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A SEDIMENTARY RECORD OF INTENSE STORMS AND ENVIRONMENTAL CHANGE FROM A COASTAL FRESHWATER LAKE IN REHOBOTH BEACH, DELAWARE

Stephen G. Smith
University of Rhode Island

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A SEDIMENTARY RECORD OF INTENSE STORMS AND ENVIRONMENTAL CHANGE FROM A COASTAL FRESHWATER LAKE IN REHOBOTH BEACH, DELAWARE

BY

STEPHEN G. SMITH

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ABSTRACT

Located along the Mid-Atlantic coast of the United States, the state of Delaware is vulnerable to both tropical storms tracking from the warmer water of the southern Atlantic Ocean as well as strong extratropical storms, such as nor'easters, that are more common in the northern Atlantic. Although no hurricane has made direct landfall over Delaware in the past 200+ years of historical record keeping, several have passed with enough proximity to cause significant damage and erosion throughout the state's coastal communities. Effects from the Ash Wednesday Storm of 1962, which inflicted widespread flooding and destruction across coastal Delaware, indicate that extratropical storms are an equal threat for this stretch of Atlantic coastline. In order to better characterize the frequency of similar intense storm impacts throughout Delaware's history, five sediment cores were retrieved from Silver Lake, a small body of freshwater located in the coastal town of Rehoboth Beach. Separated from the Atlantic ocean by a ~200 meter wide coastal barrier, Silver Lake is susceptible to overwash processes resulting from intense storm systems that track over or near the area. Preserved as thin veneers of sand within otherwise fine-grained mud and silt-sized sediment, these layers of washover preserve a record of past storms strong enough to transport sand into the back-barrier lake environment. Sedimentological and mineral magnetic properties suggest that storm surges have, on multiple occasions, formed temporary inlets through the barrier fronting Silver Lake in the past ~500 years. As such, core sediments have alternating facies indicative of low-energy lake-bottom and saltwater marsh deposition. Despite this environmental variability, storm signals are preserved throughout both facies, and likely represent the most severe storm events impacting the Silver Lake area. Stratigraphic and geochronological analyses of sediment cores suggest that approximately eight storms have deposited washover sand into Silver Lake during the past ~500 years. Several of these storms likely occurred in the midst of cooler Atlantic Ocean sea surface temperatures during the Little Ice Age (~1550-1850 A.D.), suggesting that the frequency of intense storm events in Delaware is not controlled by changes in sea surface temperature. Additional first-order comparisons of the storm record with changing phases of the Atlantic Multidecadal Oscillation, the North Atlantic Oscillation, and the El Niño/Southern Oscillation also failed to indicate any possible correlations. However, spectral analysis suggests that the periodicity of mean grain size in Silver Lake may be influenced by the alternating positive and negative phases of the North Atlantic Oscillation. Apart from mean grain size, the record of overwash deposition is likely dominated by individual storm characteristics and pre-storm morphology of the adjacent beach. Understanding the patterns, if any, defining these types of extreme storm events is crucial for predicting the frequency of future storms as well as planning for the mitigation of potential storm impacts.

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Danielle Cares, Carol Gibson, and Chip Heil helped guide me through the various technical aspects of this project. Many thanks go out to them for their patience and excellent instruction. Without their assistance I'd have little, if any, useful data for this thesis. Jim King and Nate Vinhateiro deserve special recognition for supplying additional manpower throughout the trip down to Delaware and subsequent fieldwork around Silver Lake. As an aside, I also want to acknowledge Nate for all the advice he has shared with me during our days spent conducting the beach survey. On a similar note, the state of Rhode Island made this thesis possible by funding my graduate studies through the beach survey program.

Thanks to the Delaware Department of Natural Resources and Environmental Conservation (DNREC) for their logistical assistance and help with data acquisition. Also, the lab of Brad Moran deserves recognition for conducting ^{210}Pb and ^{137}Cs isotope analyses of my sediment samples. The age model in this thesis would not have been the same without the data they supplied.

On a personal level, I want to thank the former and fellow students and workers of South Lab, who have helped make my time on campus quite enjoyable and

often hilarious. Also, thanks to the friends I've made during my time living and going to school in Rhode Island. They are responsible for the camaraderie, support, and fun that has characterized this chapter of my life. Additionally, I can't forget my family and friends elsewhere, for the motivation, encouragement, and love that they've given me despite our distance from one another.

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INTRODUCTION

1.1 Statement of the Problem

With a rapidly changing climate, it is crucial to develop accurate predictions of the impacts that future storm activity and rising sea level will have on coastal environments. A more complete understanding of storm history from specific areas is arguably the most important aspect in building models of potential coastal response. Although recorded history provides fairly accurate documentation of storms that have impacted the U.S. and world coasts in recent times, evidence of storms on longer timescales is much more beneficial for gaining insight into storm cycles and how these cycles may relate to larger-scale climate patterns. Focusing on the state of Delaware, the ultimate goal of this particular project is to expand the record of intense storms in southern Delaware using coastal lake sediments. Knowledge of storm frequencies on the order of several hundred years may facilitate modeling of future storm patterns, which is essential for proper planning and hazard management of the seashore.

1.2 Justification for and Significance of Study

Located along the Mid-Atlantic coast of the United States, Delaware is vulnerable to both tropical storms tracking from the warmer water of the southern Atlantic Ocean as well as strong extratropical storms, such as nor'easters, that are more common in the northern Atlantic (Figure 1). Although hurricanes are typically

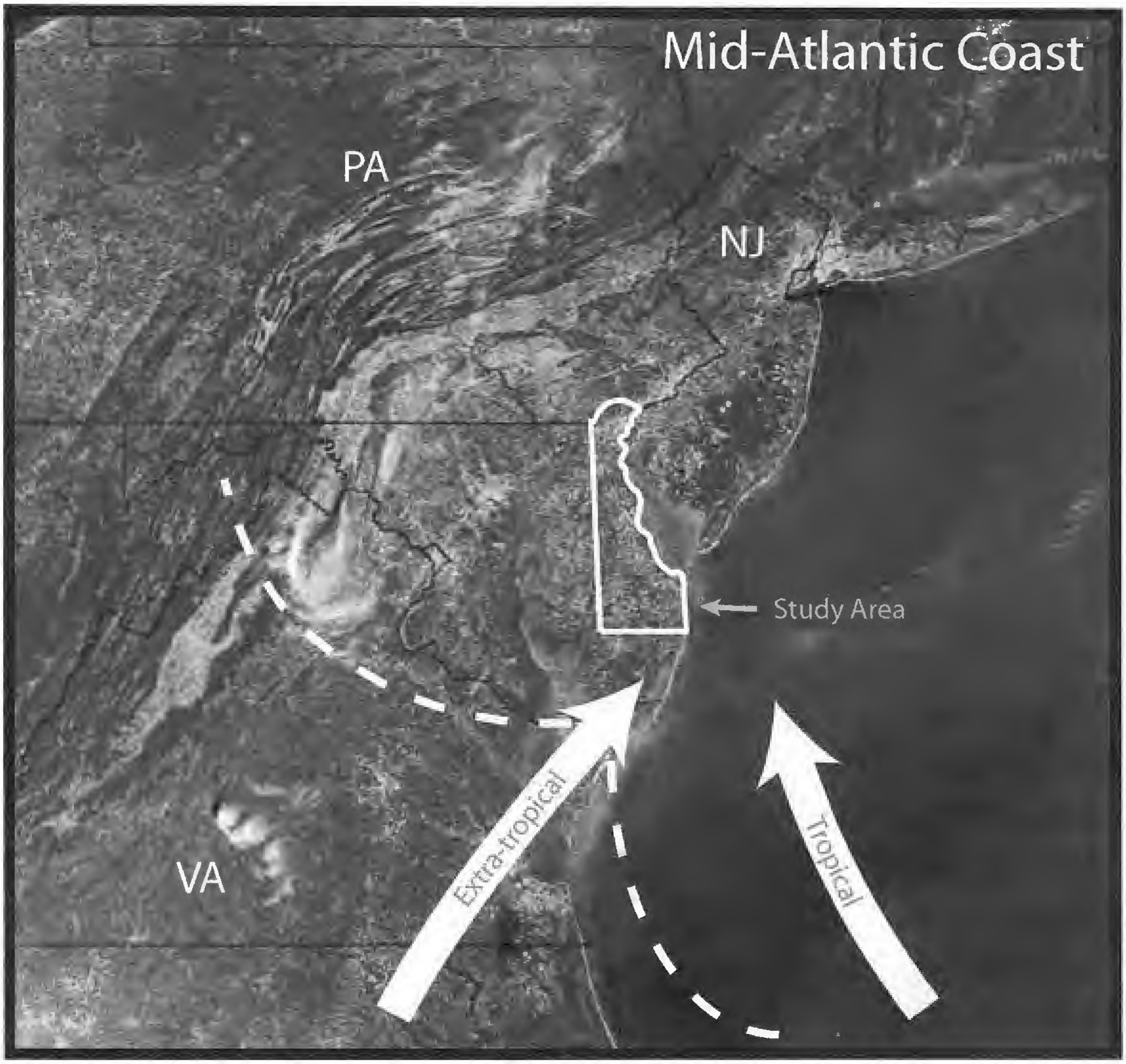

Figure 1. Satellite image of the U.S. mid-Atlantic coast. The state of Delaware is outlined in white, and the red arrow indicates the approximate location of the Silver Lake study area. Generalized tracks of tropical and extratropical storms that have the greatest impact on the Delaware coast are indicated by arrows. Although extratropical storms may originate in a variety of locations relative to Delaware, a southerly approach would bring the most destructive onshore winds.

stronger and more damaging, extratropical storms occur more frequently, are of longer duration, and are capable of producing comparable storm surges during extreme events (Leatherman, 1988). A storm surge is defined as an onshore rush of water that occurs in response to the heavy onshore winds and low-pressure systems of intense storms. These surges, along with elevated surface waves, result in a process known as overwash. Overwash is defined as an overflow of water and sediment beyond the crest of the beach (Donnelly et al., 2006). Due to the relationship between storm surge and overwash, the power and intensity associated with a fierce storm, whether a hurricane or nor'easter, has the potential to create a much more lasting impact on a sandy coastline than a series of indirect strikes from more frequent, but weaker storms (Morton and Sallenger, 2003).

Lying south of the entrance to Delaware Bay, the southern stretch of the Delaware coast is of particular interest because it is characterized by a set of sandy coastal barriers, back-barrier marshes, and coastal lagoons. Although this area consists mostly of larger lagoons, such as Rehoboth Bay, there are also a series of much smaller, isolated coastal ponds that exist without a connection to the ocean. One of these ponds, known locally as Silver Lake, is a freshwater environment situated just ~200 meters inland from the Atlantic Ocean (Figure 2). During periods of high wind and wave activity, waves may overtop the adjacent barrier dune and flood into Silver Lake, depositing sand on the lake floor. Because of its proximity to the shoreline (< 200m) and low elevation (< 2m), Silver Lake is an ideal environment for reconstructing the history of overwash events. Within a basin dominated by low-energy deposition of clay and silt-sized material, storm events are preserved as

Figure 2. Aerial photograph of Silver Lake and vicinity. Core locations are marked with yellow dots. Inset map indicates location of study area within Delaware (in red). 2007 orthophotographs obtained from Delaware Datamil.

intermittent layers of sandy material within the lake-floor sediments. The abundance of these sand layers provides the basis for establishing a several hundred-year history of storm impacts along the southern Delaware coast (Figure 3).

Distinct sand layers within Silver Lake are ideal for the determination of specific storm events, but the variability of other sedimentary facies in each core can lead to conclusions about prior environmental conditions, whether characterized by large storms or not. For instance, changes in the type of sediment and amount of organic material in Silver Lake cores may reflect salinity variations indicative of shifts from freshwater to saltwater throughout the history of the lake. Thus, even if a washover deposit is not preserved at a certain depth in the lake sediments, the indication of a saltwater environment suggests that there was at least a temporary connection with the ocean. With respect to the current morphology of Silver Lake, a breach would only occur as the result of an extreme storm event with waves powerful enough to erode a channel through the barrier dune. As such, sedimentary evidence of prior shifts from freshwater to saltwater may indicate this type of event in the past. Distinguishing these changes is crucial to developing a complete understanding of Silver Lake's geologic history and identifying the signals of past storm events.

Over fifty percent of the United States population resides within coastal counties (NOAA, 2005). Therefore, understanding the variation in storm deposition is crucial for conservation, long-term hazard management, and ecological management of the nation's seashore. In particular, the continuous development along the coast of Delaware makes hazard mitigation arguably the most important aspect of coastal life when severe storms make landfall in the area. The sudden and catastrophic impact of

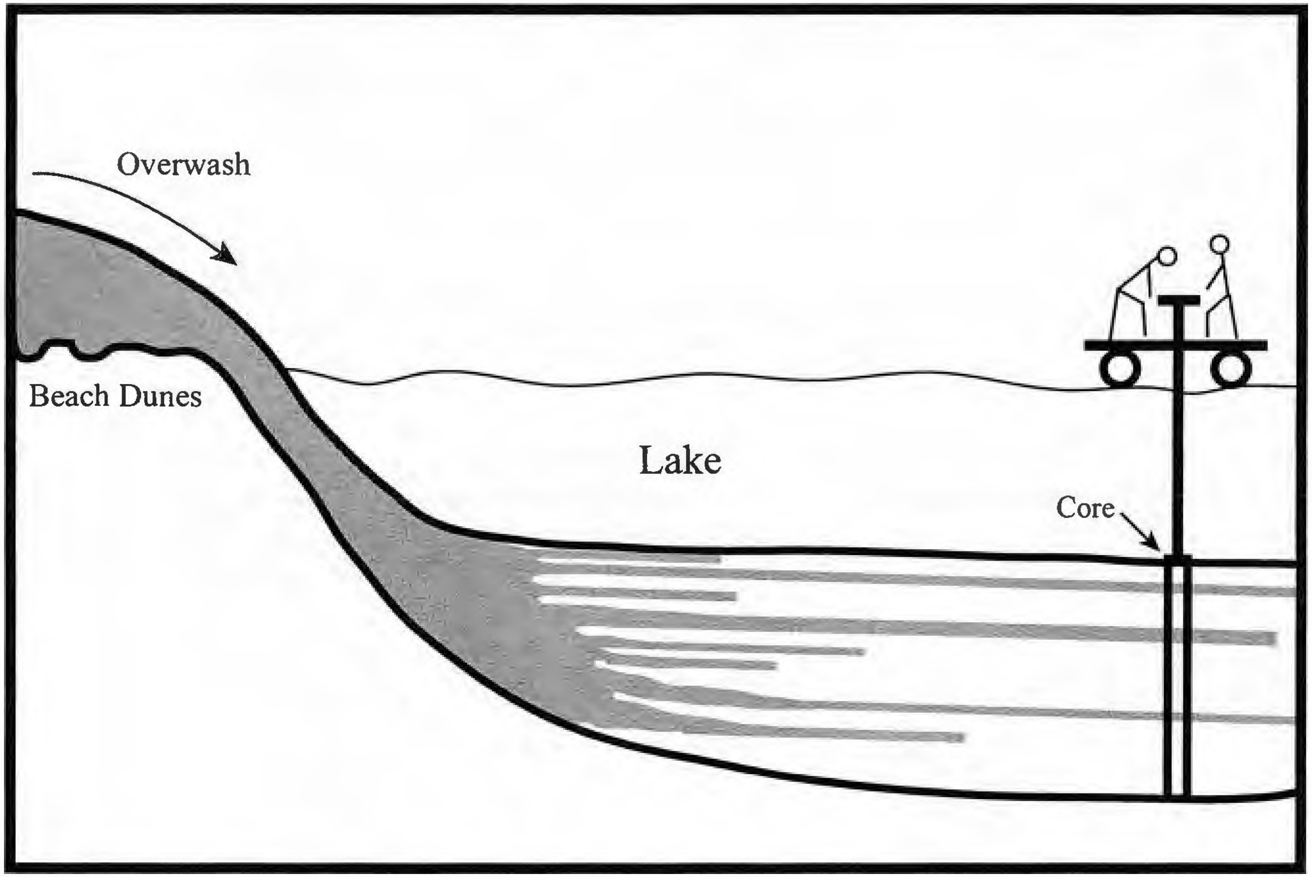

Figure 3. Model of overwash deposition within a coastal lake. The sedimentary record of overwash may be obtained by coring the lake, although the dynamic nature of overwash may lead to differing records of deposition in various parts of the lake.

storms on coastal sediment budgets can make long-term prediction of shoreline behavior and response to erosion mitigation activities difficult at best (Ritter et al., 2002). In addition, recent reports suggest that hurricanes are possibly becoming more intense in response to a warming climate (Emanuel, 2005; Goldenberg et al., 2001). Because of the substantial population, economy, and amount of diverse ecology that is prevalent all along the southern Delaware coastline, it is vital that the potential effects of severe storm systems are wholly understood. This project, along with past and future research, hopes to aid in the development of models of coastal evolution associated with potential storm impacts, climate variability, and sea-level change.

