking Dunes makes GPR an ideal method for studying their internal structure. Not only is GPR non-intrusive, which preserves the dunes, but it is also a powerful tool which can provide very clear resolution at shallow depths as well as deep within and below a dune. The different antenna configurations of the GPR make it very versatile in its ability to resolve small scale shallow features or large scale features at greater depths. In this study of the Walking Dunes, 200 MHz and 500 MHz antennas were used. The high frequency 500 MHz antenna was chosen because of its high resolution at shallow depths, ideal for observing dune slip surfaces, and limbs of buried trees. The 200 MHz antenna was chosen because its lower frequency was ideal for imaging at depths beyond the reach of the 500 MHz antenna. The 200 MHz antenna has sufficient resolution to image dune slips surfaces, but can image deep enough to see sedimentary horizons and erosional surfaces below the base of the dunes, which is commonly also the water table. With either antenna configuration, another feature of the GPR is the ability to create 3D as well as 2D data plots, depending on how the data are collected. Closely space parallel lines of data collection allows for the generation of a 3D radargram ‘cube’ by using a data processing program which interpolates between radar traces in
successive parallel lines. The GPR investigations of this study have been focused on 2D surveys on Dunes 1, 4, and 5, as well as a 3D survey on the crest of Dune 4.

The fine slip surfaces of the eolian dunes, which we are able to observe with the GPR, gives rise to a question about the dunes which is essential to understanding how the GPR creates a subsurface image. Why can we see these slip surfaces? If the dune were in fact 100% homogenous sand, no reflectors would be present; the GPR would not be able to produce images revealing the internal structure. The radar waves would simply pass right through any slip surfaces, unable to recognize them. What we have found in other GPR surveys along beach environments is that very thin layers of mafic minerals in the sand are responsible for producing the very well defined slip surfaces in the dunes visible to radar by creating an impedance contrast which the GPR images very clearly. This relatively minor component of the dunes greatly enhances the effectiveness of imaging of them using GPR.

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Ch. 4 Ground Penetrating Radar

GPR has been used for over a decade in assisting stratigraphic and sedimentological studies by creating cross sections (radargrams) in aquifer studies (Asprion, Aigner, 1996), fracture studies (Grasmueck et al., 2004), archeological studies (Grasmueck et al. 2004), and in imaging features with in dunes (Schenk et al., 1993; Bristow et al., 1996, 2000, 2005; Harari, 1996; Girardi, 2004). Such studies have been conducted in both 2D and 3D; however 3D studies of internal dune structure have not been conducted thus far.

4.1 SUNY Stony Brook GPR Equipment

The MALA Geoscience GPR equipment used in this study was funded by NSF Grant EAR0229985. The basic components of the GPR apparatus are the antennas (of various frequencies), the control unit (CU), and a laptop computer. The GPR apparatus is powered by 2 or 3 external batteries, depending on the antenna configuration. Radar data (traces) are taken each time the CU is told to signal a release of energy from the transmitting antenna, and subsequently listen for reflected wave information, recorded by the receiving antenna. Signal acquisition can be triggered by a preset odometer programmed to initiate traces at a specific distance interval, or by manually tapping the keyboard of laptop computer at the desired intervals. At each trace the CU is told by the laptop or odometer to coordinate the sending by the transmitting antenna of EM wave energy through the ground and the simultaneous instruction to the receiving antenna to listen for reflected wave signals. As the receiver records reflected wave information and sends it to the control unit, the CU records this information in a buffer from which it is continually sent to the laptop to be automatically saved in order to prevent data loss in the event of power failure. Reflections recorded in each trace are caused by differences in electric permittivity, which can results from contrasts in mineralogy, porosity, or saturation. The laptop computer is able to interface with the control unit via GROUNDVISION software. A nice feature of this set-up is that data is displayed on the laptop screen as it is collected, allowing for the users to verify that the desired targets are being imaged with sufficient data quality and to take corrective action if it is not.

What is viewed on screen (or during data processing) will vary for different antenna configurations, even over the same surface. This is because of their varying resolution and penetration
have the same penetration depth, which depends upon the frequency-dependent attenuation of EM energy by the ground. For lower frequencies, less attenuation occurs and the distance of signal penetration is greater. This is perhaps easiest understood by an analogy to the frequency-dependent attenuation of sound waves: when one is listening music with a loud bass (low frequency sound waves), the thump of the bass can be heard through walls, while the high frequency treble component that is not reflected off the wall is attenuated and lost within it. Therefore, although higher frequency antennas (those which produce a signal with smaller wavelength) resolve fine-scale detail, they have limited penetration depth. Conversely, low frequency (large wavelength) antennas resolve less detail but have greater penetration depth. Shown below (figure 4.1a) are the two different antenna configurations used in this study, the high-frequency 500 MHz antenna and the lower frequency 200 MHz antenna.

![Figure 4.1a](image)

*Figure 4.1a* The 500 MHz antenna (left) is monostatic which means that the transmitter and receiver are in the same shielded electronics unit. Note the well vegetated limbs of Dune 5 in the background. This antenna can be pushed along with a cart which also holds the computer, CU (control unit), odometer, and batteries. The 200 MHz antenna (right) has a larger antenna separation (due to the larger wavelength) and so this antenna is commonly dragged along the dune surface using the “rug,” but can also be manually moved to each trace interval. This 200 MHz survey is located on the crest of Dune 4. Note how the tops of trees in the surrounding forested area, being overrun by the dune, can be seen just ahead of the dune.
4.2 Causes of Radar Reflections and Data Processing

*Radar Reflections*

Before discussing data processing, a brief explanation on the causes of the reflections which are processed is appropriate. Reflections from seismic imaging are caused by changes in velocity and density changes; GPR reflections are caused by changes in electric permittivity (which also causes changes in velocity). In the case of the Walking Dunes radar reflections within the dunes are the result of bands of iron oxide minerals (magnetite, illmentite). This is based on the observation of lag deposits composed of mafic minerals present at the base of foreset beds which are exposed in portions of eroded dune crests (figure 4.2a). Lag deposits such as these have been explained as forming due to the density of these minerals causing them to fall out of the wind flow (Bagnold, 1941). Studies of iron oxides as the cause of GPR reflections have been shown that they can cause a significant decrease in the radar wave velocity (Van Dam et al., 2002).

*Figure 4.2a* Exposed dune stratigraphy on the crest of Dune 4. The denser iron oxide minerals collect at the bottom of bedding planes and are slightly more resistant to erosion resulting in the protruding of the base bedding planes from the outcrop.

*Data Processing*

As mentioned earlier, the GPR equipment, as sophisticated as it is, can not produce high quality data without computer processing. This processing is done using REFLEX software which can apply many different filters and other functions to the wave data, in order to process it in a such manner as to eliminate as much bad data as possible while keeping the real signal. We commonly refer to the field
data collection as the easy part (as grueling as moving the GPR equipment over beaches and sand dunes may be) because it can take days or weeks to properly process the radar data collected in a single outing, especially when creating a 3D radargram.

After data is initially collected and backed up on a computer, it can then be imported into REFLEX which converts the Ground Vision (.rd3) files into raw data files (.DAT). Raw data is generally indecipherable as the energy decay of wave data makes it such that amplitudes of wave data are too small to observe. This decay in amplitude is a result of the attenuation of energy through the ground and can be corrected; however, the necessary correction to the data which must always be done first is to adjust for electronic drift of each data trace. Electronic drift is when a trace will veer to one polarity, typically with increasing time the drift will be greater. Figure 4.2b is an example of raw data; this line is one of the 61 parallel lines which comprise a 3D radargram on the crest of Dune 4. Note how weak the data signal appears, with reflectors disappearing around 30 ns. In the AGC (automatic gain control) version, wave data has had amplitudes adjusted, only for onscreen viewing, so that weaker signals can be observed. From the wiggle window of the AGC line the electronic drift is quite clear. This drift can be corrected using a 1-D filter (one which acts on each trace independently) known as the de-wow function. The results of this data processing step are shown in figure 4.2c; note from the wiggle window that the data trace is now centered at zero. Also in this line, which has been AGC gained to show more wave data, we can see some other problems which need to be processed out. It is necessary to use AGC to see these problems this early in the processing sequence because otherwise the wave amplitudes are too small to be observed.

