

THE DEVELOPMENT AND STABILITY
OF A COOL-WATER CARBONATE BEACH SYSTEM, MAINE

By

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B.S. Boston University, 1998

A THESIS

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

(in Geological Sciences)

The Graduate School

The University of Maine

August, 2000

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An Abstract of the Thesis Presented
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Sand Beach is a cool-water carbonate beach system that lies on the southeastern side of Mount Desert Island, Maine. Adjacent south-facing beaches on Mount Desert Island, Otter Cove and Hunter's Beach, have a similar offshore supply of comminuted shell material but are composed of terrigenous rather than calcium carbonate. Therefore, the existence of Sand Beach raises the question of why there is a high-latitude carbonate beach system in this area. This study uses vibracores, surface samples, ground-penetrating radar and topographic beach profile data to address this problem. Vibracores and ground-penetrating radar suggest that this beach has built up on former glacial deposits. Dune material overlies lagoon and tidal flat material, which lie unconformably on glacial-marine clay and till deposits. The barrier most likely migrated into its present bayhead position during Holocene sea-level rise. In recent history there is a dynamic stability of carbonate input and degradation.

Profile data between April and December 1999 show that at Sand Beach large volumes of sand accreted during the summer when there was a westward-moving current within the cove. In late fall and winter months, there was a loss of material at the berm, but a gain towards the vegetation line. The total flux of sand in the beach system was

16,675 m³ while adjacent Otter Cove Beach showed only marginal seasonal change in beach volume.

Sand Beach is mostly a combination of reworked glacial material and bioclastic remains of barnacles, echinoderms and molluscs. The overall carbonate concentration decreases from 70% in the nearshore zone to 30% in the backbarrier region. This change in concentration is most likely a result of selective transport processes within this beach system. Downcore the carbonate concentration was mostly constant with the exception of a drop at the water table to 5-15%, possibly due to dissolution. The Sand Beach data suggest that cool-water carbonate beach development is dependent on a high benthic productivity to counterbalance degradation of carbonate and dilution of the carbonate concentration from terrigenous input.

ACKNOWLEDGEMENTS

This project was by no means a single effort. I would like to thank my committee D. Belknap, J. Kelley, and J. Allen for their patience, enthusiasm, and guidance over the course of this project. Numerous volunteers offered their afternoons (in some truly bad weather conditions) to help take beach profiles including E. Hildreth, L. Ogden, M. Kelley, D. Reusch, R. Nestor, A. Gontz, N. Gardner, and H. Heinze. I would like to especially note J. Daly for her time and assistance with processing the ground-penetrating radar data and obtaining cores. This project would not have been possible were it not for the support and interest of the officials of Acadia National Park. The Association of Graduate Students provided partial funding for this project. The Maine Geological Survey's loan of aerial photographs from 1966 and 1983 was most appreciated.

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1. INTRODUCTION

Early paleoclimate studies assumed that carbonate beaches were indicators of tropical settings (Leonard et al., 1981). Are carbonate beaches simply a low-latitude phenomenon? The discovery of cool-water carbonate beaches around the world raises questions concerning the abundance and stability of high-latitude beach systems (Friewald, 1998; Fornos and Ahr, 1997; Gillespie and Nelson, 1997; Barnhardt and Kelley, 1995; Barnhardt, 1992; Farrow et. al., 1984; Nelson, et. al., 1988; Smith, 1988; Bornhold and Yorath, 1984; Merefield, 1984; Leonard and Cameron, 1981; Leonard et al., 1981; Milliman, 1974; Lees and Buller, 1972; Chave, 1967; Raymond and Stetson, 1932). Understanding the nature of temperate-water carbonate beach systems will provide important parameters for separating tropical carbonate beaches from their cool-water counterparts. In order to achieve this task it is necessary to examine the development of these systems as well as their stability. 1) Are high-latitude carbonate beach systems ephemeral? 2) What conditions are needed for cool-water carbonate beaches to develop?

I have studied a cool-water carbonate beach system on the coast of Maine, using field and laboratory analyses, to help answer these questions. Sand Beach is a natural beach lacking significant engineering structures, making it ideal for studying the behavior of cool-water carbonate beach systems. This study tests the hypothesis that climate, terrigenous input, and benthic productivity play critical roles in the development of a high-latitude carbonate beach. The formation of temperate-water beaches requires a high benthic productivity to counterbalance terrigenous clastic sediment input and dissolution.

If terrigenous input were too great, the material would dilute the carbonate concentration (Milliman, 1971; Chave 1967).

Climate also plays a role in the dissolution of carbonate. The solubility of carbonate is sensitive to temperature, pH, salinity, and wave agitation. A relatively high production of material is necessary to counterbalance any dissolution that might occur (Smith, A.M., 1988). If the dissolution rate became higher than the production rate, the carbonate beach system would retreat. Assuming a stable sea level, the beach system should advance if the input of calcium carbonate is greater than dissolution. A state of equilibrium (no net sediment gain or loss) would be possible if the two forces were in balance. Sand Beach on Mount Desert Island, Maine appears to have the perfect balance of terrigenous input, benthic productivity, and dissolution.

Adjacent to Sand Beach are two pocket beaches that have properties similar to Sand Beach: a high offshore production of calcium carbonate, a south-facing shoreline, the same temperature and climatic setting, and similar salinity. Nonetheless, the beaches adjacent to Sand Beach are lacking in carbonate material. Are these beaches simply out of equilibrium between dissolution, terrigenous input, and production? Were these beaches once calcareous? These beaches provided a control for Sand Beach data but also were a means for understanding other factors related to cool-water beach formation.

2. PREVIOUS STUDIES

2.1 Temperate vs. Tropical Carbonate Beaches

There are several minor differences between temperate and tropical carbonate beaches. Ooids and pellets are rare in temperate-water settings. Cool-water carbonate beach systems also have different constituents than common tropical carbonate beaches. Lees and Buller (1972) classified two possible types of carbonate beach assemblages: foramol and chlorozoan. Temperate water organisms belong to the foramol group and include mollusks, echinoderms, foraminifers, calcareous red algae, and barnacles. Organisms that are characteristic of the chlorozoan group are corals and green algae. Species that are found in the chlorozoan grouping are generally confined to low-latitude, tropical regions. Although foramol species are also found in tropical regions, they tend to be less important contributors in warm-water environments (Lees and Buller, 1972).

Isotopic variations exist between high and low-latitude carbonate beaches. Gillespie and Nelson (1997) found that cool-water carbonate material in New Zealand was enriched in ^{18}O and depleted in ^{13}C compared with low-latitude beaches. These differences are most likely a response to temperature, salinity, and carbonate mineralogy (Gillespie and Nelson, 1997; Lees, 1975). The variations between the assemblages found in temperate versus tropical carbonate beach systems are also partially related to dissolution rates and conditions affecting CO_2 solubility.

2.2 Carbonate Preservation Potential and CO_2 Solubility

2.2.1 Factors Affecting Solubility

Factors affecting the solubility of CO_2 in water include pH, salinity, temperature, and wave agitation. Conditions favorable for carbonate material to remain stable require a high salinity, high temperature, high pH, and moderate wave activity. The solubility of

calcite shows an exponential decrease with increasing salinity (Millero, 1979). Therefore one would expect to see high carbonate concentrations in tropical areas where salinity is high (Lees, 1975). Similarly, the role of pH does not follow a linear trend in relation to the solubility of CO_2 (Morse, 1974). Because pH varies greatly from offshore to the backbarrier region of a beach system (lowering onshore), it is likely that dissolution of carbonate material increases from offshore to onshore, where freshwater fluxes and acid rain could play a role in destroying carbonate material.

Wave agitation decreases the solubility of CO_2 , favoring production of carbonate. Waves play an additional role by flushing out terrigenous fines that dilute the carbonate concentration of the sediment. However, high wave energy may cause negative impacts on the carbonate material. Too much wave activity can lead to abrasion and fragmentation of carbonate material. This abrasion will increase the surface area of particles, allowing dissolution to occur more rapidly (Walter and Morse, 1984). Merefield (1984) suggests that the existence of shell hash on beaches may primarily be related to the relative resistance of particles to abrasion. Barnhardt (1992) agrees that shallow water destruction of CaCO_3 is mostly a result of abrasion. Chave (1964) tested this theory in the laboratory by using a tumbling barrel to monitor the effects of the abrasion of silica-rich sand on various shell fragments. Barnacles were most resistant while sea urchins disappeared within 10 hours and red algae in one hour. Chave's experiment implies that the preservation potential for barnacles would be much greater than that of other benthic species.

Temperature is the most important control on the production and dissolution of carbonate (Burton and Walter, 1987). Chave (1954) investigated the role of temperature

on individual carbonate species by comparing the percentage of MgCO_3 of shells of particular species at different temperatures. Of the species investigated, barnacles showed the least drastic change in composition with temperature. Barnacle fragments are typically one of the main constituents of cool-water carbonate beach systems in Maine (Barnhardt, 1992), Southwest England (Merefield, 1984) and Scotland (Farrow, 1984). The resistance of barnacles to dissolution at cold temperatures provides an answer as to why the preservation potential of this species in temperate beach settings is higher than other species.

2.2.2 Preservation Potential

One reason that there is preferential preservation of various species is directly related to the shells' composition. Aragonite species are more common in low-latitude settings (Wray and Daniels, 1957). Aragonite is less stable than magnesium calcite at low temperatures. In cool waters, aragonite may convert to magnesium calcite due to changes in carbonate solubility as a function of temperature (Nelson et al., 1988; Burton and Walter, 1987; Farrow et al., 1984; Wray and Daniels, 1957). At cold temperatures shells made of low-Mg calcite are more resistant than those made of aragonite (Nelson et al., 1988; Farrow et al., 1984). Gillespie and Nelson (1997) concur that in New Zealand, facies dominated by low-Mg calcite secreting species had a greater preservation potential than facies containing infaunal bivalves that were predominantly aragonitic.

Can these relationships between aragonite and temperature be tied to low-latitude versus high-latitude carbonate beaches? Roselle (1985) points out that due to factors such as salinity and pressure, there is no continuous increase of aragonite with

decreasing latitude. Although aragonite may be tied to the chlorozoan-type species, its concentration alone cannot be used as an indicator for a temperate or tropical carbonate beach system.

Multiple factors may account for the loss or gain of specific carbonate species on a beach system. Three critical factors appear to be temperature, the composition of shell fragments, and the mechanical abrasion of material. The association of barnacles with foramol environments is not surprising. Barnacles show the most durability towards abrasion (Chave, 1964), exhibit little change in composition with temperature (Chave, 1957), and are composed of mostly low-Mg calcite. Therefore, barnacle fragments would demonstrate more resistance to dissolution and corrosion than skeletal remains of other carbonate species, which are more vulnerable to dissolution and abrasion. Provided that barnacle production existed offshore, preservation of their skeletal fragments is more enhanced than that of other species. In high latitude areas, species more susceptible to dissolution and abrasion would require a high productivity offshore to counterbalance their low preservation potential.

Temperature, pH, salinity, wave agitation, and depth are critical factors for the precipitation and dissolution of carbonate. These factors account for whether carbonate can form and provide conditions in which skeletal material of particular species may dominate the carbonate concentration. Other parameters concerning the preservation potential and or dissolution rates of shell fragments are composition of shell material and resistance to abrasion. The combination of these factors may account for

discrepancies between onshore and offshore records of carbonate species and also provides clues for the variation between species dominant in temperate versus tropical environments.

3. PHYSICAL SETTING

3.1 Sea-Level Rise and Glaciation

Many of the deposits and features in Maine are a result of the Late Wisconsinan Laurentide Ice Sheet. The ice sheet, at its maximum, filled the Gulf of Maine roughly between 18,000 and 20,000 B.P. (Hughes et. al., 1985; Denton and Hughes, 1981). The ice sheet deposited a thin, discontinuous layer of till over Maine (Thompson and Borns, 1985). The weight of the ice sheet caused downwarping of the crust (Stuiver and Borns, 1975; Bloom, 1963). The ice sheet then retreated rapidly to the present coast of Maine around 14,000 B.P. (Belknap et al., 1987).

After 14,000 B.P., there was a marine transgression followed by a regression and a second transgression (Barnhardt et al., 1995, 1997, Kelley et al., 1992, Belknap et al., 1987) (Fig. 1). Rapid glacial retreat between 13,500 and 12,500 B.P. allowed the sea to invade the land. Rebound soon equaled the rate of sea-level rise, causing a stillstand or marine limit that varies from 60-130 m in Maine (Thompson and Borns, 1985). The deposition of glaciomarine sediment called the Presumpscot Formation (Bloom, 1963, 1960) marks the extent of this limit.

When isostatic rebound became dominant, sea level started to fall. The sea level fell to approximately 60 m below its present day level based upon lowstand terraces, paleodelta deposits and dated shallow-marine fossils (Barnhardt et al., 1995, 1997). Estimates for the timing of the lowstand suggest that it occurred at 10.8ka (Barnhardt et al., 1997, 1995; Kelley et al., 1992).

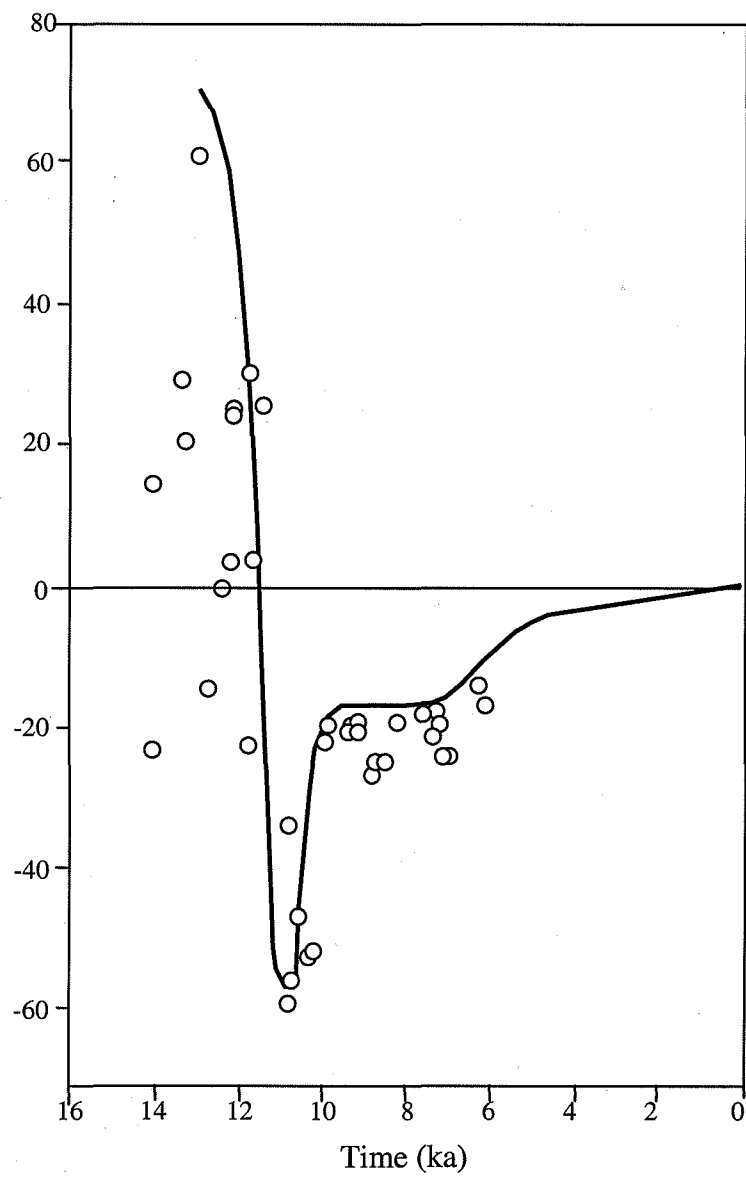


Fig. 1 Sea-level history for the Gulf of Maine showing elevation versus time (modified from Barnhardt et al., 1997).

This fall was followed by a second marine transgression. The second sea-level rise was a result of eustatic changes. This rise was at first rapid, followed by a slower rise. The rise slowed at approximately 9.2ka, allowing intertidal and shallow-marine communities to thrive in estuarine and bluff-toe habitats (Kelley et. al., 1992). After 8.5ka, glacial deposits were reworked into the present day shorelines (Kelley et al., 1992). Currently sea-level rise on the coast of Maine ranges from 2-3 mm. per year (Belknap et al., 1989). This rise has serious implications for the stability of our present day shoreline.

The glacial and sea-level history of the area heavily influenced the topographical features of Mount Desert Island. U-shaped valleys are common. Glacial scour exposed most of the bedrock on the island, leaving few sediment deposits behind (Lowell, 1989). However, there are thin deposits of till and glaciomarine sediments on the island and offshore. Moraines are visible in the valley behind Otter Cove. Outwash and kame terraces form bluffs marking the sides of Newport Cove. Close to the low-tide line on Sand Beach and in Otter Cove till deposits are visible on the beaches. Offshore seismic records indicate high-relief bedrock is overlain by till followed by the Presumpscot Formation and Holocene deposits (Barnhardt and Kelley, 1995; Barnhardt, 1992).

3.2 Coastal Compartment

Kelley (1987) classified the Maine coastline into four coastal compartments based on the underlying bedrock and coastal features associated with the regions. Mount Desert Island is within the Island Bay Complex (Fig 2). This area consists of Devonian granite with small outcrops of Precambrian to Ordovician metamorphic rocks (Osberg, 1985).

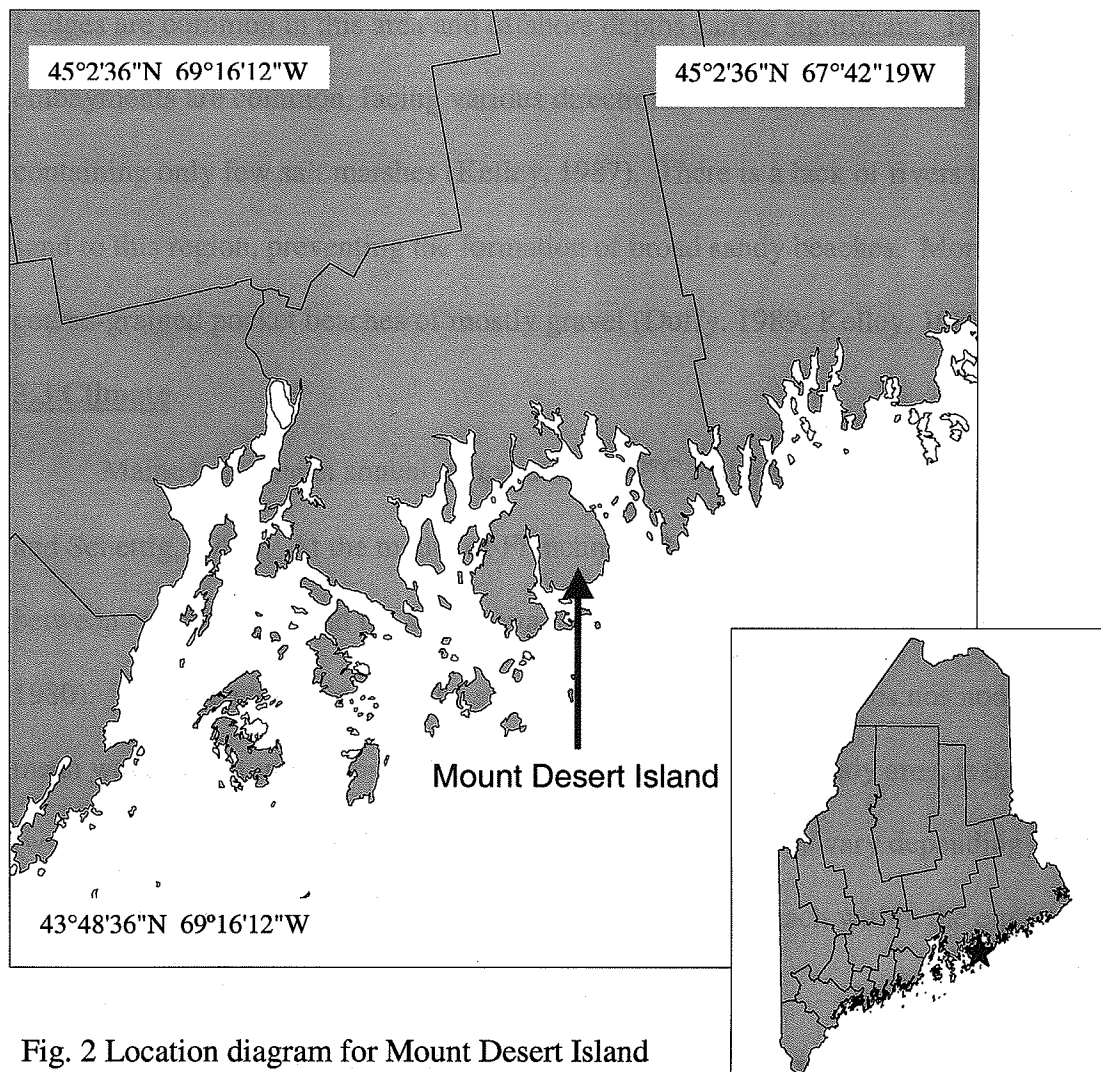


Fig. 2 Location diagram for Mount Desert Island

Ledges are common in this area and offshore depths can be significant. Broad, deep embayments are common, facing various directions. The shoreline is tidally influenced, containing only few salt marshes (Kelley, 1987). There is a lack of rivers to distribute sand to this region, preventing the formation of broad sandy beaches. More common are coarse-grained pocket beaches of mostly gravel (Duffy, 1989; Kelley, 1987).

3.3 Climate

Maine has a mean annual temperature of 7°C and precipitation of 112 cm (Fefer and Schettig, 1980). At the mouth of Frenchman Bay the water temperature ranges between -1° and 12°C and the salinity varies between 31 to 33 ppt (Fefer and Schettig, 1980). The mean tidal range of the study area is 3.3 m (www.co-ops.nos.noaa.gov) and mean wave height in Penobscot Bay, which is adjacent to the study area, is 0.61 m (www.co-ops.nos.noaa.gov). Actual wave heights in the coves vary depending on the fetch as well as the location and orientation of the pocket beach within the embayment (Kelley, 1987; Belknap et. al., 1986).

During the summer, S-SW winds create low-energy swells offshore (Barnhardt and Kelley, 1995). The wind pattern switches to a N-NW direction during autumn and winter months. Nor'easters are common, creating strong winds and heavy surf conditions. Although hurricanes and tropical storms are less common, during September 1999, in the midst of this study, Tropical Storm Floyd (which had started as a category 4 hurricane in Florida) struck the coast of Maine, creating large waves and heavy surf.

3.4 Mount Desert Island

Mount Desert Island is the largest island in the west-central coastal compartment (Kelley, 1987). The bedrock is mostly Devonian granite that intrudes Precambrian

Ellsworth Schist (Osberg, 1985). Siluro-Devonian sandstones of the Bar Harbor formation overlie the schist. Cutting through all the rock types are large basaltic dikes (fig. 3).

Barnhardt (1992) found high carbonate concentrations offshore of the south side of Mount Desert Island (Fig. 4). High percentages of barnacles, echinoderms and bivalves in bottom samples collected at the mouths of Hunter's Beach, Otter Cove, and Newport Cove suggest there is either: 1) a high benthic productivity offshore or 2) a proper wave climate to concentrate shell fragments (Barnhardt and Kelley, 1995; Barnhardt, 1992). Carbonate production may be aided by the presence of rocky substrates offshore, which provide suitable habitats for benthic organisms. The presence of rocky ledges coupled with a large tidal range provides a large habitat for animals dwelling on "hard bottoms" (Leonard and Cameron, 1981).

3.4.1 Sand Beach

Sand Beach is a pocket beach in Newport Cove on the southeastern side of Mount Desert Island, Maine (Fig. 5). The cove reaches depths of 10.7 m offshore. The beach is within a U-shaped valley hosting a marsh and lagoon system. The barrier beach is approximately 300 meters long from east to west. Two headlands mark either side of the barrier system. Great Head is a stubby headland on the eastern side and is 425 m long. The headland on the western side, which extends to Otter Cliff point, protrudes 2500 m offshore. These features, like the majority of the island, are made of Devonian granite cut by basaltic dikes (Gilman et al., 1988; Osberg et al., 1985). The headlands pose steep cliffs on either side of the embayment which bottom into rocky ledges on the western side of the cove.