1.3 Storms and Responses

Much of the erosion and deposition that occurs along U.S. East Coast coastal barriers is driven by storms (Dolan et al., 1988). While fair-weather wind and wave activity does have an effect on the coast, storms have the power to transport large amounts of sediment, form new inlets, and shift entire islands (Morton and Sallenger Jr., 2003). Since this project focuses on the mid-Atlantic coastline of southern Delaware, both tropical and extratropical systems are considered capable of creating storm surges large enough to overwash into Silver Lake.

Tropical storms are a constant threat during the summer season in the Mid-Atlantic region of the United States. Hurricane season officially commences on June 1 each year (National Hurricane Center, 2006), the time when ocean water in the south Atlantic becomes sufficiently warm for tropical storms to form (NOAA, 2006). In general, tropical storms are considered warm-core systems that evolve as deep, atmospheric low-pressure systems originate and gain intensity with the evaporation of warm ocean water (Ritter et al., 2002). They are termed "tropical" because most storms of this kind form in the tropical latitudes, such as the Caribbean Sea (NOAA, 2006). Once formed, tropical storms track north and have the potential to make landfall along the Atlantic Coast of the United States (Wayland and Hayden, 1985). These storms may grow in size and strength as they move, and a tropical storm becomes classified as a hurricane if the wind velocity of the system exceeds 74 mph (NOAA, 2006). Thus, even without making landfall, a hurricane tracking close to the coast can create high winds and fierce waves in certain areas (Kochel and Dolan, 1986). Although the probability of a hurricane making landfall in a given area is low for any one year, the irregular pattern of hurricane timing and spacing throughout history makes much of the Atlantic coast vulnerable to potential hurricanes every year (Zhang et al., 2000). Therefore, the fact that a major hurricane has not made direct landfall over the state of Delaware in recent history has no bearing on the probability of a landfall in the near future.

In contrast to tropical systems, extratropical storms are considered cold-core systems that derive energy from horizontal temperature gradients present in the atmosphere. Most of these low-pressure, cyclonic disturbances that affect the Atlantic Coast originate in the middle-latitude westerly wind belt and are driven by these winds across the eastern seaboard of the U.S. (Dolan et al., 1988). Typically, the most destructive extratropical storms affecting this area are nor'easters, named for their leading northeast winds. Nor'easters are most frequent and strongest between September and April, but may occur during any time of the year. These storms usually develop close to the coastline at various locations between Georgia and New Jersey, subsequently moving north or northeastward upon formation (Dolan et al., 1988). Extratropical storms are common along the U.S. Mid-Atlantic region because of the area's favorable climate conditions for storm development. During winter, the polar jet stream transports cold Arctic air southward and eastward toward the Atlantic Ocean while warm air from the Gulf of Mexico and the South Atlantic Ocean tries to move northward. This frontal zone of temperature differences between the warm air over the water and cold Arctic air over the land is where nor'easters are born (NOAA, 2010). In addition to heavy snow and rain, nor'easters can bring gale force winds greater than 58 miles per hour, producing rough seas, coastal flooding and beach erosion (NOAA, 2010). Notable nor'easters occurring during recent history are the Ash Wednesday Storm of 1962, the Halloween or "Perfect" Storm of 1991, and the "Storm of the Century" in 1993.

Previous research on storm deposits has suggested that the power and intensity associated with a fierce hurricane has the potential to create a much more lasting impact on a barrier island than any erosional processes driven by extratropical storms. Using this logic, most previous studies concerning overwash have attributed sandy back-barrier deposits to the effects of tropical storms (Donnelly et al., 2001; Liu and Fearn, 1993, 2000; Morton and Sallenger, 2003). Although this may be true for certain stretches of the U.S. Atlantic or Gulf coasts, hurricanes have been quite scarce in the recent history of Delaware, whereas extratropical storms have regularly brought widespread precipitation and gale-force winds to the coast. Nor'easters have been especially destructive throughout the state's history, and thus are the likely sources of any recent overwash occurring in Silver Lake. As such, there is not sufficient evidence to attribute all past washover deposits to hurricanes, and this study aims to decipher the record of those infrequent, yet extremely severe storms that may have been either tropical or extratropical in nature.

1.4 Historical Storms in Delaware

Modern climatological records indicate that no storm in the past 200+ years has made direct landfall over Delaware while maintaining hurricane intensity (Ludlum, 1963; Blake et al., 2005). While many storms track just outside of the state's boundaries, this apparent lull in tracks crossing directly over Delaware may reflect the tendency of hurricanes to track to the north and northeast in the western North Atlantic under the influence of prevailing westerly winds (Donnelly et al., 2001). Nevertheless, historical records covering this same 200+ year span suggest that there have been at least five powerful hurricanes passing closely enough to Delaware to result in substantial storm surge and flooding (NOAA, 2006).

The first of these storms with a clearly defined impact along the Delaware coast was the October Hurricane of 1749. A report from Boston News Letter indicated that the storm created a 5-foot inlet in the beach near Cape Henlopen, uprooted trees, and drove several boats ashore (Ludlum, 1963). The next noteworthy storm to affect the Delaware area was a hurricane that tracked across the coast on September 3, 1821. Reports indicate that the eye of the hurricane passed over the entrance to Delaware Bay during the span of about 3 hours, creating a scene of "widespread desolation and ruin" across the coast of the Delmarva Peninsula.

Additional reports of heavy rainfall and storm tides of several feet above normal imply that this storm likely created a significant amount of overwash in the vicinity of Rehoboth Beach, DE (Donnelly et al., 2001; Ludlum, 1963).

Limited accounts of hurricanes in 1830 and 1839 suggest possible impacts in the Silver Lake area, but reports surrounding the Great Hurricane of 1846 were much more definitive. The U.S. Gazette in Philadelphia noted that the storm produced the greatest storm surge in 70 years along Delaware Bay, implying a somewhat similar impact in the Silver Lake study area. Thirty-two years later, the Gale of 1878 resulted in analogous reports of damage across Delaware, with winds of up to 85 mph measured in the nearby town of Lewes. Additionally, the hurricane made landfall during a perigean high tide, which, in combination with heavy onshore winds, created a substantial storm surge across the Delaware coast (Ramsey and Reilly, 2002). Although precise measurements of the surge near Rehoboth Beach are unavailable, overwash was likely widespread.

A hurricane that made landfall near Atlantic City, NJ, in 1903 also brought hurricane-force winds to the coast of Delaware. Despite storm tracks that failed to cross Delaware directly, the 1903 hurricane and the Gale of 1878 are the only two storms to bring hurricane-force winds to Delaware since 1850 (NOAA, 2006). However, the 1933 Chesapeake-Potomac hurricane, which caused $150,000 ($2.03 million 2005 USD) in damages along the coast, may have gusted over 74 mph at times. Although direct evidence is lacking, both of these early 20th-century storms may have created washover deposits in the vicinity of Silver Lake.

Perhaps the storm of the century for Delaware is the Ash Wednesday Storm of 1962. This storm, characterized as a nor'easter, had a devastating and lasting impact on the state, and is considered to be one of the worst storms in recorded history to impact the Mid-Atlantic region of the United States. It persisted for more than five consecutive, semi-diurnal, perigean spring tidal cycles, maximum winds reached 112.7 km/hr (70 miles/hr), waves were an average of 6-9 m (20-30 ft), and the storm surge reached 2.9 m (10 ft) (McCarty, 2009). Even though aerial photographs and post-storm analysis indicate that the Rehoboth Beach area experienced the least amount of flooding and erosion along the Atlantic coast of Delaware, the majority of Delaware's coastal towns were greatly impacted by flooding and overwash. The resultant widespread washover deposition along the coast of southern Delaware further suggests that both tropical and extratropical storms should be considered when examining the sedimentary record of storm deposition within Silver Lake.

1.5 Previous Work

Although it is a fairly recent field of study, other researchers have used coastal lake sediments to reconstruct long-term storm histories. For instance, Liu and Fern (1993) initially used washover deposits from Lake Shelby, Alabama as a proxy for the reconstruction of hurricane strikes during the past ~7000 years. After this pilot study, they subsequently conducted analogous studies at other coastal lakes in Florida and Mississippi (Liu and Fearn, 1997, 1998). They inferred that the presence of sand layers within the lake-floor sediments indicated prior instances of overwash, which is the hypothesis also used with respect to Silver Lake.

In addition to coastal lakes, researchers have also obtained similar prehistoric storm records by studying coastal marsh sediments. Some of these study sites include North Carolina (Culver et al., 2006), Maine (Buynevich, et al., 2004), southern New England (Donnelly et al., 2001a), New Jersey (Donnelly et al., 2001b), and South Carolina (Collins et al., 1999; Scott et al., 2003). In each of these studies, whether the site was a lake or marsh, the general research principle remained the same – low-energy back-barrier environments should preserve a record of storm-induced washover deposition. Using the same premise, this project aims to extend the history of extreme storm events in southern Delaware using the sedimentary record of overwash.

Expanding the historical record of storms is important for predicting their future behavior as well as determining linkages with other climate variables. For instance, several researchers have postulated that hurricanes may be changing in frequency and intensity as global average temperatures slowly rise, but the lack of long-term storm records is severely limiting to this aspect of climate science (Emanuel, 2008; Goldenberg, 2001). While the dynamic nature of coastal environments normally destroys any sedimentary signature of storms older than a few thousand years, this is still an order of magnitude greater than the historical record, and can be very beneficial for developing models of future storm activity.

The connection between intense storms, especially hurricanes, and other distinct climate variables has been the focus of much research over the past decade. A significant body of evidence suggests that hurricanes are less frequent during El Niño events, and that a variety of other atmospheric and oceanic factors may influence the occurrence rate of such storms as well (Bove et al., 1998; Zhang and Delworth, 2006;

Gray, 1984; Sabbatelli and Mann, 2007; Donnelly and Woodruff, 2007). For some of these variables, such as El Niño years, the historic record of hurricane activity is sufficient to establish a meaningful correlation. However, for climatic phenomenon such as the Atlantic Multidecadal Oscillation, which operates on a substantially greater timescale, a record of storms stretching into the prehistoric period is necessary for making any confident associations. Once relationships between storms and such variables are established on centennial to millennial timescales, models regarding the future behavior of storms can be more appropriately constructed. Thus, an additional goal of this project is to determine whether or not there are any obvious linkages between the sedimentary record of overwash within Silver Lake and large-scale climate fluctuations such as the Atlantic Multidecadal Oscillation (AMO), the North Atlantic Oscillation (NAO), or the El Niño/Southern Oscillation (ENSO).

Some of the issues surrounding research associated with deciphering the history of prehistoric storms involve the integrity of the sedimentary record itself. Otvos (1999) argued that the work done by Liu and Fearn (1993) lacked definitive evidence concerning the provenance of sand layers found in Lake Shelby. According to Otvos, the morphology of the lake had likely changed throughout the 7000-year history recorded by Liu and Fearn, and sand may have been deposited by former inlets as opposed to overwash. Because the record contained in the Silver Lake cores spans less than 1000 years, this uncertainty is greatly reduced. In addition, the goal of this study was to interpret the record of storm deposition while simultaneously deciphering the environmental history of the Silver Lake area. Understanding changes in the morphology of the lake are crucial to the proper interpretation of sand layers.

Subsequently, great care was taken to ensure that all hypothesized storm events were evaluated in the context of larger-scale geologic changes. The inferred geological history of Silver Lake and its potential influence on the sedimentary record of storms within the lake is discussed further in a later section.

STUDY SITE AND METHODS

2.1 Geologic Setting

Silver Lake (38° 42'22 N, 75° 04'41 W) is located in the town of Rehoboth Beach, Delaware. Separated from the Atlantic Ocean by a 200-meter wide coastal barrier, the lake's freshwater environment is quite rare considering its proximity to the open ocean. According to USGS topographic maps, the lake covers an area of approximately 0.195 km^2, or 195,000 m^2. The elevation of the lake surface is about 1 meter above mean sea level, and the elevation of the adjacent barrier dune ranges from 2-3 meters above sea level. Silver Lake, a closed freshwater system with an average water depth of ~1 meter, is not fed by any freshwater streams, has no active connection with the ocean, and thus has a lake level maintained through the balance of precipitation and evaporation (DNREC, 2005).

Separate from the longer stretches of barrier coastline fronting Rehoboth Bay and Indian River Bay, Silver Lake is perched on the Scotts Corners Formation, a geologic unit composed of light-gray to brown to light-yellowish-brown, fine to coarse sand with discontinuous beds of organic-rich clayey silt, clayey silt, coarse to very coarse sand, and pebble gravel. The sands are quartzose with some feldspar and muscovite. Laminae of opaque heavy minerals are common (Ramsey, 2010). These sediments represent transgressive deposits consisting of stream, swamp, marsh, estuarine barrier and beach, tidal flat, and shallow offshore estuary environments (Ramsey, 2010).

The shape of Silver Lake, along with the description of the Scotts Corners Formation, suggests that it may occupy a former river channel that was flooded during the Holocene transgression. Since much of the current Delaware coast was part of a vast drainage network for the Delaware River during Pleistocene glacial times, the Silver Lake basin was likely one of many tributaries feeding into ancestral Delaware Bay. (Figure 4) (Kraft, 1971). This Pleistocene environment likely set the framework for the current morphology of Silver Lake as well as its environmental history leading to its evolution into a closed freshwater lake. Figure 4B shows an artistic rendering of the possible antecedent morphology of Silver Lake during the middle Holocene. Note the channel that cuts through the center of present-day Silver Lake, which probably persisted as the main inlet channel during periods when Silver Lake may have maintained an active connection with the Atlantic Ocean. This channel may have created the topographic low where present-day Silver Lake is located.

Silver Lake's geographic position is located on what is considered the Rehoboth Headland. The Delaware Geological Survey and the Delaware Department of Natural Resources and Environmental Control used Light Detection and Ranging (LiDAR) data to construct a Digital Elevation Model (DEM) of the entire Delaware coast. It is immediately clear from the LiDAR data that the area surrounding Silver Lake is topographically higher than the land surrounding Rehoboth Bay to the south (Figure 5). Furthermore, although it is not abundantly clear from the scale of the LiDAR map, the majority of the Delaware coastline is less than 3 meters in elevation, whereas the Rehoboth Headland reaches elevations of up to 6 meters. Due to this

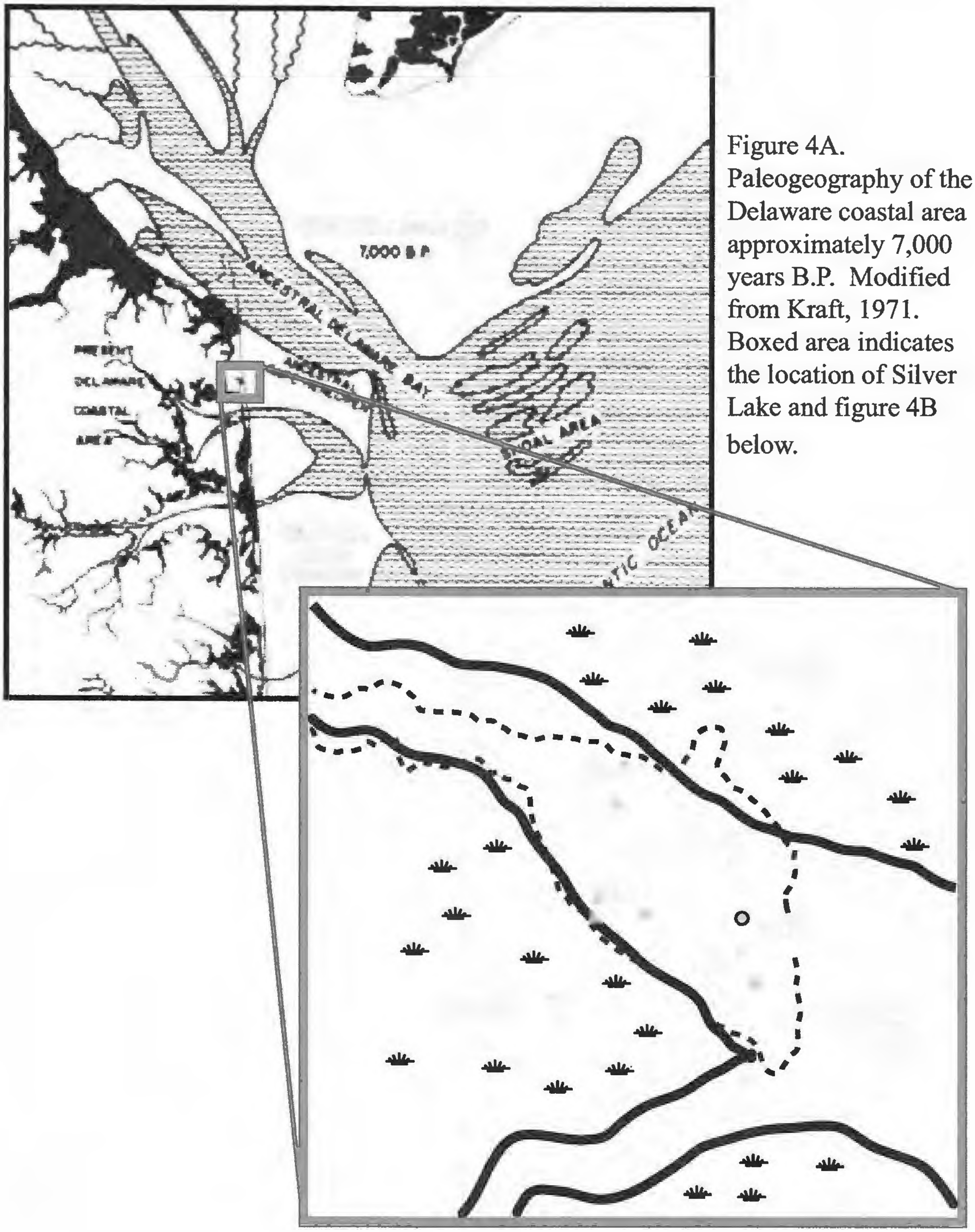

Figure 4A. Paleogeography of the Delaware coastal area approximately 7,000 years B.P. Modified from Kraft, 1971. Boxed area indicates the location of Silver Lake and figure 4B below.