Slight banding can be seen from 10 – 20 ns, this is the result of some electronic artifact of data acquisition, on this line it is only slight but needs to be removed. Also at depth the data appears to become fuzzy, this feature can be removed to sharpen the reflectors. To remove the banding, a subtract average function or background removal function can be used. Both are 2D filters (defined as those which perform an operation in which the result for each trace is a function of the signal in adjacent traces). Both filters work by calculating the average amplitude of every time position. The average value is then subtracted from the value at that position on the trace, in this method any horizontal features can be removed, since any horizontal feature would have a wiggle at the same time on each trace. When there is horizontal banding on data from a survey which had any topography it is likely that it is the result of an electronic artifact that must be removed in this manner. Although horizontal
Example of early stages in processing GPR data:
Figure 4.2 b) Top: raw data; Bottom: raw data shown in AGC gain with wiggle window showing an individual trace. Note how the trace veers to one polarity with increasing time.
Figure 4.2c) De-wow function has been applied to the raw data to correct for electronic drift, note how this trace is centered in its wiggle window.
reflectors could also be real horizontal stratigraphy as well, in the case of parabolic dunes, we know that bedding planes are typically deposited at high angles (20 – 30 degrees), so any persistent, purely horizontal features appearing within a radargram of the dune must be removed. Care must be taken when using this filter to not remove any real data which may be recorded as a horizontal reflector; for this reason the *subtract average* function is more commonly used because it allows more options on time ranges as well as the number of traces over which to average.

“Fuzzy” data, the result of excessive high frequency wave noise, can be caused by any of several types of signal picked up by the GPR. Common causes include the use of cellular phones and walkie-talkies, which operate on frequencies in the range of the GPR antenna, as well as radio-frequency emission from various utilities. Signal losses due to geometric spreading, attenuation and scattering cause the signal to noise ratio to decrease with depth, so it is commonly in the lower portions of radargrams where the problem of high-frequency noise is observed. To remove this noise, a process known as frequency filtering is required. There are several methods of frequency filtering in REFLEX; a *bandpass frequency filter* is commonly used because it is the most versatile in omitting unwanted frequencies. Although each antenna is labeled at a certain frequency, in fact a wide range of frequencies is emitted from the antenna, with the peak energy at or near the antenna specification. Using the *bandpass frequency filter*, an upper and lower bound can be specified, as well as a plateau - together, these parameters define a trapezoidal filter shape in frequency space. All signal from the lower to upper frequency bound of the plateau is kept: beyond the plateau, decreasing portions are retained and all frequencies outside of the outer bounds are omitted. The goal of this filtering is to remove unwanted frequencies, yet not destroy the data. It is necessary to maintain a wide range of frequencies to have proper generation of reflectors since the different frequencies will combine to give a single trace. If the frequencies are kept to a narrow range, their wavelengths will be nearly the same, yielding less information than a wide range of frequencies (and corresponding wavelengths) which will yield a more accurate trace from the superposition of many different wavelengths. The results of *subtract average* function and *bandpass frequency* filter are shown in figures 4.2d which is gained to show the results of these processing steps.

Following frequency filtering, the *gain function* is applied. Previous processing steps acted to remove unwanted portions of data; the gain function is used to amplify the signal so that it can be observed at depths where the reflected wave energy was too low to observe otherwise. Gaining of data
must occur only after the data has been processed using the previous steps; this is because any anomalies or electronic features will be amplified along with the real data which makes an accurate geologic interpretation difficult. The *gain function* can be used to gain (increase) amplitudes of reflectors in both the time (vertical) and distance (horizontal) domain. Care must be taken when using the *gain function* not to over-gain reflectors to make them appear inappropriately significant. Another consideration is
that when all reflectors are over-gained, subtle details can become difficult to decipher. In figure 4.2d the gained version of this radargram is shown, revealing data from higher times (deeper reflections) not previously visible.

The final processing step is topographic correction. This will enable us to see the true apparent orientation (any cross section always reveals apparent dips) of the reflectors by moving each trace to its proper position relative to adjacent traces. In order to process GPR data in such a way as to remove the effects of topography on the apparent orientation of reflectors imaged by the GPR, the area must be carefully surveyed to record topographic relief. The orientation and distances of radar transects (which are used to confirm odometer reading) must also be recorded. The orientation (azimuth) of radar transects is necessary to record so that the true orientations of reflectors can be determined. Topographic information is used to adjust each individual trace to its position relative to adjacent traces. This is necessary because unprocessed GPR data traces are all oriented in the same starting position, time zero. As sophisticated as the equipment is it cannot tell a hill from flat surface, and it is necessary to make this correction to allow for the proper interpretation of data.

Figure 4.2e shows the final product, processed and topo-corrected. When desired, an additional step (migration) may be used to return reflectors to their true position below the ground surface. If the assumed velocity structure is correct, migration will collapse hyperbola reflections, considerably aiding identification of reflectors. Migration also corrects for the erroneously shallow orientation of reflecting layers due to changing radar velocity which can be determined from hyperbola fitting. Note that the radargrams in figures 4.2a, 4.2b, and 4.2d are unmigrated; this allows them to retain the hyperbolic reflectors which indicate buried trees with in the dune, and glacial sediments (boulders and cobbles) below the dunes. Hyperbolic reflectors are caused by point reflectors such as boulders or the tops of buried trees. Unlike planar reflectors, which image as a line, point reflectors image as a hyperbola due to the differential travel time as distance while traversing over the target, leading to the hyperbolic shape on the radargram that makes it easy to identify point reflectors. The shape of the hyperbola is velocity dependant, with a faster the velocity leading to a wider hyperbola. By fitting the shapes of the hyperbolas to calibrated shapes in REFLEX, a velocity profile can be created allowing for accurate migration, and also for accurate time-depth conversion.

GPR data collected from the Walking Dunes was uncommonly free of erroneous electronic artifacts. The nearly homogenous sand was an ideal material to conduct such a study, and as a result the
processing did not require extensive steps. Occasionally data needed additional processing steps but generally this was the processing sequence of data from the Walking Dunes: 1) de-wow, 2) bandpass frequency filter, 3) subtract average, 4) gain, 5) migration (if desired), 6) topographic correction.

* * * * *

4.3 GPR Data from Walking Dunes - Description of Internal Structure

Initial GPR investigations of the Walking Dunes were conducted on Dune 5 in an attempt first focused at familiarizing ourselves with how well GPR would work in imaging internal structure of these dunes. We quickly realized that this dune was an excellent GPR target - revealing complex internal dune structure, as well as pre-dune stratigraphy and erosional surfaces. In order to understand this complex stratigraphy better, GPR investigations were next conducted on Dune 4 for comparison. As expected, the radargrams of Dunes 4 and 5 revealed similar internal structure characteristic of parabolic dunes. Later GPR investigations of Dune 1 were conducted to see if this older stable dune varied in any way from the actively migrating dunes. Dunes 2 and 3 are difficult to access, as a result they have not yet been studied using GPR.

Our use of diverse methods, including GPR data combined with field observations and the study of aerial photographs, has enabled us to understand better the growth history of these dunes, and also has led to interesting insights to this region’s geologic past. The following discussion of GPR data is the main focus of this study and strongest supporting evidence in our interpretation of the growth history recorded in the internal dune structure, as well as pre-dune field (glacial) geologic processes based on stratigraphy imaged below the base of the dunes.