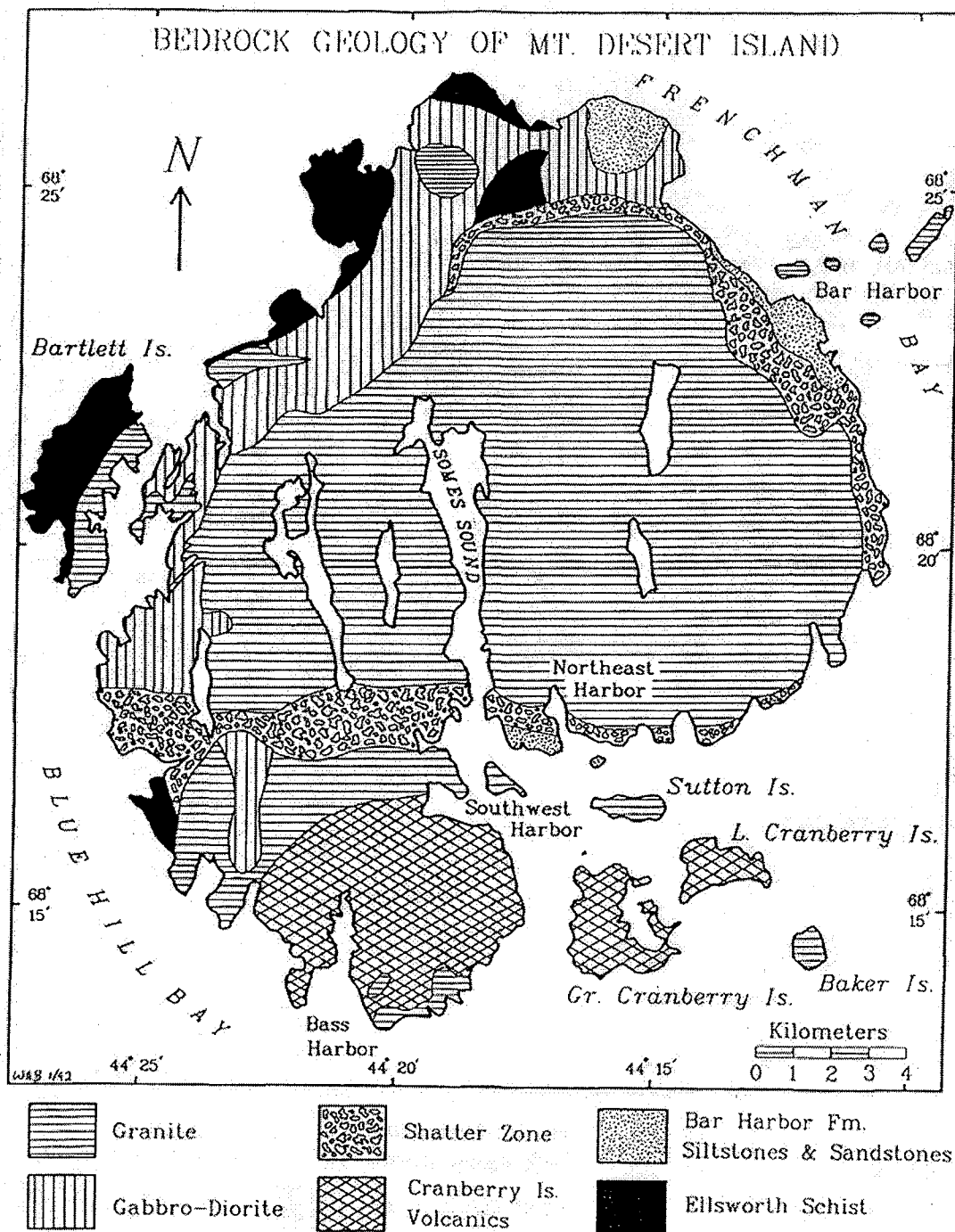


Fig. 3 Bedrock geologic map of Mount Desert Island.
(modified from Gilman et al, 1988)

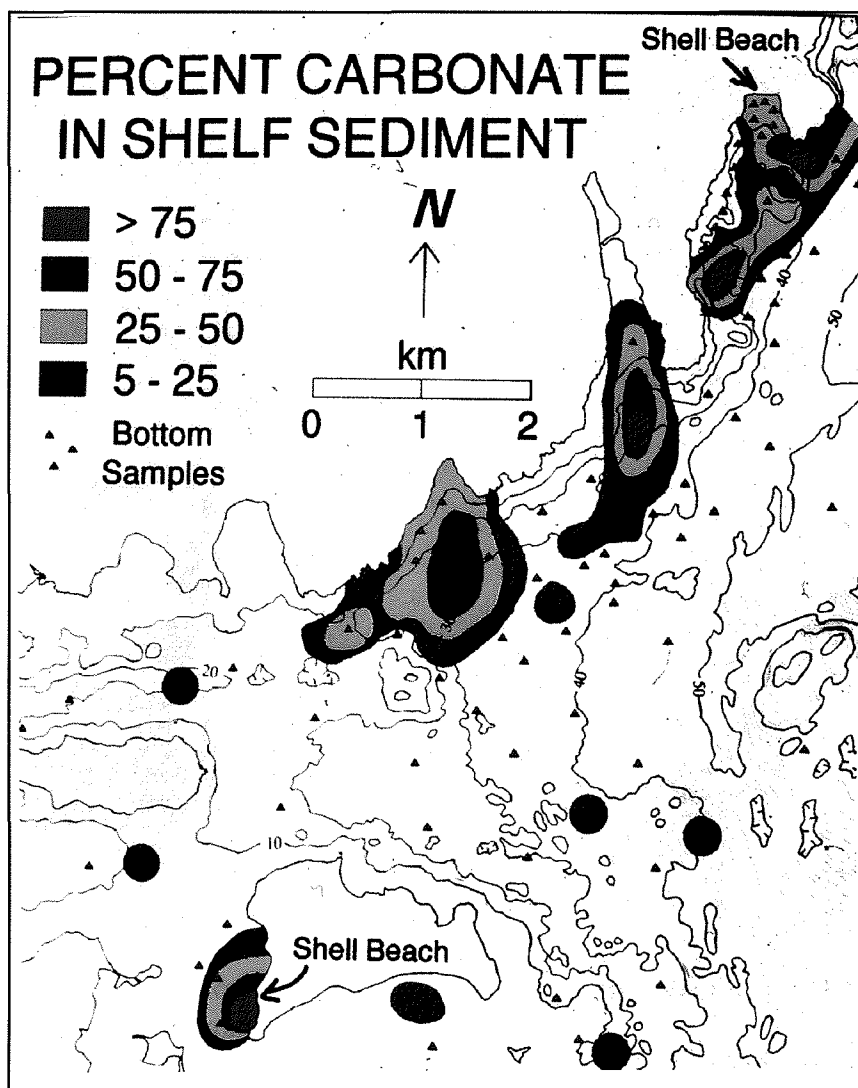


Fig. 4 Offshore carbonate concentrations based on bottom samples (Barnhardt, 1992).

44°20'N 68°09'35"W

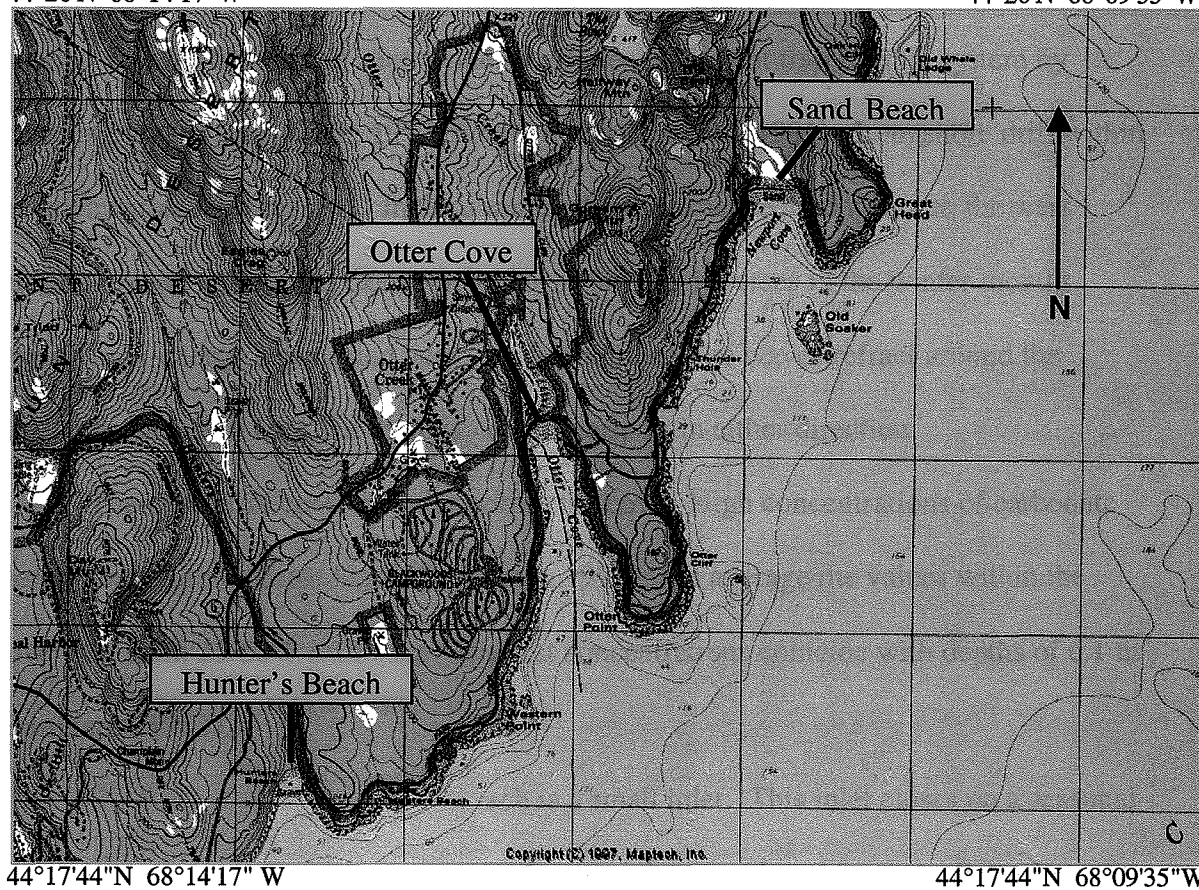


Fig. 5 Location of field sites on Southeastern side of Mount Desert Island. USGS topographic map, 15' quad.

Offshore there is an islet called Old Soaker located directly in front of the beach system. The headlands and islet create an efficient sediment trap for this system by refracting waves (Barnhardt, 1992; Leonard and Cameron, 1981). Longshore drift within the cove varies with seasons. In the summer there is a net sediment flux to the west within the cove (Allen and Connery, 1991). This flux reverses in the winter months. During high-energy storms and heavy surf conditions, the waves refract around the headlands in such a way that there is no net transport in either direction.

The carbonate content varies within the cove. High concentrations of carbonate were found close to Great Head (Barnhardt, 1992). On average the values within the cove vary from 25-50% carbonate. Highest concentrations coincide with depths of 6.1 m (Barnhardt, 1992).

On the eastern side of Sand Beach is a small inlet. This inlet closes on a seasonal basis (Appendix A). During the field study, this inlet was closed from the first week of June until mid-October. When open, the inlet allows the exchange of waters to a lagoon behind the barrier system. Previous research (Allen and Connery, 1991) found that the inlet is closed through the summer and early fall and opens in the winter and spring. The opening of this inlet may have important implications for seasonal sediment transport.

A wooden fence separates the backbarrier from the beach face. The fence is meant to deter tourists from walking on the dunes behind the beach. The tourist season at the park is at its peak between May and September. Human activity may be an important factor in understanding this beach system. Prior to the early 1980's, the dunes were subject to trampling due to several footpaths in the backbarrier. Since that time, the Park built a fence at the vegetation line in order to try to deter tourists from walking in

vulnerable areas. However, dune grasses are trying to grow seaward of the fencing but may have difficulty thriving due to trampling from tourists.

The dunes are heavily vegetated with *Ammophila breviligulata* and small quantities of *Lathyrus japonicus*. Closer to the lagoon *Juncus gerardii* becomes the dominant plant type. These grasses further protect the dune system.

3.4.2 Otter Cove

Just west of Sand Beach is a series of pocket beaches composed of sediment derived from terrigenous material. Otter Cove is a mid-bay barrier (Duffy, 1989). Two long headlands are on either side of the system, creating a calmer wave climate than on Sand Beach. Water depth in the cove, less than 5.5 m, remains shallow in comparison with Sand Beach. Bluffs along the headland consist of cobbles and sand on the western side and mud on the eastern side of the cove.

The beach contains numerous cobbles and boulders that continue as an offshore substrate. These offshore rocks are covered with barnacles. Barnacles and mussel bars are also found inshore alongside the inlet where a tidal pool exists. At the mouth of the cove the carbonate content is about 25% with values greater than 75% farther offshore (Barnhardt, 1992).

Otter Cove Beach falls between National Park land and private land. Anthropogenic activity has altered the beach system. Loop Road runs directly along the crest of the pocket beach. A bridge underneath the road allows an inlet on the western side to exchange waters with the lagoon behind the system. At high tide and during storms, the waterline creeps up to the riprap along the roadside, leaving little beach exposed.

3.4.3 Hunter's Beach

Hunter's Beach is west of Sand Beach and Otter Cove, between Seal Harbor and Little Hunter's Beach and north of the Cranberry Islands. This beach is a bayhead barrier (Duffy, 1989). It is marked by two stubby headlands. Behind and alongside the beach are steep bluffs of sand and cobbles. This beach consists mostly of boulders. Rocks on the eastern side are covered by lichen.

The wave energy observed in this cove appears much higher than in the other two coves. Offshore the depth reaches 12.2 m. The carbonate content within the cove is between 25 and 50% (Barnhardt, 1992).

4. METHODS

4.1 Field work

4.1.1 Profiles

Field work took place between April and December 1999. Bimonthly profiles obtained using the Emery method (1961) and a Sokkia Set 4B Total Station allowed assessment of seasonal changes in overall beach volume. Three transects for the profiles were established at Sand Beach (Fig. 6) and two additional profiles measured the relief across Otter Cove (Fig. 7). Oranges were periodically thrown in the water during these measurements to note longshore drift.

The compiled profile data helped determine a sediment budget for Sand Beach. I calculated the annual flux within the system by measuring the area under both the lowest and highest beach profiles of all three transects across Sand Beach. Subtracting the two areas from each other revealed the total flux of sediment along each of the transects. I then averaged those amounts across the beach in order to calculate an average total flux within the system.

4.1.2 Ground-Penetrating Radar

Sensors and Software ground-penetrating radar (model EKKO100) enabled investigations of subsurface features. Ground-penetrating radar (GPR) transects "allow continuous information concerning shape, extent and internal structure of electromagnetic facies" in the horizontal plane (van Heteren et al., 1996, p. 472). Eleven transects created a grid pattern from the shoreline to the backbarrier using the 100 MHz antennae (Fig. 8). Spacing for the antenna was at a one meter interval along each transect. The number of records per transect varied with length. Vertical stacking of 32 (whereby the

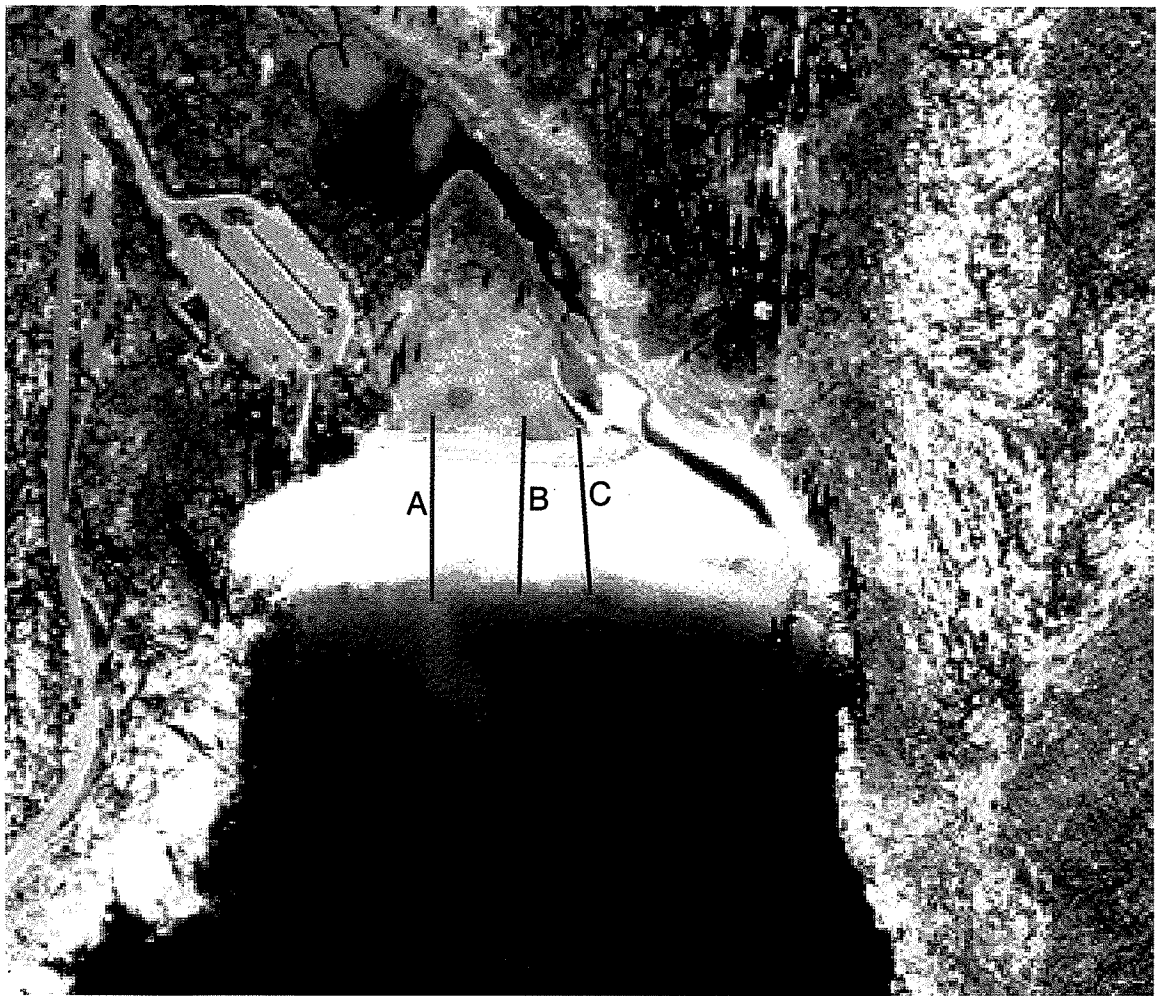


Fig. 6 Profile locations on Sand Beach



Fig. 7 Otter
Cove Profile
Locations.
Starting stake
was at road
edge. Back-
ground photo
from 1966.

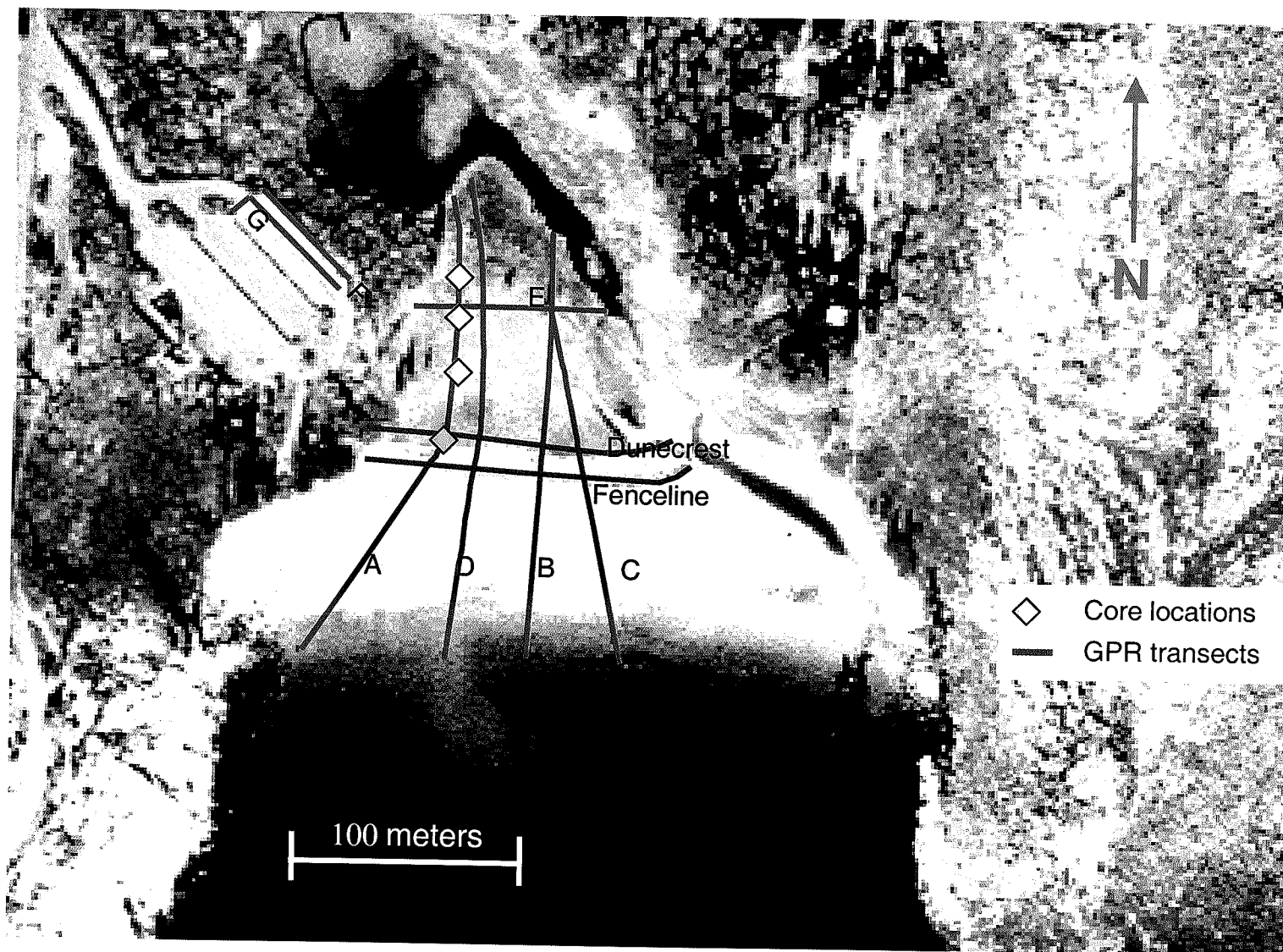


Fig. 8 Ground-penetrating radar transect locations and cores. Core from north to south are ACVC9901, ACVC9902, ACVC9903, and ACVC9904. Background photograph from Maine Geological Survey, 1966.

equipment and software average multiple electromagnetic pulses for a single trace) helped reduce outside noise. Half-meter steps with a 200 MHz antennae enabled collection of higher resolution data for two transects. High-resolution (200 MHz) data does not penetrate as deep as the 100 MHz antennae. Because salt or brackish water interferes with the signal sent out by GPR, transects ended at the berm of the beach.

Common mid-point data (CMP) tested time-depth relationships to assign an accurate velocity to the layers. A CMP was conducted by placing the antennas at intervals farther and farther apart. This method operates under the principal that the two-way travel time of a reflection increases as the distance between the transmitter and receiver increases. The rate of increase is a function of the velocity of the material that is transmitting the signal. The CMP method allows computation of the average velocity for the subsurface material, which in turn is used to determine true-depth of underlying material. To calculate this velocity, I chose a clear, representative trace to graph time vs. distance. The slope of the line determined the average velocity of the layers by the following equation:

$$T_x^2 = T_o^2 + x^2/v^2 \quad (\text{equation 1})$$

In the equation, T_x represents the time of reflection for the transmitter-receiver at offset x ; T_o is the travel-time of reflection at $X=0$; x represents the transmitter-receiver offset and v is the velocity.

The GPR data automatically set the zero depth to be the arrival of the groundwave. When measuring over areas that are not flat, a topographical correction is required to allow for variations in relief that the raw data do not show. I measured points along each of the GPR transects with the Sokkia Total Station to allow adjustments for

topographical change of the surface. The pulseEKKO software then created a linear interpolation of the surface between surveyed locations. All GPR data were corrected in this fashion.

4.1.3 Cores

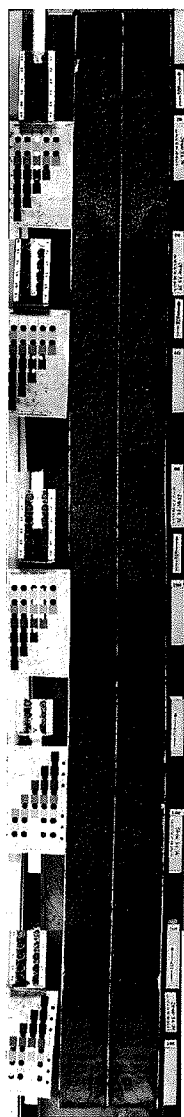
Four vibracores (Fig 8) taken along transect A (from the edge of the marsh to the dune crest) assisted in ground-truthing the GPR data and also helped reconstruct the physical stratigraphy of Sand Beach (Fig 9). Core ACVC9901 taken at the edge of the marsh penetrated 1.38 meters with 20 centimeters of compaction. The core met refusal in gravel. Core ACVC9902 penetrated 2.28 meters to clay with 35 centimeters of compaction. ACVC9903 had a total penetration of 3.13 meters after reentering the hole. The base of the core was a clay unit. Overall, there were 49 centimeters of compaction. The final core (ACVC9904) located on the dune crest penetrated 3.31 meters (after reentering the hole) to a shell hash layer. ACVC9904 had 24 centimeters of compaction. These cores were compared with an offshore core collected in 1994 off the coast of Hunter's Beach to examine the onshore record with the offshore.

The core data were compiled with the GPR data to determine sand volumes in the backbarrier region of the beach system. Two of the cores revealed the total vertical extent of sand. The core data were used to ground-truth GPR data. Flat-lying basal reflections with no reflections beneath were assumed to mark a boundary between the penetrable sand layer and underlying material. This depth, in conjunction with surface topographical adjustments, was used to calculate the volume of sand in the exposed area of the backbarrier region. This information was averaged over four transects.

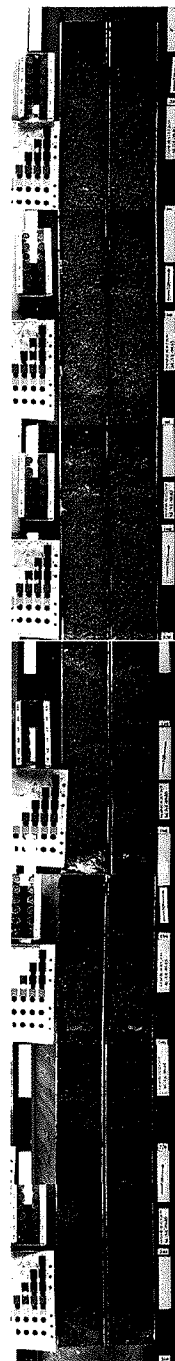
ACVC9901



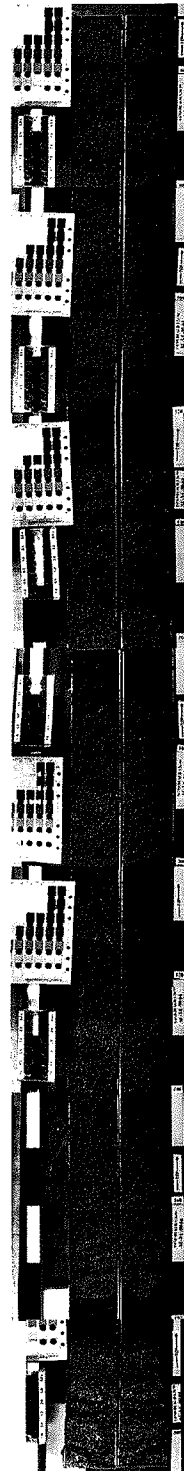
ACVC9902



ACVC9903



ACVC9904



50 centimeters

Fig. 9 Four cores obtained from Sand Beach

4.1.4 Surface Samples

I collected a total of 45 surface samples from both Sand Beach and Otter Cove over the course of the field season (early May, late August, and early December) in order to identify possible seasonal variations of sediment sources. Sampling of the beach enabled assessment of both lateral and vertical changes in sediment composition. Samples were from the swale of the frontal dune, the berm, the high-tide swash zone, and the low-tide terrace.