Figure 4B. An interpretation of the paleogeography of Silver Lake during middle Holocene. A former fluvial channel may have created the basin for the present-day lake.

Figure 5. LiDAR elevation map (in meters) of the Rehoboth Beach area. Note that the land surrounding Silver Lake is higher than that surrounding Rehoboth Bay further south. This higher elevation is a result of Silver Lake's location on the Rehoboth headland composed of the more resistant Scotts Corners Formation. Adapted from McCarty, 2009 (Vertical Reference: NAVD88).

location, the beach fronting Silver Lake has shown an accretionary trend since 1968 (McCarty, 2009). While total progradation of the beach is negligible (< 10 m), other areas of the Delaware shoreline have retreated as much as 100 m during the same timeframe (Figure 6). This discrepancy is a result of the general northward longshore transport of sand toward the Cape Henlopen Spit, which replenishes the sediment supply to the Silver Lake area and thus limits the rate of shoreline erosion (McCarty, 2009). The combination of higher surrounding elevations and a recent accretionary trend possibly signifies that overwash events are less frequent in Silver Lake than along the rest of Delaware's Atlantic Coast. Therefore, the sedimentary record of storms within Silver Lake likely represents only the most severe storms or those with tracks that led to a direct impact over the Rehoboth Beach area.

2.2 Historic Maps and Aerial Photographs

Interpretation of sedimentary facies is the main method for inferring prehistoric environmental changes in Silver Lake. Conversely, during the period of human inhabitance, collections of maps and photographs are helpful tools for visualizing and quantifying environmental change regarding the lake. The earliest map acquired for this project dates to 1868 and was provided by the Delaware Geological Survey. A 1918 topographic map was obtained from the USGS, as well as a series of aerial photographs from the Delaware DataMil. The aerial photographs were taken in 1937, 1954, 1961, 1968, 1992, 1997, 2002, and 2007. Although neither the maps nor the aerial photographs show direct evidence of washover deposits in

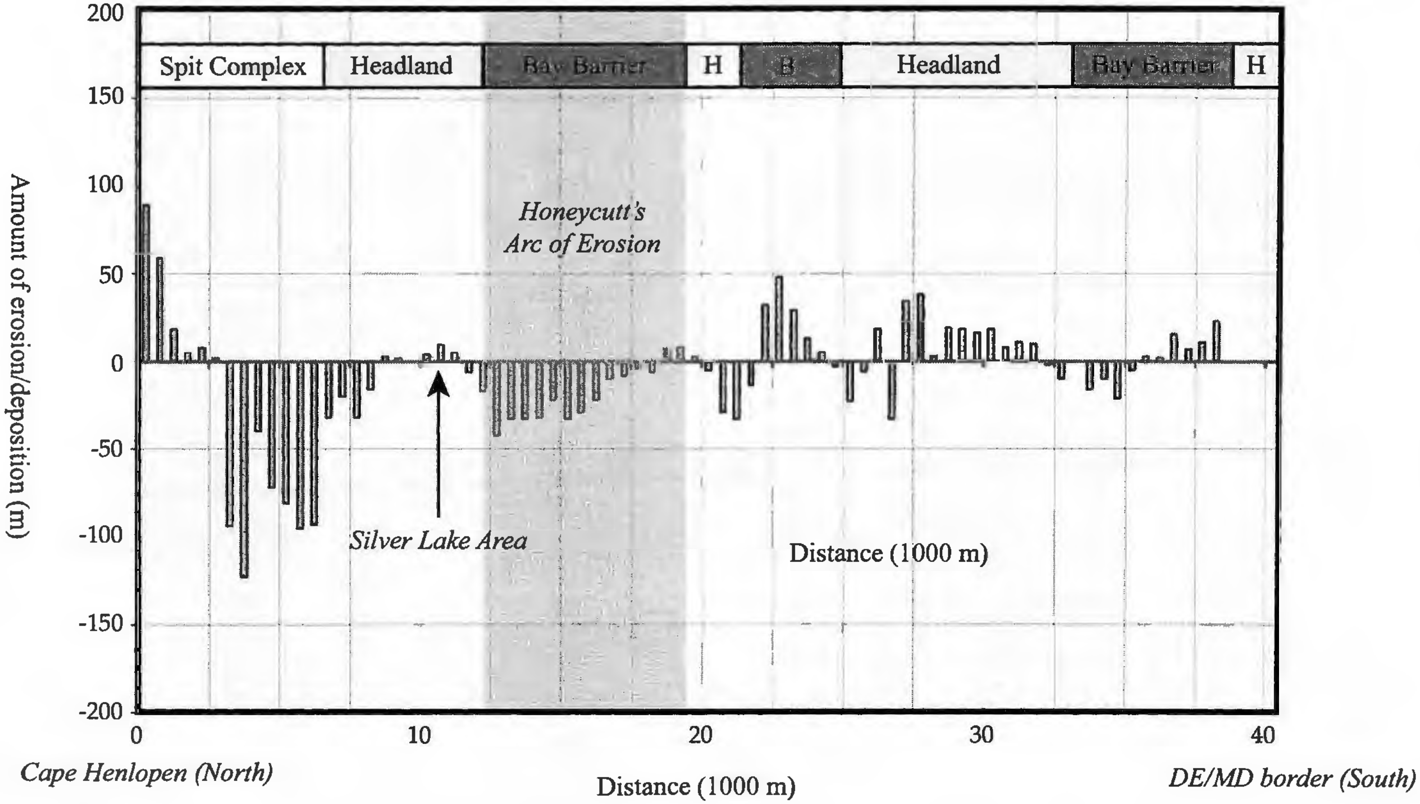

Figure 6. Erosion/Deposition along the Delaware shoreline between the years 1968 and 2002. Adapted from McCarty, 2009. Physiographic regions and "Arc of Erosion" are based on the Delaware Geological Survey Special Publication No. 25 and Honeycutt, 2003, respectively. Note the location of Silver Lake in an area of accretion.

Silver Lake, they are very useful for determining the recent history of the area. Visual confirmation of morphological and environmental changes provides valuable data for correlation with variations in the sedimentary record. If robust, these relationships can then be used as a proxy for deposits older than the available sources of maps and/or photographs.

The aerial photographs are especially useful for assessing the scale of anthropogenic influence on Silver Lake. One of the key impacts on the dynamics of overwash sedimentation in Silver Lake is housing development on the adjacent beach. The sequence of aerial photos aids in quantifying the scale of land-use change and also tracks long-term beach erosion/accretion along the Silver Lake barrier (Figures 7-16).

2.3 Core Analysis

Five sediment cores were retrieved from Silver Lake using a modified piston corer and floating coring platform during June 2009 (Figure 2). Upon returning the cores to the Rhode Island Graduate School of Oceanography, each core was promptly split and logged using a GeoTek® core logging system. Set to a resolution of 1-cm, the GeoTek® produced detailed images of each core and created a down-core log of density and magnetic susceptibility. Magnetic susceptibility is defined as the degree of magnetization of a material in response to an applied magnetic field, and can be used to determine the concentration of magnetic minerals present in the sediment.

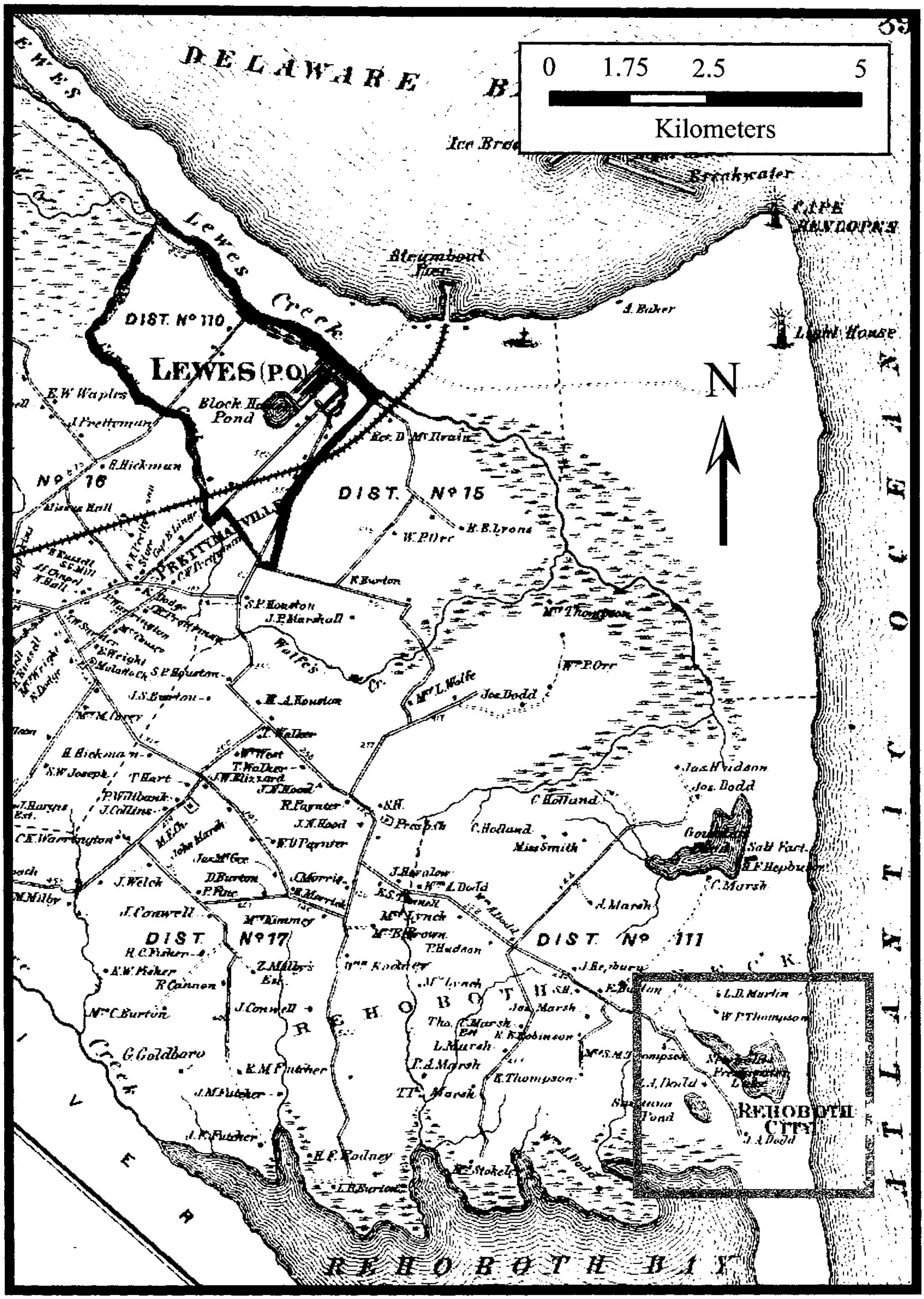

Figure 7. 1868 map of Lewes and Rehoboth Beach, DE. Silver Lake is boxed in red. In this map, Silver Lake is labeled as "Newbold's Freshwater Lake", providing concrete evidence that Silver Lake was a freshwater environment approximately 140 years BP. Map obtained from the Delaware Geological Survey.

Figure 8A. 1918 topographic map of the Silver Lake area. Note that the southeast corner of Silver Lake is separated from the Atlantic Ocean by just a thin strip of sandy coastal barrier. This is also evident in the 1937 aerial photograph in Figure 10.

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Figure 8B. 2010 topographic map of the Silver Lake area. From this map, it is clear that the sandy barrier has accreted substantially, most likely as a result of the longshore transport of sand along the Delaware coast.

Figure 9. 1937 Aerial Photographic view of Silver Lake, Delaware. Note the lack of structures immediately surrounding the lake, as well as the relatively undisturbed coastal barrier separating Silver Lake from the waters of the Atlantic Ocean.

Figure 10. 1954 Aerial Photographic view of Silver Lake, Delaware. Note the greater density of trees in the vicinity of the lake, as well as the increase in number of nearby houses. In addition, the coastal barrier separating Silver Lake from the waters of the Atlantic Ocean remains mostly undeveloped..

Figure 11. 1961 Aerial Photographic view of Silver Lake, Delaware. Other than a slight increase in the number of houses, the lake area remains generally unchanged from 1954. Note that the coastal barrier separating Silver Lake from the waters of the Atlantic Ocean still remains mostly undeveloped.

Figure 12. 1968 Aerial Photographic view of Silver Lake, Delaware. Note the increase in housing development along the southeast corner of the lake. While the majority of the coastal barrier remains undeveloped, a few structures are beginning to encroach from both the north and south ends.

Figure 13. 1992 Aerial Photographic view of Silver Lake, Delaware. Note that the surrounding area is now highly developed with few open areas adjacent to the lake. Nevertheless, the coastal barrier has not been further developed since 1968.

Figure 14. 1997 Aerial Photographic view of Silver Lake, Delaware. Since 1992, a few more houses have been constructed along the coastal barrier that separates Silver Lake from the open waters of the Atlantic Ocean.

Figure 15. 2002 Aerial photographic view of Silver Lake, Delaware. In the time between 1997-2002, nine additional houses were constructed along the coastal barrier that separates Silver Lake from the open waters of the Atlantic Ocean.

Figure 16. 2007 Aerial Photographic view of Silver Lake, Delaware. Between 2002-2007, one additional house was constructed along the coastal barrier that separates Silver Lake from the open waters of the Atlantic Ocean. As of June 2009, no further construction had taken place since the time of this photo.

Cores SL-1, SL-2, and SL-4 were sampled for average grain size at 1-cm intervals along the entire length of each core. This sampling resolution is necessary since washover deposits may be on the scale of 1 cm or less (Liu and Fearn, 1993). The grain size procedure began by treating each sample with 1N acetic acid to remove carbonates, then with 30% hydrogen peroxide to eliminate all organic material. By removing non-siliciclastic material, these steps ensure that the grain size analysis is consistent and unbiased. Once these reactions were complete, a particle dispersant (sodium hexametaphosphate) was added to each sample, and then each sample was placed in a sonic bath for ten minutes. The sonic bath agitates the sample so that the dispersant binds with individual grains for proper measurement. After this process, each sample was analyzed using a Malvern Mastersizer2000 Hydro2000G sample dispersion unit. The Mastersizer unit creates a suspension of particles that is measured via laser to determine grain size. Once the grain size analysis was completed, the corresponding data were output according to the Wentworth and USGS grain size classification scales.

Percent water and percent total organic material were also determined for each core at 1-cm intervals using loss-on-ignition analysis. Loss-on-ignition results are determined by first heating each sample to 100°C to evaporate all water, then to 550°C to combust all organic material. Percentages were calculated based on mass differences before and after each heating cycle.

Once the GeoTek logging, grain size, and loss-on-ignition analyses were completed, Deltagraph® and Adobe Illustrator® were used to produce composite figures containing full-length images and relevant physical properties for each core.