200 MHz Data from Dune 4 and Dune 5

Due to the similarities between the 2D radargrams of Dunes 4 and 5, they will be addressed simultaneously. It is important, however to note that these similarities do not necessarily mean that these dunes formed in exactly the same way, but rather that there are some characteristic features of parabolic dunes, and specifically to the Walking Dunes common in both radargrams. Figures 4.3b and 4.3c are 200 MHz radargrams of Dune 4 and Dune 5 respectively. In both figures part (a) indicates our
Figure 4.3a) An enlarged image of Dune 4 and Dune 5 indicating locations where GPR data was collected. Blue and black lines indicate 2D GPR surveys, while the red square on the crest of Dune 4 indicates the location of a 3D GPR survey.

interpretation of the main features in the radargram shown unmarked in (b). The location of the radargram for Dunes 4 and 5 is shown in figure 4.3a (above), indicated by blue and black lines respectively. In order to aid in interpreting these radar data, the radargrams have had topographic correction applied with an assumed radar velocity of 12 cm/ns. That estimate of velocity is based upon fits to the shapes of reflection hyperbolas and hand auguring to confirm the presence and depth of water table. The radar velocities were found to be the same for each dune, as expected in this homogenous region. Vertical exaggeration is applied to show more clearly the dipping stratigraphy (foreset bedding planes). In both figures it is roughly 2:1 within the dune, and only slightly more exaggerated below the water table where velocities in the glacial deposits have been found by hyperbola fitting to be about 10 cm/ns. Note the well-developed pre-dune stratigraphy, which appears weakly folded, not unlike the sediments in the nearby Hither Hills. The slightly curved nature of the pre-dune reflectors (stratigraphy) might also indicate melt water fluvial channels of glacial outwash. Apparently, they are either post-glacial in age or perhaps glacial sediments from below the zone that was heavily deformed by the glacier.
Figure 4.3b) 200MHz 2D radargram from Dune 4, indicated by blue lines in figure 4.3. Vertical exaggeration is roughly 2:1 in the dune and slightly greater below the water table where radar velocities are lower. GPR surveys were run parallel to each other to check for the along-strike continuity of the reflectors imaged. The top portion (a) is our interpretation of the radargram shown unmarked below (b). Note the strong and continuous reflectors which dip downwind within the dune, these are foreset beds (previous slipfaces of the dune). Changing orientations of these reflectors are interpreted to be the result of a migrating blowout which has been observed in aerial photographs of this dune. The bright reflector along the base of the dune corresponds to water table (confirmed by hand auguring) and also previous glacial deposits (from hyperbolic reflections in the radargram indicating boulders and cobbles). There are also numerous hyperbolic reflections within the dune certain from buried trees it encountered as it migrated across the forested area. Below the dunes are near horizontal reflectors presumably from stratified glacial deposits which may be deformed (folded) not unlike the nearby Hither Hills.
Figure 4.3c) 200 MHz 2D radargram from Dune 5, indicated by black line in figure 4.3a. Vertical exaggeration is roughly 2:1 in the dune and slightly greater below the water table where radar velocities are lower. The top portion (a) is our interpretation of the radargram shown unmarked below (b). Note the strong reflectors which dip downwind within the dune; these are foreset beds (previous slipfaces of the dune). The numerous buried trees and shrubs within this dune have created many hyperbolic reflections within the dune which make the foreset beds appear less continuous. The orientation of these foreset beds appears to vary just as in Dune 4, suggesting that the blowout of Dune 5 changed position throughout this dune's growth history as well. The bright reflector along the base of the dune corresponds to water table (confirmed by hand auguring) and also previous glacial deposits (from hyperbolic reflections in the radargram indicating boulders and cobbles). Below the dunes are near horizontal reflectors presumably from distal glacio-fluvial deposits. Note that here they are cut off by pre-dune erosional surfaces which are dipping toward Napeague Bay.
The most easily recognized feature of each radargram is the slip surfaces (foreset beds) within the dunes that create many strong and continuous reflectors which are dipping in the down wind direction. These reflectors, corresponding to former slipfaces of the dune front, are at a typical spacing of about 50cm. Bedding planes may be 1 – 10 cm thick, as observed in exposed areas at the crest and from hand augur samples; however the resolved reflectors are at a greater spacing because depending on the layers’ physical separation, the impedance contrasts of several bedding planes (where mafic minerals collect) may combine to create a radar reflection. More reflectors are resolved with the 500 MHz antenna, which has higher resolution (figure 4.2d). It is important to note that the orientation of the foreset beds changes slightly throughout each radargram, shown most clearly in figure 4.2d. Although the reflectors show uniformly steep dips near the crest, the dip changes significantly throughout each radargram. This changing apparent dips of the reflectors as they are imaged in topo-corrected lines such as these could result either from true changes in dip or changes in strike – the fact that the latter turns out to be the case is (as described later) a clue to the complex growth history of these dunes.

Below the dune sand, numerous hyperbolas indicate the presence of glacial material with boulders and large cobbles. Water table is found near the interface between the dune sand and the glacial material, producing the bright sub-horizontal reflector seen running across both radargrams. This association has been confirmed by data from hand auguring and a crossing radar lines showing the lateral extant of this reflector. From a hand auger site at the 86 m mark on the radargram of Dune 4 it was possible to correlate reflectors to any changes in sediment composition along the borehole, strong reflectors correlate to zones of high mafic mineral content (>15%). The 200 MHz radargram of Dune 5 (figure 4.2b) shows two apparent erosional surfaces at left, dipping to the left (toward Napeague Bay; discussed in greater detail later). Note that one of them clearly cuts off the sub-horizontal pre-dune stratigraphy. Several bright hyperbolic features within the dune result from diffractions, almost certainly off of buried trees which we have observed these dunes to migrate over in aerial images.

500 MHz Data – Dune 4

500 MHz radar data were collected in addition to 200 MHz data in order to better understand the complex internal dune structure through higher resolution imaging. This was particularly important in the understanding of why the internal structure recorded changing orientations of reflectors (foreset beds) in the radargram of Dune 4. Figure 4.2d, a 500 MHz radar line in Dune 4, indicated in Figure 4.3a
by the blue lines, is one of several parallel lines run at the same positions as the 200 MHz radar lines to allow comparison of the nature of the reflectors imaged. What the higher frequency, and thus higher resolution, radar lines reveal is a more detailed image of what is of interest to us - the packages of bedding planes which vary in dip angle (shown by red lines and vertically exaggerated 4:1 to show clearly even subtle changes). The 200 MHz antenna lacks the resolution to show these subtle changes in dip angles – the result being a composite of several layers, more of which can be seen using the 500 MHz antenna.

The changing orientations of beds are interpreted to correspond to past positions of the blowout on the dune crest. Places along the radargram with steeper apparent dips correspond to times when the axis of the blowout was close to the radar line, while lower apparent dip angles indicate that the blowout was located some distance away from the radar line, so that what is shown is not a true dip section. In order to get a true sense of the orientation of these beds, each of which is a slip face deposited radially as a depositional lobe of a migrating blowout, a 12m x 25 m grid consisting of 61 parallel high frequency (500 MHz) lines was run on the crest of Dune 4. The closely spaced (20 cm) parallel lines allow us to create a 3D radargram (figure 4.2g) where data is interpolated between each parallel radar line. By creating a 3D radargram we are able to see the true orientations of each slip face of the advancing dune – a parabolic dune which is characterized by a migrating blowout. This method will also help us to better understand the growth history of Dune 4 as it responded to barriers to its migration (trees and stabilizing vegetation), changes in wind dynamics (from the development of the upwind Dune 5) and anthropogenic pressures (hiking trails), as well as the complex nature of blowout deposition.

3D GPR Imaging of Dune 4

As mentioned earlier, 3D radargrams can be produced from the interpolation between parallel radargrams using REFLEX GPR processing software. When radar lines are run perpendicular (or at a high angle) to each other, true orientation and dip angles can be obtained by plotting the trend and plunge of the corresponding reflectors in the 2D radargrams on a stereonet, and finding the plane (great circle) which contains the two lines. This is the same method used to attain three dimensional stratigraphic relations in earlier studies which used excavated trenches. To fully interpret complex dune stratigraphy using this method would take hundreds of measurements and many stereonets!
Figure 4.2d) [Top] A 500 MHz radargram from Dune 4 run in the same location as the 200 MHz lines, indicated by blue lines in figure 4.2c. Here vertical exaggeration is 4:1 to clearly show the changing orientations of reflectors (shown in red) which are now more apparent through higher resolution imaging. Note the reflector indicated by the blue line, this is same reflector in figure 4.2a - the water table/glacial deposits, however here the higher resolution 500 MHz antenna resolves a more complicated bi-parallel reflector which suggests the water table lies just above the reworked glacial deposits, this relationship has been confirmed by hand auguring. The last 12m of this radargram represents the “parallel” component of the 3D radargram. Arrows indicate hyperbolic reflections caused by buried trees.