4.2 Laboratory Methods

4.2.1 Carbonate measurements

Surface samples and samples from the various units in each core were analyzed to determine their carbonate content and grain size. I counted 300 grains for each sample and separated each grain into one of the following categories: terrigenous material, barnacle, echinoderm, mollusc, gastropod and foraminifer. When possible, individual species, such as the blue mussel *Mytilis edulis*, were placed into subcategories. Some fragments were too small or fragmented to identify and were simply lumped together as "undifferentiated shell hash." The purpose of the point counts was to evaluate the overall abundance of particular carbonate species and to segregate some differences. Due to differences in particle sizes, it is possible that this procedure has some bias associated with the importance of particular species. Measuring the total weight percent carbonate was a way of verifying the results from the point counts and eliminating bias associated with size.

Employment of a weight-loss on acidification procedure (Molnia, 1974) evaluated the total percent carbonate of each sample. First, dry samples of roughly 1 gram were weighed. The application of dilute (10%) hydrochloric acid repeatedly to the sample

enabled leaching of carbonate. A vacuum suctioned the leached material through Millipore filter equipment. After repeatedly rinsing the sample with de-ionized water and drying the sample in a dessicator jar, I re-weighed the sample to determine the loss of weight due to carbonate. Errors may have been incorporated due to spillage of individual grains, or the inability to entirely leach all the carbonate from the sediment, or the retention of salt on the filter.

4.2.2 Grain Size

Grain-size analysis included use of both a settling tube and nested sieves. The initial dry weight for the settling tube samples was approximately 5 grams. Twelve samples were chosen in a control experiment using nested sieves at 0.25 phi intervals. These samples each weighed roughly 50 grams. This control was a means for checking errors that could have resulted from varying particle shapes and densities. The concern was that settling tube data would incorporate error due to the flat, angular fragments and low densities of the shell material. Likewise, there was equal concern that sieving would cause shells to abrade and break into smaller fragments during the shaking process. The two methods together allowed verification of the grain-size data to determine if these errors were negligible. Comparison was made between the two methods using Folk and Ward grain-size statistics.

4.2.3 Aerial Photographs

The Maine Geological Survey provided aerial photographs from 1966 and 1981. A differential, real-time Global Positioning System (GPS) collected data for points along Loop Road, the parking lot, and other recognizable features on the aerial photographs. These points helped register the photographs into a Geographic Information System

(GIS), assigning map coordinates to locations on the image. In order to minimize errors associated with possible tilt of the photographs, the camera lens, and relief distortion (Anders and Byrnes, 1991; Leatherman, 1983; Crowell et al., 1991), I used only the center-most section of each photograph.

After registering the images, I digitized the high water line as an indicator for shoreline change, denoted on the photographs as a change in grey. This line is subject to seasonal and diurnal fluctuations (Coyne et al., 1999); therefore, it was only useful in examining general shoreline trends. The reason the high water line was chosen over the vegetation line (the break between the beach sand and dune grasses) was that the vegetation line had been altered by human activity, specifically in the placement of the fence. Therefore, the vegetation line would not make a useful indicator of shoreline position.

Transects perpendicular to the shoreline at 25 meter intervals measured the difference between the two shorelines. An average was taken of the total distance from each transect to determine the average amount of change and rate of retreat.

5. RESULTS

5.1 Cores

5.1.1 ACVC9901

ACVC9901 had four distinct lithologic units (Appendix B). The topmost layer was a muddy, fibrous peat, containing some *Juncus* and *Spatina alterniflora* roots. This layer was overlying a unit 83 cm thick, a mixture of carbonate, quartz, and feldspar, which was very well-sorted subrounded to subangular medium sand. By weight, the unit had a 24-33% carbonate content, consisting mostly of barnacle fragments.

A sharp contact at 93 cm marked the boundary of a mud lens layer. This layer corresponded with the location of the water table.

From 96 cm to the base of the core was a dark grey sand, indicating reducing conditions. The unit consisted of very well-sorted, subrounded to subangular medium sand fining to moderately-sorted fine sand. The carbonate content dropped to 16% at the base of the core (Fig. 10). Most of the constituents were barnacles, followed by echinoderms and bivalves. In layers of heavy dissolution (as evidenced by pitting and a chalky appearance), only minor to no fragments of echinoderms and bivalves remained.

5.1.2 ACVC9902

Five major units were recorded in core ACVC9902 (Appendix B). The topmost unit consisted of dark brown well-sorted medium sand with roots. Grains were subrounded to subangular. The unit was less than 7cm thick and contained a carbonate concentration of 37% by weight (Fig. 11), consisting of barnacles, echinoderms and bivalves. A coarse-grained shell hash layer marked the boundary of this layer with the adjacent unit.

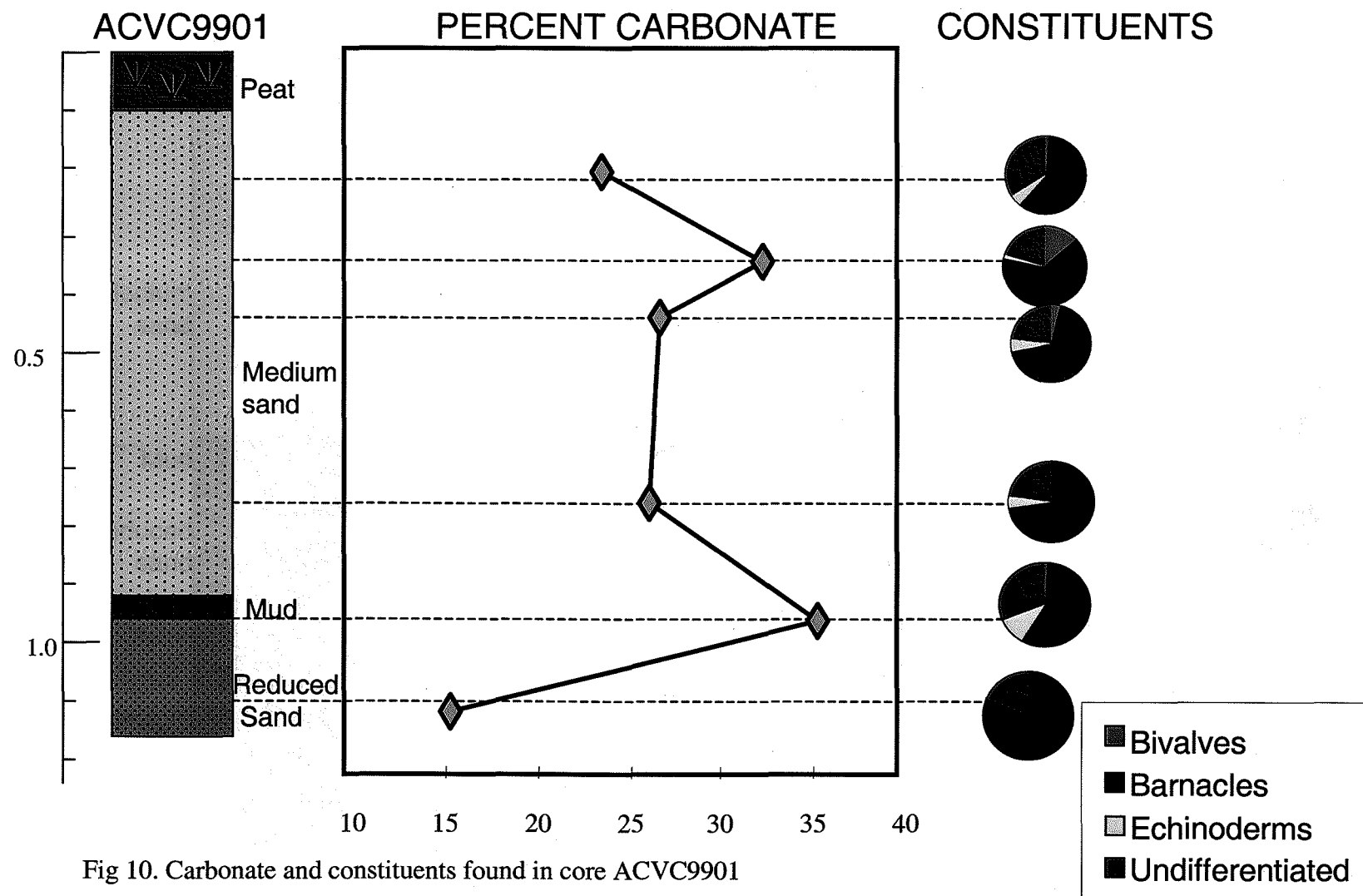
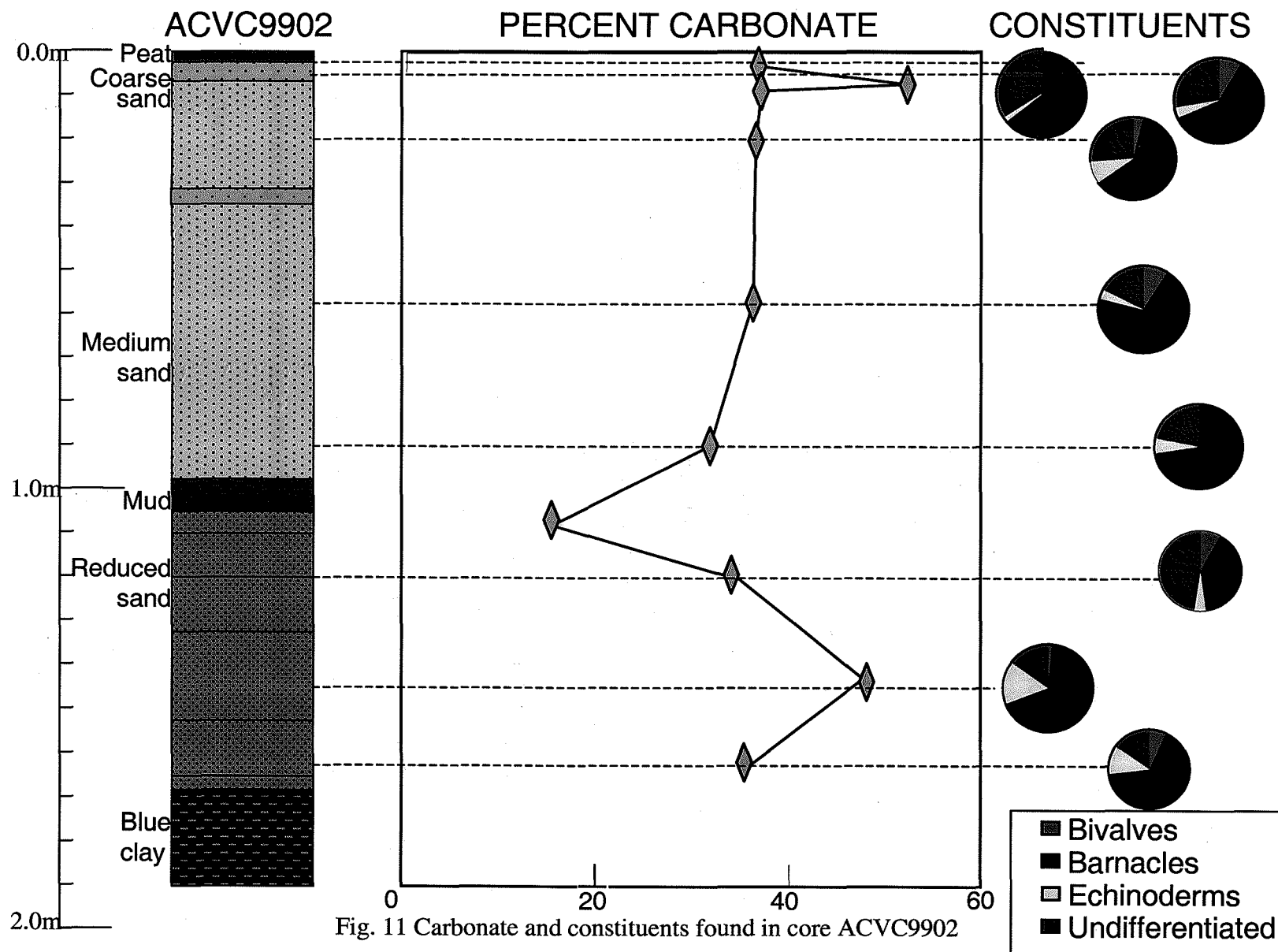


Fig 10. Carbonate and constituents found in core ACVC9901



The second unit was a lighter-colored carbonate material having a carbonate concentration of 32-37% by weight. Constituents consisted of mostly barnacles followed by echinoderms and molluscs. The grains were well-sorted, sub-angular to sub-rounded medium sand with average size between 1.3 and 1.8 phi.

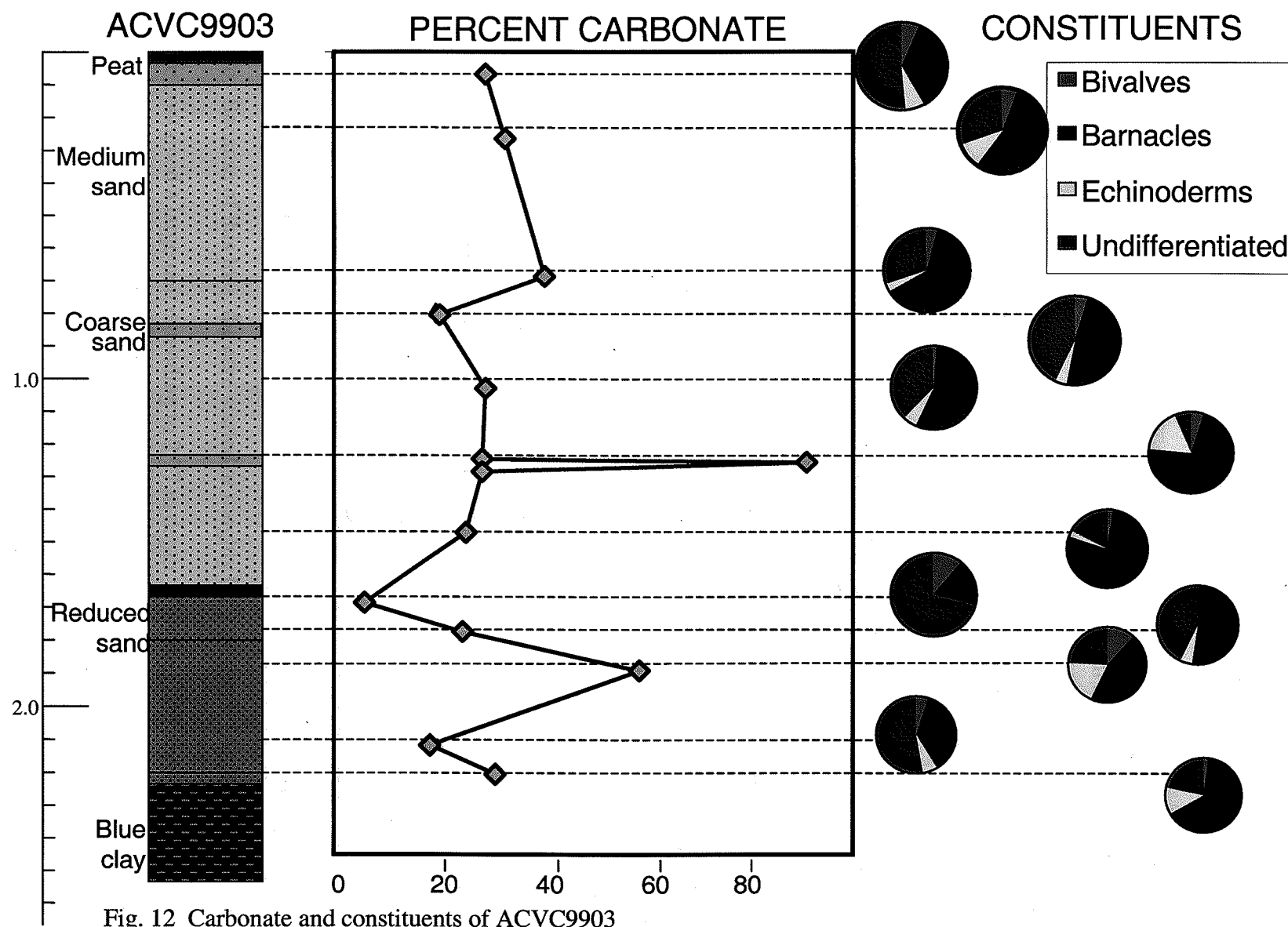
There was a sandy-mud lens at 1m. This 2 cm thick lens had no visible carbonate material within it. This layer corresponded with the depth of the water table. The carbonate concentration at the groundwater table and directly below this unit was dramatically lower than the previous unit, having only 14% carbonate by weight at 1.07m depth. Constituents were difficult to identify as some were chalky and pitted in appearance under microscope, and thus no pie diagram is presented.

Beneath the muddy layer was a grey sand unit, indicating reducing conditions. The carbonate content generally increased to 48% downcore (except for the bed at the base of the unit, which is 36%). Constituents were mostly barnacles. Several beds were visible within this unit as well as thin laminations. The grain size was variable, consisting of moderately-well to very well-sorted sands of 1.2-1.3 phi medium sub-rounded to sub-angular sand.

There was an erosional surface at 1.78 m marking the boundary between the grey carbonate material and glaciomarine sediment. The base unit was a very dense blue-grey mud containing no visible carbonate material and is interpreted as the Presumpscot Formation.

5.1.3 ACVC9903

There were four major units in core ACVC9903 (Appendix B). The top unit comprised sandy organic material containing carbonate material and roots. Below was an



extensive carbonate unit from 0.04m depth to 1.65m. This unit was, on average, 30% carbonate by weight, containing small laminations of shell hash material having concentrations as high as 95% carbonate (fig. 12). The material was very well-sorted sub-rounded to sub-angular medium sand, 1-1.25 phi. Again, barnacles dominated the assemblage, followed by roughly equal amounts of echinoderm and bivalve fragments. One sample was a very thin lamination and could not be accurately sampled for a point count.

The water table was between 1.65 m and 1.68 m. The exact location was not known due to lost material between cores upon reentry of the hole. Just below the water table (1.71m) the carbonate concentration was only 5%.

The unit below the water table was a dark, reduced layer of carbonate and terrigenous material. The unit contained thin laminae. A 0.5 cm. diameter pebble was found at 189 cm but for the most part this unit was well to very well-sorted sub-rounded medium sand having a carbonate concentration of about 25%. Barnacles dominated the carbonate material. Two beds within this unit showed slight fining-upward sequences. This unit rested unconformably on top of grey (N4) dense mud. The unconformity was at 2.26 m. The mud extended to the base of the core.

5.1.4 ACVC9904

Unfortunately the top-most material was lost upon removal of the core from its hole. Because of this loss, the core started at roughly 0.50 m. depth (Appendix B). This core contained a large unit extending to 2.77 m depth. This unit had several visible beds with smaller shell hash layers. The average carbonate concentration was 33.8%

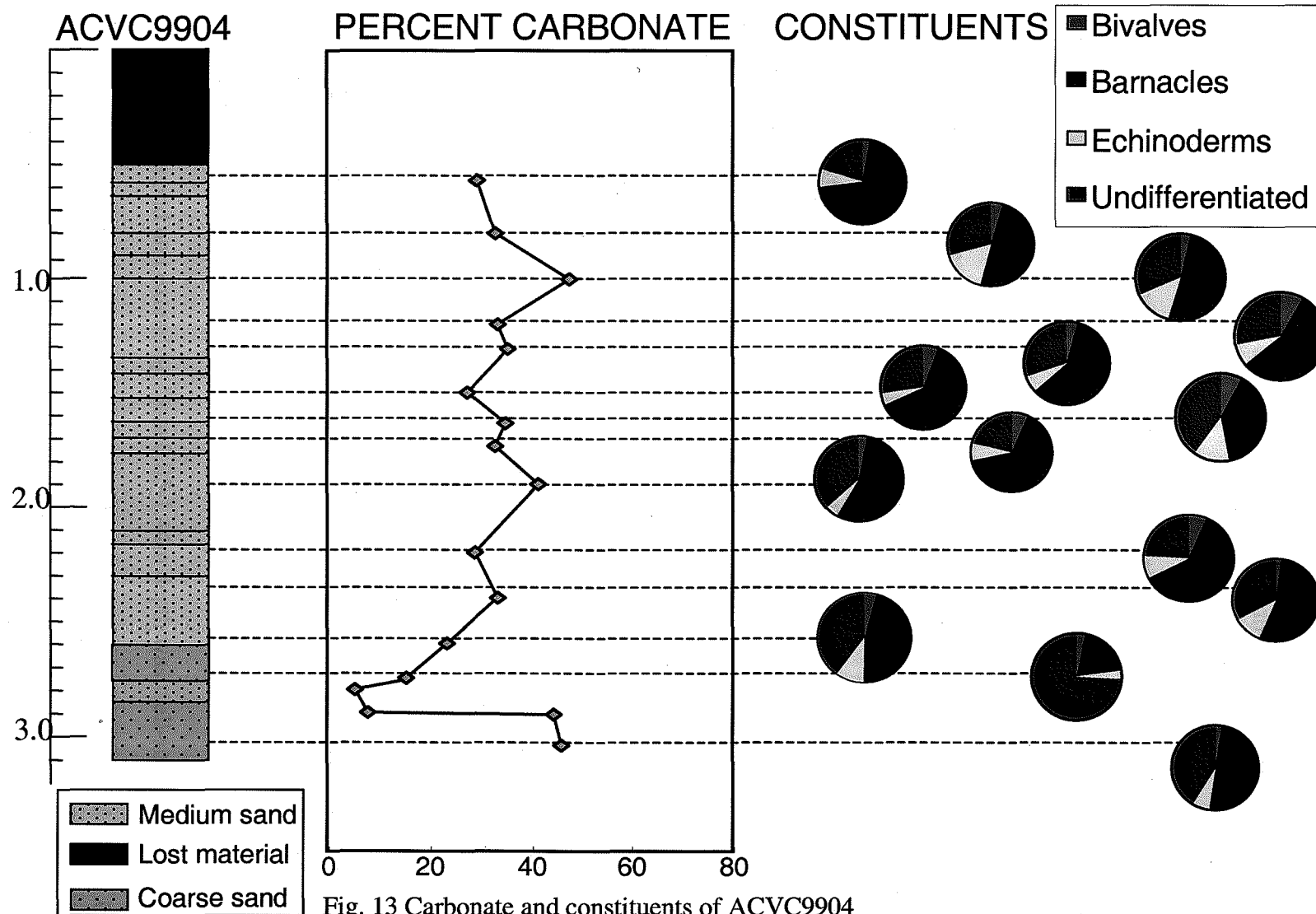


Fig. 13 Carbonate and constituents of ACVC9904

carbonate by weight (fig 13). Barnacle remains were dominant amongst the carbonate material. Sub-angular to sub-rounded quartz and feldspar comprised the terrigenous material. Burrows were at the base of this unit. The sediment was very well-sorted, medium sand.

An unusual layer fell between 2.77 and 2.85 m. This layer contained only 5% carbonate. It was very well-sorted sub-angular medium sand with average grain size approximately 1.5 phi. Terrigenous material consisted mostly of quartz and feldspar. Contacts on either side of this layer were sharp.

The basal unit extended from 2.85 m. to the base of the core (3.07 m.). This material was well-sorted medium sand. The unit contained multiple laminations of shell hash material. The carbonate content of this layer was 31% by weight. Barnacles were dominant amongst the constituents.

5.1.5 MDI 94-04

I analyzed an offshore core collected off the coast of Hunter's Beach in 1994. The core had a total length of 2.14 m. It comprised four major units (Appendix B). The top unit reached 85 centimeters depth. The top 42 cm was oxidized material, which was followed by a grey color change below this depth. The material was medium-grained sub-angular to angular sand with a calcium carbonate content of 51-65% by weight. The constituents were mostly barnacles followed by bivalves and echinoderms. Small traces of foraminifers and gastropods were also present.

The second unit extending from 0.85-1.44m depth was well-sorted, sub-angular to angular medium sand with faint laminations. It contained a muddy interval from 1.03 to 1.15 m depth. The carbonate content was variable with a low of 20% by weight. The

variability was probably due to large shells interspersed amongst the muddy material. A sharp contact marked the base of the unit.

The third unit fell between 1.44 and 1.75 m. The material was very coarse and poorly sorted and contains whole shells. A muddy layer cuts across the unit from 1.60-1.65 m depth.

The basal unit was grey silt, and the unit was marked by an unconformity. This unit is most likely the Presumpscot Formation.

5.2 Surface Samples

5.2.1 Grain size

Surface samples of the beach were medium sand as determined by both the sieve and settling tube data. However, there were minor discrepancies between the calculated mean grain sizes, skewness, sorting, and standard deviations between the two subsets (Appendix C). Generally the most variation (particularly of mean grain size) between data of sieved and settling tube samples was from samples from the berm. Since the berm material often contained coarse deposits and a mix of heterogeneous material, I would expect varying shell sizes to cause different results for this material.

Minor differences between the sieve and sample data may represent errors incorporated by the two mediums. Sieving may have caused shell fragments to break up slightly in the shaking process. In addition, the shape of shell fragments could have caused problems with sieve data depending how the particles fell through the mesh. Fragments of sea urchin spines were particularly problematic because of their long versus short axis.

Settling tube data is also skewed. The settling tube analysis relies on the assumption that all material was of the same density. However, the material was not

homogeneous. Shell material would have had a lower density than quartz fragments.

The shape of the particles may also have influenced the settling velocity. Therefore, the two data sets show discrepancies due to the nature of the heterogeneous material that was sampled.