This approach helped to not only establish relationships between certain properties, but also to make qualitative correlations across cores.

2.4 Identification of Storm Layers

One of the goals of this project was the identification of washover layers within the sediment of Silver Lake. The wind and wave energy associated with a hurricane or particularly intense extratropical storm may result in waves overtopping the barrier and carrying sand into Silver Lake. The thickness and horizontal extent of the resultant washover deposits depends upon several variables such as the strength of the storm, its duration, and the tidal phase at the time of landfall. It is assumed that a generally positive relationship exists between the size of a storm and the sedimentary deposit, but this may not hold in all instances (Liu and Fearn, 1993).

Washover deposits are normally composed of fine-to-medium grained sand with varying amounts of heavy minerals depending upon pre-existing beach conditions. Washover sand can be differentiated from wind-blown sediments since eolian deposits are typically structureless units of well-sorted clean quartz sand with minor heavy minerals (Kochel and Dolan, 1986). In addition, any high wind events capable of carrying large quantities of sand across the surface of the lake were likely associated with a substantial storm system that also created an appreciable storm surge. Thus, any sand layer within the sediment of Silver Lake is assumed to be a storm deposit. Furthermore, the majority of each core is composed of gyttja or similar sediment that is abundant in organic material. Any sandy material in the cores more than likely originated from the adjacent beach and was subsequently carried through or over the barrier dune into Silver Lake. As such, the main method for identifying storm layers within the cores was the analysis of average grain size. Since the wave and wind energy associated with a powerful storm is capable of transporting much larger grains than what normally accumulates on the lake floor, storm layers create distinct high peaks in the average grain size data. Based on previous studies of storm reconstructions, ~63 μm was used as the general minimum grain size threshold for interpreting a storm layer, corresponding to the lower limit of very fine sand on the Wentworth scale (Donnelly and Woodruff, 2007).

Although average grain size alone is a strong indicator of storm deposition, additional physical properties were used to corroborate evidence of storm events in certain cases. For instance, loss on ignition is a useful procedure because total organic carbon content may provide insight into the fresh vs. saltwater history of the pond. Abrupt shifts in percentages of total organic content may mark a significant change in the depositional environment of Silver Lake. Because of Silver Lake's proximity to the shoreline, any change in depositional environment is likely driven by storm events, whether it is the creation of an ephemeral inlet or a significant change in the morphology of the adjacent beach. Therefore, if certain intervals of the Silver Lake cores have anomalously higher or lower percentages of organic material compared to recent sediments, it may suggest that such a change in environment had taken place.

For magnetic susceptibility, a positive peak indicates a higher concentration of magnetic minerals. Because of their high density, these minerals are more resistant to transport relative to lighter beach sands, which is why black streaks are often visible along the beach after a storm or period of heavy wind. During an intense storm, it is inevitable that some of these minerals would ultimately be carried landward by wind or water. Thus, if there is a peak in the magnetic susceptibility of Silver Lake sediments, it is very good evidence that storm deposition took place. However, while the presence of a susceptibility peak indicates a storm event, the absence of a peak does not necessarily indicate the lack of a storm event. The abundance of magnetic minerals on the beach at anytime is a function of the recent sediment fluxes that carry sand along the beach as well as between the berm and shoreface (McMaster, 1960). Thus, it is just as likely that a layer of washover will have a high concentration of heavy minerals as that it will have a low concentration of heavy minerals. Therefore, loss-on-ignition and magnetic susceptibility are helpful tools in aiding interpretation of storm events, but lack the definitive evidence of a spike in average grain size.

2.5 Dating Procedures

Since it is believed that the rate of deposition in Silver Lake has varied through time, multiple dating techniques were used to better constrain the timing of sedimentary changes and individual storm layers within the cores. Due to its central location nearest to the beach, and the general suitability of the core, SL-1 was used for each dating method.

In order to obtain an initial age assessment and sedimentation rate estimate for the Silver Lake cores, SL-1 was sampled for trace metal concentrations of copper and lead. Ten samples, spaced at ~20 cm intervals, were collected spanning the entire length of the core. Measured in µg/g, the concentrations of these metals are used as tracers of industrial pollution that first began during the industrial revolution of the mid to late 19th century. In addition, the concentration of lead is a reliable indicator of the use of leaded fuels that began in the early 1920s and persisted until the 1970s (Salomons and Förstner, 1984; Scileppi and Donnelly, 2007).

After the preliminary trace metal measurements, the next dating procedure measured the activity of ^{137}Cs, a byproduct of hydrogen bombs that were detonated by the U.S. military for testing purposes in the 1950s and 1960s. More specifically, an increase in the activity of ^{137}Cs in sediment can be linked to the onset of testing in 1954, whereas the peak in ^{137}Cs activity can be constrained to maximum testing during 1963 (Delaune et al., 1978). For this project, the activity of ^{137}Cs was measured in 16 samples collected from core SL-1. The goal was to aid in deciphering the recent sedimentary history of Silver Lake by constraining the years 1954 and 1963 to certain sediment depths in the core. Samples were collected at approximately 10 cm spacings from 2 cm depth to 136 cm depth.

Measurements of ^{210}Pb activity, conducted simultaneously with measurements of ^{137}Cs activity, were made for the same 16 samples from core SL-1. Age assessment of sediments using the ^{210}Pb isotope is based on the measurement and interpretation of excess ^{210}Pb that escapes into the atmosphere during the decay process from ^{238}U. This excess ^{210}Pb is eventually incorporated into the sediment, and the age of a sediment layer may be determined based on how much ^{210}Pb it contains (Appleby and Oldfield, 1983). Like the activity of ^{137}Cs, this technique is useful for relatively recent sediments, as it takes about 7 half-lives, or 150 years, for the ^{210}Pb in a sample to reach near-zero radioactivity (USGS, 2003). Thus, the depth at which the core sediment displays ^{210}Pb levels above background radioactivity can be correlated to a point in time approximately 100-150 years before present.

When analyzing raw ^{210}Pb data, there are three models that may be used to calculate dates and a rate of sedimentation from ^{210}Pb abundance. The simplest model, Constant Flux : Constant Sedimentation (CF:CS) assumes a constant flux of excess ^{210}Pb from the atmosphere and a constant dry-mass sedimentation rate. Where these assumptions are satisfied the ^{210}Pb concentration will vary exponentially in accumulating sediment. The second model, Constant Rate of Supply (CRS), also assumes that there is constant fallout of ^{210}Pb from the atmosphere to lake waters that results in a constant rate of supply of ^{210}Pb to the sediments. However, the CRS model allows for varying rates of sedimentation. Intuitively, this model seems to apply to most sedimentary systems where the sediment supply may vary in response to climatic or anthropogenic changes. Conversely, the constant initial concentration (CIC) model assumes that an increased flux of sedimentary particles from the water column will remove proportionally increased amounts of ^{210}Pb from the water to the sediment. Thus, the ^{210}Pb supply for a certain core depends on both the atmospheric input and sediment accumulation rate (Robbins, 1978; Appleby and Oldfield, 1983). Since the homogeneity of the upper sediment in SL-1 suggests that the sedimentation rate has remained relatively constant over the past 100-150 years, the CF:CS model was used for this study.

The final dating technique used was the determination of pollen percentages within sedimentary sample collected from SL-1. This technique is useful because the rise in abundance of *Ambrosia* (ragweed) can be linked to the onset of local land clearing and agricultural practices. After land is cleared for agriculture, ragweed tends to colonize the open area, leading to the subsequent deposition of its pollen signature in nearby sediments. In southern Delaware, land-clearing likely began circa ~1750-1800 A.D. and reached an initial peak around 1880 A.D. (Willard, 2003). Twelve 1cm^3 samples were collected from SL-1 for pollen analysis, ranging in depth from 4 cm to 196 cm.

All of these described methods (trace metals, ^{137}Cs, ^{210}Pb, pollen) have proven useful in previous studies of overwash sedimentation (Liu and Fearn, 1997; Donnelly et al., 2001) and were the basis of the age model established for the sedimentary history of Silver Lake.

2.6 Magnetic Stratigraphy

Core SL-1 was selected for a series of magnetic u-channel measurements. Identifying the types, amounts, and grain size of magnetic minerals in sediment can provide further insight into the environmental history of an area (Heil et al., 2009). In addition to magnetic susceptibility (K), which was measured during core-logging, anhysteretic remnant magnetization (ARM), saturation isothermal remnant magnetization (SIRM), and "hard" isothermal remnant magnetization (HIRM) were measured at 1-cm intervals using a 2-G® Enterprises small-access cryogenic magnetometer. Variations in these parameters are what provide evidence for changing environmental conditions (Heil et al., 2009).

K, ARM, and IRM all reflect the concentration of magnetic minerals in the sediment, but vary in their sensitivity to the individual types and grain sizes of these same minerals. For instance, K is typically biased toward coarser magnetic grains, whereas ARM and IRM are more sensitive to very small grains that contribute to the magnetic signature of the sediment. Perhaps most useful to this study is the HIRM parameter, which is a measure of the concentration of high-coercivity minerals (e.g. hematite and goethite) in the sediment. High HIRM values are linked to the erosion of surface soils, which may indicate land-use changes and/or climate variability in the vicinity of Silver Lake (Heil et al., 2009).

2.7 Spectral Analysis

A power spectrum of grain size was created using several grain size parameters from cores SL-1 and SL-2. The program kSpectra was employed to create plots of power vs. frequency using the multi-taper method with confidence intervals of 90%, 95%, and 99%. Power is the square of the amplitude of all the cosine components that comprise the grain size record (Lacey and Peck, 1998). From the plot, peaks in the frequency reflect the number of grain size cycles per centimeter. The frequency values invert into periods of varying depth intervals. Using the established age-model, these intervals were calculated into years, which were then compared to recurrence intervals of known climate oscillations. These comparisons were made in an attempt to decipher whether or not the frequency of storm deposition in Silver Lake is influenced by varying states of Atlantic oceanic and atmospheric climate.

RESULTS AND DISCUSSION

3.1 Sedimentology of Silver Lake

The five cores retrieved from Silver Lake reflect a variety of sedimentary environments. The images and logging data indicate that each core has a unique sedimentary record, which implies that Silver Lake is characterized by a history of heterogeneous deposition throughout each part of the lake basin (Figures 17-21).

SL-1 (Figure 17), the primary core used for dating and magnetic analyses, spans 218 cm and is composed of mostly dark, organic-rich silt and mud with centimeter-scale sand layers interspersed throughout the core. This stratigraphy is in sharp contrast to SL-5 (Figure 21), which was collected 100 m north of SL-1 and, other than the top 10 cm, is composed almost entirely of sand. SL-2 (Figure 18) was collected 100 m north of SL-5, and has similar lithologies to SL-1 with only small lenses of sand and a majority of organic-rich silt and mud. SL-4 (Figure 20), located landward (west) of SL-1, 2, and 5, is also composed of mostly organic rich sediment, and is abundant in plant matter from 85 cm depth to the base of the core (173 cm). Lastly, SL-3 (Figure 19), which was collected ~200 m north of SL-4, is composed of organic-rich mud down to a depth of 90 cm. From 90 cm to the base of the core (178 cm), there is a gradual transition to coarser, sandy layers with little organic material.

Because of the abrupt sedimentary changes across relatively short lateral distances, interpreting the history of Silver Lake is somewhat complicated. Hypothesized transitions between freshwater lake and saltwater tidal cove

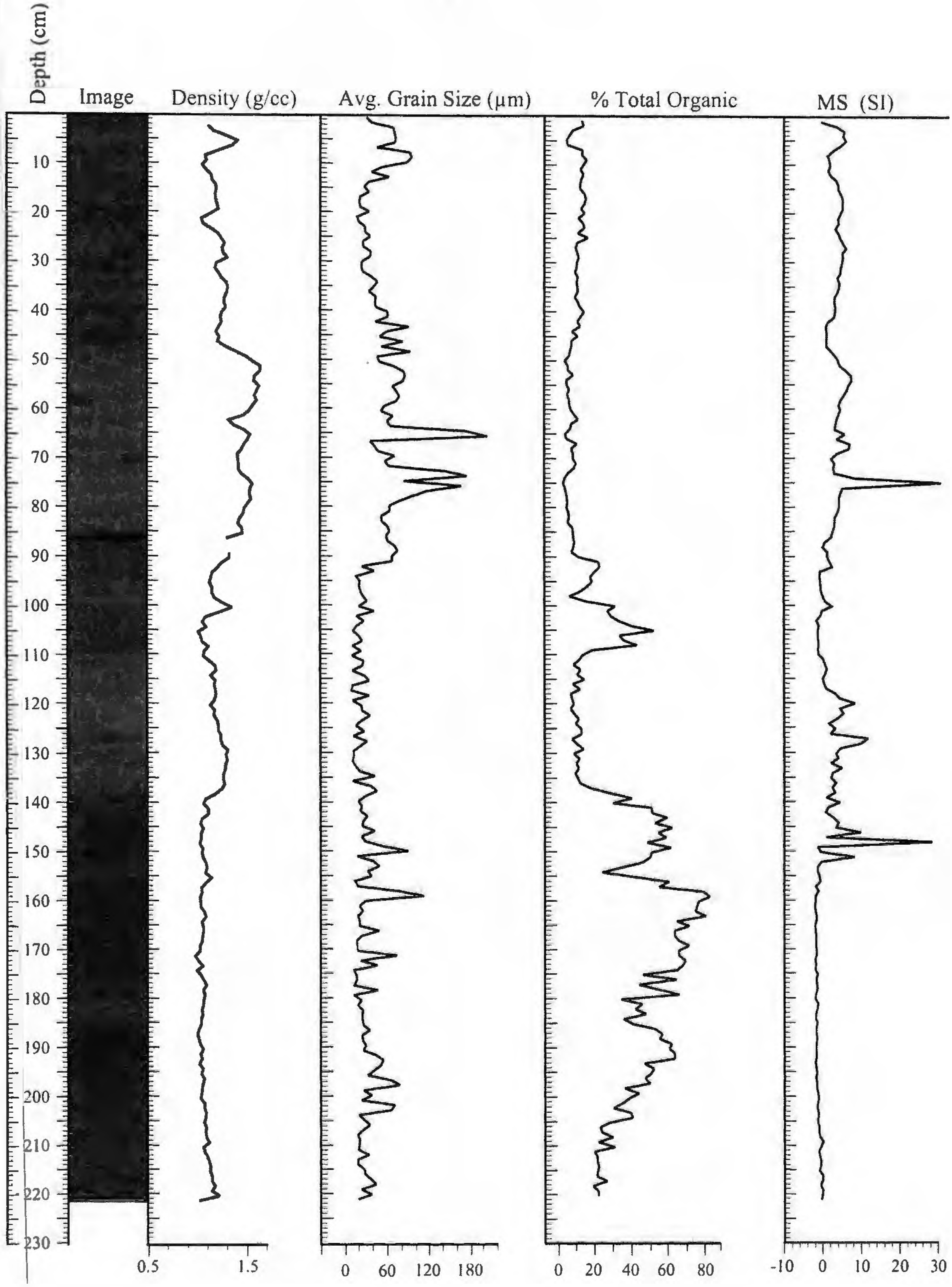


Figure 17. Log for core SL-1. Density and magnetic susceptibility were calculated by Geotek® core logger. Average grain size and total organic content were determined by sampling at 1-cm intervals.