Figure 4.2e) [Bottom] This is a 500 MHz 2D radargram from the crest of Dune 4. It is oriented perpendicular to the radargram shown above and centered at about the 90m mark. Note how the changing orientations of foreset beds in figure 4.2d correspond to crossbedding in this radargram, indicated by the red lines. Although the orientation of reflectors (beds) can be determined from these two radargrams. Only through 3D imaging can we thoroughly study growth history of this dune, which is recorded in the changing orientations of the foreset beds within it.
Figure 4.2f is a 500 MHz radargram parallel to the direction of dune migration, and figure 4.2e is a 500 MHz radargram perpendicular to the direction of dune migration. Note the differences in the GPR imaged cross sections. The radargram parallel to dune migration images nearly down dip, while the perpendicular line images nearly along strike. The perpendicular line, a 500 MHz radar line in Dune 4, is one of the 61 parallel lines which comprise the 3D radargrams show in figures 4.2f and 4.2g. Note that these radar lines are perpendicular to the radar lines shown in figures 4.2a and 4.2d; they are also roughly perpendicular to the direction of migration and reveal a complex stratigraphic sequence. Highlighted in red are changing cross bedding orientations. This complex sequence, combined with changes in dip angles observed in figure 4.2d (down wind direction) suggests a complex growth history of this dune, a growth history consistent with our model for a migrating blowout in response to barriers to dune migration (forest trees) and sand transport (grasses which grow on the dune crest).

Using these two intersecting lines the orientations of reflectors (foreset beds) can be attained. However, as mentioned earlier in Chapter 3, only the orientations of beds at this intersection would be known. To fully understand and interpret the dunes growth history, as recorded in the internal structure, a 3D radargram must be created so that the changes in dip angles of foreset beds can be visualized continuously along strike, allowing us to understand the depositional nature of a migrating blowout and the complex growth history of this dune. An example of a 3D radargram is shown in figure 4.2f, in comparison to the 2D radargrams, reflectors can be seen across faces and edges of the “cube.”

The ability to image in 3D allows us to see the internal dune structure continuously along strike at any depth within the dune, eliminating the need for stereonet projection. Only through 3D imaging can we see the stratigraphic evolution of the dune crest as the migrating blowout changed position with
Figure 4.2g) 3D radargram generated from 61 parallel lines run on the crest of Dune 4, in an area indicated by the red square in Figure 4.3a. The cube labeled A has corner cut B removed to reveal internal dune structure from deeper within the dune. Note the consistency of reflectors along each face of the cube, as well as across edges and into adjacent faces. This shows how remarkably continuous these reflectors (due to slip surfaces) are continuous along strike. These beds become cross stratified as the migrating blow-out deposits new slip faces radially as depositional lobes which are at differing angles to pre-existing strata. Highlighted in this 3D radargram are some key features of the dune stratigraphy visible only through 3D GPR imaging. Shown in yellow are reflectors (beds) which are continuous across several face and edges of the radargram; in blue and purple are foreset beds deposited by two different blowouts, the purple being younger and superimposed over the one indicated in blue.

respect to the axis of the dune. Figure 4.2g is an example of a 3D radargram, indicating features only visible through this method. This radargram is composed of 61 parallel lines run on the crest of Dune 4, indicated by red square in Figure 4.3a. Using REFLEX processing software, a 3D radargram can be created by interpolating between the traces of adjacent parallel radar lines. For the proper display of data, this 3D radargram has been topography corrected, as well as migrated. What this means is that we
are looking at the true orientations of the dune stratigraphy; each trace has been adjusted to its correct position on the dune crest as well as migrated to return the reflections to their true position relative to the surface of the dune crest.

The advantage of 3D imaging it that it allows viewing of internal dune stratigraphy from multiple angles and time (horizontal) slices within the 3D radargram. A unique feature of the 3D radargram is the ability to cut in from a corner point to reveal internal structure along orthogonal planes of the cut out. In figure 4.2g the cube labeled A has corner cut B removed to reveal internal dune structure from deeper within the dune. Note the consistency of reflectors along each face of the cube, as well as across edges and into adjacent faces. This shows how remarkably continuous these reflectors (due to slip surfaces) are along strike. These beds become cross stratified as the migrating blowout deposits new foreset beds radially, as depositional lobes, and at differing angles to pre-existing strata due to changes in strike along the slipface of the blowout. Highlighted in this 3D radargram are some key features of the dune stratigraphy visible only through 3D GPR imaging.

Shown in yellow are reflectors (beds and closely spaced sets of beds) which are continuous across several faces and edges of the radargram. The presence of such continuous reflectors is significant, showing that foreset beds are (as expected) continuous since the slip face of a parabolic dune, though curved, is continuous. It also indicates the excellent nature of the dunes for imaging such reflectors. The exposed continuous stratigraphy revealed from the removal of a corner-cut makes it possible to visualize the orientation of foreset beds. It is also possible to view the 3D radargram on surfaces parallel to the top of the cube (time slices before topo-correction, horizontal slices after topography has been accounted for). Such a perspective reveals an along strike view of reflectors, showing their radial continuity. Note the two reflectors highlighted in purple and blue in figure 4.2g, these two reflectors correspond to different blowout positions on the dune crest. The purple reflector, being younger than the blue reflector, is clearly superimposed over the blue one. This is indicative of a migrating blowout where younger radial packages of foreset beds are superimposed over older packages as a blowout migrates or when new blowouts form. When viewed in a cross-section oriented down wind (NW – SE) this superposition of blowouts corresponds to changes in apparent dip angles of foreset beds consistent with our model for the depositional nature of a migrating blowout in explaining the changing dip angle of reflectors in the 2D radargram figure 4.2d.
Figure 4.3h) An interpolated section normal to the parallel radargrams which compose the 3D grid (left) compared to a radargram (right) which is oriented in exactly the same location to allow a comparison of the reflectors imaged. The interpolated radargram has less resolution due to a larger trace spacing of 20cm compared to 3cm in a standard radargram. This side by side comparison shows how remarkably similar these radargrams are and also confirms that aliasing is not a problem in the 3D cube.

To further our ability to interpret the 3D dune stratigraphy, as well as demonstrate our capability using REFLEX software, a movie was created to show a 3D radargram in different orientations, time slices and corner-cuts. The creation of a movie is necessary because for each new orientation of the 3D radargram the data needs to be replotted, such that a continuous view of changing orientations is not possible. A movie can be created by exporting successive JPEG images of the radargram as the orientation of the cube and the nature of the slices into it are changed in REFLEX, and then stringing the images together using Quick Time Pro media software. The movie shows the GPR imaged dune rotated about a vertical axis and a horizontal axis, followed by scrolling down through successive time slices, and vertical sections, and the removal of a corner cut to reveal stratigraphy within the 3D radargram. It will be placed on the lab web site for widespread and easy access.

Through the rotation of the radargram about a vertical axis, it can be seen that the continuity of reflectors across faces and edges of the cube is excellent, even across faces where data is interpolated every 20 cm. The two 12m faces, which are parallel to the wind direction have a trace increment of 20 cm, because the 61 radar lines were run perpendicular (with a trace spacing of 3cm) to these faces. It
makes sense then that these faces have about $1/7$ the resolution of the parallel lines, but their resolution is still good enough that reflectors are coherent and continuous, a testament to the excellent nature of these dunes for GPR imaging. Figure 4.2h (previous page) compares the interpolated radar line with a radar transect at the same position but at the same 3 cm trace spacing as the 61 parallel lines. The ability to view different time slices in REFLEX is also shown in the movie. As the radargram slowly moves down in the time domain, the moveout in the direction down dip of reflectors is apparent, showing the vertical continuity of these reflectors. Also, as progressively deeper time slices are viewed the changing morphology of the dune crest can be observed; in this case clearly revealing superimposed and migrating blowouts and different surfaces of the dune crest and slip face.

Using this powerful software we can scroll horizontally through each adjacent parallel radar line revealing nearly identical stratigraphy; the move out of these reflectors down dip can also be observed when scrolling through the radargram towards the dune front (in the direction of migration). Perhaps the most stunning portion of the movie is the removal of a corner cut to reveal internal structure from within the dune. Through the removal of corner cuts, it is possible to visualize the true orientations of beds by seeing how they intersect adjacent faces of the radargram (as shown earlier in figure 4.2h). To fully interpret internal dune structures, and growth history, a combination of all the data display methods previously mentioned is necessary: this is the only way to study internal dune stratigraphy in this high of detail.