Both sieve and settling tube data indicate the sample set is bimodal (or polymodal). Both sieve and settling tube data found one of the modes to be between 1.25 and 1.5 phi. The sieve data clearly display a second mode across the entire sample set to be at 2.5 phi. The two modes were most likely a result of two distributions within a given sample: a coarse one of shells and a finer distribution of terrigenous material. The coarsest sizes of the sieved data were higher in carbonate than the finer grained material (Appendix D).

5.2.2 Spring

Spring, summer, and winter surface samples showed similar trends in regard to carbonate distribution across the beach. Unlike the six samples in Otter Cove, which comprised less than 20% carbonate, Sand Beach samples ranged in composition from 25% to 70% between the dune and low-tide terrace. Samples taken in May demonstrated lateral and vertical variability (Fig. 14). Along Profile A the samples increased in carbonate content approaching the water, from 38% carbonate by the dune vegetation line to 69% on the low-tide terrace. Profile C also increased in carbonate content towards the shoreline, but it was less drastic a change. The content increased from 24 to 44% carbonate. The Eastern side of the beach had less carbonate material than the western side according to these results. Profile B had an anomalous sample close to the water,

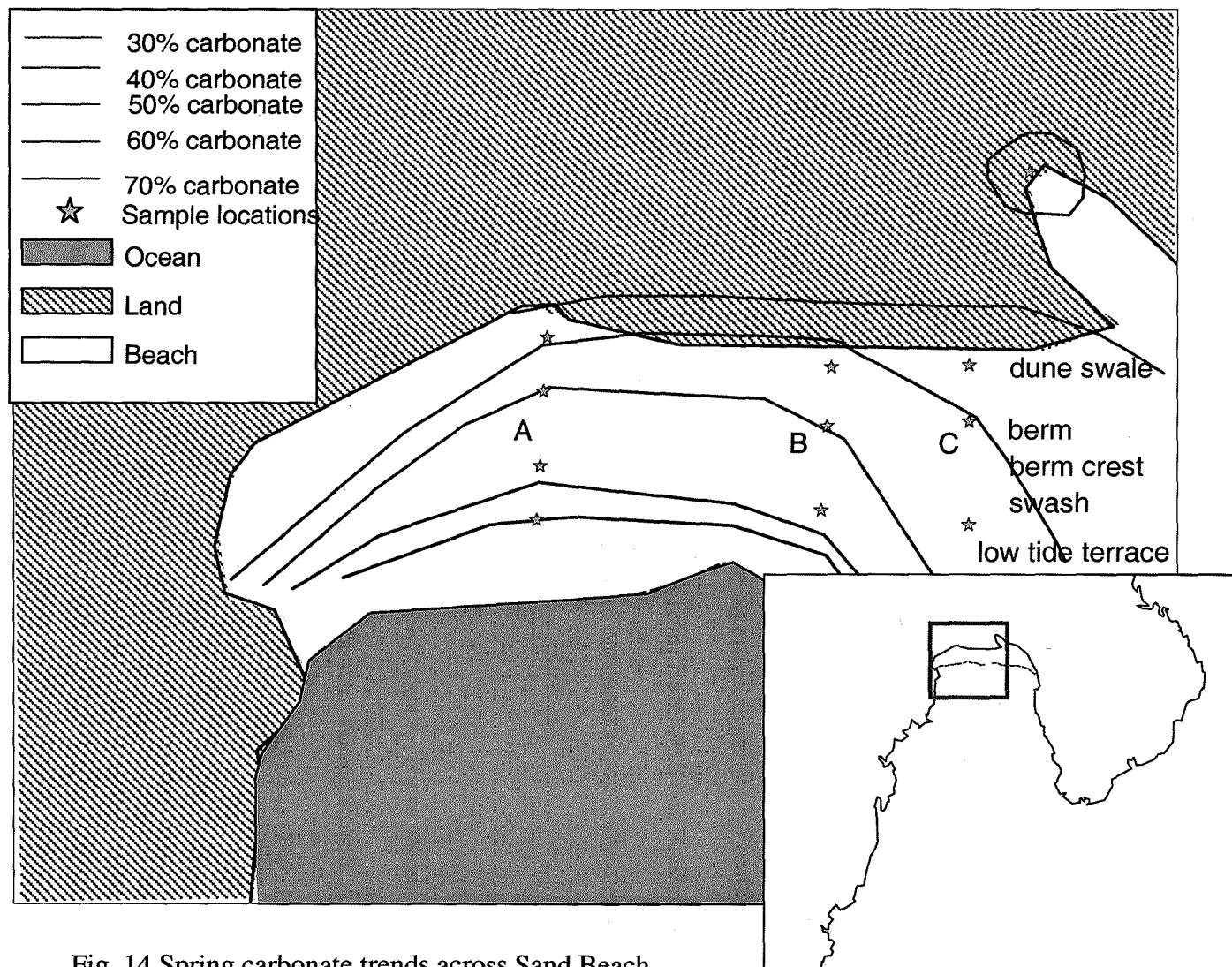


Fig. 14 Spring carbonate trends across Sand Beach

which contained only 26% carbonate by weight. It is possible that more reworked till was cropping out at this location, which would account for the lower carbonate content of this particular sample. The other two samples along Profile B did not change in carbonate content.

Barnacles were the dominant species in the assemblages of each sample. Along Profiles B and C there was a fairly equal ratio of bivalves to echinoderms (Appendix D). Samples from Profile A had a higher percentage of echinoderm fragments than bivalve.

Settling tube data demonstrates that the grain size is finest near the waterline and near the fenceline. The berm is slightly coarser. Samples along Profile A contained slightly larger material than along the other two profiles at both the berm and low-tide terrace locations. As the shell fragments tended to be larger than terrigenous clasts, the bimodal distribution was most likely a result of the heterogeneous mix of carbonate material with terrigenous. These results match data from Barnhardt and Kelley (1995) and Leonard and Cameron (1981) who found the total carbonate concentrations highest in the coarse-grained fraction of samples.

5.2.3 Summer

Summer samples also show a trend in carbonate content. These trends were more uniform alongshore but had drastic changes across the beach. Along Profile A, the content increased from 37% at the fenceline to 67% at the low tide line (Fig. 15). Samples along Profile B increased seaward from 30% on the dune swale to 71% on the low tide terrace, and samples along Profile C changed from 39% to 70%. The most drastic change in composition along all three of the profiles occurred between the berm

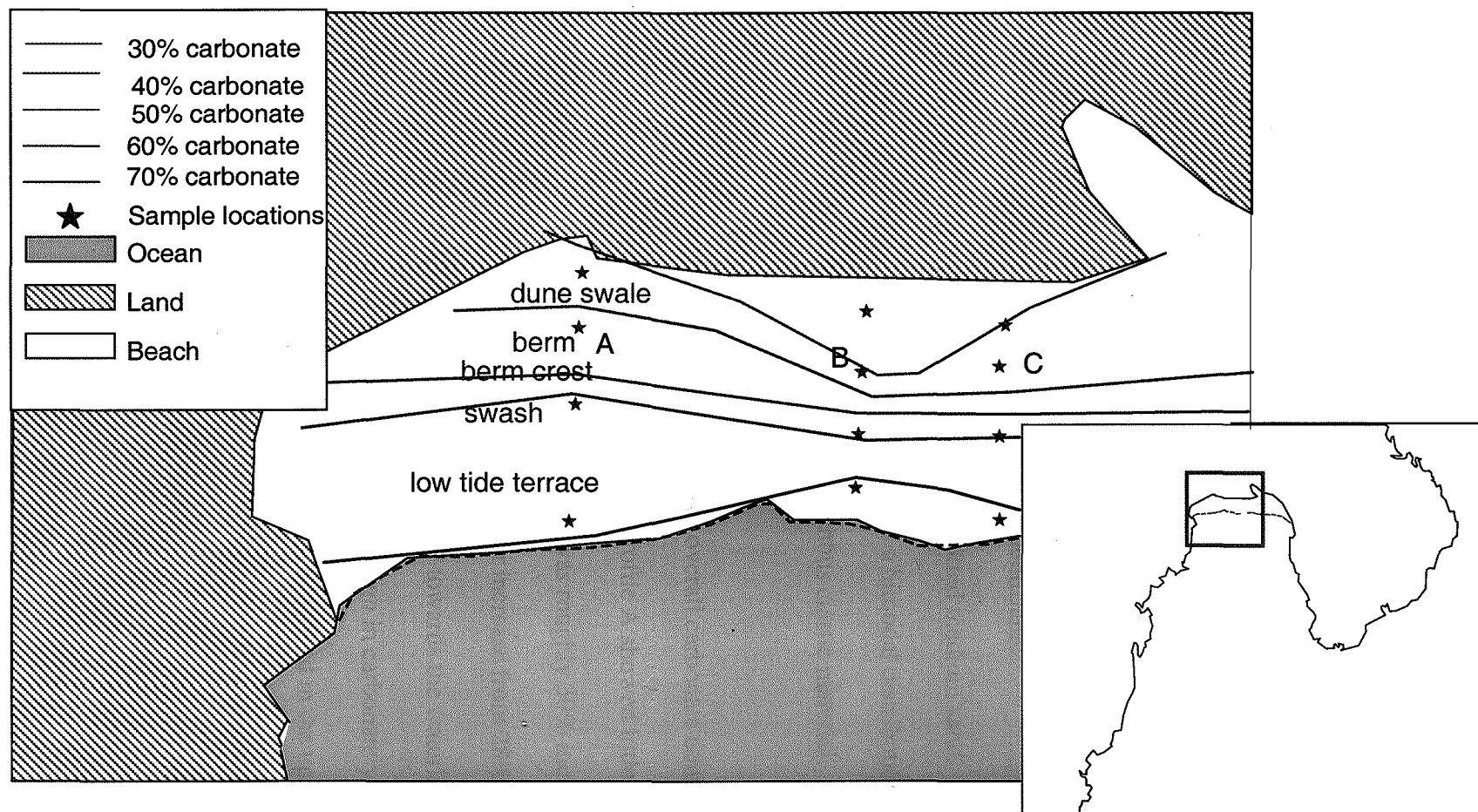


Fig. 15 Summer carbonate trends across Sand Beach

and the high-tide swash line. The carbonate concentration of the area between the berm and high tide zone increased seaward from 15-28%.

Barnacles dominate the assemblages of all of the samples (Appendix D, Table 2). There was a 2:1 ratio of echinoderm fragments to bivalve fragments from samples along Profile A. Fairly equal amounts of echinoderm and bivalve remains were in samples from Profile B. There were roughly 3 times more echinoderms than bivalves along Profile C. Some error may be incorporated into these findings as each sample had a fairly large percentage of constituents that were unidentifiable.

The samples tended to be mostly very well-sorted medium sand. Mean phi size decreased slightly towards the shoreline. There was a bimodal distribution for each sample, again due to the mix of shell versus terrigenous clastic material.

5.2.4 Winter Samples

December samples contained a much lower overall carbonate content than the previous samples (Fig 16). The distribution along Profile A showed little change except for below the high-tide line. The carbonate content was roughly 30% increasing seaward to 49%. Along Profile B there was a steady but minor increase from 28% to 39% carbonate seaward. Samples from Profile C increased towards the waterline from 25-43%. A lag deposit at the berm crest was particularly high in carbonate yielding a content of 53%; however, this concentration was only contained in the upper few millimeters of the surface. Material below the surface was finer and contained only 33% carbonate. It should also be noted that due to the tides, the locations of the winter samples did not extend as far across the low-tide terrace as the previous samples from August and May.

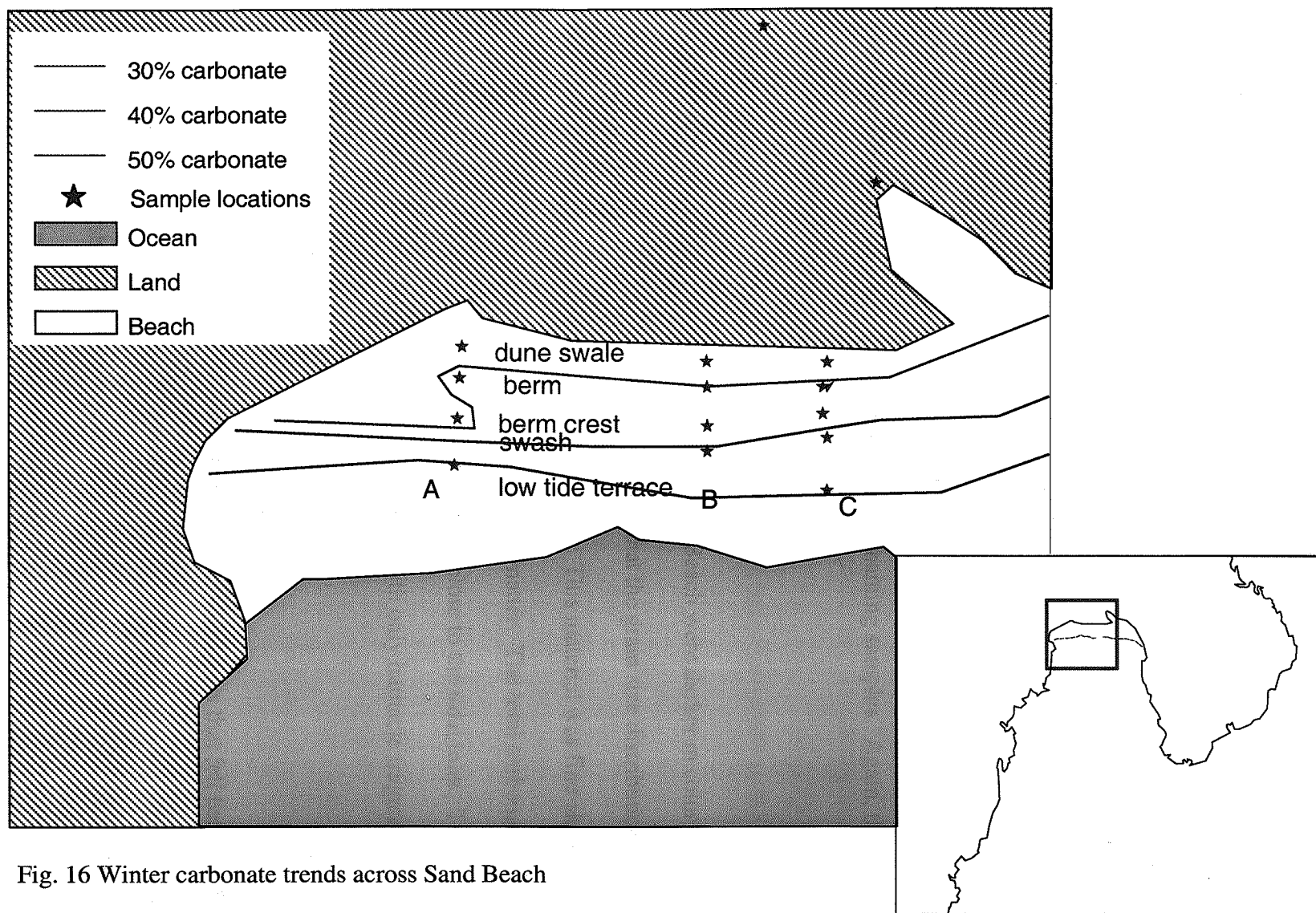


Fig. 16 Winter carbonate trends across Sand Beach

Each of the winter samples had a high percentage of barnacle remains (Appendix D, Table 2). Along Profile A, the ratio of echinoderm skeletal remains to bivalve was a 1:1 relationship, not previously seen. Profile B had slightly more echinoderm fragments than bivalves especially in samples taken closer to the waterline. Along Profile C, the samples had an echinoderm fraction more than twice as great as the bivalve assemblage. In terms of lateral variation, samples along Profile C had the fewest bivalves and Profile A the most.

The grain size of the samples was mostly very well-sorted medium sand. The material on the berm was slightly coarser than the remaining samples. Again, the grain size distributions were bimodal.

5.2.5 Lagoon

Samples taken from the lagoon behind Sand Beach were darker in color than those from the beach. Settling tube data suggested that the grain size distribution is well-sorted, sub-rounded medium sand of roughly 1.3 phi. This material was fine-skewed. Samples also contained a small percentage of organic matter. The total carbonate by weight was 22% in the winter and 40% in the summer close to the tidal inlet. The constituents were often dissolved beyond recognition with only barnacle fragments being identifiable.

5.2.6 Otter Cove Samples

Sand samples from Otter Cove had carbonate concentrations that fell between 6 and 19%. On average the concentration was 12%. Clasts varied across the beach from sand to boulders. Offshore the material consisted of mud and boulder-sized material. Bivalve remains were more common carbonate contributors in Otter Cove than on Sand

Beach, while echinoderms were rare. Shells comprised the largest phi size of sandy material. Whole mussel shells and mussel bars were also commonly found in areas offshore and in the tidal inlet.

5.3 Ground-Penetrating Radar

In order to process the ground-penetrating radar (GPR), I first used data from the common mid-point gathers (CMP) to find a velocity which could then be used to determine depths of electromagnetic facies. The CMP found that the average velocity was 0.158m/ns (Appendix E, Fig. E-1). This closely matches the average calculated velocity of dry sand (Annan and Cosway, 1992). Using this velocity in the data sets, the overall depth of penetration was about 6 meters.

Four transects ran east-west, parallel with the trend of the shoreline. Two transects across the dune crest contained U-shaped reflectors to the east of a scarp (Fig. 17, Appendix E, Fig E-2). This feature appeared on both the high-resolution and low-resolution data of these transects. This feature also correlated with curved reflectors which appeared on data from the transect taken across the fenceline (Appendix E). Data from these transects also revealed a convolute pattern directly beneath the surface overlying two strong flat-lying signals.

The transects perpendicular to the shore had two strong flat-lying reflectors which extended from the dune crest to the backbarrier (Fig 18, Appendix E). These reflections tended to disappear towards the beach face. These flat-lying reflectors were at approximately 4.5 meters directly below the dune crest. On the frontal dune, directly above the flat-lying reflectors, the data contained a convolute network of reflectors.

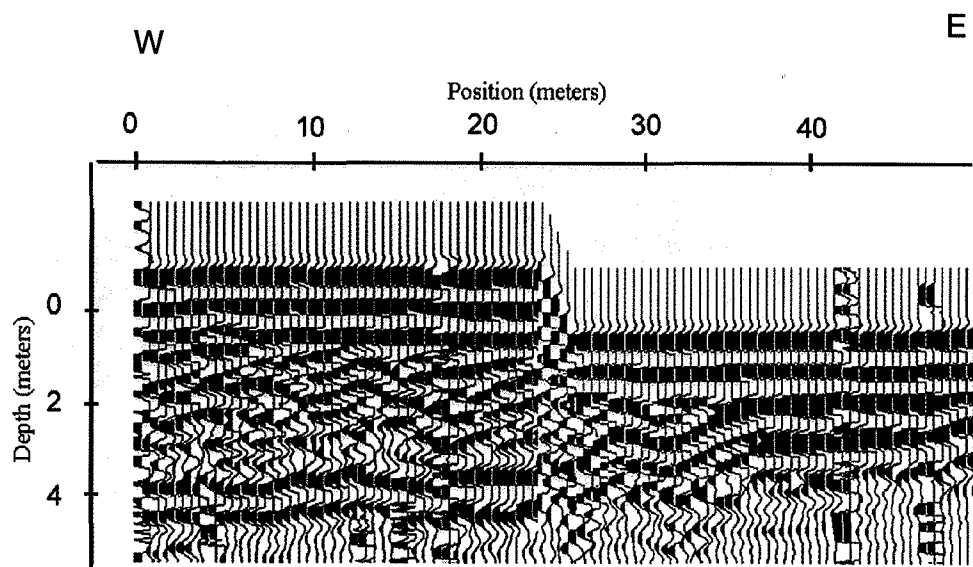
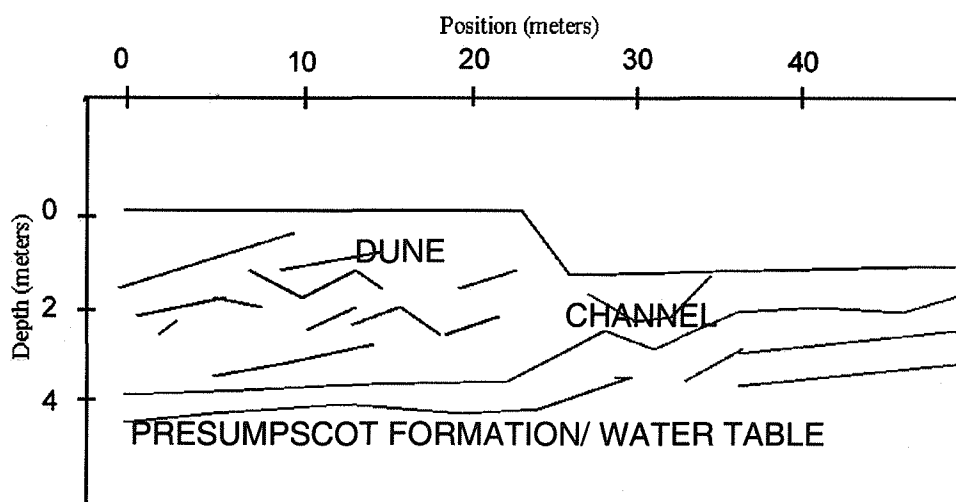


Fig. 17 Linear interpretation and GPR data from dunecrest transect

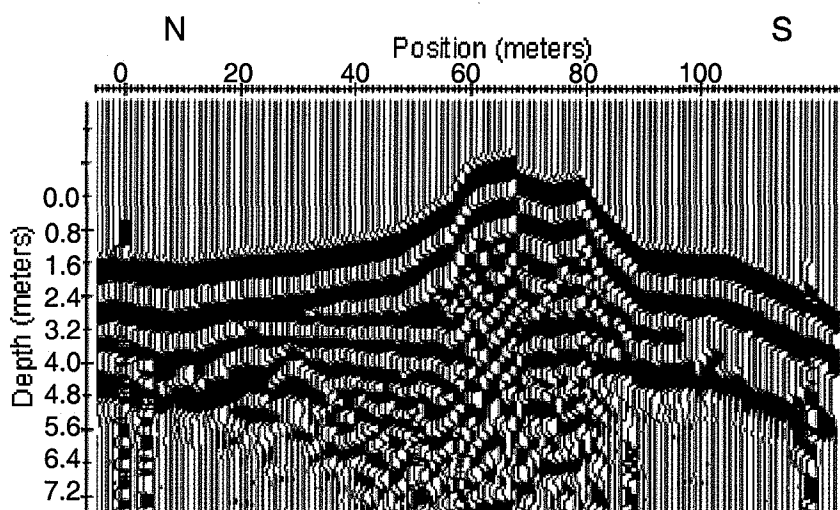
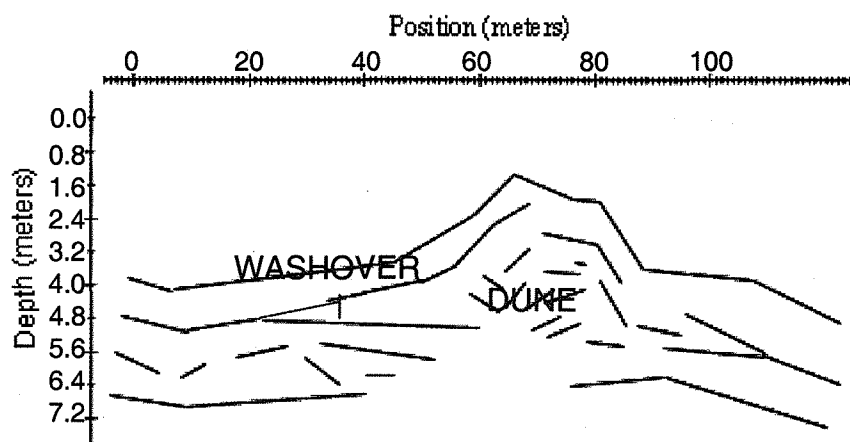


Fig. 18 Linear interpretation and GPR data of transect D from north to south.

Two pine trees in the backbarrier were on a topographically higher area than the surrounding material. The pattern underneath the pine trees was similar to that which lay underneath the frontal dunes (Appendix E, Fig E-3). A lens of sediment pinched out on the edges of this topographically high area. A similar lens effect is apparent on north-trending profiles taken across the dune to backbarrier regions. Reflectors taper out on the lee side of the frontal dune, ending abruptly in a thin wedge.

Transects across the beach face mostly contained reflectors that mimicked the overlying topography. The reflections were typically flat-lying. The signal was lost at the berm crest and penetration could not exceed 4 meters on the beach due to saltwater intrusion.

GPR transects taken across the parking lot showed dipping reflectors. The reflectors dip SE at a 2.4° angle (Fig. 19). A concern was that the parking lot would contain fill and would not satisfy an understanding of the overall stratigraphy of the area. However, dipping reflectors penetrated 6 meters; since the fill should not be that deep, these reflectors were revealing the strata underneath the parking lot.

Total accumulation in the backbarrier suggests that there was as much as $17,130\text{m}^3$ of sand in the backbarrier. There was about 4.9 meters of sand directly below the dune crest decreasing to about 1.2 meters towards the tidal marsh.