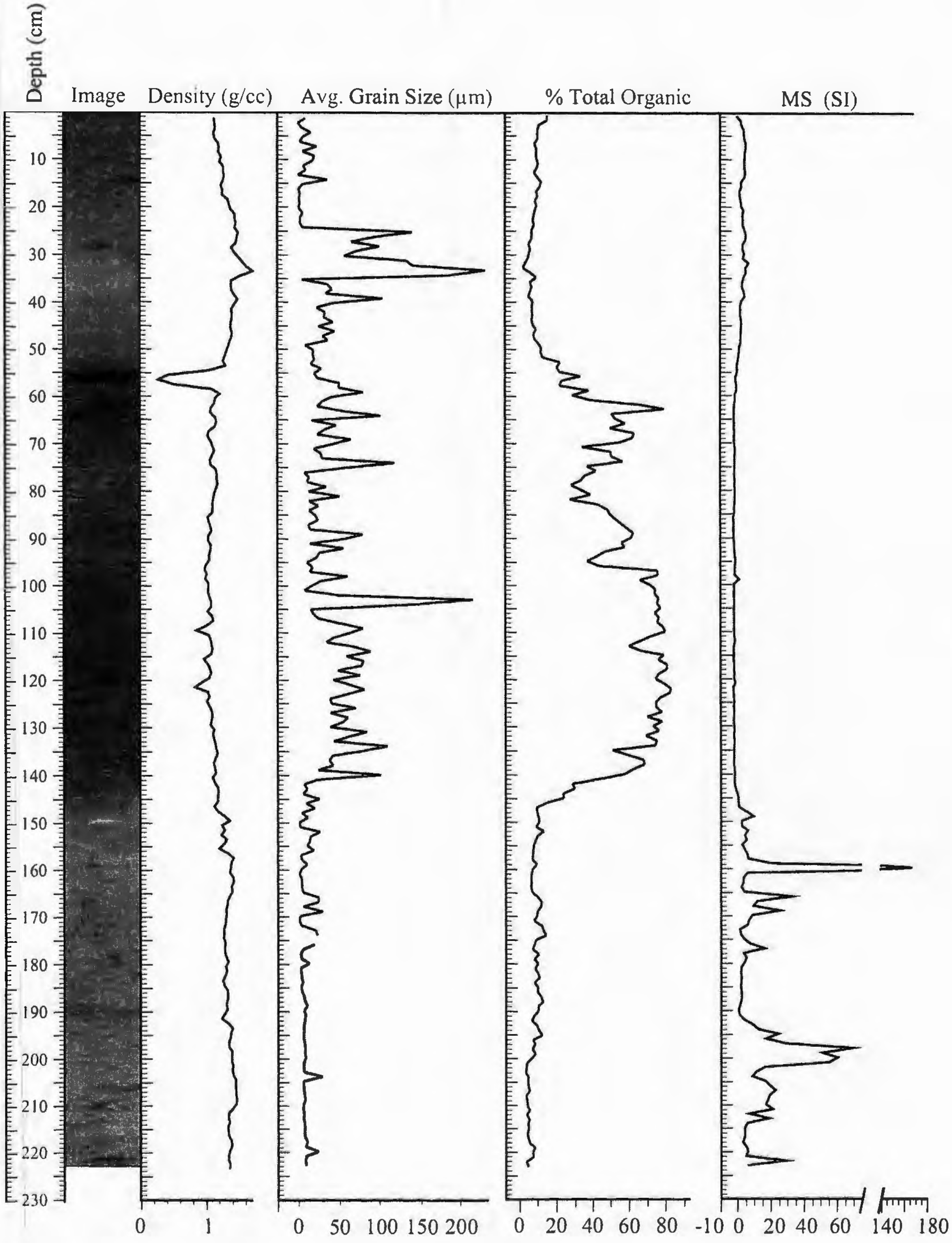


Figure 18. Log for core SL-2. Density and magnetic susceptibility were calculated by Geotek® core logger. Average grain size and total organic content were determined by sampling at 1-cm intervals.

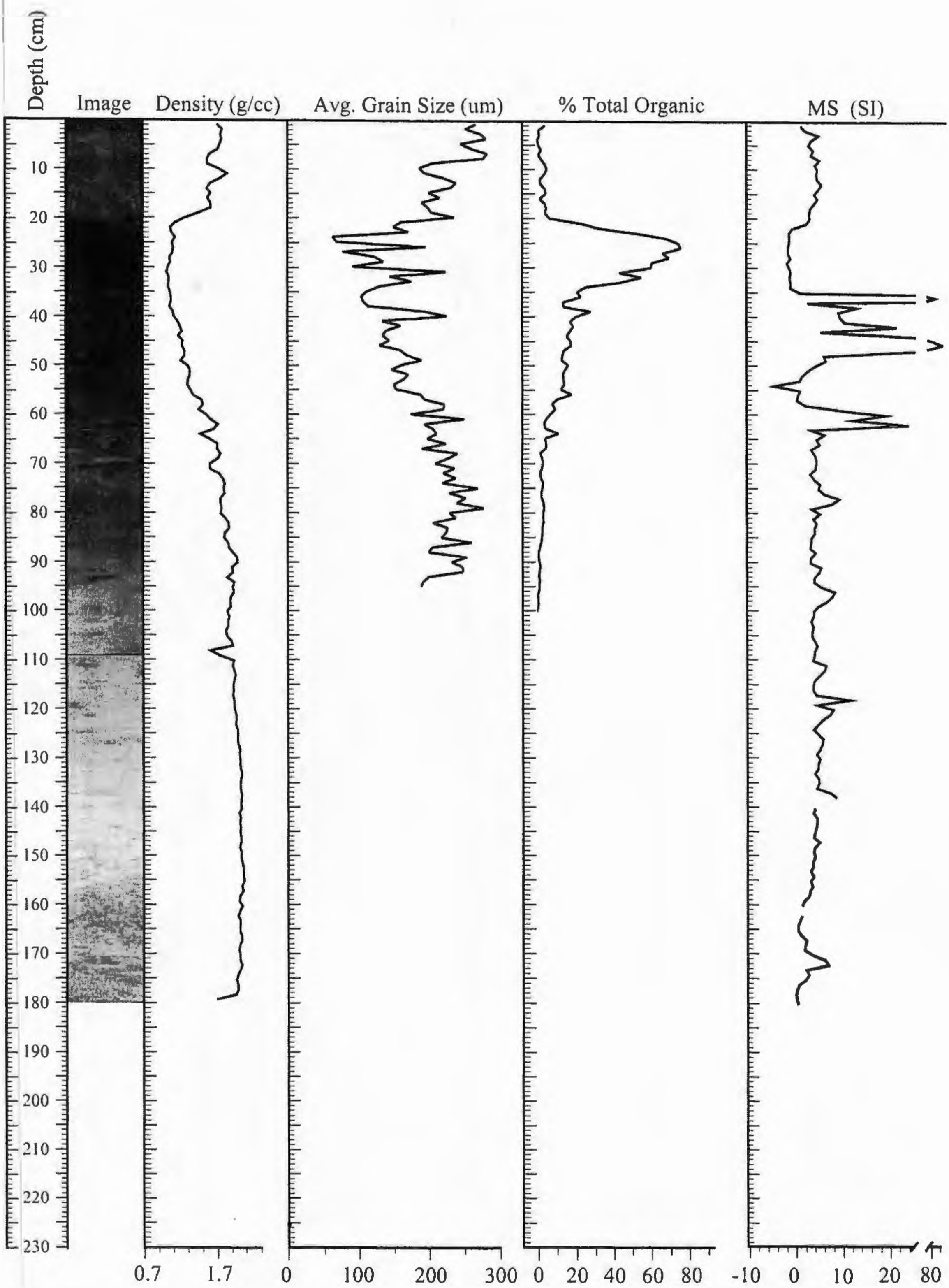


Figure 19. Log for core SL-3. Density and magnetic susceptibility were calculated by Geotek® core logger. Average grain size and total organic content were determined by sampling at 1-cm intervals for only the top 100 cm due to abundance of sand below this depth.

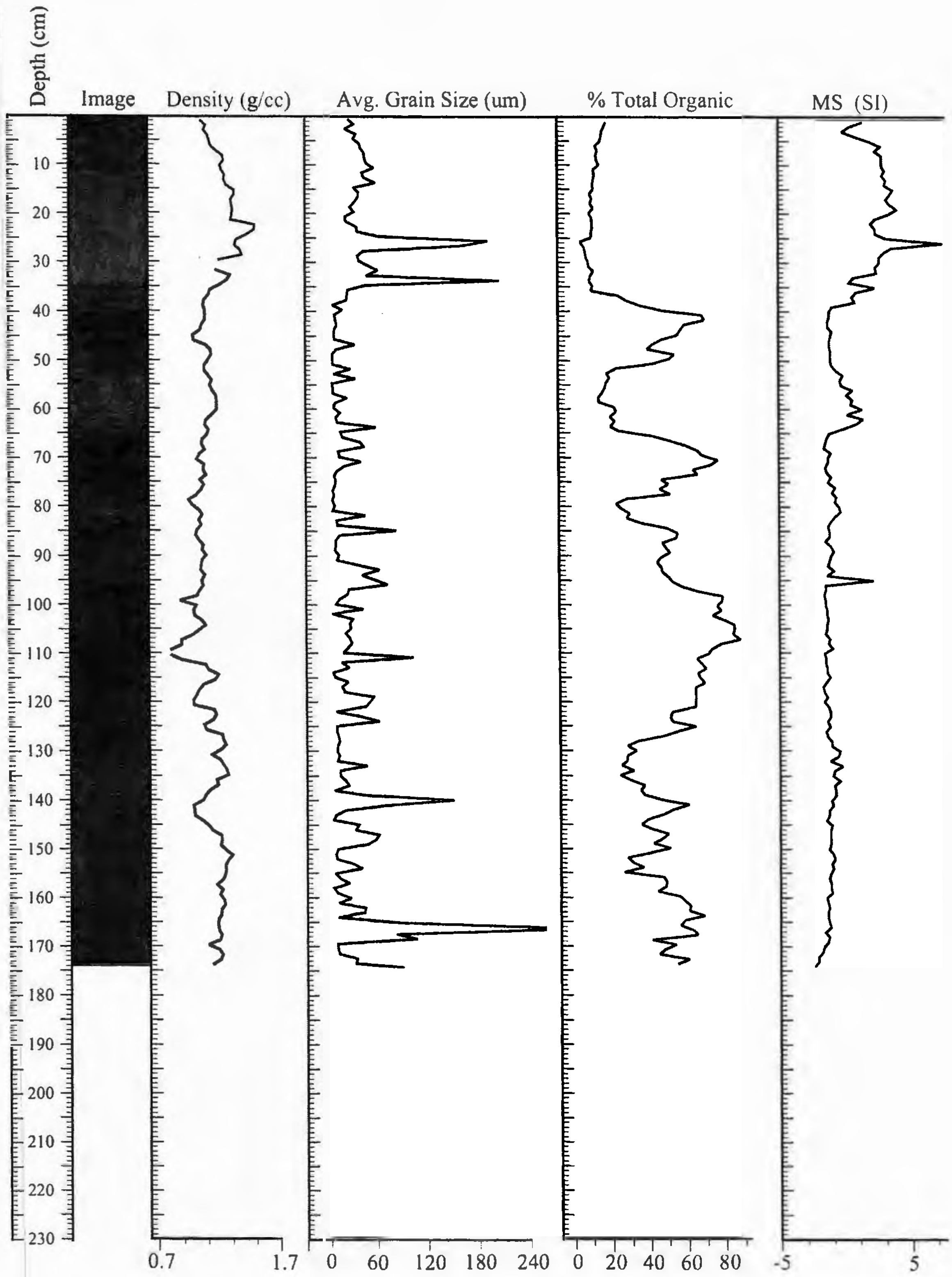


Figure 20. Log for core SL-4. Density and magnetic susceptibility were calculated by Geotek® core logger. Average grain size and total organic content were determined by sampling at 1-cm intervals.

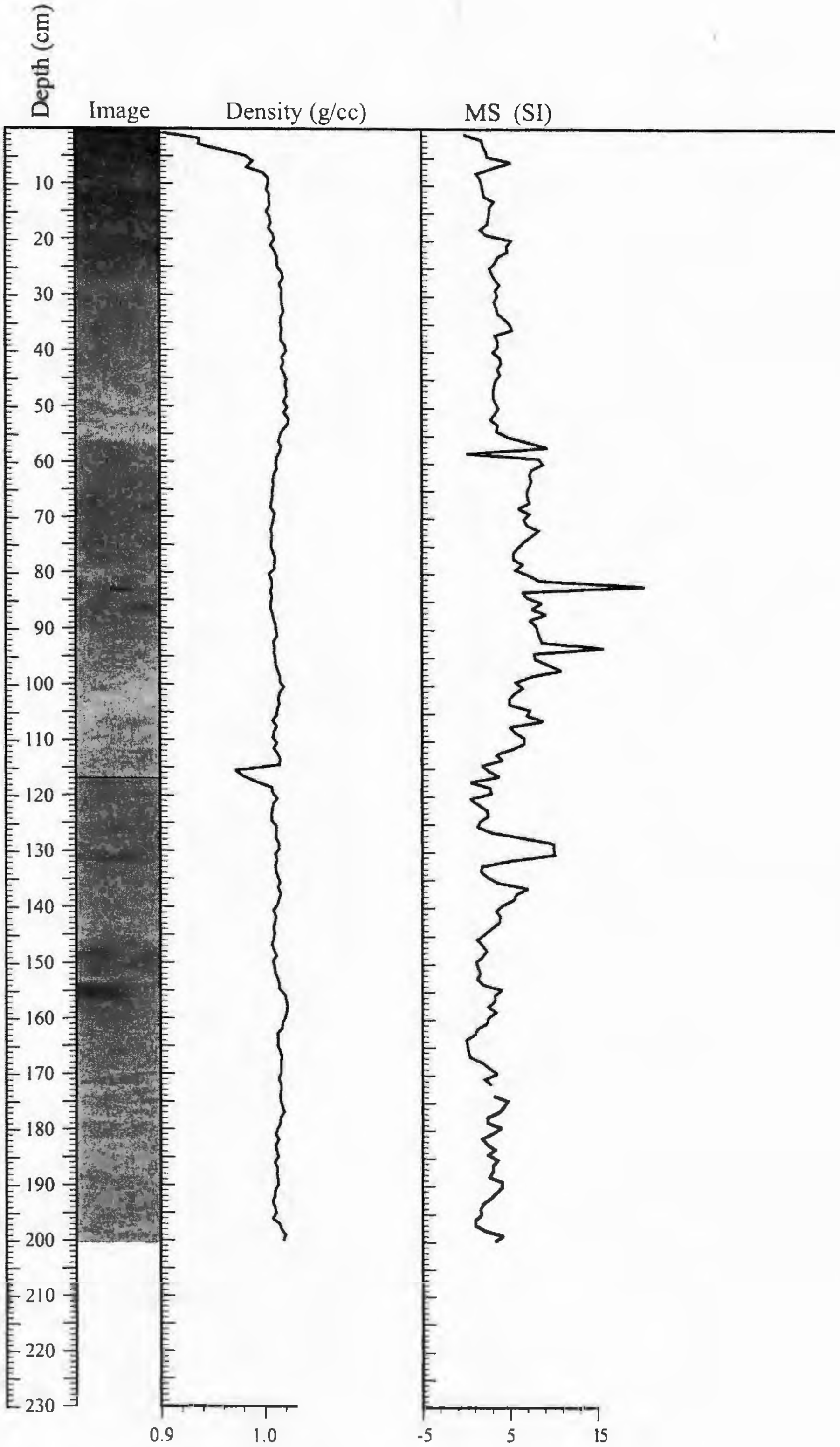


Figure 21. Log for core SL-5. Density and magnetic susceptibility were calculated by Geotek® core logger. Average grain size and total organic content were not measured due to the predominance of sand throughout the core.

environments suggest that Silver Lake has been host to a variety of depositional processes throughout its history. Thus, the sand present in SL-5 and SL-3 could have been deposited in the former inlet channel of a saltwater cove during an interval of time when the Silver Lake basin and Atlantic Ocean were actively connected (Figure 22).

3.2 Core Correlation

Changes in the color, texture, and grain size of sediment are normally sufficient for correlating specific sedimentary horizons across cores. However, the nature of the cores retrieved from Silver Lake necessitated the use of more precise techniques to establish the relationships among cores. The repetition of facies, thin veneers of sand, and very gradual contacts led to a lack of precision in visual correlation. Thus, the cm-scale logs of total organic content and mean grain size were used to establish more robust connections from core to core.