Extensive GPR studies on Dune 4 and Dune 5 have yielded new insights into the growth history of these dunes. In particular, 3D GPR imaging which has never before been used in such high resolution to study internal dune structure, has shown that the crest of Dune 4 is composed of several superimposed blowouts, and has enabled us to infer the complex mechanisms and conditions of this dune’s growth history as revealed in its internal structures. Through the study of aerial images to compliment our GPR studies, it became apparent from aerial views that there were some significant differences between Dune 1 (the southern most stable dune) and Dunes 3, 4 and 5 (the actively migrating dunes). The most significant difference was the size of Dune 1 which was taller (as determined from topographic maps and by field observations) and much more laterally extensive than any other dune in this dune field. In addition, it appears to be a compound dune composed of three blowouts which are very close in proximity. In order to better understand the conditions of this dunes growth history and its large size, a 200 MHz GPR survey was conducted on Dune 1 (figure 4.3i).
Figure 4.3i) 200 MHz radargram from Dune 1. Part (a) is our interpretation of the data shown unmarked in (b). This dune has characteristic high angle foreset beds of parabolic dunes, but also shows evidence of a northward redeposition of shallow angle beds. Below the base of the dune, which corresponds to a palesol horizon, are sandy to pebbly glacial deposits (confirmed by hand auguring) with some large boulders indicated by large hyperbola reflections. Key features highlighted in this figure are discussed in this section.
200 MHz Data – Dune 1

On Dune 1 we were able to collect data from the bottom of its slip face up the crest and down the windward slope, along the axis of the dune. Unlike the actively migrating dunes Dune 1 is heavily vegetated even on its crest and leeward slipface, allowing us to walk carefully up its crest without fear of destroying the dune. A 200 MHz radargram of Dune 1, figure 4.3i, is indicated by the black line in figure 4.3j.

On this heavily vegetated dune, it was necessary to change the bearing along portions of the radar transect in order to avoid forested areas on the dune; the changes in bearing are shown in figure 4.3i. This radargram reveals internal dune structure similar to Dune 4 and Dune 5 with foreset beds being well defined and dipping in the downwind direction of dune advance. There is also a well defined reflector at the base of the dune (indicated by blue line in figure 4.3i), representing the contact between it and pre-dune glacial deposits. Hand auguring has confirmed this reflector to correspond to a paleosol, and below it mostly sandy - pebbly glacial deposits which appear deformed (folded) in GPR data as indicated by the dashed purple line in figure 4.3i. It is apparent from this radargram, as well as hand auguring, that the height of this dune is largely due to its superposition over glacial deposits, although in some places (at around 115 m) Dune 1 rises 16m above the underlying glacial deposits.

A significant difference in the internal structure of Dune 1 is the cross bedding observed at shallow depths between 80 and 140 meters of the radargram. This cross bedding is inferred to be the result of countervailing winds from the Atlantic Ocean. The foreset beds of Dune 1 appear to have distinct packages of varying dip angles; but it is not clear if these are analogous to the packages of beds related to the migrating blowout observed in Dune 4. The packages of foreset beds appear to be more laterally extensive: note the presence of beds in the same orientation from 0m – 50m and from 60m – 110m. Laterally extensive packages of foreset beds suggest that conditions during the dunes growth were less variable than for the younger Dune 4. The absence of parabolic reflections within the dune...
indicates that this dune did not migrate over a forested area, or perhaps that the dune has been stable for so long that the trees have decomposed. The presence of cross bedding from countervailing winds suggest that reactivations of the stable dune have caused new younger blowouts to redistribute sands; this is also commonly observed in field observations of Dune 1 where blowouts have exposed the roots of trees which are left dangling over the edge of a trough blowout. GPR data from crossing radar lines, roughly perpendicular to the direction of dune migration have revealed slight cross bedding indicating some irregularities in blowout deposition. which are responsible in part for the stabilization of this dune as well as the erosion of sands at is crest and re-depositing them on the concave windward slope. The boundary between these deposits and eariler high angle foreset beds is indicated by the dashed red line in figure 4.3i. Cross bedding such as this is commonly observed in tall dunes when winds are not able to transport sand over the dune crest, resulting in shallow upwind dipping beds (McKee, 1966). From the GPR data of Dune 1 it appears that the dip angles of this package of cross beds is too high to be formed by this model and therefore they are more likely the result of countervailing winds from the Atlantic Ocean.

GPR investigations of the ancient Grandifolia Dunes (figure 4.2k) reveal internal structure similar to the Walking Dunes; both the modern and ancient dunes reveal characteristic parabolic dune internal structures such as high angle foreset beds. The base of the Grandifolia Dunes corresponds to the contact between dune sands and glacial till, as confirmed by hand auguring (Davis, 2000). The more
uniform orientation of foreset bedding planes suggests is that the Grandifolia Dunes migrated under conditions of very consistent wind patterns and amounts of vegetation, resulting in a uniform advance of the dune front.

GPR investigations have lead to new insights on the development and growth history of dunes in the Walking Dune Field. Although GPR data indicates that these dunes have had complex growth histories, it is hard to visualize the constantly changing overall dune morphology responsible for the internal structures imaged in the GPR data. In order to study changes in the dune morphology which are reflected in the changing orientations of internal structures such as foreset beds, many digitized and georeferenced aerial photographs spanning 74 years (1930 – 2004) of dune migration were studied using ArcMap GIS software. Using this software we were able to study changes in the dunes such as size, amount of free sand, amount of vegetation and position of the blowout. The ability to see the entire dune field as well as surrounding terrain enables us to make some broader observations on the origin and evolution of the Walking Dune Field as well as morphological changes to this region. The details of how GIS augmented our GPR findings and understanding of the evolution of the Walking Dune Field will be included in the discussion of GPR data in the following chapter.

* * * * * *
The extensive use of GIS and ArcMap software have allowed for the comparison of many aerial photographs and maps. These photos and maps date from 1848 – 2004, and enable us to study the morphological changes with in the Walking Dune Field as well as this entire geomorphic region that lies between the recessional moraine at Hither Hills and the terminal moraine to the west of Napeague Bay. Sirkin (1995), who revised the earlier work of Fuller (1914), identified these separate moraines as being connected by marine processes following sea level rise. Initially they had been cut by glacial melt water and existed as islands before being connected approximately 8-9 ka. Through the aerial photographs and maps of the Walking Dune Field, as well as GPR investigations we have been able to observe the most recent geologic changes to this region: erosion of the peninsula from high tides and storms, the growth of sand splits, and the development of various dune types including migrating parabolic dunes.

The georeferenced aerial photographs and maps have allowed us observe changes in the amount of vegetation and free sand (sand that can be transported by wind) on the dunes, and have aided in the interpretation of GPR data. As mentioned earlier in Chapter 2, changes in the amount of vegetation affect the development of dunes, in this case affecting the growth histories of the actively migrating dunes of this dune field, growth histories which we have been able to study using GPR imaging. Of particular interest to us was the use of GIS to compare changes in dune morphology observed in photographs with the changes in internal dune structure imaged in 2D and 3D GPR data. Our use of these techniques was focused on understanding the growth history and evolution of Dune 4 and Dune 5, the youngest and most rapidly changing dunes of this system. Our findings on these dunes are used to infer conditions for the development and migration of other older dunes in the Walking Dune Field.

Dune Development and Onset of Dune Migration

It is clear from the aerial photographs that Dune 4 and Dune 5 did not form as blowouts from the linear primary dunes, or from the “snow fence effect” as described by Black (1993, 1996) where the exposed linear pavements trap wind blown sediments which eventually build up in to a mound which migrates under the effective wind direction and eventually becomes a parabolic dune. This model of dune development is more likely to be possible for Dune 3 and the older stable dunes which may have formed under different conditions than the younger dunes. Dune 4 developed as a blowout on the
western limb of Dune 3, and Dune 5 developed as a blowout on the western limb of Dune 4 (figure 2.2d, 2.2e) The origin of Dune 3 is still unknown, but there are several possibilities. It may have formed from a blowout on a primary dune farther to the north in the dune field, by the “snowfence effect,” or it could have originated as a transverse dune. Distinct linear dune features in the 1848 map (figure 2.2b) do not suggest that Dune 3 originated as a transverse dune (under conditions of high winds and abundant sediments) but rather as a blowout on an existing linear primary dune. The inland position of the linear dunes may possibly indicate relic primary dunes from a time when the peninsula was smaller. The inland position of the linear dunes may also represent the mapping of only one arm (the one closer to shore) of a parabolic dune. It is difficult to say with any certainty how Dune 3 formed, however it is clear that it did form much farther to the north than Dune 4 and Dune 5 which may potentially have implications for understanding how the older Dune 1 and Dune 2 may have formed.