5.4 Profiles

A wide berm developed during the summer months (Appendix F). Accumulation corresponded with months when there was prevailing wind and waves from the southwest. The flux of sand between the winter and summer profiles was greatest on the western end of the beach, which had a gain of $95.5\text{m}^3/\text{m}$ of sand along Profile A (fig. 20, 21) compared

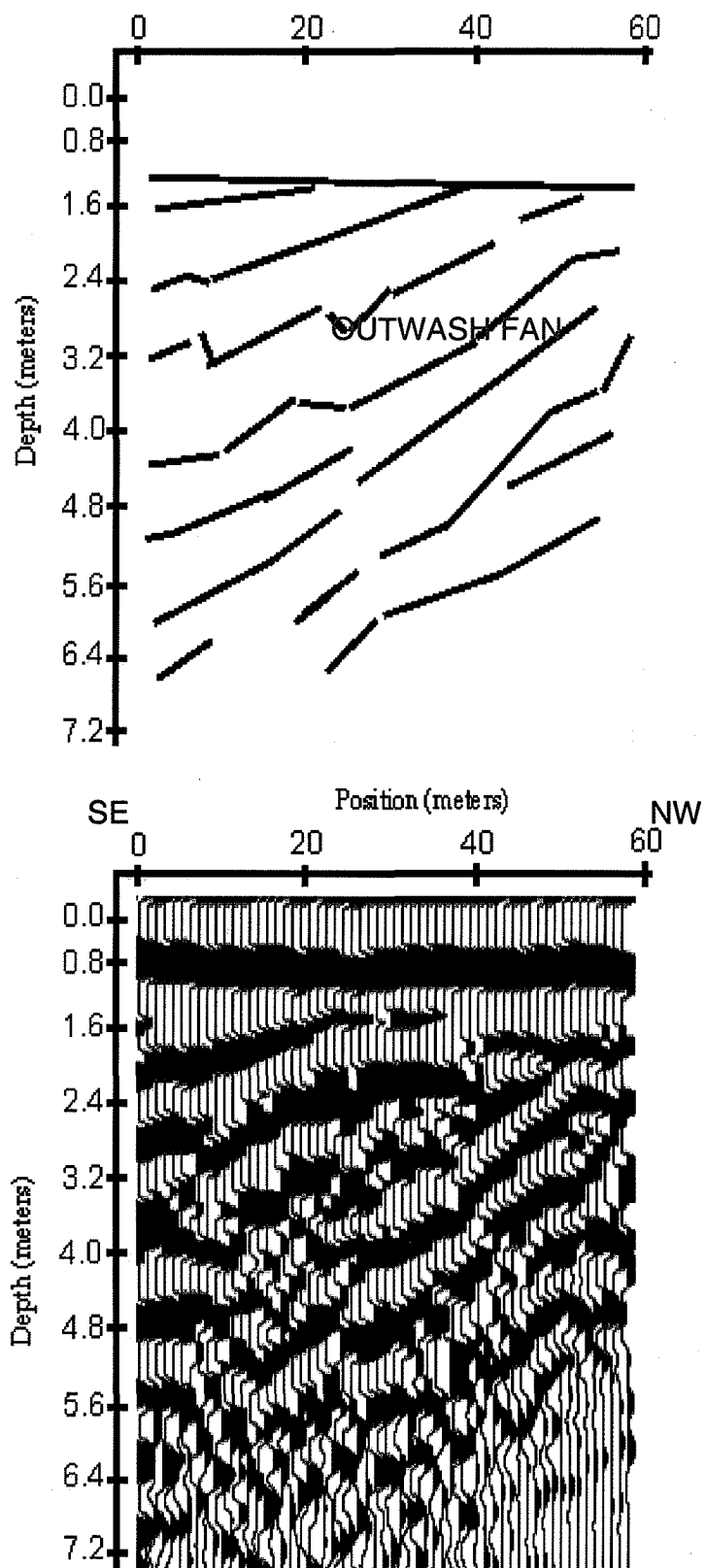


Fig. 19 Interpretation and GPR transect G across the parking lot.

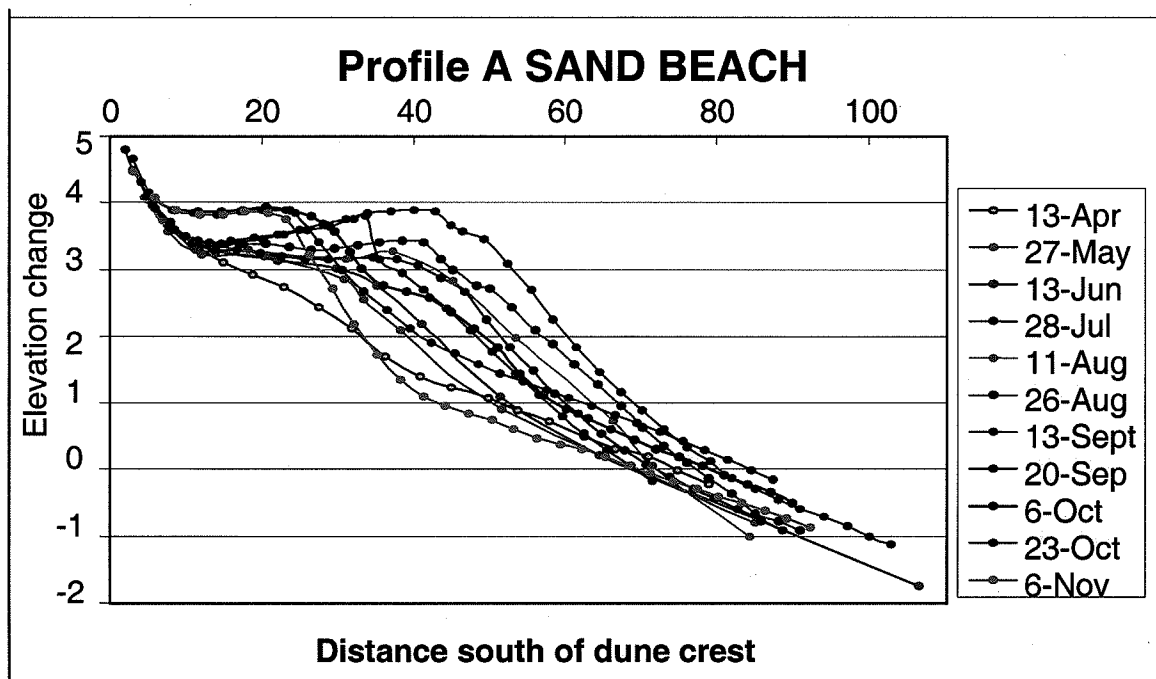


Fig. 20 Sediment accumulation changes during the 1999 field season along Profile A. Accumulation is visible close to the vegetation line during October and November. Most accumulation and build up of the berm occurs in the summer, peaking mid-September. Greatest loss occurs September 20, corresponding with Hurricane Floyd V.E. is 10 m.

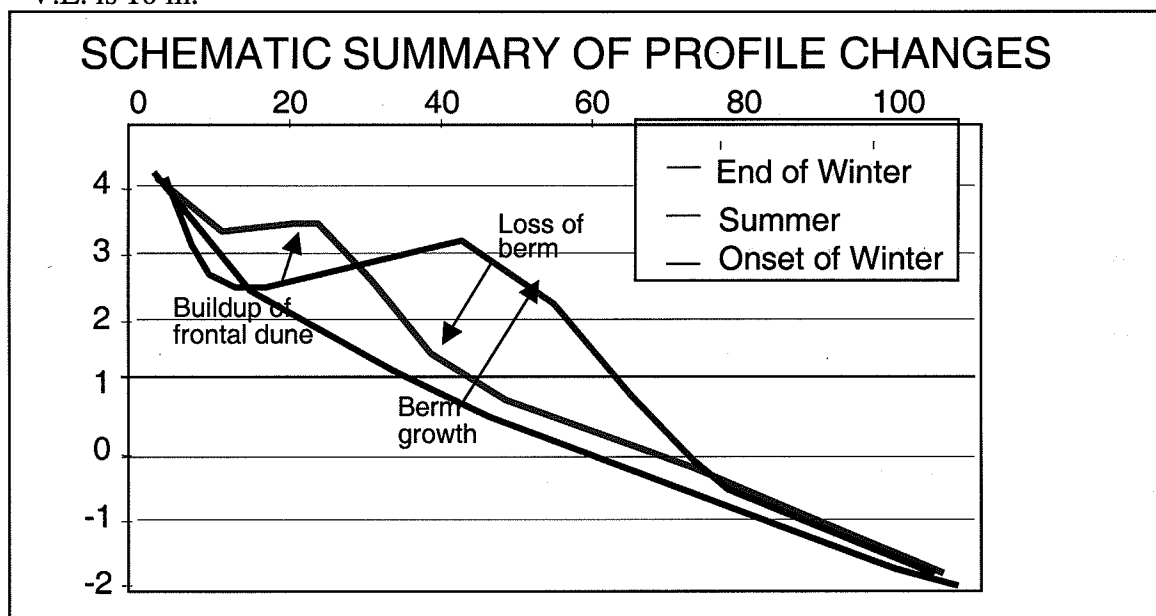


Fig. 21 Summary of changes at Sand Beach. Accumulation of the berm occurs with summer swell conditions. Loss of the berm occurs in the fall while there is an accumulation of the frontal dune.

with only $42.6\text{m}^3/\text{m}$ along the center of the beach (Profile B) and $44.6\text{m}^3/\text{m}$ at Profile C. The total flux of sediment into the beach system was approximately $16,675\text{m}^3$.

Two stations at Otter Cove showed little or no change throughout the season (Appendix F). There was no net longshore current in either direction along the beach system.

5.5 Aerial photographs

A comparison of the shoreline of the 1966 photograph with the 1981 photograph negligible shoreline change (Fig. 22). The 1981 shoreline was on average 8.36 m landward of the 1966, yielding a rate of retreat of 56 cm/yr. However, it should be noted that the amount of retreat that was calculated falls within the error incorporated by this mapping technique. In addition the difference between the two shorelines falls within the sweep zone of the profile data and could simply have been caused by a change in seasons or a difference in tides. More studies would be necessary to accurately look at long-term trends.

5.6 Other Sand Beach Observations

The lagoon/inlet system showed dramatic changes during the field season. The inlet was closed on all visits between June and November (Appendix A). During the time the inlet was closed, the lagoon rapidly dried, diminishing to only a small pool in the backbarrier system. With increasing storm frequency, the lagoon started to fill with rainwater until it breached the berm in November. While closed, presumably the lagoon would have gone through drastic changes in temperature, salinity and pH due to evaporation and the eventual filling in with fresh water. These changes were not measured in the field.

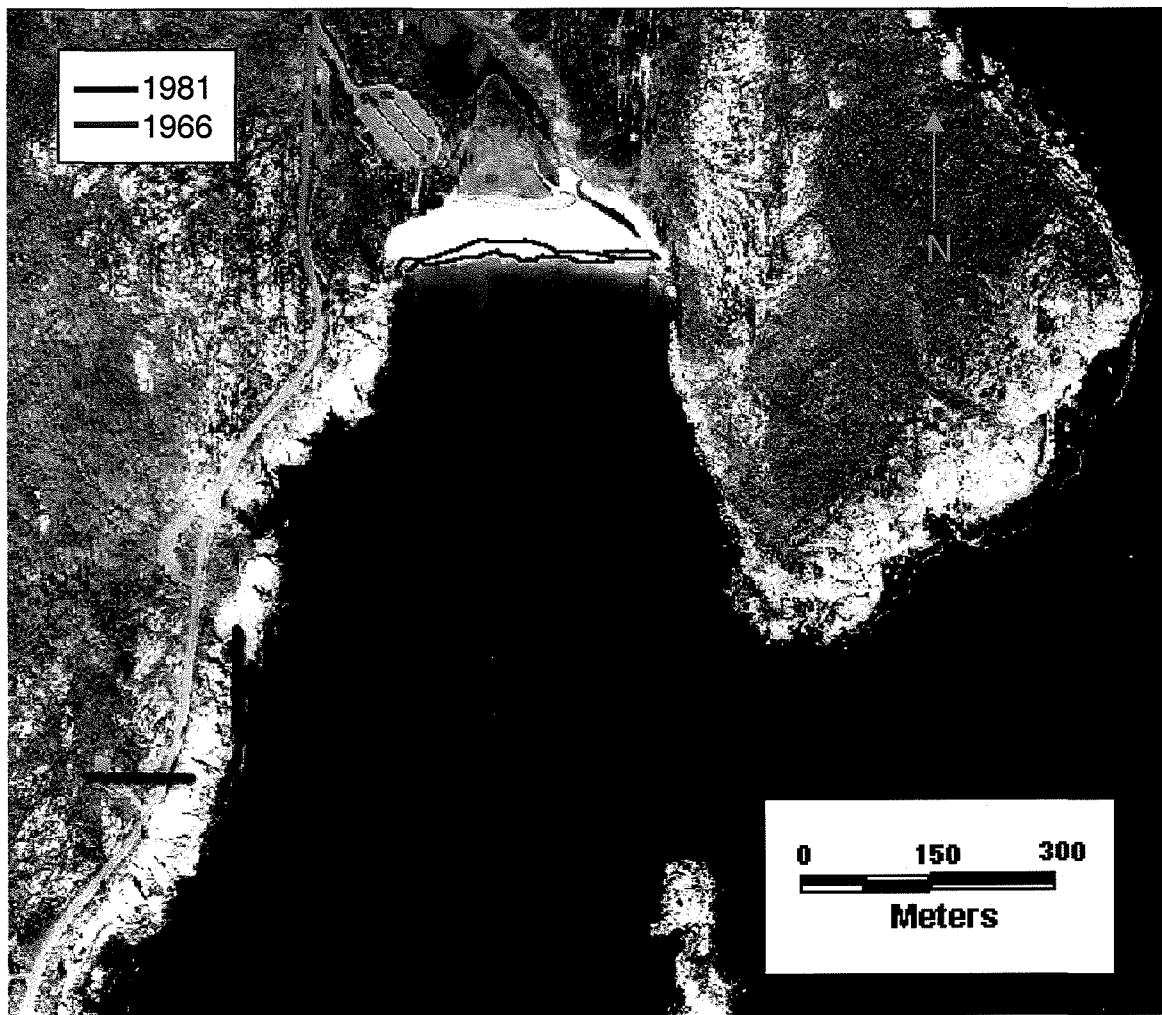


Fig. 22 Change in shoreline positions across Sand Beach based on aerial photographs from October 26, 1966 and June 18, 1981. Background photograph from 1966.

There was a weak net longshore current during the summer months to the west as shown by movement of an orange that was thrown into the water each month of observation. During the fall, there appeared to be no net current direction during times of heavy surf conditions. In November the current along shore switched to the east (shown by the movement of an orange in the water), corresponding with north-northwest wind patterns. These observations of changing currents match observations of previous studies at Sand Beach (Allen and Connery, 1991).

The system tended to show fast recovery from storms, often returning to normalcy within the two-week profile interval. Cusps typically formed along the beach, especially water). These observations of changing currents match those of previous studies at Sand Beach (Allen and Connery, 1991).

The system tended to show fast recovery from storms, often returning to normalcy within the two-week profile interval. Cusps typically formed along the beach, especially after storms. Often these storms left heavy lag deposits across the beach face reaching areas as high as the swale of the foredune.

There were two dune crests. One of the crests extended farther into the backbarrier region and probably marked the scarp from the 1978 storm (Nelson and Fink, 1980). The dunes were heavily vegetated with *Ammophila breviligulata* and *Lathyrus japonicus*. Some *Ammophila* had grown seaward, in front of the fence line.

6. DISCUSSION

6.1 Sand Beach

6.1.1 Physical Stratigraphy and Development

I compiled the core data and GPR data to interpret facies in the backbarrier region and determine the physical stratigraphy of Sand Beach (Fig. 23). The strong, flat-lying GPR reflectors at depth in the backbarrier and dune areas are most likely a continuation of the Presumpscot Formation recognized in the cores. The cores and GPR data match closely for the depth of this unit. Above this is dune material. The lower portion of this unit is reduced due to differences in oxidation above and below the water table. Some of the bedding and laminations in the reduced unit may be a result of water table changes.

GPR transects taken in the parking lot revealed the internal structure of another glacial feature. The dipping reflectors along these transects in conjunction with the area topography suggest that the feature underneath the parking lot is an outwash terrace that overlies glaciomarine sediment.

The till deposits that crop out at the low-tide line and on the eastern and western side of Sand Beach may be part of a moraine. Exposure of this feature on either side of the cove suggests it is continuous across the beach from east to west. Moraines are common in most of the large valleys on Mount Desert Island (Gilman et al, 1988). At Sand Beach this deposit has most likely provided a foundation upon which carbonate material could accumulate (Fig. 24). The placement of this feature, along with the facies found in the backbarrier, suggest that Sand Beach formed in situ. This is different from models that suggest barrier systems migrate into place during sea-level rise. Evidence from shoreline data (discussed later in this paper) in addition to the burial of a ship on the western side of Sand Beach suggest that this beach is not migrating.

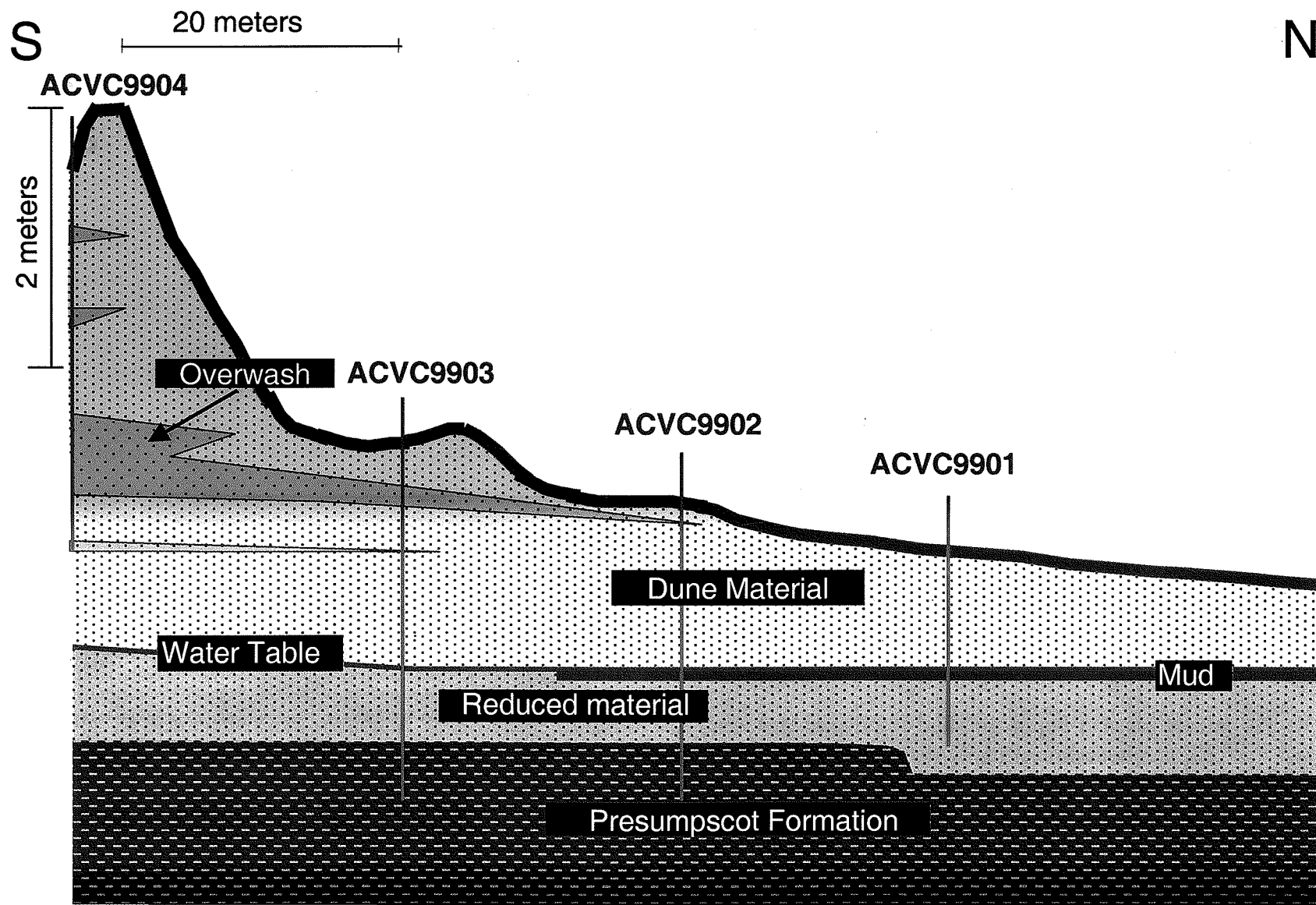


Fig. 23 Interpretation of GPR and core facies. These sequence shows a transgressive sequence.

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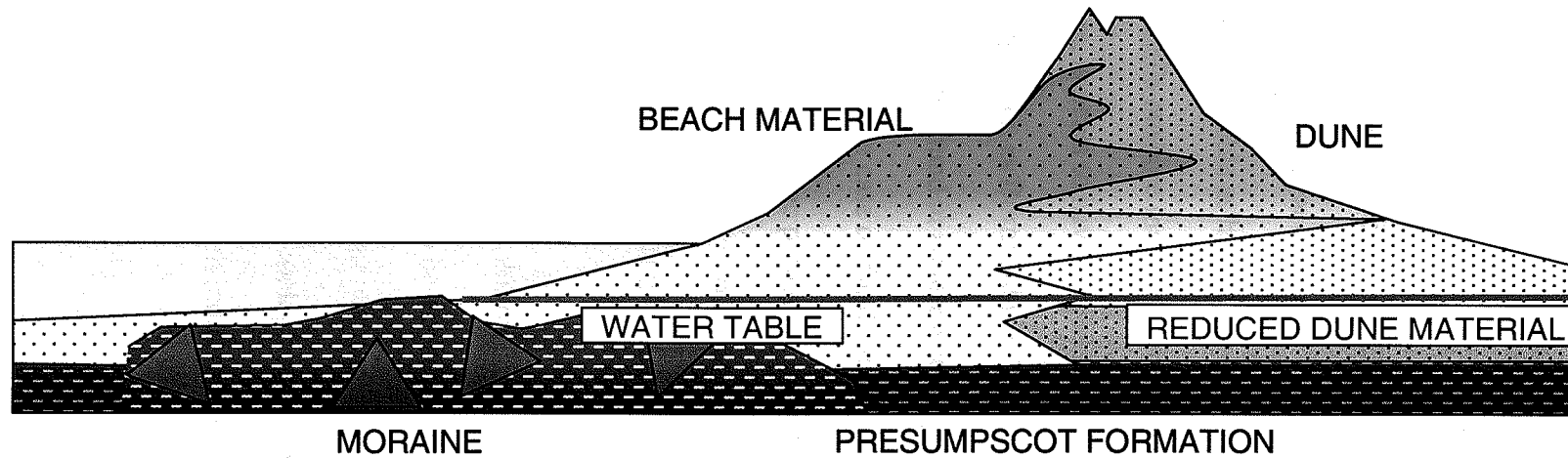


Fig. 24 Schematic cross-section of Sand Beach. Offshore new carbonate material is building on pre-existing glacial deposits. Approximate thickness offshore would be a meter of carbonate material overlying Presumpscot material.

An evolutionary model for this beach system would suggest that first the Laurentide ice sheet deposited moraines in the major valleys of Mount Desert Island. After the ice retreated, the sea invaded the land, depositing the glaciomarine material that was found both onshore and in the offshore marine core. This deposit may have been capped by a subaqueous outwash fan in the valley. During the Holocene, the rising sea level reworked glacial deposits into a beach system. Offshore scour created areas of exposed bedrock and boulders suitable as habitat for attached, carbonate organisms to grow. Waves moved the shells onshore into the cove and covered much of the moraine.

Glaciation, therefore, appears to have played an indirect role in the formation of Sand Beach. This is not surprising, as Bornhold and Yorath (1984) found many cool-water beach systems are typically found in areas associated with glaciation, including Vancouver Island and Alaska. In the case of Sand Beach, glaciation and sea-level rise scoured bedrock offshore, creating a large productive zone for benthic organisms. In addition, the glaciers deposited till in the form of what appears to be a moraine, which provided a hard surface from which carbonate material could then build up and accumulate.

The curved reflectors on the high-resolution data and on low-resolution data taken across the dune crest and fenceline appear to be a past channel. These data suggest that the inlet was formerly 20 m west of its present position. Aerial photographs from 1966 suggest that the closing of that inlet position took place within the past century. Sandy deposits west of the channel in the photograph indicate the former channel path.

6.1.2 Sediment Accumulation and Transport

The large flux of sediment on the western end of Sand Beach appears to be a result of longshore drift that carries sediment westward during the summer and eastward during the winter. As sediment accumulates, it appears to block off the tidal inlet. Once the inlet closes, the lagoon becomes vulnerable to evaporation during summer months. In the fall, input from rain and storms allow the area to fill with water until it eventually breaches the beach deposit. It is unclear whether opening and closing of the inlet and the eastward and westward currents along shore are directly related to one another. Do the reversing currents cause the inlet to open? Does the opening of the inlet cause the currents to change direction? The movement along shore seems to correspond with wind directions rather than mere opening and closing of the inlet. Months when wind is dominantly from the north-northwest, net transport was to the east. During months when there was a prevailing wind from the south, the longshore current moved westerly. This correlation would seem counterintuitive. It is more likely that the refraction around the headlands and Old Soaker are different during summer and winter months, causing the currents to reverse directions. Accumulation in the cove is greatest in the summer when the longshore current is moving westerly.

6.1.3 Carbonate Distribution

Most dramatic changes in carbonate stability are in the lagoon and tidal flat environments. This area is subject to changes in salinity and pH on a seasonal basis in conjunction with the opening and closing of the tidal inlet. Because the solubility of CO_2 is sensitive to both of these factors, the carbonate in this area may be more susceptible to dissolution during particular times of the year. The carbonate found in this area was very

difficult to identify because the material was starting to dissolve, destroying its original appearance.

The backbarrier regions would also be vulnerable to dissolution from rainwater, particularly acid rain. Downcore analysis shows that most dissolution appears to happen at the groundwater table, where the level dropped by as much as 20% carbonate. There was mud at this level as well, possibly diluting some of carbonate material.

Leonard and Cameron (1981) found average carbonate concentrations in Newport Cove was 70% while Nelson and Fink (1980) found the concentration to range from 30-40%. The discrepancy may be a result of how they sampled. The surface samples from this study suggest that the beach can undergo dramatic changes in carbonate concentrations with season and location on the beach. This study suggests that when measuring carbonate concentrations of samples, it is important to be aware of both alongshore and across shore variability. Samples taken on the low-tide terrace have much higher carbonate concentrations than sediment on the berm and dune. Samples taken from only one location on the beach could cause an unrepresentative view of the overall carbonate concentration of the beach system.

It was no surprise that barnacles were the dominant species. Laboratory experiments have proven barnacle plates to be resistant to abrasion and dissolution (Walter and Morse, 1984; Chave, 1964).