A total of four distinct facies were identified in the Silver Lake cores and are described in Table 1. These facies were interpreted to represent marsh, tidal channel, lake, and washover deposition, and provide a general outline of the environmental history for each core (Figure 23). When combined with visual identification of these sedimentary facies, total percent organic material proved to be the most useful tool for aligning sedimentary horizons between SL-1, SL-2, and SL-4 (Figure 24). From the loss-on-ignition data, it is clear that each core shows a distinct interval that is very abundant in organic material. In addition, within this interval there are sub-peaks

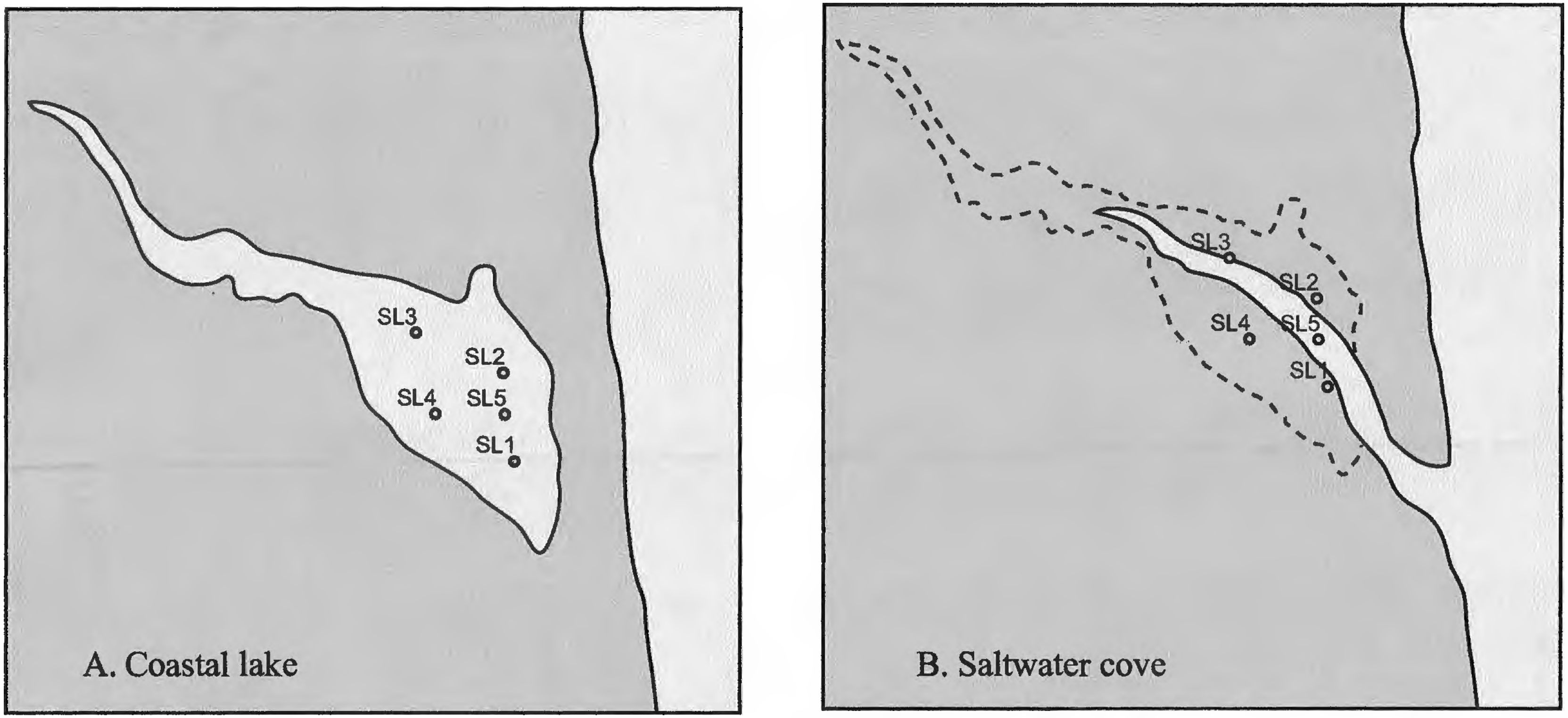


Figure 22. Graphic depictions of coastal lake and saltwater cove depositional environments. It is hypothesized that the Silver Lake area has fluctuated between these two environments throughout the sedimentary history contained in the cores.

Facies	Description	Interpreted Depositional Environment
1	Light to dark grey, fine-grained unit with low organic content. Homogeneous silt and clay with no discernable sedimentary structures.	Low-energy lake-bottom
2	Dark brown to black, fine-grained unit with abundant organic material such as roots, leaves, and other plant matter. High water content and less dense than facies 1.	Marsh
3	Tan to grey, thick sand unit composed of mostly fine to medium grained sand with come coarse sand interspersed. Very low water and organic content.	Tidal creek channel
4	Thin-bedded sand units ranging in grain size from 63 µm to 300 µm. Generally indistinguishable from surrounding sediment when analyzed visually. Devoid of organic matter.	Washover deposit

Table 1. Descriptions of major sedimentological units found within the Silver Lake cores.

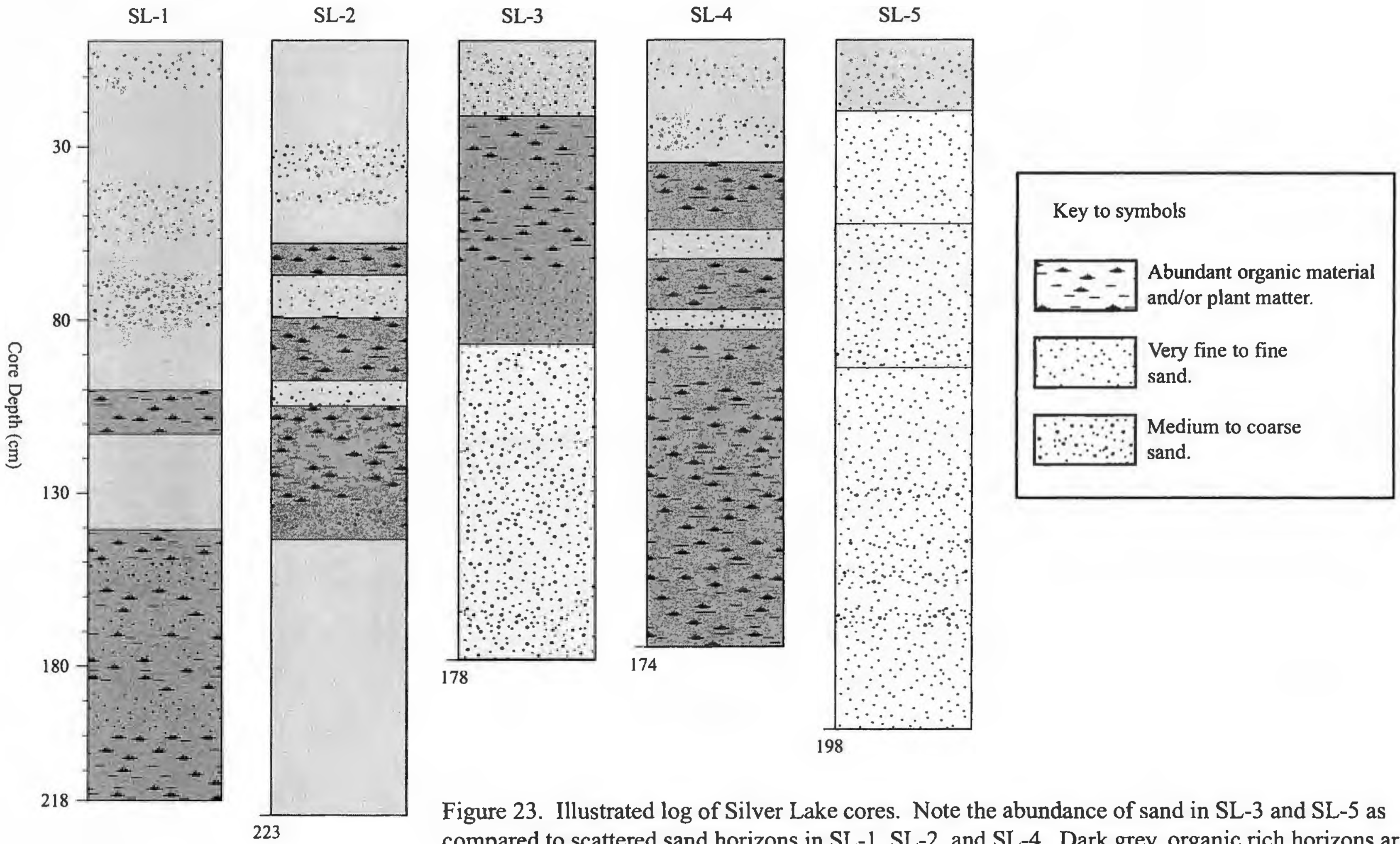


Figure 23. Illustrated log of Silver Lake cores. Note the abundance of sand in SL-3 and SL-5 as compared to scattered sand horizons in SL-1, SL-2, and SL-4. Dark grey, organic rich horizons are interpreted as marsh deposits; Grey horizons with sparse sand layers (washover) are interpreted as lake deposits; Light grey horizons with adundant sand are interpreted as tidal channel deposits.

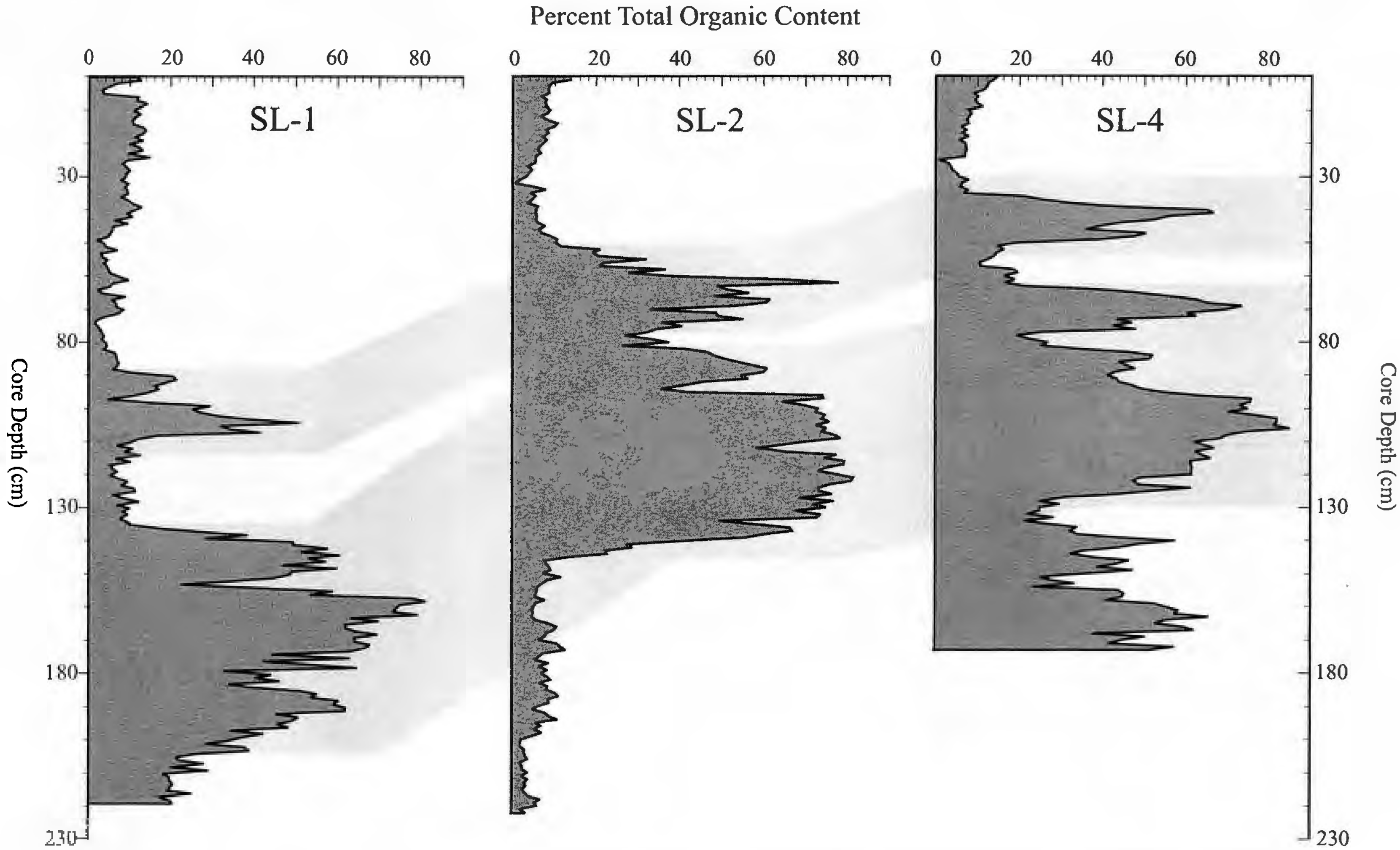


Figure 24. Total % organic matter downcore for SL-1, SL-2, and SL-4. Distinct peaks enable correlation between cores (shaded areas). Note that SL-1 has a substantially higher sedimentation rate in recent times compared to SL-2 and SL-4. This difference is discussed more thoroughly in the text.

that correlate fairly well in each core. High percentages of organic material are associated with marsh depositional environments throughout each core, whereas gaps between these peaks represent intervals of clayey and silty sediment generally lacking in any type of plant matter.

Once these sedimentary horizons were used to correlate SL-1, SL-2, and SL-4, it became clear that SL-1 is characterized by a substantially higher sedimentation rate during intervals of time characterized by a coastal lake depositional environment. This hypothesis is based on the significantly thicker layer of low-organic sediment present at the top of SL-1 compared to SL-2 and SL-4. The reason for this difference in relative rates of deposition is the probable result of sediment focusing in Silver Lake. Although most of Silver Lake has a uniform water depth of ~1.1 m, the morphology of the lake bottom may have lead to sediment focusing in the area of SL-1 during intervals of coastal lake deposition. For instance, the location of SL-1 may have been a topographic low relative to the rest of the basin, and as a result was more prone to sediment infilling. Regardless, this variation in sedimentation rate applies only to intervals interpreted as coastal lake deposition. Thicknesses of marsh facies are comparable across cores, suggesting that the hypothesized marsh environment was characterized by homogeneous rates of sedimentation across the SL-1, SL-2, and SL-4 core locations during these intervals of time.

Correlating sedimentary horizons via loss-on-ignition data was also crucial for interpreting washover deposits in the history of Silver Lake. After using loss-on-ignition results to adjust for variable sedimentation rates between the cores, several peaks in average grain size showed lateral continuity across the cores. Most noteworthy is a set of peaks occurring ~70 cm depth in SL-1, ~35 cm depth in SL-2, and ~30 cm depth in SL-4. These intervals, along with similar peaks that are consistent throughout the lake sediments, are good indicators of overwash events that have left a record of sand deposition in Silver Lake. The interpretation of these overwash events is discussed later in the text.

3.3 Age Model

Copper and lead trace metal, ^{137}Cs, ^{210}Pb, and pollen abundance data were compiled for the purpose of constructing an age model for core SL-1 (Figure 25). Due to low sample resolution, activity and/or concentration data were interpolated between each data point. Once ^{210}Pb activity was measured, a sedimentation rate was calculated based upon the half-life of ^{210}Pb and the slope of ^{210}Pb concentrations in the samples. This calculation followed the CF:CS model by establishing a linear relationship between the decay of excess ^{210}Pb and depth in the core. In accordance with this model, only samples down to a depth of 64 cm were used in the calculation since all deeper samples do not contain values of ^{210}Pb above normal background levels. The resultant sedimentation rate was calculated as 0.45 cm/yr, which equates to an approximate 500-year history for 220 cm of core (Figure 26). However, sedimentation rates and degrees of compaction may vary slightly throughout the depth of the core, especially prior to European settlement. Therefore, although referenced throughout this text, 500 years is a minimum estimated duration for the model.

^{137}Cs measurements, conducted simultaneously with ^{210}Pb, provide a recent age constraint at the peak of measured activity. When evaluating the results of the

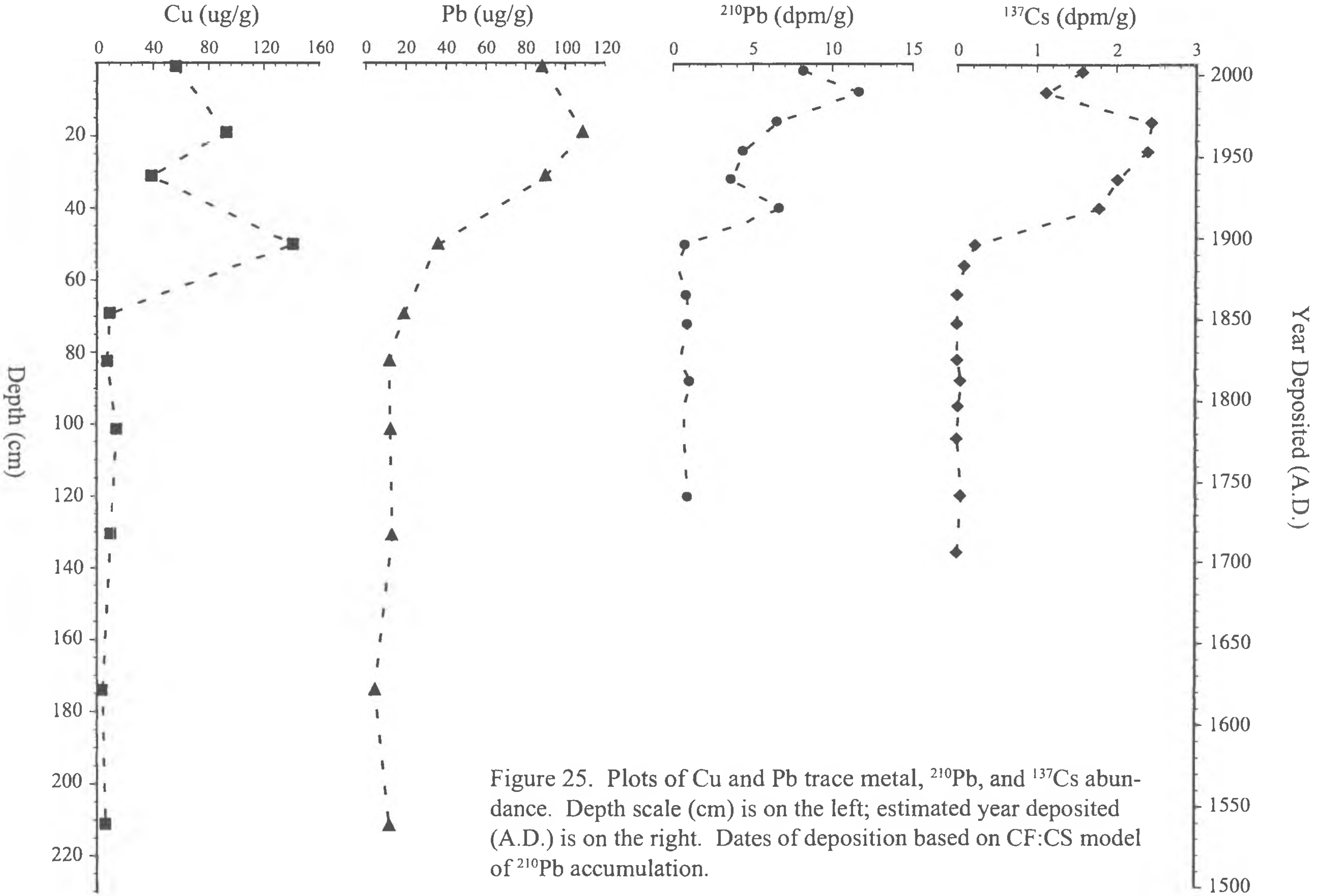


Figure 25. Plots of Cu and Pb trace metal, ^{210}Pb, and ^{137}Cs abundance. Depth scale (cm) is on the left; estimated year deposited (A.D.) is on the right. Dates of deposition based on CF:CS model of ^{210}Pb accumulation.