The origins of Dune 1 and Dune 2 are perhaps the most difficult questions to answer. In all of our aerial photographs and maps these dunes have been stable, providing a minimum age of stabilization at 167 years for both dunes, although it is likely that Dune 1 became stabilized before Dune 2. In order to provide a viable model for their development and onset of migration the ages of these dunes must be determined. By constraining dune ages we can better understand climate conditions which would have played and important role in the formation of these dunes. For example if the dunes were many thousands of years old, relicts of a post-glacial climate like the Grandifolia Dunes, sea level would have been lower and other models for dune formation are possible. During the late Pleistocene, when the Grandifolia Dunes formed, sea level was lower and winds were increased due to the high pressure air mass above the glacier. The abundant sediments that were exposed in what is now Long Island Sound would have easily been transported by these strong winds; from abundant ventifacts along the north shore we know that eolian processes have been operating on Long Island since the glaciers retreated (Fuller, 1914). It appears that the Grandifolia Dunes formed on the coastal plain that is now Long Island Sound to the north of the Harbor Hill Moraine during a time of lower sea level (Engelbright et. al., 2001). The near linear orientation of these parabolic dunes suggests they formed as a transverse dune and subsequently into a parabolic ridge that eventually became stabilized on the moraine before the dunes could evolve down wind to become basic parabolic dunes. These dunes became stabilized as they
encountered the moraine and also as winds coming off the glacier may have decreased as it retreated farther north, slowing their rate of advance and allowing stabilizing vegetation to take root.

A similar model of dune formation would be plausible for Dune 1 and Dune 2 if we can prove their onset of migration to be old enough (~1 ka) for sea level to be significantly lower than present for this to be plausible. At a time when the shallow Napeague Bay (1-3 ft in most places) was exposed these dunes may have been able to form as a transverse dune, then migrate on land were they were preserved as sea level rose. These dunes would have become stabilized by the onset of vegetation as the climate warmed and wind speeds from off the glacier decreased. They would have remained dormant for many centuries - perhaps millennia - until they were reactivated by changing climate conditions or possibly anthropogenic pressures.

Recent work has been done to clarify the age of these dunes; in May 2005 sand samples from Dune 1 were collected for OSL dating. From an augur hole at 88m (figure 4.2i) samples were collected from 5.5 m depth below the surface, and from 1.5 m depth below the surface at the 88m mark to attain dates on both the initial deposition as well as the cross bedding. Dr. Michel Lamonthe, University of Quebec at Montreal, reports that preliminary investigation of the 5.5 m deep sample suggests that it is hundreds, not thousands of years since that sand last saw sunlight. Although further work needs to be done in order to refine the age of the samples, it is clear that conditions were not the same as they were for the Pleistocene aged Grandifolia Dunes. This does not mean that that Dune 1 and Dune 2 could not have formed in a similar fashion. If the age of onset of migration can be proven to be of an age when sea level was low enough to expose much of Napeague Bay, it is plausible that these older dunes may have initiated as transverse dunes (under conditions of high winds and abundant sediments) and subsequently evolved into parabolic dunes as they moved down wind.

In order to predict as accurately as possible when the onset of migration was, in addition to the age of stabilization, rates of migration must be known. Unfortunately for the older Dune 1 and Dune 2 migration rates are not possible to attain since they have been stable throughout our record of maps and aerial photographs. From the migration rates of the actively migrating dunes we can infer how fast the older dunes may have migrated and estimate the time it would take for the older dunes to migrate to their current location from where we believe their origin to be. Using GIS to calculate the active dunes’ rates of advance by measuring the distance between dune fronts in successive aerial photographs, the
estimated age of the onset of these dunes can be determined. The older Dune 1 and Dune 2 may have originated from anywhere along the coast as a blowout of the linear primary dunes or by the “snow fence” effect where the exposed linear pavements trap sand which eventually build into a mound which then moves in the direction of effective winds these models where proposed by the earlier work of Black (1993, 1996). It appears however that these dunes may have formed from what is now Napeauge Bay at a time when sea level was lower and there was a much greater supply of available sediment which would in part explain why these dunes are much larger than the younger actively migrating dunes. Also Dune 1 and Dune 2 may have formed at a time when this area was significantly less vegetated explaining both their size and extent of inland migration. If it is the case that Dunes 1 and 2 formed in what is now Napeague Bay, then it will be difficult to determine a time for the onset of dune migration; we can only speculate where these dunes would have most likely formed and determine an age from that point.

If we are to assume that the conditions under which Dune 1 and Dune 2 migrated under where similar to that of Dune 3, the closest in age to these dunes, then we may be able to estimate the age of onset for these dunes if we make some further assumptions. Based on the position of Dune 3 in an 1891 map we can infer that Dune 1 and 2 may have also been likely to form farther north (up-wind) than this point, also we must assume that the rate of these dunes was the same as for Dune 3 during the time of its most rapid migration (1891 – 1930). The rate of migration for Dune 3 during this period of 1891 – 1930 is used because this was a time when this dune was mostly void of vegetation (from 1930 aerial photograph) and also apparently did not migrate over a forested area (from 1848 and 1891 maps). It is important that the migration rate be based on a period when this area was not forested because it is believed that Dune 1 and Dune 2 may have migrated over this area at a time when it was not yet as heavily forested (based on absence of hyperbola reflection (trees) in radargrams of Dune 1). The age of the onset for these dunes would be the OSL age (indicating the age of stabilization) plus the amount of time it would have taken to migrate to that location. We can attain an extreme lower-bound if we assume these dunes to form at exactly the same location of Dune 3 in the 1891 map. Similarly we can attain a reasonable upper bound on the age by assuming that these dunes initiated from the most northern point of the peninsula, if they did form here as opposed to somewhere in Napeague Bay, sea level may have been lower anyway providing and abundance of sediments that can explain the much
larger size of these dunes. At a rate of 5.6 m/y (the rate of Dune 3 during the period 1891 – 1930), from the location of Dune 3 in the 1891 map it would take 258 years to reach the current location of Dune 1; it would take 500 years from the most northern location on the peninsula. The duration of migration and age of onset are calculated for Dune 1 are of particular interest because they would indicate when the Walking Dunes began to form.

Based on the work of Gayes and Bokuniewicz (1991) which studied paleo-shore ling features in Long Island Sound, it would have been approximately 1000 years before present when sea level was low enough to expose much of Napeague Bay. From this information we can determine that the OSL ages must be about 500 - 742 years old for it to be possible that Dune 1 formed between the 1891 position of Dune 3 and the northern most part of the peninsula, or possibly in what is now Napeague Bay. The age of onset does not necessarily have to be time when all of Napeague Bay was exposed; a time when the Bay was smaller exposing much more of the shore line may have also provided enough sediment supply to explain the large size of these dunes.

It is apparent from the growth history, which we have studied using GPR, of the older Dune 1 and those of the younger Dune 4 and Dune 5, that conditions under which the dunes grew were possibly very different. From the numerous hyperbolas (indicating buried trees) present in the younger dunes, we can see that these dunes had significant interactions with trees from the forested area which they migrated over. As a result of these interactions with barriers to their migration, the growth histories of these dunes are characterized by changing orientations of foreset beds due to the lateral migration of blowout. Through out the radargrams of Dune 4 and Dune 5 (figure 4.3b and 4.3c), moderate to large changes in apparent dip angles can be attributed in part to the interactions with buried trees and in part to changes in vegetation on the dune crest which also affect blowout position on the dune crest. In contrast to the growth history of the younger dunes, the growth history of the older Dune 1 is characterized by more consistent foreset bedding plane orientations revealed within its 2D radargram (figure 4.2i). The more consistent orientations of these forest beds indicate that the conditions under this dunes growth were much more consistent than for the younger dunes. The absence of hyperbolic reflectors within the radargram indicates that this dune did not migrate over a forested area which may also explain the consistency of its forest bedding planes.
Dune 4 – A Growth History Characterized by a Migrating Blowout

Studying aerial photographs has shown that during the time period of 1966 – present the blowout of Dune 4 has been rapidly changing in response to different amounts of vegetation on the dune crest, as well as in the forest it was actively overrunning. The rapidly changing morphology of the dune crest was mainly due to the migration of the blowout in response to changes in the amount of vegetation. The migration of this blowout has been reflected in the changing orientations of slip surfaces revealed in GPR imaging (Figure 4.2a), as well as in aerial photographs (Figures 2.2e). This is very different from the idealized model of parabolic dune migration, where the slipface is continuous at the crest as successive depositions over the crest maintain the slipface shape and orientation; as the dune migrates the amount of sand that is removed from the windward slope and deposited over the dune crest is the same as the amount of new sand added to the windward slope. As a dune migrates in this manner it is able to retain the same profile since the addition of new sand to the dune equals the amount of sand deposited over the crest. This idealized model is based on unidirectional winds and consistent vegetation cover. When a dune retains the same profile as it migrates, as in the idealized model, it is said to be in steady state (Tsoar, 1985).