6.1.4 A Model for Carbonate Accumulation, Loss, and Transport

Why does the concentration of carbonate decrease rapidly across the beach face towards the dunes? There are several possibilities. One hypothesis is that sediment, once onshore, becomes exposed to rain and groundwater, and thus vulnerable to dissolution. A

second possibility is that transport mechanisms operating on the beach system are preferentially removing shell material from the beach face, perhaps because of its aerodynamic shape. A combination of either or both of the above situations could account for the carbonate distribution.

Is dissolution the cause for the drop in carbonate landward of the low-tide terrace? When comparing winter versus spring and summer concentrations, it seems likely that dissolution is playing a role. The overall concentrations dropped during the winter when no new material accumulated. With no new material to replenish the carbonate supply the carbonate concentration may have decreased as dissolution and abrasion removed material. The beach is subject to major foot traffic by tourists, which may be abrading material that can then be removed by coastal processes or dissolved. Winter and fall are also times of colder temperatures and high precipitation, which would alter the CO_2 solubility. However, dissolution is not the only factor at play. Dissolution alone could not account for the fact that the major change in carbonate concentrations occurs at the high water line.

Selective transport appears to be key to the puzzle of carbonate beach development (Fig. 24). Waves are necessary for generating currents strong enough to bring in shell material. Carbonate-rich areas may be restricted to areas where production is high and currents can concentrate material (Fitzgerald et al., 1979; Milliman, 1974). Waves bring in carbonate material and allow it to accumulate in areas depleted of clastic sediments (Barnhardt and Kelley, 1995; Raymond and Stetson, 1932). This occurs at Sand Beach during summer months when westward currents dominate. I would also

expect a higher productivity in summer months when light and temperature are more favorable for growth and production of benthic organisms.

After waves and currents bring in carbonate material, what happens to it? In the fall and winter a great volume of material is carried back offshore where it undergoes reworking by coastal processes. Some of this reworked material is sent eastward during winter months with a change in current directions. Particularly during winter months, winds are strong, carrying material to the dunes where *Ammophila* catches and traps the sediment. The effect of the wind in Winter months was best shown by the accumulation of material near the vegetation line (Appendix F). During the field season, a great deal of sand accumulated over a month's time (from November to December) along the frontal dune, covering the bottom rung of the fence (approximately 30 cm); this accumulation clearly demonstrated the force and volume with which the wind can move sediment in this system. The scattering of carbonate by winds provides a better explanation of the drastic change in composition between the berm and high-tide swash zone since winds will readily pick up dry material and possibly preferentially removes shell material. In the swash zone material is damp and cannot be easily removed or carried by winds. Other material can be filtered out. The shapes of the shell material allow it to transport more easily by air. Shell material in laboratory studies was easily entrained because of its "aerodynamic" shape (Olivera and Wood, 1997; Pilkey et al., 1967).

After material has been deposited, it would become subject to pH changes, salinity changes, and other variations caused by rainwater and groundwater input. The evaporation of the water in the lagoon in the summer and its consequential filling with fresh water should have created lower pH values. This freshwater input may cause

dissolution to occur, reducing carbonate concentrations. These changes were shown by the 20% variability in carbonate between samples taken along the shore of the lagoon during winter and summer.

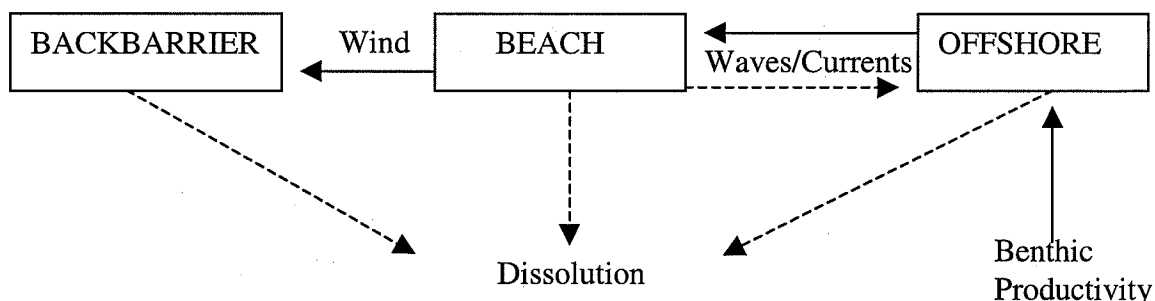


Fig. 25 Model for selective transport at Sand Beach. High benthic productivity is brought in by ocean currents and waves in summer and reworked and carried back offshore in Winter and Fall. Remaining carbonate is carried from the berm to the backbarrier by wind. Dissolution and abrasion would also be counterbalancing the input of carbonate in the offshore and onshore areas of the system.

Summer allows for new replenishment of shell material and concentrations. The process can repeat itself: transport, dilution, replenishment. It is this cycle that has allowed Sand Beach to maintain a dynamic equilibrium. Abrasion, dissolution, and transport counterbalance new carbonate material that enters the system. Waves and climate are important in this process. The waves bring in material to the beach system while preventing the deposition of terrigenous muds that could dilute the carbonate concentration (Bornhold and Yorath, 1984). As the seasons change, so do the wind patterns and so do the currents along shore. These changing currents allow sediment to accumulate in summer months while reworking that sediment in the winter.

6.1.5 Longterm Stability

Shoreline data from aerial photographs from 1966 and 1981 show possible retreat of the beach system. Profile studies (Allen and Hazen-Connery, 1991) found that the shoreline retreated 10 m between 1981 and 1988. However, a follow-up study by Allen in 1994 comparing a GPS transect of the mean high waterline with the high waterline mapped on an 1872 NOS T sheet found that the modern shoreline coincided with the historic one within a few meters (Allen, pers. comm.). The overlap of the two shorelines implies that Sand Beach is a stable beach. The beach system may undergo periodic minor fluctuations from year to year but maintains itself in the long term.

The modern beach further provides evidence that it is stable and "healthy." It is "healthy" in that Sand Beach shows no signs of major erosion, contains a large sediment supply, and has a thick cover of protective dune grasses. The seaward growth of *Ammophila* stabilizes the dunes and allows new sediment to become trapped. Furthermore the wide berm not only indicates that the beach is healthy, but also implies that the beach has existed for a few thousand years. Barnhardt and Kelley (1995) placed a minimum of 4.5k years for the beginning of carbonate accumulation based on radiocarbon dates and previous accumulation rates calculated for cool-water carbonate beach systems (Farrow et al, 1984; Taviani et al., 1993).

6.1.6 A Potential Threat to Bivalves?

There appeared to be higher offshore concentrations of bivalves than onshore. This loss may be due to dissolution. *Mytilis edulis*, which makes its shell from aragonite, was the major bivalve contributor. The remains of this species were fragile, easily crumbling under the microscope. Therefore, it is likely that even with a high offshore

production, the species is less abundant onshore due to the effects of dissolution and abrasion.

However, dissolution and abrasion cannot be the only factors at play. Previous investigations on Sand Beach (Leonard and Cameron, 1981) found virtually equal ratios of barnacles to bivalves with a particularly high percentage of *Mytilis edulis*. The point counts taken from both surface samples and cores during the 1999 field season found fewer bivalves in the assemblages. Why is there such a drastic difference between the results from this study and the results from Leonard and Cameron (1981)? It is possible that if the undifferentiated material could have been identified, the total bivalve population may have represented a larger population than current results indicate. However, the data from the 1999 season does correspond with results from point counts taken by Barnhardt (1992) and Barnhardt and Kelley (1995) who found material to be 41% barnacle, 12% echinoderm, and 6% mussel shells. Could there have been a decline in the mollusc population over the past two decades? A possibility for the difference between Leonard and Cameron's (1981) results and these results is that the onshore activity of tourists may be accelerating the abrasion and destruction of the material, causing mussels to be less important contributors. Competition by other organisms may also provide an explanation for this difference in bivalve abundance. The offshore core had lower bivalve remains in the top 8 centimeters. However more data would be necessary to determine if competition in recent years is truly causing a decrease. The change may simply be an annual or decadal fluctuation. This data is limited in that can only cover the scope of one year.

6.2 Otter Cove

Why does Otter Cove have such a high offshore concentration of carbonate, but negligible onshore concentration? Rocks and boulders can often entrap carbonate material and protect it from being transported, allowing carbonate to accumulate on boulder beaches (Myers, 1982). If that is the case, why is there little or no carbonate material between the boulders of Otter Cove? This area, as already mentioned, has a low wave-energy due its shallow depth and headlands that extend well offshore. Profiles suggest that material does not accumulate or erode from the beach. The only supply of sediment is from the underlying till deposits that appear to be eroding in situ.

There are barnacles and gastropods on the rocks within the cove, but their remains may be diluted by the terrigenous input from eroding glacial deposits. Mud trapped between the rocks cannot be removed due to the lack of wave energy. The mud could be masking possible carbonate shells that accumulated between grooves in the rocks offshore. However, without wave energy to remove the mud and bring in carbonate material, it does not seem likely that a carbonate beach could accumulate in this area.

The cove is quite shallow. Bottom bathymetry suggests there is a high area near the mouth of Otter Cove (Barnhardt, 1992). The presence of cobbles and sediment at this location suggests it is possibly an offshore moraine. This feature may be acting as a breakwater, dampening wave energy that could enter the cove and preventing the winnowing of fines. Wave energy is critical in carbonate beach development (Frey and Pinet, 1978; Pilkey et al., 1967).

This beach is not a healthy beach defined by the lack of a wide berm, as well as access to dune material. The backbarrier lagoon appears to be sediment-starved. At high

tide, water consumes the beach close to the rip-rap that protects the road. The presence of the road across the beach prevents any retreat of this barrier system. Unless new sediment enters this system, with rising sea level, this beach will drown.

6.3 Hunter's Beach

Hunter's Beach also fails to accumulate any carbonate material despite the high offshore concentration. This beach is between rather stubby headlands and experiences much more wave attack than Sand Beach or Otter Cove. The presence of lichen on the eastern side of the beach suggests that Hunter's Beach is an inactive beach, failing to accumulate new sediment. Even though the bluffs alongside the beach contain sand and cobbles, the beach itself only consists of boulders. Therefore, the beach appears to be incapable of withholding small particles. Sand-sized particles are most likely swept offshore by these high-energy waves. No small particles, terrigenous or carbonate, can accumulate on this beach. Likewise, high-energy waves may also be preventing the accumulation of carbonate by creating conditions of more intensive abrasion.

This beach is a bayhead barrier. It has no room to retreat or migrate with rising sea level and, with a continued rise in relative sea level, will eventually drown.

Both Otter Cove and Hunter's Beach in comparison with Sand Beach indicate that wave climate can promote or hinder carbonate beach development. Sand Beach has enough wave and current energy to bring in new carbonate material and flush out suspended fines that could dilute the carbonate concentration. Otter Cove and Hunter's Beach both have a high offshore production, providing the beaches with the potential for accumulating high concentrations of carbonate. The two terrigenous beaches lack the proper wave climate to either bring carbonate material or retain it.

7. CONCLUSIONS

7.1 Itemized conclusions

The results from the 1999 field season lead to the following conclusions:

- 1) The physical stratigraphy of Sand Beach suggests that it formed in situ. Carbonate material and reworked glacial deposits built up upon pre-existing glacial deposits left behind from the Late Wisconsin Laurentide Ice Sheet. Glaciation appears to have played an indirect role in Sand Beach development. The till deposits appear to have provided a veneer or foundation by which the carbonate material could accumulate. In addition, glaciation and sea-level rise scoured and exposed offshore bedrock, providing suitable habitats for benthic organisms.
- 2) A former inlet is 20 meters westward of the current inlet location. GPR records from three different transects confirm the location of a former channel to have been closer to a scarp on the backbarrier dunes. An examination of more detailed history of the site from aerial photographs may better help determine the timing for the closing of this channel.
- 3) The inlet closes on a seasonal basis. The timing of closings and openings of the inlet corresponds with summer accumulations of material and storm energy. Large quantities of material brought in during the summer close off the channel and evaporation occurs. Fall storms fill in the lagoon until the inlet breaches.
- 4) Point counts compared with previous research (Leonard and Cameron, 1981) at Sand Beach suggest that there may be a loss of mussels to the beach environment. The cause, although uncertain, may be related to competition or abrasion. The fact that the data only covers one year is limiting and may be presenting a biased view of the data as there may be high variance of the species on a year to year basis. Future

studies examining the potential loss of these organisms in multiple offshore cores could better address this problem.

- 5) The carbonate content of Sand Beach varies with season and sampling location on the beach face. Sediment concentrations of carbonate can vary with a range of 25-70% carbonate by weight. This distribution is most likely a function of onshore and offshore transport mechanisms, wave and current processes in the nearshore zone and wind transport onshore. Core data and seasonal variations also suggest dissolution to be at play in the system.
- 6) Sand Beach appears to be in dynamic equilibrium between benthic productivity, dissolution, and transport. Otter Cove and Hunter's Beach lack the proper wave climate to attain this equilibrium.
- 7) Sand Beach appears to be a stable beach system given the presence of a large wide berm and the flourishing seaward growth of *Ammophila*. The shoreline at Sand Beach may undergo annual fluctuations and minor retreat but appears to be stable in the long-term.
- 8) The annual flux of sediment on the beach is approximately 16,675 m³ of material. There is roughly 17,130 m³ in the backbarrier.

7.2 World view and further research:

The carbonate distribution on Sand Beach suggests that it is a function of wave energy and transport. Follow-up studies in this area might involve wave refraction studies and a closer examination of the currents along shore in relation to the opening and closing of the tidal inlet. In addition studies on other high-latitude cool-water carbonate beaches could test for similar sample distributions across the beach to determine if such a

carbonate distribution is common. If the pattern is common, then new sampling techniques need to be employed for determining the overall carbonate concentration of a carbonate beach system.

Point counts provide field data that barnacles are the most resilient of the carbonate species. The resistance of the plates to abrasion and dissolution enables the fragments to remain preserved on cool-water carbonate beaches.

This study was unable to examine fluctuations in salinity and pH of the lagoon, although fluctuations seem to be inevitable due to the opening and closing of the inlet. The appearance of the material in the lagoon suggests that it may undergo more degradation than that onshore. By placing shells in the lagoon area and making close seasonal observations of the loss of this material, one could better assess the loss of carbonate in relation to these fluctuations and the opening and closing of the inlet.

Cool-water carbonate beaches have been located in areas such as Maine (Barnhardt and Kelley, 1995; Barnhardt, 1992; Leonard and Cameron, 1981; Leonard et al., 1981; Raymond and Stetson, 1932), New Zealand (Gillespie and Nelson, 1997; Nelson, et. al., 1988); Vancouver (Bornhold and Yorath, 1984), Norway (Friewald, 1998), Spain (Fornos and Ahr, 1997), and England (Farrow et. al., 1988; Roselle, 1985; Merefield, 1984). The stability of Sand Beach suggests that cool-water beaches are not necessarily ephemeral features that can be ignored as a fluke in the geologic system. Rather cool-water beaches call into question previous paleoclimate studies that used carbonate as an indicator for warm climates. This project suggests that carbonate beaches are not merely a low-latitude phenomenon and that such beaches can be stable in temperate environments given the proper conditions. In order for a cool-water carbonate

beach to maintain itself it needs a high productivity and proper wave climate to concentrate shell fragments and counterbalance dissolution and abrasion. It also requires limited input from terrigenous clastic material. Sand Beach is in a state of dynamic equilibrium of these forces.

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APPENDIX A: INLET STATUS

Table A-1 Status during 1983-1984 (from J. Allen, pers. com)

DATE	INLET
January 3, 1983	open
January 11	closed in storm
January 12	closed
January 15-June 2	open
June 20	closed
July 11	closed
July 19	closed
July 25	closed
August 1	closed
August 8	closed
August 14	closed
August 21	closed
Sept. 11	closed
Sept. 20	closed
October 9	closed
October 21	closed
October 27	closed
November 5	open at 4pm
November 15	closed
November 24	opened in storm
December 2	open
December 14	open
January 1, 1984	open
January 7	open
January 19	open

Table A-2 Inlet status during 1999 field season.

DATE	INLET
April 13, 1999	open
May 7	open
May 19	open
May 21	open
May 25	open
May 26	open
May 28	open
June 9	open
June 13	closed
June 29	closed
July 17	closed
July 28	closed
Aug 26	closed
Sept 11	closed
Sept 13	closed
Oct 6	closed
Oct 23	open
Nov 6	open
Nov 26	open
Dec 6	open

APPENDIX B: CORE LOGS

Fig. B-1 Core log of ACVC9901 from high marsh in backbarrier of Sand Beach

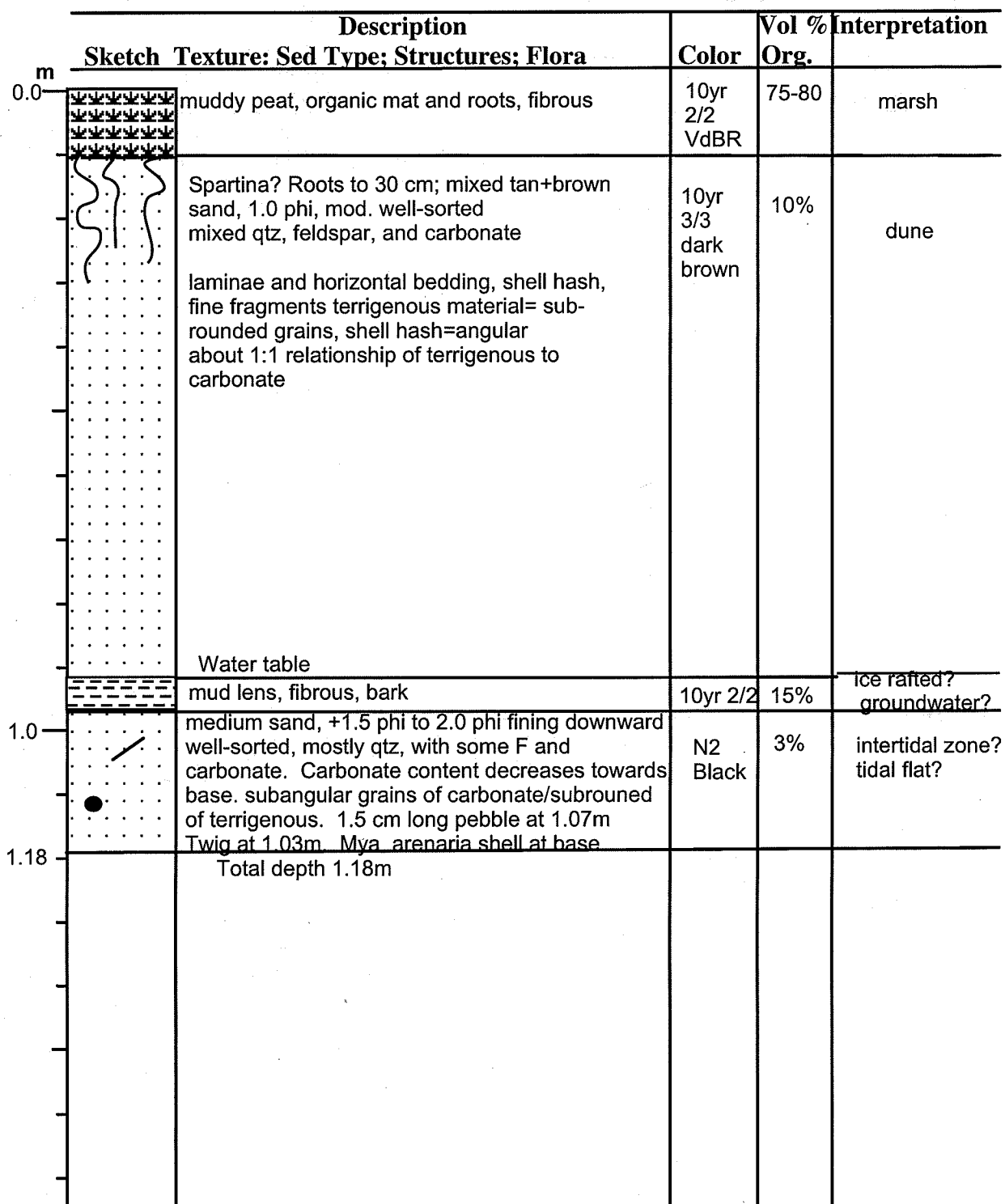


Fig. B-2 Core log from ACVC9902 taken from lee side of backbarrier dunes

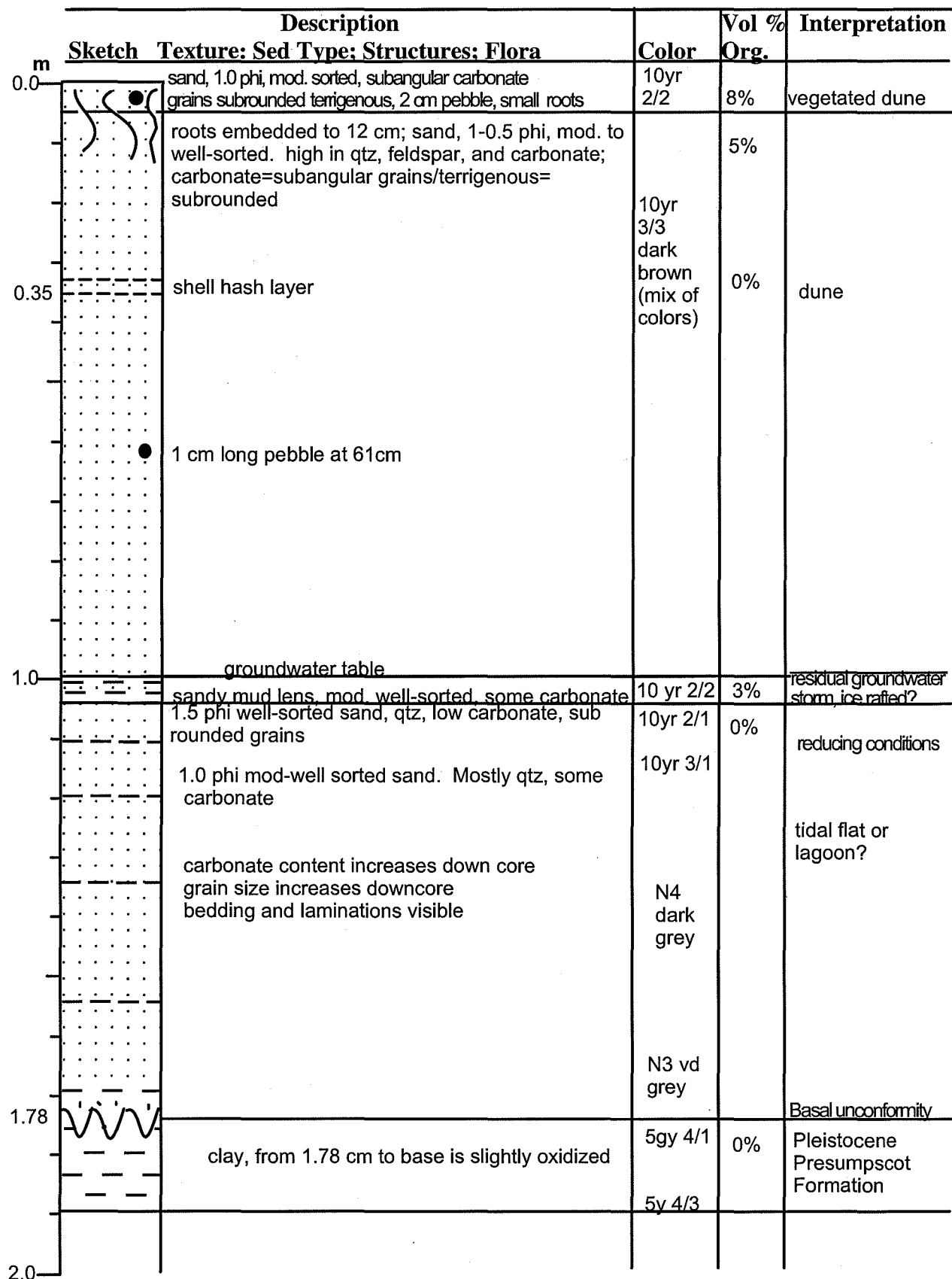


Fig. B-3 Log of core ACVC9903 taken from backbarrier of Sand Beach below dune crest.