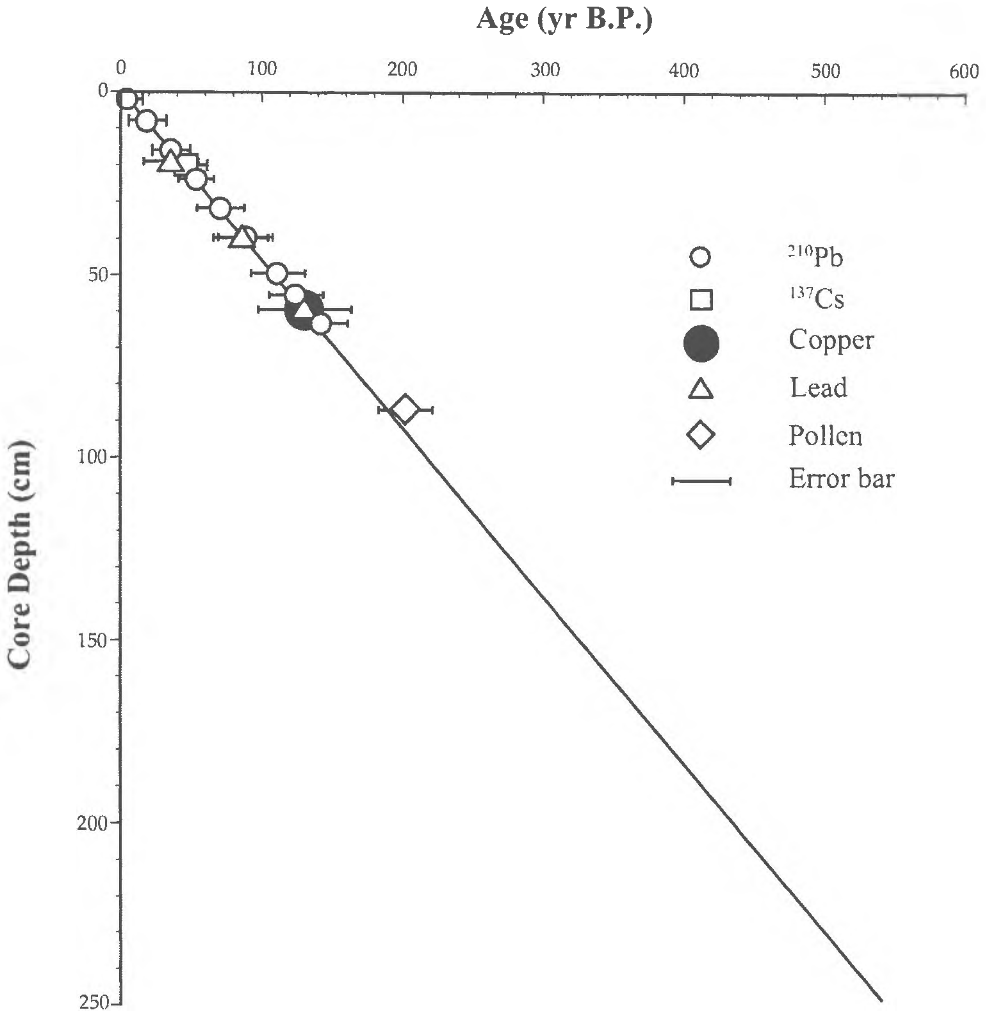


Figure 26. Plot of age versus depth for all dating procedures. Solid black line represents a sedimentation rate of 0.45 cm/yr based on ^{210}Pb concentrations.

^{137}Cs analysis in SL-1, the highest ^{137}Cs activity (1963) was measured at 16 cm depth. However, the general trend of the data suggests that the true peak of ^{137}Cs in the core is somewhere between the samples collected at 16 cm and 24 cm depth. Based on the rate of sedimentation calculated through ^{210}Pb (0.45 cm/yr), the year 1963 corresponds to a depth of 21 cm. This estimate agrees with the interpretation of a true activity peak between 16 and 24 cm depth, and thus provides an age constraint of ~46 years at a depth of 20-21 cm. Due to significant concentrations of ^{137}Cs at greater depths than expected, no point in the core was tied to the onset of hydrogen bomb testing in 1954. Previous research indicates that it is possible for ^{137}Cs to travel downward through the sediment profile via diffusion and/or biological activity, which makes determination of the initial signal of ^{137}Cs highly inaccurate (Milan et al., 1995). For this reason, only the peak of measured activity was used as an age constraint for this study.

Measurements of copper and lead trace metal abundance provided additional constraints for the ^{210}Pb age model. Results indicate a copper concentration of 141.4 μg/g at 50 cm depth, which is a jump from near-zero values in all samples deeper in the core. These data suggest that copper began accumulating in Silver Lake sediments between 50 cm depth and 69 cm depth (next deepest sample with a near-zero copper value). According to the 0.45 cm/yr sedimentation rate, this gives an age range of 111-153 years before present, corresponding to calendar years 1856-1898 AD. This result agrees well with the onset of widespread copper mining in the United States, and thus provides additional support for the validity of the ^{210}Pb age model (Salomons and Förstner, 1984).

Trace metal counts for lead also align well with the ^{210}Pb age model. The initial increase in lead pollution concentration occurs between 60 and 80 cm depth, and is assumed to reflect early industrial activity in the United States in the mid-late 1800s. The age model gives a very compatible range of 1831-1875 AD for this depth interval. A sharp rise in lead pollution is attributable to the use of leaded gasoline, which began in the early 1920s and culminated in the 1970s (Scileppi and Donnelly, 2007). Calculated using the ^{210}Pb age model, the year 1920 is associated with a depth of 40 cm. Relative to SL-1 lead results, 40 cm is in the midst of a large increase in lead abundance between values at 31 cm and 50 cm, implying that the data supports the possibility of a sharp increase occurring around 40 cm depth. In addition, the lead abundance data peaks at 19 cm depth, which is linked to the year 1975. Although the true peak may not lie exactly at 19 cm depth due to the low sampling resolution, this provides substantial evidence that the age model is accurate for the upper section of the core.

Pollen abundance results indicate that the rise in Ambrosia percentages occurred between 80 cm depth and 96 cm depth in SL-1. Samples above 80 cm depth contain greater than 10% ragweed, the sample at 80 cm depth contains 3.5% ragweed, and samples at and below 96 cm depth contain no detectable ragweed pollen. Therefore, the initial rise occurred somewhere between 80 cm and 96 cm depth, corresponding to a time interval of 1796 – 1831 A.D. This estimate not only agrees well with estimates of first land clearance, but is also supported by increases in both mean grain size and magnetic mineral concentration throughout the same depth interval (Figure 17). Increases in these parameters suggest a change in the source characteristics of the lake sediments, which was likely caused by land clearance and the onset of agricultural practices in the vicinity of Silver Lake.

The limitation of the age model is in its applicability to depths at which measurements indicate there is no apparent excess ^{210}Pb. As such, this study provides no age constraints below ~100 cm depth to demonstrate that the calculated sedimentation rate is valid for this section of the core. However, the majority of sediments below 100 cm in SL-1 are composed of organic-rich mud indicative of a marsh environment. Published rates of marsh sedimentation along the coast of Delaware and nearby states (VA/MD/NY) give an average of 4.425 mm/yr, which is within 0.075 mm, or 2%, of the calculated sedimentation rate of 0.45 cm/yr for the upper ~100 cm of Silver Lake (Orson et al., 1985). Therefore, these published rates indicate that the age model may be somewhat applicable to the entire length of the core.

3.4 Abrupt Environmental Changes in Silver Lake

Although the age model for SL-1 suggests that sediment at the base of the core was deposited approximately 500 years ago, the correlation with SL-2 implies that sediments at the base of SL-2 are substantially older. While the precise age of the basal sediments of SL-2 is not known, a sharp decrease in both mean grain size and percent total organic material at ~145 cm depth imply an abrupt shift in the Silver Lake environment. Below this depth, percent total organic material is generally less than 10%, and average grain size is generally less than 20 μm. Similar values are found at the top of SL-2, but these sediments are nevertheless a marked change from the increased grain size and organic content at depths immediately shallower than 140 cm. Although this depositional change is also apparent in SL-1, it is less prominent since the shift is preserved at the very base of the core (~210 cm depth).

If a sedimentation rate equivalent to SL-1 (0.45 cm/yr) is assumed for SL-2 below 140 cm depth, then the ^{210}Pb age model calculates that this environment of reduced grain size and low organic content persisted from at least 675 years BP to approximately 500 years BP. Since similar sedimentary characteristics are also found at the top of the core, and also because the change occurs ~500 years before present, it is highly unlikely that the cause of this change was anthropogenic in nature. According to historical records, settlement did not occur until ~300 years BP at the earliest, and development has been fairly continuous since that time (Munroe, 1993). Instead, this change in sediment characteristics likely reflects a transition from a closed lake to a tidally active saltwater environment (Figure 22). The similarities between the most recent sediment in Silver Lake to the sediment below 145 cm depth in SL-2 suggest that the depositional environments were also similar. There are only four distinct sedimentary facies preserved in the Silver Lake cores, and it is not uncommon to find repetition of sedimentary sequences in coastal environments (Leatherman, 1983).

Locally minor transgressions and regressions can shift environments slightly landward or seaward and back again, thus reproducing the same depositional sequences in one distinct area. In the case of Silver Lake, a sharp and abrupt increase in total organic content at ~150 cm depth in SL-2 suggests that a closed freshwater environment was likely present from ~675 years BP to ~500 years BP, at which point in time an event occurred that created an active connection with the ocean (Figure 23). This event was probably a hurricane or other intense system that created a storm surge substantial enough to breach the Silver Lake barrier. After the storm subsided, the breach persisted, providing an inlet for tidal waters to flood and ebb. Once this event occurred, the sedimentary record indicates that the areas of SL-1, SL-2, and SL-4 became marsh environments. At present, the surface of Silver Lake is ~1 m above local MSL, which is essentially equal to the water depth at these sites. Assuming a similar morphology ~500 years ago, a breach in the barrier would have lowered the water level to MSL, leading to sub-aerial exposure of the areas surrounding SL-1, SL-2, and SL-4. This exposure at the fringe of a saltwater body (assuming the breach transitioned the area into a tidal cove or analogous environment) would likely lead to the development of saltwater marsh at elevations very close to MSL, which supports the sedimentary evidence of marsh formation in cores SL-1, SL-2, and SL-4.

This hypothesis also provides an explanation for the abundance of sand in cores SL-3 and SL-5. The location of these cores forms a line along the NW/SE strike of Silver Lake, whereas SL-1, SL-2, and SL-4 are all outside of this line. Upon the hypothesized formation of a tidal inlet ~500 years BP, this line of strike was the likely location of the main tidal channel, and a fringing marsh began to form adjacent to this main channel. Although salt marshes are generally considered low-energy environments, sand may be common in the channels draining the marshes, and the newly breached barrier provided an abundant source for this sand (Kennedy, 1987). As such, this hypothesis agrees with the sedimentology found throughout the Silver Lake cores, in which those located along the NW/SE strike of the lake (SL-3 and SL-

5) are predominately sand, whereas those on the outskirts of that strike (SL-1, SL-2, and SL-4) are composed almost entirely of organic-rich silt and clay-sized material.

Although it seems unlikely that a barrier inlet would remain open and stationary for a period of approximately 200 years, the sedimentary record of Silver Lake indicates that the area did not the transform back to a less-salty lake environment until about 300 years BP (~135 cm depth in SL-1). During this ~200 year period, Silver Lake may have been characterized by a different hydraulic regime that worked to maintain an open inlet. The current morphology of Silver Lake suggests that this additional hydraulic input could have originated from an antecedent river or stream emptying into the northwest tip of the lake. Nevertheless, this transition back to a closed lake environment filled the basin so that the locations of SL-1, SL-2, and SL-4 were again submerged, changing the deposition process back to low-energy lake-bottom accumulation of clay and silt. Core sediments at this depth have no detectable pieces of plant material, and are characterized by a smooth, muddy texture more indicative of a low-energy, submerged environment. This facies continues up-core until ~110 cm depth (SL-1), when it is broken by another span of organic-rich, marshy sediment. Although much shorter in duration (~25 years) than the interval of similar sediment from ~135-210 cm depth, the repetition of this facies suggests another transition back to a shallower saltwater environment possibly induced by overwash and breaching of the barrier. This interval spans ~15 cm of core and is overlain by sediments once again indicative of accumulation in a low-energy lake-bottom, which persist through to the top of the core.

Based on this sequence of facies changes, Silver Lake was a freshwater lake environment from ~675 years BP to ~500 years BP, ~300 years BP to ~240 years BP, and ~215 years BP to the present. Conversely, the basin likely transitioned into a tidal creek/marsh environment during the intervening spans of time encompassing ~500 years BP to ~300 years BP and ~240 years BP to ~215 years BP. Additional fluctuations in organic content are prevalent within each of these larger facies changes, but are on the order of 1-2 cm in thickness and probably represent single storm events or seasonal changes that did not have a long-term impact on the lake's depositional environment.

3.5 Storm Events

Although the aerial photographs provide no direct evidence of overwash occurring at Silver Lake, written records offer detailed descriptions of historical storms that have affected the Rehoboth Beach area (Ludlum, 1963; Ramsey and Talley, 1992; Ramsey and Reilly, 2002; Blake et al., 2005; NHC). Since no hurricanes have made direct landfall in the area during the past 200 years, there is no analog for the type of depositional signature that a storm of such magnitude would create in Silver Lake. However, the ^{210}Pb age model can be used to correlate sandy deposits with historical storms that are believed to have caused substantial overwash throughout the area. In order to confidently assume that a peak in grain size is associated with a storm event, whether occurring during the historical record or not, only those peaks that are correlated across two or more cores are considered. This approach aims to eliminate any confounding variables that would lead to anomalous sand deposition at a single site in the lake. Several grain size parameters, in addition to mean grain size, were also plotted for cores SL-1, SL-2, and SL-4. Consistency of peaks across multiple grain size attributes ensures that the results are not skewed by the volume-weighted formula used to determine mean grain size (Figures 27-29).

The most recent storm signal is a peak in grain size very close to the surface in cores SL-1 (~10 cm) and SL-4 (~15 cm) (Figure 30). This sand may have been deposited during the passage of Hurricane Gloria in 1985, which caused substantial flooding throughout the southern part of the state. However, there is no peak in SL-2, and the peak in SL-4 is several centimeters lower in section and right at the threshold for sand-sized particles. Therefore, this layer may not reflect deposition from overwash, but may be an anomalous peak resulting from anthropogenic activity or other unknown variables. Nevertheless, perhaps the most noteworthy aspect of the recent sedimentary record is the lack of a signal from the Ash Wednesday Storm of 1962. Often considered one of the most damaging storms to strike the Mid-Atlantic coast during recorded history, this nor'easter caused extensive flooding and destruction along the U.S. east coast from North Carolina to New England. Aerial photographs taken just days after the storm clearly show widespread washover and erosion along the Delaware beaches. However, Rehoboth Beach was spared the worst of the damages, and escaped with a relatively small amount of washover compared to the rest of Delaware's Atlantic shoreline (McCarty, 2009). This observation helps to explain why Silver Lake does not contain a record of the 1962 event - simply because overwash may not have breached the adjacent barrier.