Any change in wind, sediment supply, or vegetation will cause a change in dune morphology – creating negative feedback that controls how a dune responds to return to a new state of balance where the input and output of material and energy are equalized (Tsoar, 1985). In the case of Dune 4 in the Walking Dune Field, this dune responded to changes in vegetation, wind, and perhaps anthropogenic pressures by a migration of the blowout to maximize energy efficiency until equilibrium (steady state) was achieved. It does not appear that Dune 4 has been in steady state for any long period of time. The packages of changing dip angles in shown in GPR data on Dune 4 (figure 4.2a, 4.2d) show that the blowout was changing position with respect to the dune axis for its entire recorded growth history. From the study of aerial photographs it appears that changes in blowout position have changed in approximately decadal intervals. For each set of uniform dip angles the dune may have been in steady state before it was forced out of this state by changes in vegetation and/or wind pattern. It is difficult to determine if Dune 4 is currently in steady state. If this is the case it is likely that it will not remain in this state for long due to the constantly changing vegetation as well as anthropogenic pressure of hiking trails which may active another blowout. It is possible that any spring season that was particularly rainy
could have allowed for increased vegetation providing a barrier to wind erosion which would force the blowout to change its position on the crest slightly to where there is less vegetation. Conversely an extremely hot and dry summer could have killed enough vegetation to allow for a new blowout to form, or for the enlargement of and existing blowout. The anthropogenic pressure of tourists hiking over vegetated parts of the dune may also be responsible for forming new blowouts. Reactivation of dune and the development of blowouts as a result of increased anthropogenic pressure specifically related to hiking trails has been documented in other studies. As a result of hiking trails, large linear (trough) blowouts and the inundation of coastal roads by migrating dunes have been observed at Prince Edward Island, Canada (N. Catto et al., 2002). In the Walking Dune Field the development of trough shaped blowouts along unmarked hiking trails has decreased the sediment availability for dunes farther downwind, increasing the likelihood of stabilization of these dunes.

*Sediment source for the actively migrating dunes*

The Walking Dunes, which have been poorly understood in terms of sediment source and age, have had some questions better answered from the study of maps and aerial photographs. When observed in an aerial photograph it is apparent that the size of the dunes in the Walking Dune Field is decreasing in the upwind direction indicating a starving of sediments to this system. An explanation proposed by the work of Dubecky and Maher (1994), was that the destruction of exposed pavements along the beach by off road vehicles is limiting the ability of exposed pavements to trap sands blown in from and off shore ridge. It appears that a more likely cause of sediment starvation is the closing of the inlet to Napeague Bay by the formation of sand spits which have nearly connected Goff point on the east side to Hicks Island on the west side of the bay. In figure 2.2b, an 1848 map of the study area, the inlet to Napeague Bay is clearly unobstructed and depths up to 17 ft. are indicated within the opening to the bay. The gradual closing of this inlet has been observed in aerial photographs from 1930 – present; in the 2001 aerial photograph of this area (figure 2.1a) the inlet is nearly closed by the formation of sand spits. The cut off of marine currents which bring sediments into Napeague Bay can explain the decrease in sediments that ultimately make it to the shore and then into the dune field where eolian processes ultimately create dunes. This evidence more conclusively explains the decreasing dune size in the Walking Dune Field. This inlet which was 400m wide in 1930 is currently only 50m at its widest point, strongly supporting this theory.
In addition it appears from the recent deposition of sand bars (visible in the 2001 aerial image) that the flow into and out of Napeague Bay has switched. In the past flow into the bay is interpreted to be on the eastern side parallel to shore, as indicated by a narrow but significantly deeper (17 ft) trough in the bay presumed to be formed from the high energy tidal and storm flows into Napeague Bay (figure 2.2b). The high energy water current which was fastest near the middle – bottom, deposited sands on the shore of Napeague Bay where the energy was less, just like a meandering stream deposits sand on a point bar as the stream channel erodes material on the other side of the river. As split forming marine currents moved elongated Goff’s Point to the west, they also extended Hicks Island to the east, nearly closing Napeague Bay. The extent of sand spit formation may have altered the way in which currents enter and exit the bay such that it appears that much of the sediments entering the bay are either forming the sand spit extending of Hicks Island, or are being deposited on the west side of the bay where they can not contribute to dune growth.

The presence of linear NW-SE trending dunes which appear discontinuous (eroded primary beach dunes of paleo-shore) on the 1848 map may have contributed to the source of sediments for the reactivation of the oldest dunes. Another possible source of sediments for the oldest dunes may have been the sands submerged below what is now Napeague Bay. If the onset of migration for Dune 1 and Dune 2 was at a time when sea level was low enough to expose the floor of the shallow Napeague Bay, then this would have been a likely source to provide large amounts of sediments to the dunes which may explain their size compared to the younger dunes.

**Anthropogenic Pressures**

It is not entirely known the extent to which this area of land was used during the mid 19\textsuperscript{th} and early 20\textsuperscript{th} centuries, but the presence of fish factories and roads in early maps (1891, 1928) suggest that anthropogenic pressures may have influenced dune development in some ways. Although further research is necessary to learn about the use of this land, we can infer that if these factories cleared any land for the building of the factory, it could have exposed enough sand to initiate dune migration, which may explain the development of Dune 3. The clearing of land for roads and
subsequent use (and erosion) of these early unpaved roads may explain the reactivation of the older Dune 1 and Dune 2 since the location of roads indicate they were very close to these dunes.

The locations of roads from old maps show an increased use of this land area from the time 1848 – 1930, a time when we see the development of Dune 3 (not shown distinctively on maps until 1891). The sediment availability for the growth of and possibly onset of Dune 3 may have been a direct result of de-vegetation caused by the creation access roads, and land clearing for the fish factories of the mid 19th century. Numerous roads/trails can bee seen in maps indicating heavy land use, especially to the north where sediments may have been made available by erosion of the land from traffic related to the factories. However, the close proximity of Dune 3 to the linear beach dunes of the 1891 map (figure 2.2f) does suggest that it may have formed as a blow-out on one of these dunes. The factories just to the north may have merely provided the means of erosion necessary to provide large amounts of sediment to this naturally formed dune.

The extent to which anthropogenic pressures have affected the younger Dune 4 and Dune 5 are largely related to hiking trails which destroy vegetation and lead to the development of blowouts. The two blowouts to the north of Dune 5 are directly related to hiking trails over portions of the dune which rely on vegetation for their support. The migration of the blowout on Dune 4 may in part be related to people hiking over the dune and killing vegetation, but is likely most affected by trees encountered as this dune migrated over a forested area and changing wind dynamics following the development of the upwind Dune 5. The development or Dune 5 to the northwest created a wind shadow on the west side of Dune 4 - the result being that winds became more focused on east side, resulting in the formation of a new blowout. There is a hiking trail located on the southwest portion of the crest of Dune 4 which has been affecting the development of stabilizing vegetation and leaves this area prone to blowout development.

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Ch. 6 Addition Considerations

**Dune 2 and Dune 3**

There exist many questions about how Dune 2 and 3 evolved as they migrated which can help us understand the conditions of the dune field at that time. It is unclear if Dune 2 owes its height to unique conditions that enabled it to grow large or if it is superimposed over glacial deposits like Dune 1. Also it is unclear if vegetation from the forested area played a significant role in the morphology of these dunes as it did for the younger Dune 4 and Dune 5. GPR investigations will enable the understanding of this dunes growth history, and give insight to the conditions which may explain its morphology. It will be interesting to know if this dune is in fact composed of one large main blowout or if it is characterized by a migrating blowout like Dune 4. OSL dating of Dune 2 will be a great aid in understanding how this dune may have formed and possibly when was the onset of its migration. Although the evolution and stabilization of Dune 3 can be observed in aerial photographs from 1930 – 2005 and the climate conditions of the past 75 years are well known, it would be interesting to compare, through GPR imaging of internal structure, how this dune evolved under the same conditions as Dune 4, only without a sediment supply.