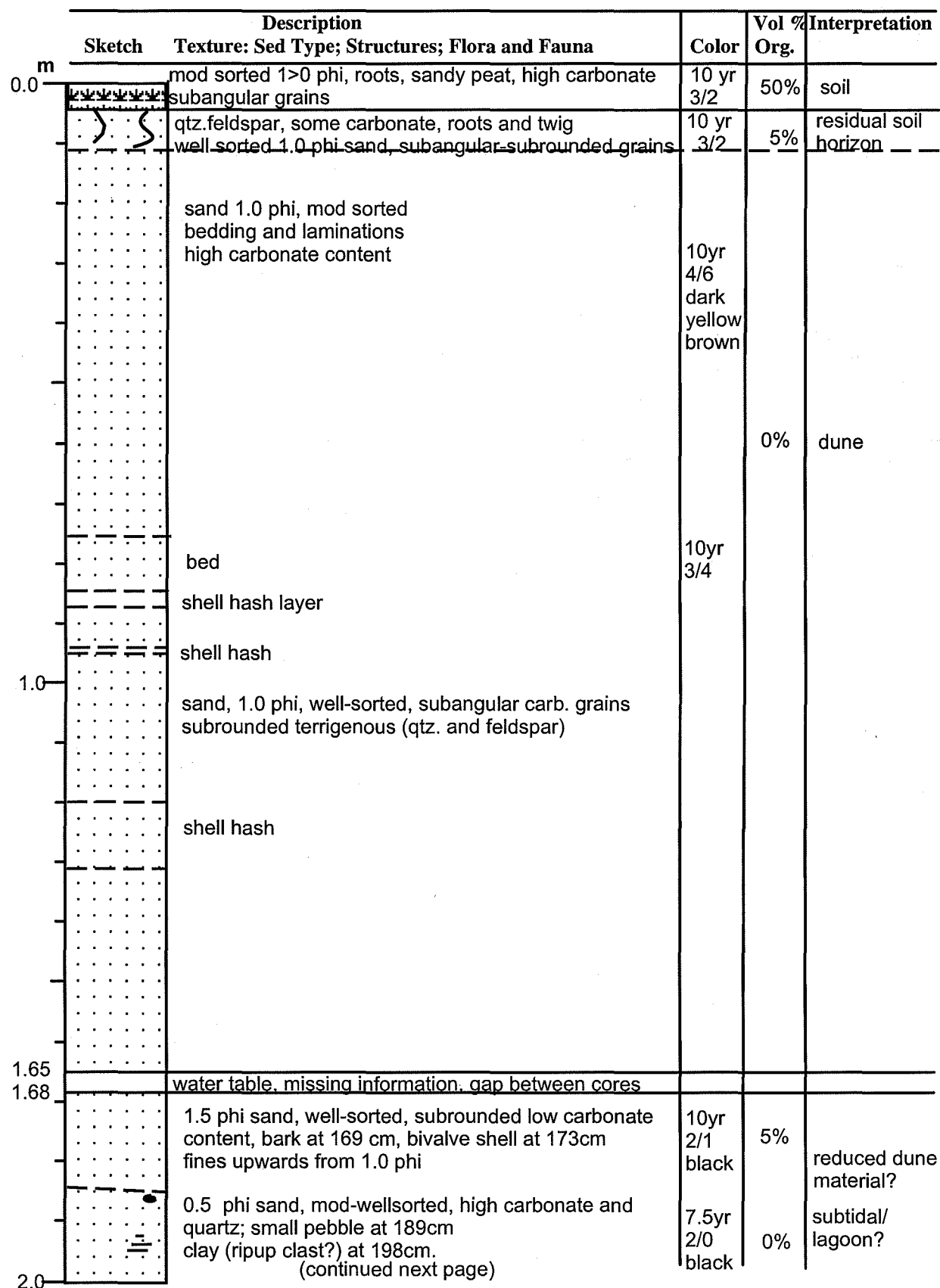


Fig. B-3 (continued)

CORE #: ACVC9903

Date: 6/10/99

Logger: Brandes

Description		Color	Vol % Org.	Interpretation
Sketch	Texture: Sed Type: Structures: Flora and Fauna			
2.0 m	0.5 phi fining upwards, carbonate, and high quartz mod-well sorted sand, very small pebbles at 2m 2.12 and 2.13 meters	2.5 yr	0%	
	1.0 phi	2.5/0 black		unconformity
	clay	N4 dark grey	0%	Presumpscot Formation
3.0				2.58 total depth

Fig. B-4 Log of core ACVC9904 taken from dune scarp.

Description		Color	Vol % Org.	Interpretation
Sketch	Texture: Sed Type; Structures; Flora and Fauna			
0.0	top 50 cm destroyed upon removal			
	sand, well-sorted 1.0 phi, subangular-subrounded grains. Rich in carbonate. Quartz and feldspar present. bedding and laminae visible	10yr 4/4 dark yellow brown	0%	dune inter- fingered with overwash deposits
1.0	sand, 1.0 phi, well-sorted, poor in carbonate. High in feldspar	10 yr 3/3		
	sand, well-sorted 1.0 phi subangular-subrounded grains. Rich in carbonate. Quartz and feldspar present. Bedding and laminae visible.			
	← start of core ACVC9904B (reentered hole)			
2.0	burrow at 1.97m			

Fig. B-4 (continued)

CORE #: ACVC9904

Date: 5/26/99

Logger: Brandes

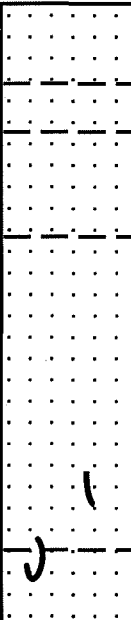
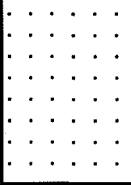
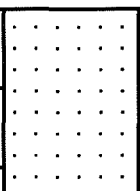
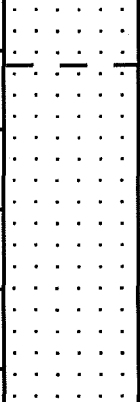
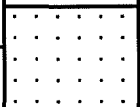
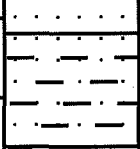
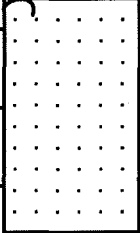
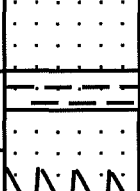
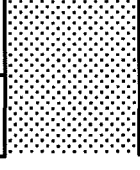
m	Description		Color	Vol % Org.	Interpretation
	Sketch	Texture: Sed Type; Structures; Flora			
2.0		continued from previous page			dune
2.77		low carbonate, high feldspar, subrounded, well-	7.5 yr	0%	
2.85		sorted 1.0 phi sand	3/4		
3.0		0.5 phi subangular moderate sorted sand. High in carbonate. Some quartz and feldspar. Many thin laminations.	10 yr 5/4 yellow brown	0%	possible overwash
		total depth: 3.07m			
4.0					

Fig. B-5 Log of core MDI96-04 taken from offshore Hunter's Beach

m	Description		Color	Vol % Org.	Interpretation
	Sketch	Texture: Sed Type; Structures; Flora and fauna			
0.0		medium to coarse sand. Upper 22 cm heavily washed. High calcium carbonate content large shell fragments	reddish	0%	shoreface (oxidized)
		large shell fragments			
		~~color change only; no grain size change~~			
		medium to coarse sand, minor granules, high carbonate content faintly laminated. Sand dollar at contact	salt and pepper dark grey		reduced
0.85		med. sand, minor granules, better sorted, faintly laminated	salt and pepper med grey		
1.0		muddy interval with fine sand and shell frags minor detrital organic material	2.5y 3/2	0%	shoreface
		medium sand high calcium carbonate content			
		strong sharp contact (erosional?)			
		very high calcium carbonate content faintly laminated, no obvious graded beds, poorly sorted Whole valve of Mercenaria, granite pebbles sandy, muddy layer	salt and pepper	0%	estuarine or all shoreface
		large shell fragments, whole shells	2.5y 3/2		
		v. fine sand. NO calcium carbonate material well sorted, densely packed continues to base of core (2.14m)	dk blue-grey	0%	Pleistocene glacial marine
2.0		2.14 meters total depth	5B 4/1		

APPENDIX C: GRAIN SIZE DATA
RESULTS FROM BOTH THE SIEVE AND SETTLING TUBE

Table C-1 Settling Tube Data from Cores with Depth (listed in centimeters)

ACVC9901	MEAN PHI	STD DEV	SKEWNESS	TYPE SAND
20	1.2143	0.3027	fine-skewed	v. well-sorted med sand
35	1.3729	0.341	Symmetrical	v. well-sorted med sand
45	1.319	0.3192	Symmetrical	v. well-sorted med sand
70	1.4637	0.2556	fine-skewed	v. well-sorted med sand
90	1.3297	0.3367	Symmetrical	v. well-sorted med sand
105	2.065	0.8906	strongly fine	mod-sorted fine sand
ACVC9902				
3	1.3045	0.4277	Symmetrical	well-sorted medium sand
7	0.8283	0.5098	Symmetrical	mod-well sorted coarse sand
20	1.3018	0.4163	near symmetrical	well-sorted medium sand
55	1.1798	0.3601	near symmetrical	well-sorted medium sand
87	1.1914	0.3829	near symmetrical	well-sorted medium sand
108	1.2578	0.6057	coarse-skewed	mod-well sorted med sand
117	1.3394	0.5198	fine-skewed	mod-well sorted med sand
140	1.1866	0.3435	near symmetrical	v. well-sorted med sand
168	1.328	0.3543	fine-skewed	well-sorted medium sand
ACVC9903				
7	1.2162	0.3049	fine-skewed	v. well-sorted med sand
27	1.1088	0.3179	Symmetrical	v. well-sorted med sand
69	1.131	0.339	Symmetrical	v. well-sorted med sand
81	1.1345	0.3276	Symmetrical	v. well-sorted med sand
104	1.2807	0.258	Symmetrical	v. well-sorted med sand
127	0.8389	0.3796	Symmetrical	well-sorted coarse sand
149	1.2628	0.2745	fine-skewed	v. well-sorted med sand
171	1.1826	0.3525	Symmetrical	well-sorted med sand
180	1.1654	0.27	Symmetrical	v. well-sorted med sand
191	1.0861	0.3999	Symmetrical	well-sorted med sand
214	1.3844	0.0298	Symmetrical	v. well-sorted med sand
223	1.2606	0.2629	Symmetrical	v. well-sorted med sand
ACVC9904				
57	1.1085	0.3054	Symmetrical	v. well-sorted med sand
70	1.2609	0.2677	fine-skewed	v. well-sorted med sand
100	1.1645	0.2496	Symmetrical	v. well-sorted med sand
120	1.3891	0.2814	fine-skewed	v. well-sorted med sand
131	1.7232	0.942	strongly fine	mod-sorted med sand
150	1.2664	0.3021	fine-skewed	v. well-sorted med sand
163	1.2114	0.321	fine-skewed	v. well-sorted med sand
173	1.3006	0.284	fine-skewed	v. well-sorted med sand
190	1.2682	0.2508	Symmetrical	v. well-sorted med sand
220	1.4458	0.2257	fine-skewed	v. well-sorted med sand
240	1.2506	0.267	Symmetrical	v. well-sorted med sand
260	1.3822	0.2743	Symmetrical	v. well-sorted med sand
275	1.5153	0.2479	Symmetrical	v. well-sorted med sand
304	1.2837	0.3874	Symmetrical	well-sorted med sand

Table C-2 Settling Tube Data for Surface Samples by Season and Transect From
Backshore to Foreshore

SURFACE SAMPLES-MAY				
Profile A	Mean phi	Std. Dev.	Skewness	Type Sand
(dune) 1	1.3523	0.3024	Symmetrical	v. well-sorted med sand
2	0.6621	0.8545	Strongly coarse	Mod-sorted coarse sand
3	0.3127	0.8759	Strongly fine	Mod-sorted coarse sand
(low tide) 4	1.1181	0.3284	Symmetrical	v. well-sorted med sand
Profile B				
1	1.2259	0.2914	Symmetrical	v. well-sorted med sand
2	1.329	0.3538	Symmetrical	well-sorted med sand
3	1.2766	0.3156	Fine-skewed	v. well-sorted med sand
Profile C				
1	1.3551	0.7886	Symmetrical	Mod-sorted medium sand
2	1.3402	0.3141	Symmetrical	v. well-sorted med sand
3	1.3568	0.3187	Symmetrical	v. well-sorted med sand
SURFACE SAMPLES-AUG				
Profile A				
20	1.3648	0.2932	Symmetrical	v. well-sorted med sand
21	1.1917	0.2806	Symmetrical	v. well-sorted med sand
22	1.535	0.3575	Coarse-skewed	well-sorted med sand
23	1.8162	0.3662	Symmetrical	well-sorted med sand
Profile B				
20	1.2397	0.262	Symmetrical	v. well-sorted med sand
21	1.2676	0.2918	Symmetrical	v. well-sorted med sand
22	1.7441	0.273	Symmetrical	v. well-sorted med sand
23	1.9032	0.2652	Symmetrical	v. well-sorted med sand
Profile C				
20	1.1718	0.293	Symmetrical	v. well-sorted med sand
21	1.5554	0.3026	Symmetrical	v. well-sorted med sand
22	1.9379	0.2674	Fine-skewed	v. well-sorted med sand
23	1.9928	0.3372	Symmetrical	v. well-sorted med sand
SURFACE SAMPLES-DEC				
Profile A				
31	1.2184	0.3202	Fine-skewed	v. well-sorted med sand
32	1.021	0.4562	Coarse-skewed	well-sorted med sand
33	1.5953	0.2968	Near symmetrical	v. well-sorted med sand
34	1.3478	0.3668	Fine-skewed	v. well-sorted med sand
Profile B				
31	1.3121	0.2533	Near symmetrical	v. well-sorted med sand
32	1.0488	0.3143	Fine-skewed	v. well-sorted med sand
33	1.5055	0.2762	Near symmetrical	v. well-sorted med sand
34	1.4867	0.3604	Near symmetrical	well-sorted med sand
Profile C				
31	1.2801	0.2867	Fine-skewed	v. well-sorted med sand
32	1.1302	0.3361	Fine-skewed	v. well-sorted med sand
33	1.5489	0.3322	Near symmetrical	v. well-sorted med sand
34	1.5545	0.3447	Near symmetrical	v. well-sorted med sand
35	1.5443	0.2975	Near symmetrical	v. well-sorted med sand

Table C-3 Sieve Data and Statistical Analysis

Sample	Mean	Std. Dev	Mode phi	Skewness	Sorting	Size
Profile A-1	1.3	0.4924	1.50, 2.50	Symmetrical	well	medium
2	1.0	0.7045	1.25, 2.50	coarse	mod.-well	coarse
3	1.0	0.5000	1.50, 2.50	Near symmetrical	well	coarse
4	1.1	0.7614	1.50, 2.50	coarse	mod.-well	coarse-med
Profile B-1	1.1	0.6057	1.50, 2.50	coarse	mod.-well	coarse-med
2	1.4	0.6382	1.50, 2.25	coarse	mod.-well	medium
3	1.2	0.4045	1.50, 2.50	Near symmetrical	well	medium
Profile C-1	1.3	0.4924	1.50, 2.50	Symmetrical	well	medium
2	1.3	0.4598	1.50, 2.50	Near symmetrical	well	medium
3	1.5	0.6129	1.75, 2.50	Near symmetrical	mod.-well	medium

APPENDIX D: CARBONATE CONTENT.

DATA FROM POINT COUNTS AND DRY WEIGHT PERCENT METHOD

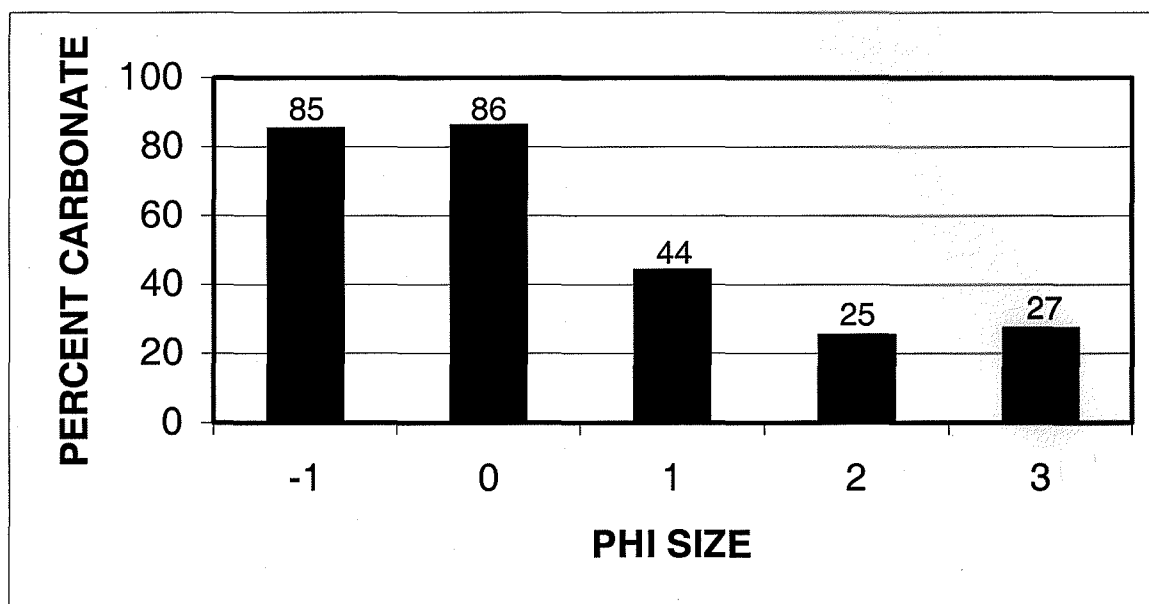
Table D-1 Otter Cove weight percent carbonate concentrations
from vegetation line to water.

Sample	% Carbonate
Profile E -1 (veg. line)	13
2	10
3	19
4	15
5	6
6 (low tide line)	11

Table D-2 Constituents found in surface samples comprising
total carbonate material at Sand Beach.

MAY SAMPLES	%bivalves	% barnacles	%echinoderms	undifferentiated
PROFILE A 1	4	56	3	37
2	6	58	1	26
3	4	65	12	18
4	4	72	11	14
B 1	9	40	12	39
2	3	46	10	41
3	7	51	3	39
C 1	6	27	6	61
2	7	44	7	41
3	5	38	3	53
L 1	3	48	8	42
AUG. SAMPLES				
PROFILE A 20	6	41	12	41
21	3	51	7	39
22	4	54	8	34
23	3	38	7	52
B 20	4	50	8	38
21	4	69	3	24
22	2	39	7	53
23	3	46	16	35
C 20	3	49	10	38
21	7	59	6	28
22	3	44	9	44
23	4	34	11	50
DEC. SAMPLES				
PROFILE A 31	11	65	11	14
32	4	75	4	17
33	5	62	6	28
34	3	70	6	21
B 31	8	51	6	35
32	2	71	5	22
33	4	51	8	37
34	4	47	1	38
C 31	1	55	5	39
32	2	67	5	26
33	2	61	7	3
34	1	91	5	3
Lagoon 1	1	63	3	33

Fig D-1 Weight percent carbonate of material from berm sample A32
at whole phi intervals



APPENDIX E: GROUND-PENETRATING RADAR DATA

Fig. E-1 CMP Results from across dunecrest. Velocity equals 0.158 m/ns

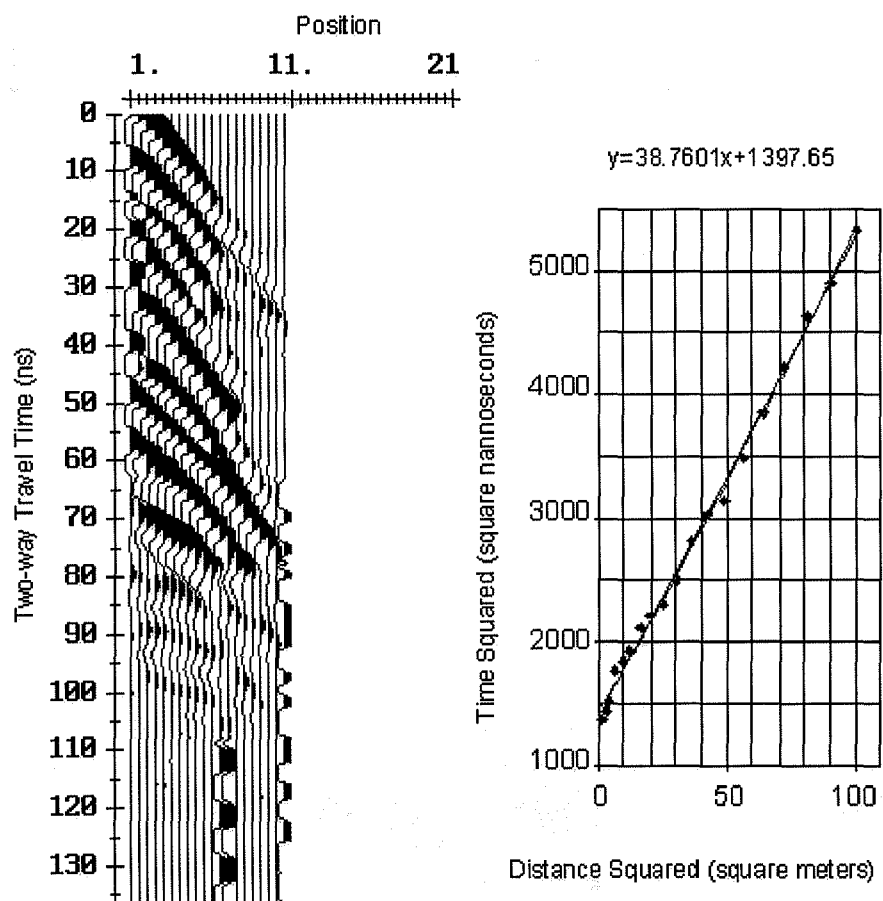


Fig. E-2 Interpretation and GPR transect across vegetation line or fenceline See figure 8 for location of transect.

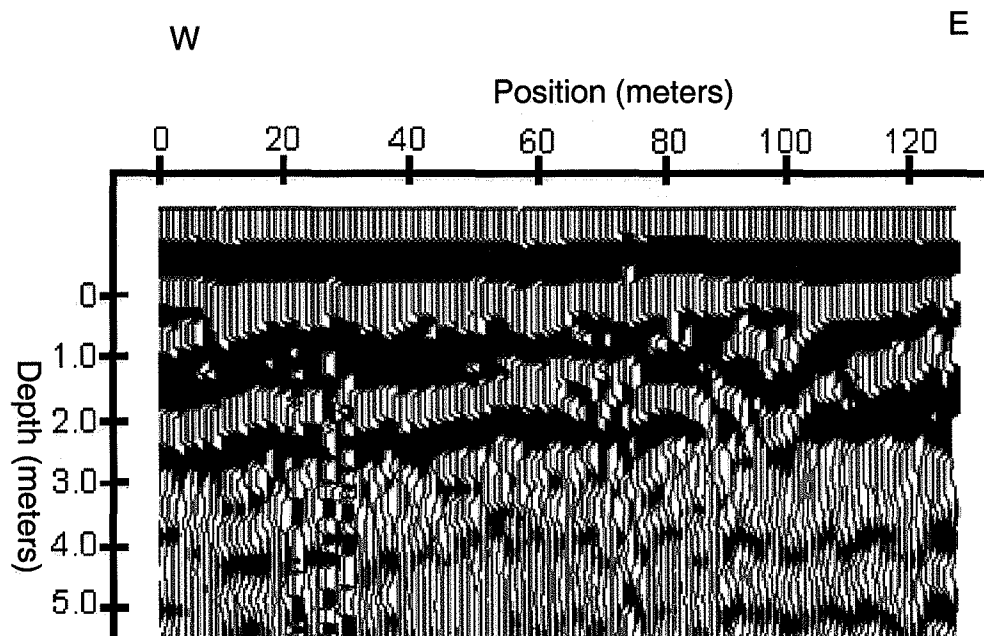
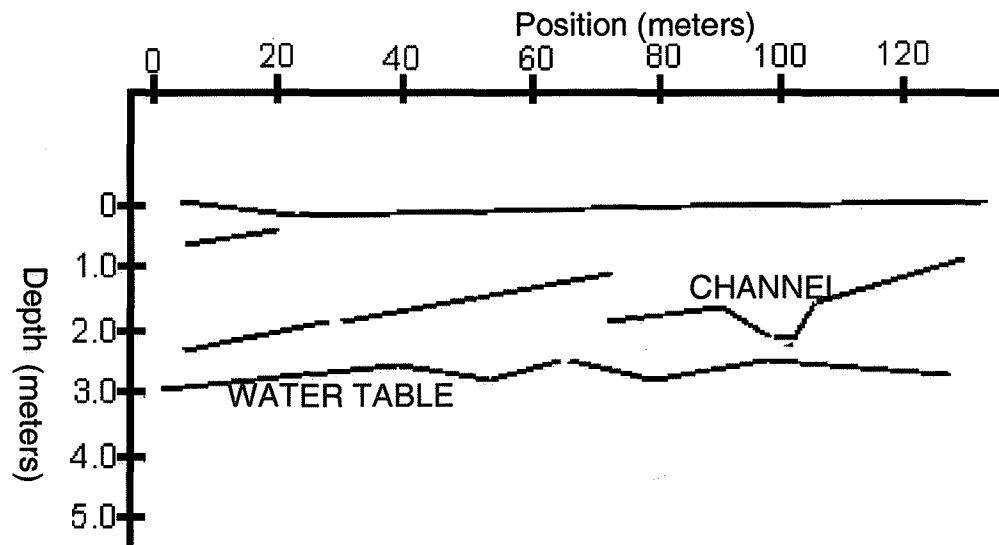


Fig. E-3 Interpretation and GPR Transect West-East to Pine Trees along transect E. See Figure 8 for location.

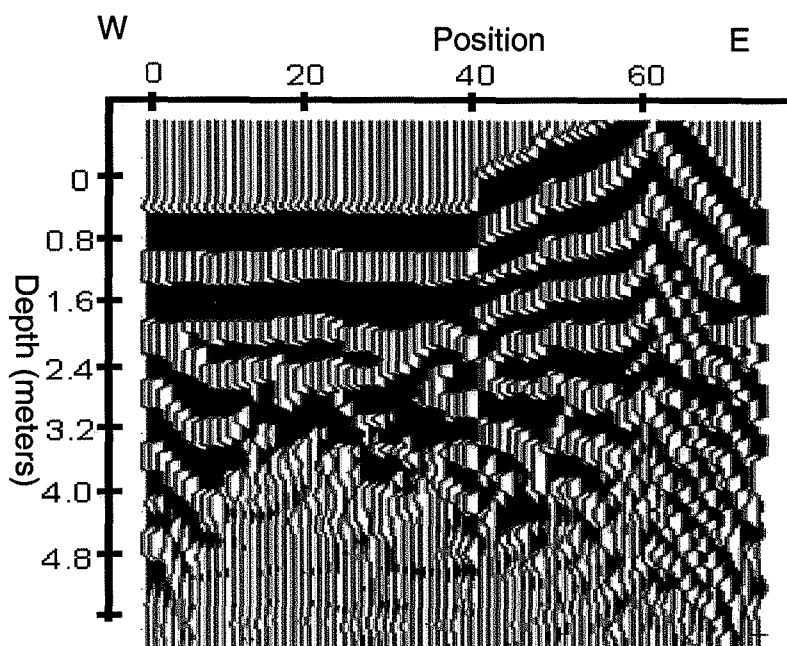
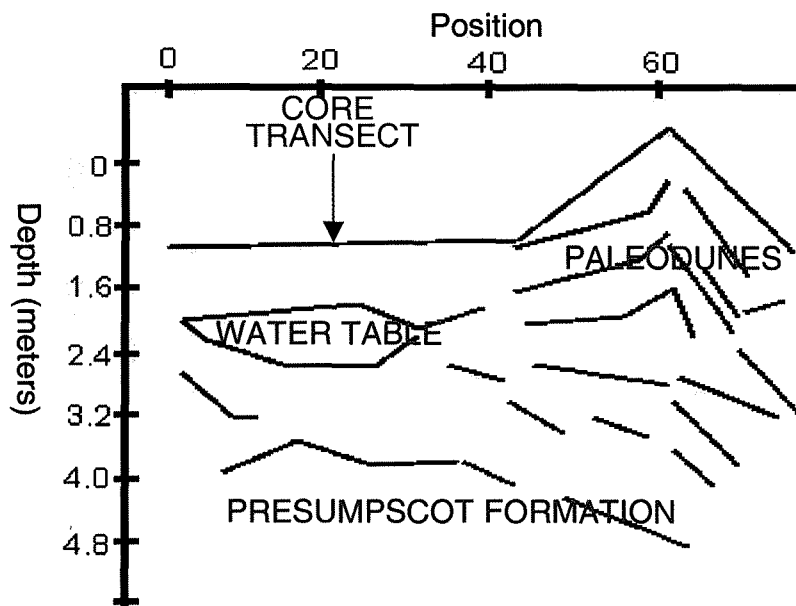


Fig. E-4 North to South from Vegetation line to berm along Transect C

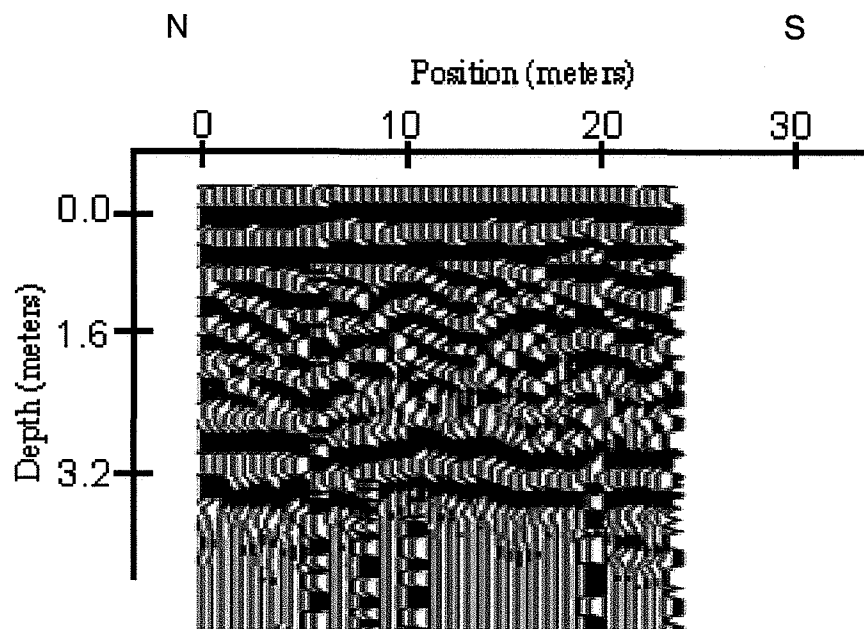
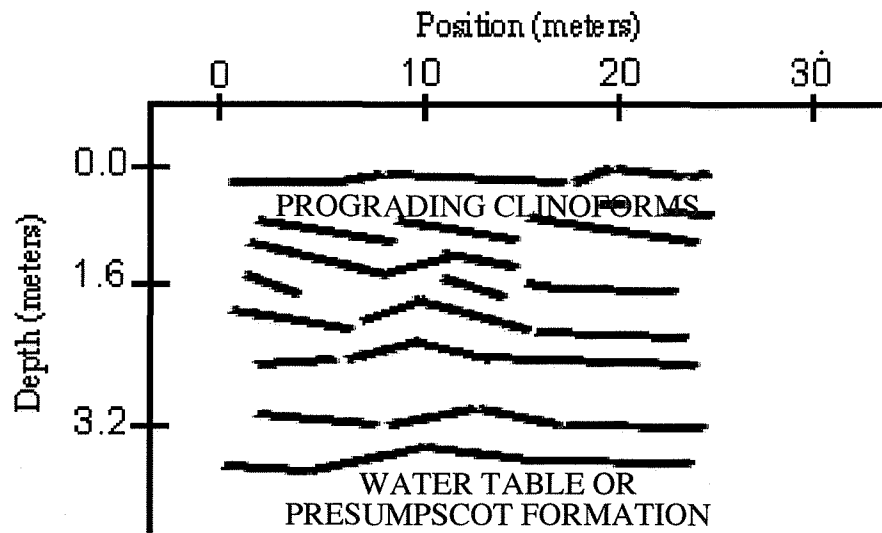
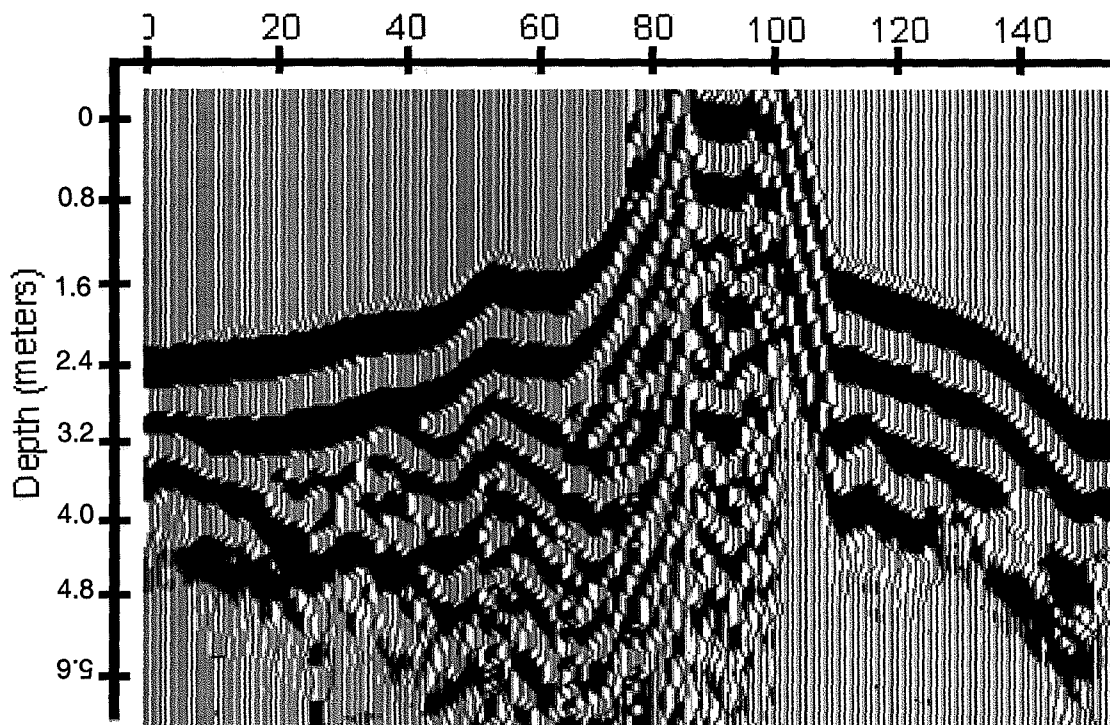
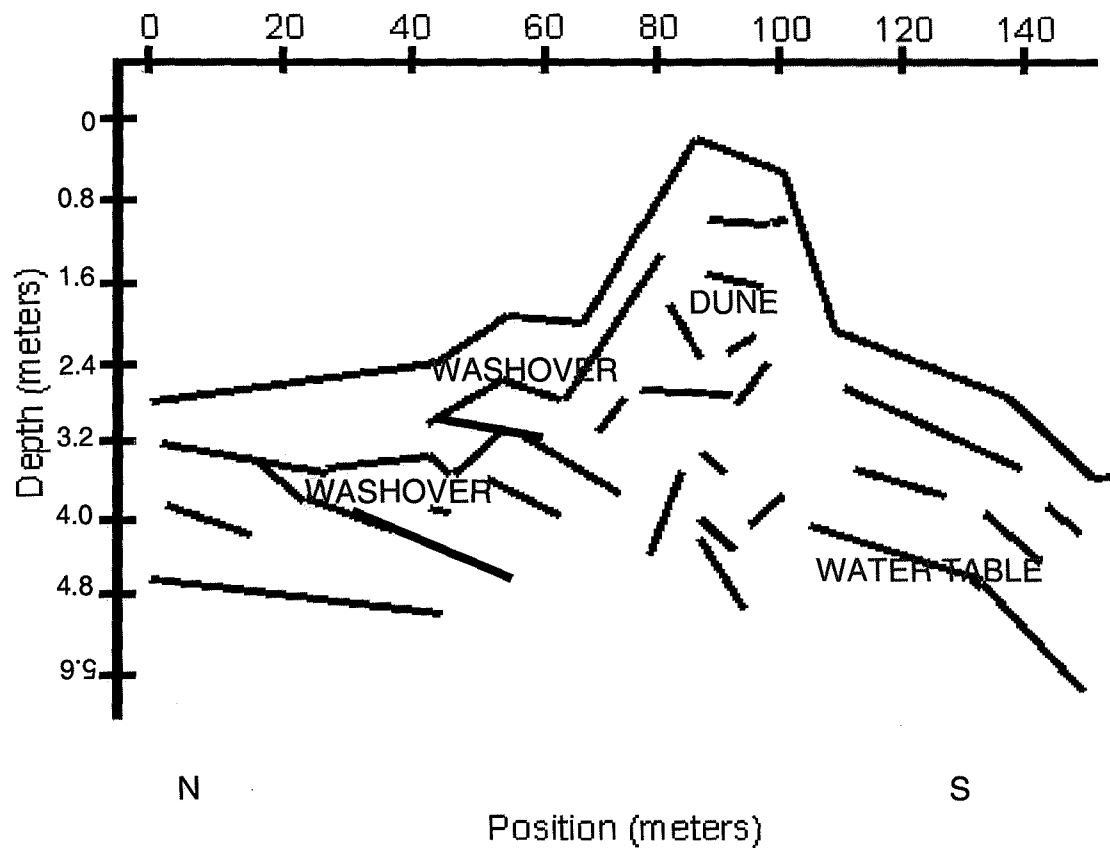


Fig. E-5 North-South Transect from marsh to berm along transect A



APPENDIX F: SEASONAL PROFILE DATA

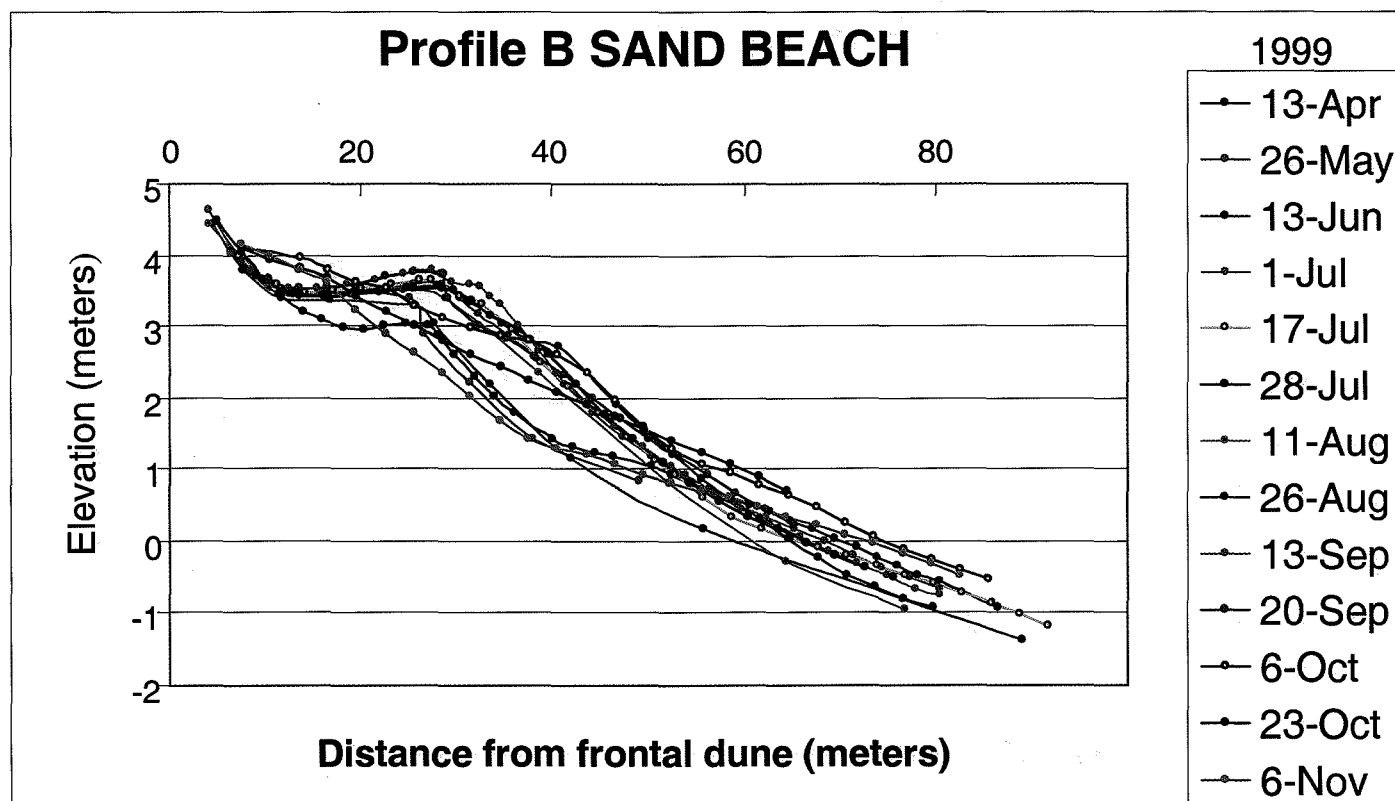


Fig. F-1 Data are archived in the sedimentology laboratory of the Department of Geological Sciences, University of Maine

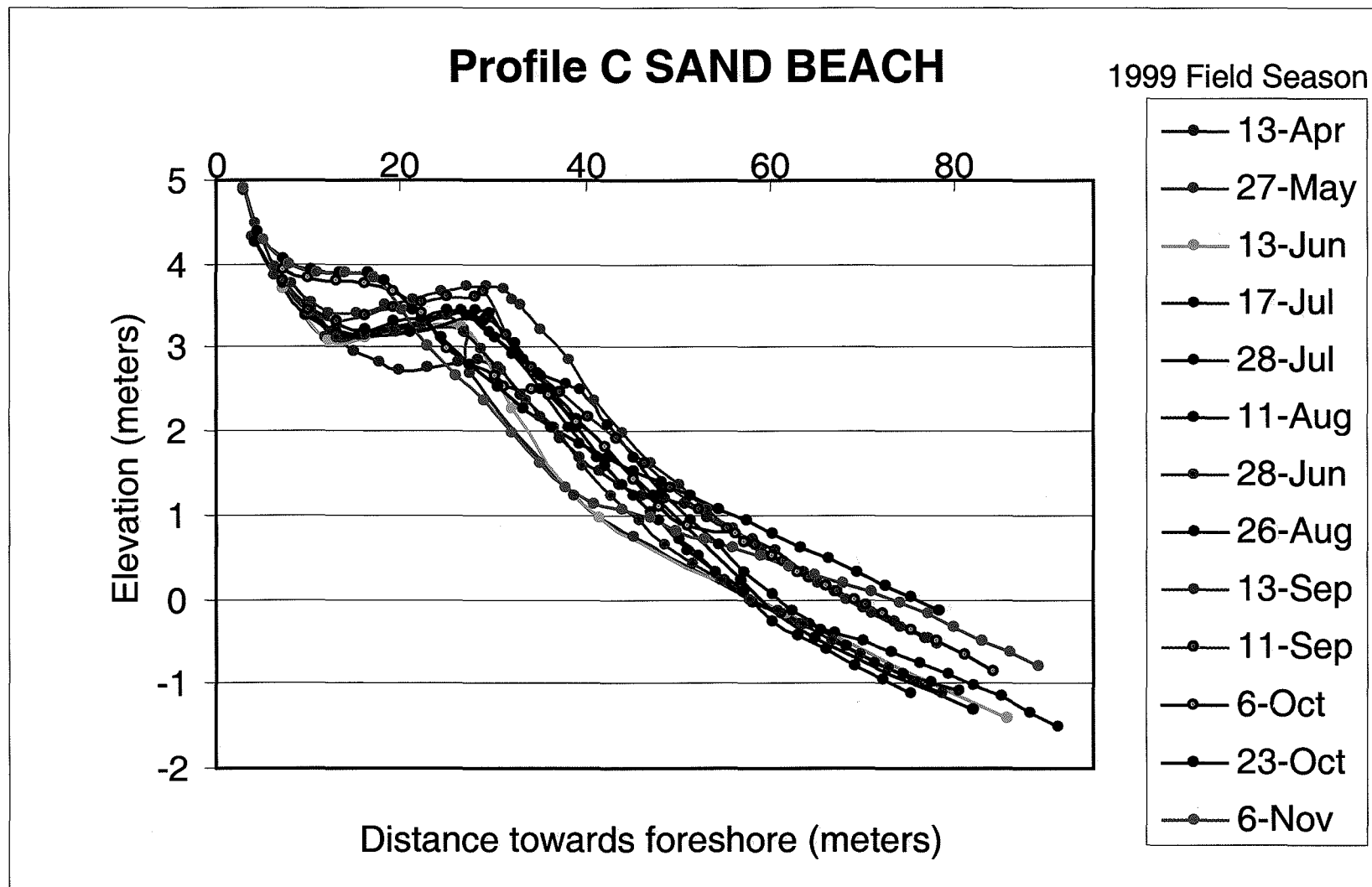


Fig. F-2

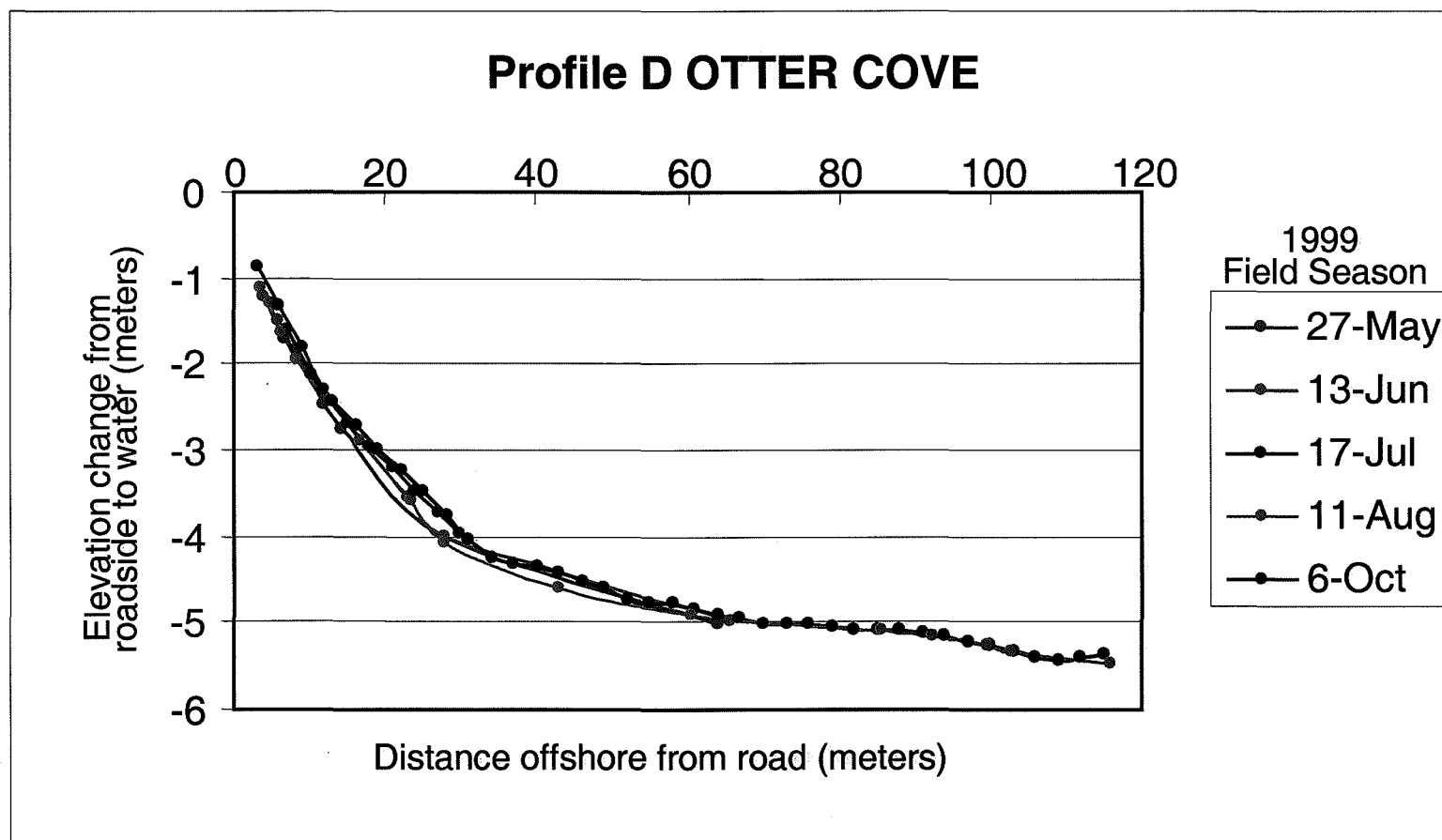


Fig. F-3 Changes along Otter Cove. See figure 7 for locations.

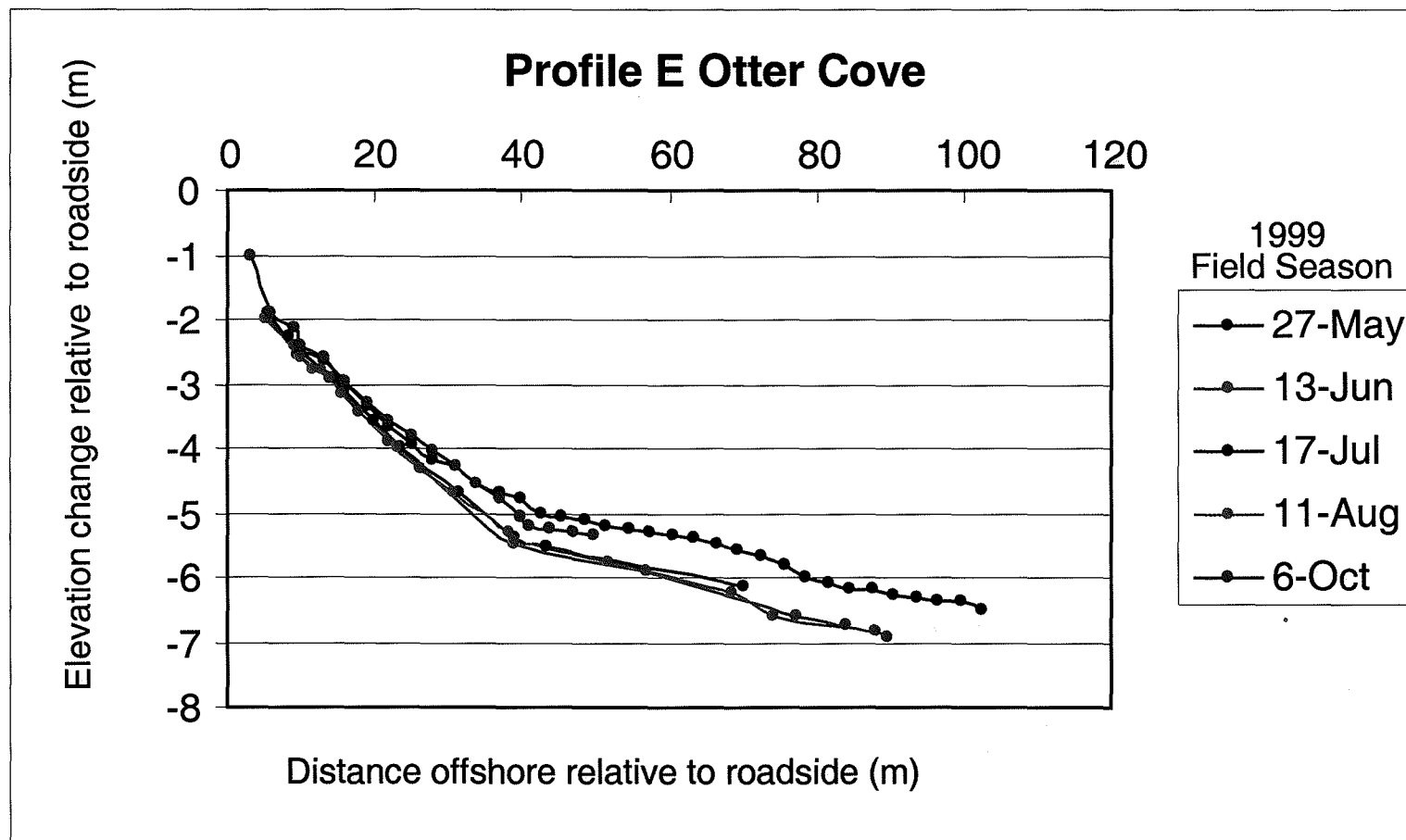


Fig. F-4

BIOGRAPHY OF THE AUTHOR

Allison Lee Brandes was born in Ridgewood, New Jersey on August 7, 1976. Having graduated from Ridgewood High School in June of 1994, she decided to attend Boston University for her undergraduate studies in English education. While at Boston University she became increasingly interested in geology and decided to add an earth science minor. While there she became engaged in a project in Wells, Maine examining ancient beach ridge and delta deposits.

She also engaged in a summer internship program through Albion College in Southwestern Wyoming. As part of a Research Experience for Undergraduates, Allison's project used paleosols as indicators for water level changes. By combining this evidence with fossil data and the physical stratigraphy, she determined depositional environments of Eocene deposits in Fossil Butte National Park.

Allison completed her Bachelor of Science degree in English education and her minor in geology at Boston University and graduated in May, 1998. Hoping to continue studies of geological processes, she enrolled in the graduate program in the Department of Geological Sciences at the University of Maine. Her research findings were presented at the Northeast GSA conference in March. Upon leaving Maine, she will teach physical science at Hawthorne-Brooke Middle School in Townsend, Massachusetts. She is a candidate for the Master of Science degree in Geological Sciences from the University of Maine in August, 2000.