**Dune 1**

Future studies of Dune 1 are already planned for the summer of 2005. GPR data is planned to be collected on the eastern and western blowouts in addition to the 200 MHz data from the central blowout in order to see if these blowouts are similar to each other which we would expect if they migrated in as a parabolic ridge under the same conditions. Of particular interest to image with GPR is where the blowouts are overlapping, it will be important to determine if they appear superimposed on one another which would indicate that a younger dune overran an older dune, or if they have continuous slip faces that overlap indicating that they are in fact a parabolic ridge as hypothesized earlier. There is a large area on the windward slope of Dune 1 that is suitable for a 3D GPR survey, which would yield the most complete image of internal structure and be a great aid in understanding this dune better. This GPR imaging combined OSL dating of each blowout will allow a complete picture of how this enigmatic dune formed.
**Erosional surfaces Imaged below Dune 5**

The reflectors, interpreted to be erosional surfaces cutting of pre-dune stratified sediments, below Dune 5 (figure 4.3c) give insights to the geologic processes that occurred in this area before the formation of migrating dunes. It is not clear what created these erosional surfaces, but they may be related to periodic draining of glacial lakes which eroded glacial deposits as fluvial waters made their way down the coastal plain to the Atlantic Ocean. The orientation of one of these surfaces was found to be striking $166^\circ$ and dipping $16^\circ$ (from crossing GPR radar lines), indicating that they are not in the same orientation as the shore line or the exposed linear pavements. Further investigation of these erosional surfaces to determine if they are in the same orientation or varying orientations, as well as the depth below the surface which they terminate, will aid in a more accurate geologic interpretation.

**Pavements**

The role of pavements in the formation of the Walking Dunes has been discussed in this paper and in previous work (Black 1993, 1996; Dubecky and Maher, 1994), however the origin of these pavements is still unknown. They appear to be reworked by marine processes into the linear trending orientation that is parallel to the present shore line, but must have initially been deposited as a glacial as a pavement due the large cobble size being unlikely to be transported by marine processes. GPR investigations both parallel and perpendicular to these pavements will enable us to understand their lateral extent below the ground surface and more definitively determine a mechanism for their deposition and current orientation.

**Factories and Roads**

Along the shore of Napeague Bay, adjacent to the present parking lot, various remnants of the old factories and roads can be found exposed in the primary dune. The exposed pipes and metal plates are indicators that the locations of “Marcy’s Factory,” indicated on the 1891 map (figure 2.2f) is accurate. These pipes and metal plates along with the presence of an asphalt road below the linear primary dunes indicate that the primary dune near to the parking area is younger in age than the pipes which it encapsulated and the road beneath it. These age relations are significant because it indicates that the primary dunes along the shore of Napeague Bay may be approximately the same age, or possibly younger than Dune 3, the only actively migrating dune during the time the factories were
operating. It is unclear from the aerial images when these dunes where forming, but it appears as if the dunes migrated rapidly over the factory land and roads due the builders not planning on this rapidly changing landscape. This implies then that these dunes could not have then been a source of sediments or place of onset for the older Dune 1 and Dune 2, based on our “index fossils.”

**OSL Dating of Dunes**

Only through a technique such as OSL dating can we determine the age of stabilization for the oldest dunes of the Walking Dune Field. This information will be useful not only in understanding the conditions under which these dunes formed and migrated, but also in determining if the Walking Dunes are a time-transgressive dune field. This would confirm my current belief that the Walking Dunes are characterized by periods of dune formation and migration followed by periods of significantly decreased eolian activity where dunes become stabilized or dormant until conditions are such that they become reactivated during periods when new dunes are also forming farther to the north. The recent development of Dune 4 is, at a extreme lower bound, 39 years younger than Dune 3 based on the 1891 coastal survey map (which shows Dune 3 well developed and simple form) and the 1930 aerial image which clearly shows the beginning stages of a developing blowout (Dune 4). Since we can not definitively say where Dune 3 initiated from it is not possible to date the onset of its migration. The extreme lower bound is only presented to show that these dunes are different in age with Dune 3 likely being atleast 100 years older than Dune 4 based on average migration rates and the time it took Dune 4 to develop into a dune comparable in size to Dune 3 in the 1891 map. Dune 5, which is largely contemporaneous with Dune 4, is at a minimum 36 years younger based on the time between Dune 4 development in 1930, and the 1976 aerial which shows Dune 5 first forming. It is hypothesized that the age of stabilization for Dune 1 will be significantly greater than the age of stabilization for Dune 2, which we know to be greater than that of Dune 3 from maps and aerial images. Dune 3 is also clearly much older than Dune 4 and 5 supporting the theory of the time transgressive nature of dune formation in the Walking Dunes. Further OSL dating of samples from Dune 1 and Dune 2 and possibly other areas of the Walking Dune Field, as well as dunes to the west of Napeague Bay, will help constrain the times of dune development and migration which is crucial in understanding how these dunes may have formed.
Dunes to the west of Napeague Bay

The presence of dunes to the west of Napeague Bay suggests that at one time this dune field may have been much more extensive, spanning across what is now Napeague Bay. Dunes were mapped in the area south and south west of Hicks Island in the 1838 coastal survey. Although some of these appear in nearly the same location in current aerial photographs (they have been stable during this time interval) other dunes appear to have been migrating inland, presumably originating from the shore, forming a parabolic ridge. This parabolic ridge may be contemporaneous with the formation and migration of Dune 3 which also was appears base of vegetation in the 1930 aerial photograph, but subsequently began to stabilize not long after as increased vegetation is very apparent in subsequent aerial images. Farther aerial images over the area of the parabolic ridge from 1930 – present will have to be studied to determine similarities with these dunes and Dune 3. OSL dating is needed to determine whether the dunes that appear to have been stable since 1848 are indeed as old as they appear to be; these ages will help determine if the Walking Dune Field may have once much larger at a time when sea level was lower exposing much of Napeague Bay.

The Fate of the Walking Dunes

The Walking Dunes of Hither Hills State Park are a remarkable geologic feature of Long Island which are unfortunately always in jeopardy of being eroded away (as is the case for all dunes). The location of these dunes, on eastern Long Island, is prone to significant storm damage during the perennial “hurricane season” which last from late August to October. The historic hurricane of 1938 did much damage to Long Island, but especially to eastern long Island where inlets were created by breaching the barrier beaches and inland flooding caused damages to property and homes. The Walking Dune Field was reportedly flooded following this storm (Black, conversation) which may have caused extensive erosion to dunes, as well as killing of vegetation which would have played and important role in dune stabilization. Fortunately there have not been any major hurricanes since 1938 to cause this much damage to coastal Long Island or to the Walking Dunes, but the chance of a major hurricane causing significant erosion to the these dunes is still possible.

Perhaps the main cause of erosion and cause of concern for the preservation of these dunes are the hundreds of tourists each summer who trounce all over the dunes with disregard for hiking trails which are carefully located to avoid damage to stabilizing vegetation. The irresponsibility of hikers not
staying on these trails has led to the formation of blowouts on Dune 5 which are starving it and Dune 4 of sands. Blowouts are likely to develop on Dune 4 as well, specifically along a hiking trail that leads hikers over a heavily vegetated limb of the dune and onto the crest. If an additional blowout were to occur at this location the crest of Dune 4 would likely be rapidly eroded down as the winds focused through the limbs of this dune would transport sand away from this dune, deflating the crest in the process. A run away situation could occur such that once erosion lowered the height of Dune 4 enough such that it not longer affected the near surface wind flow, winds would now be able to cause erosion on Dune 2 (the closest downwind dune) causing its eventual deflation and the erosion of Dune 1. Although it is difficult to predict an event like this from happening, it is easy to prevent. Preventative measures such as shutting down hiking trails which jeopardize the dunes, and not allowing the use of off road vehicles (which cause erosion to the shore of Napeague Bay and the destruction of pavements which may play a role in dune development) will certainly enhance the chances of these dunes being preserved for the indefinite future.
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