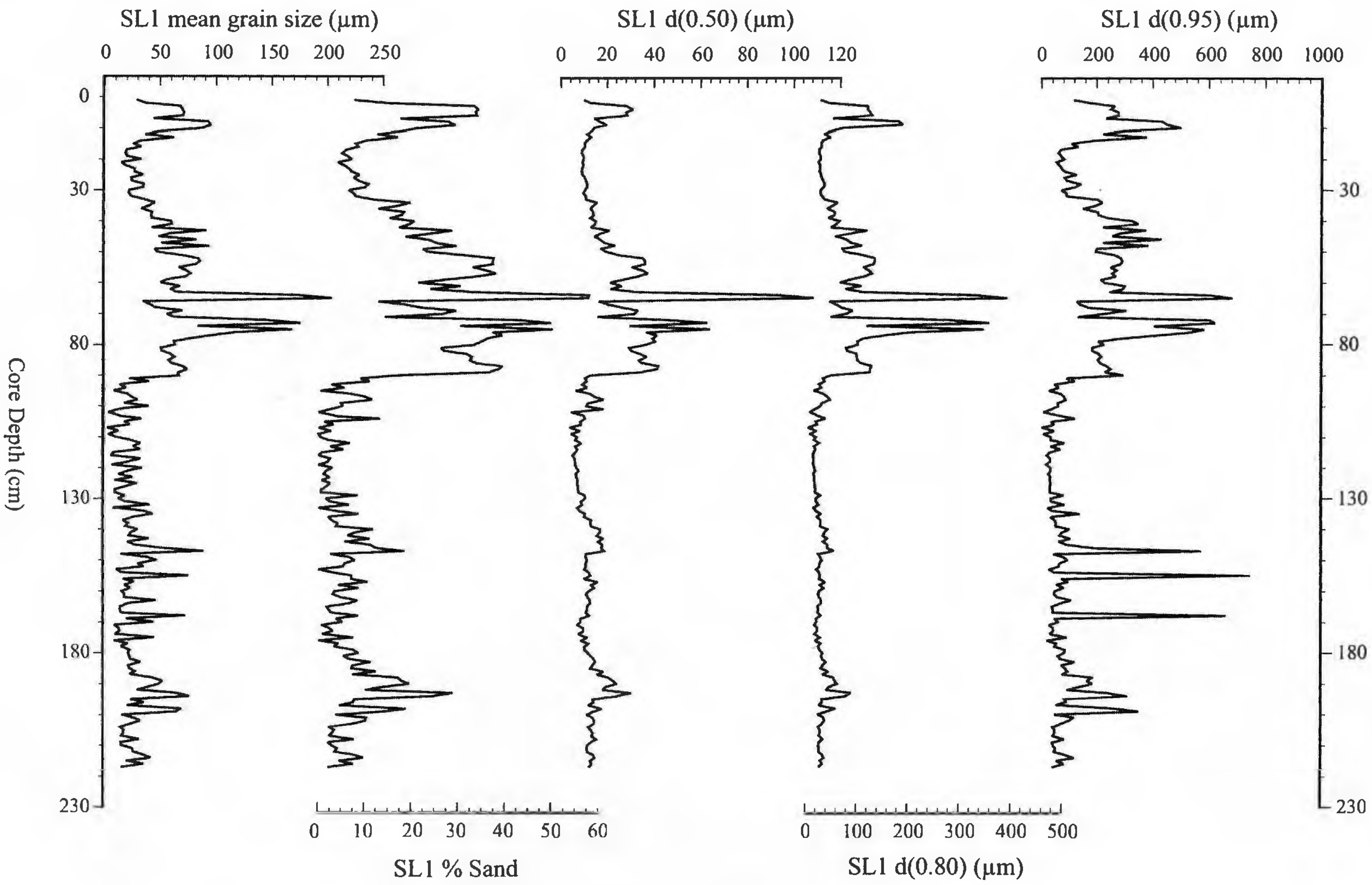


Figure 27. Plots of relevant grain size parameters for SL-1. Note that major peaks are visible across most parameters, and that the plots of mean grain size and percent sand are nearly identical.

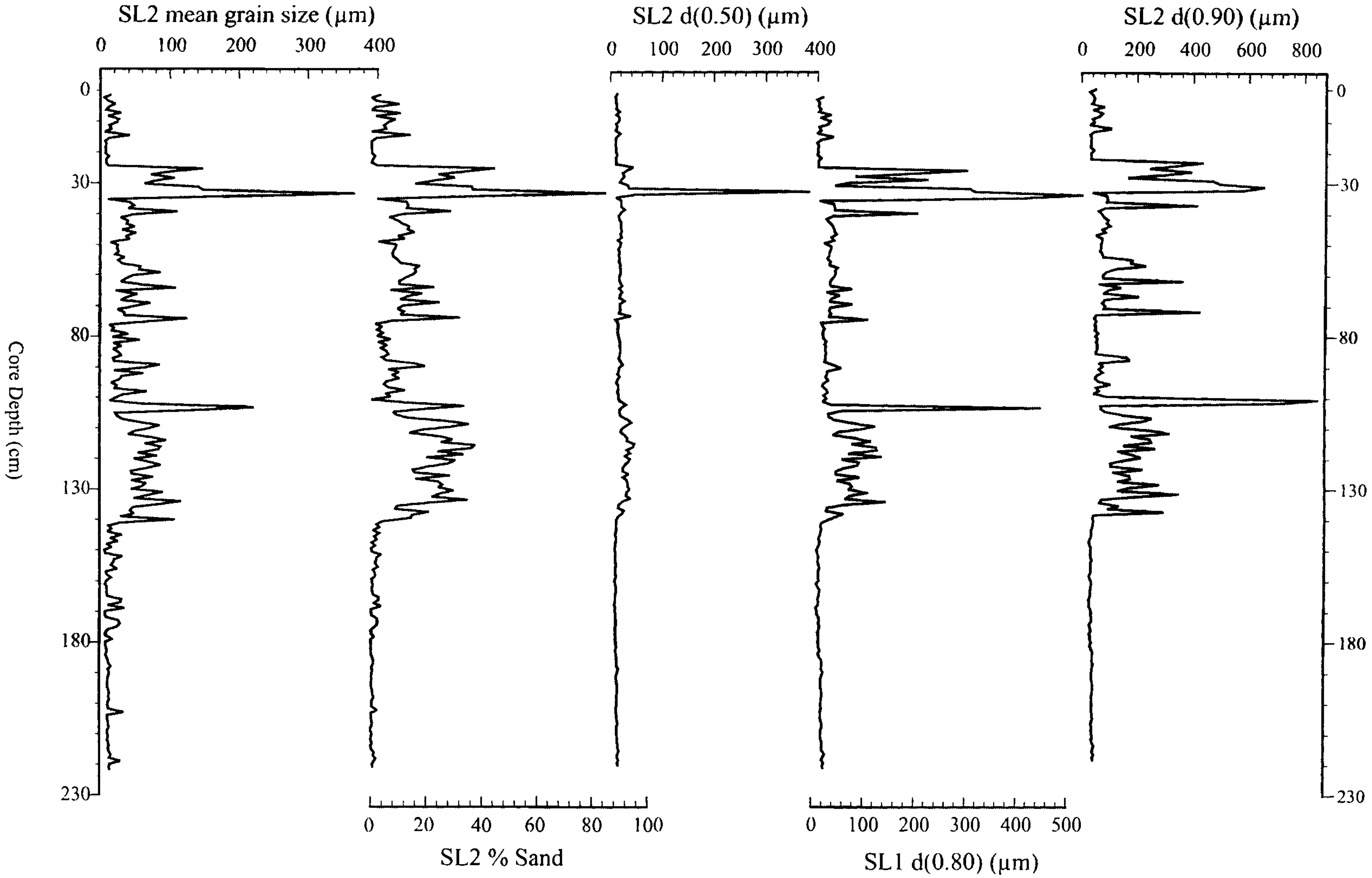


Figure 28. Plots of relevant grain size parameters for SL-2. Note that major peaks are visible across most parameters, and that the plots of mean grain size and percent sand are nearly identical.

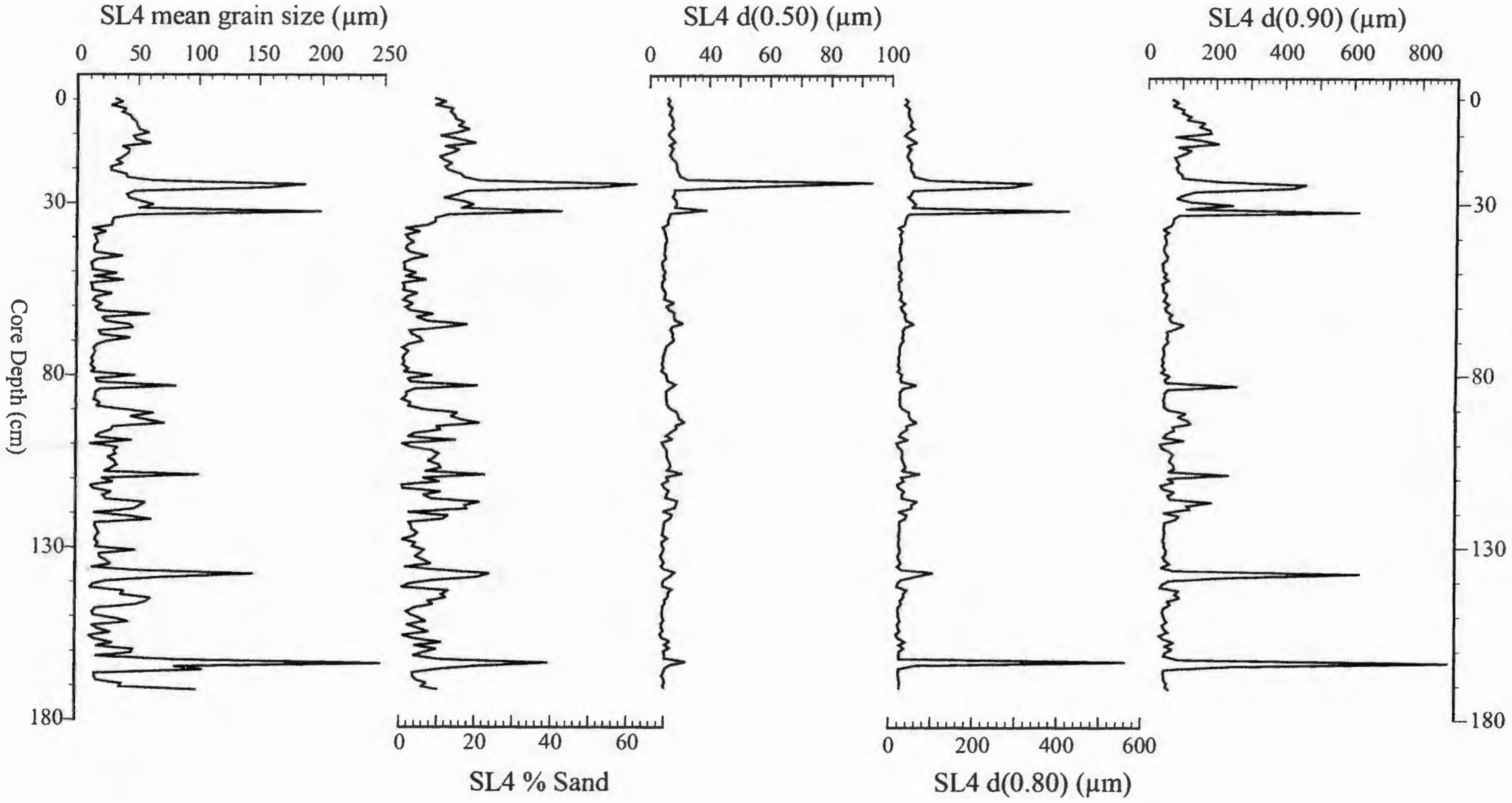


Figure 29. Plots of relevant grain size parameters for SL-4. Note that major peaks are visible across most parameters, and that the plots of mean grain size and percent sand are nearly identical.

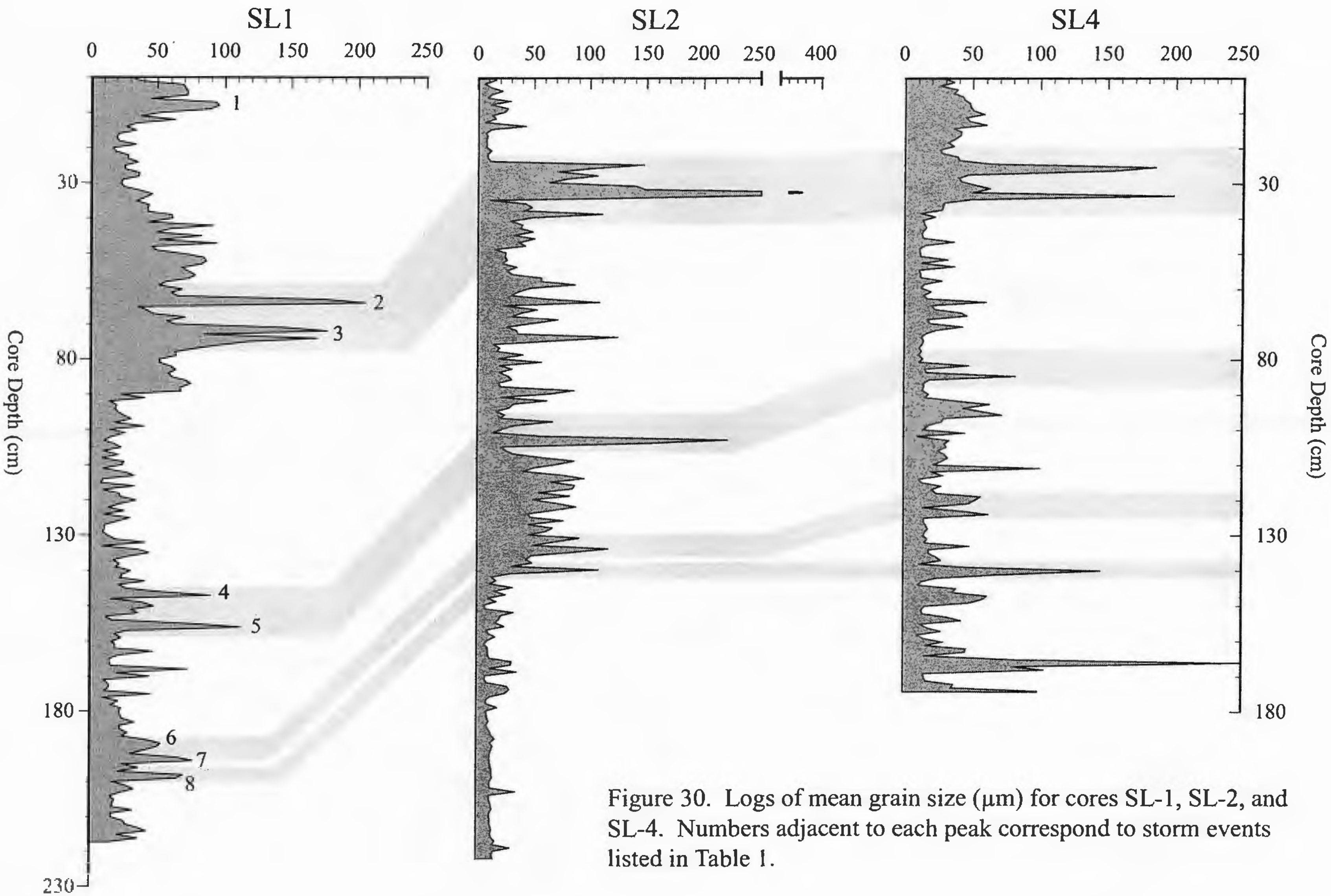


Figure 30. Logs of mean grain size (μm) for cores SL-1, SL-2, and SL-4. Numbers adjacent to each peak correspond to storm events listed in Table 1.

The next interval with sharp increases in grain size is from 60-80 cm depth in SL-1, which matches up with 25-45 cm in SL-2 and 20-40 cm in SL-4. These intervals are composed of three discreet peaks in mean grain size in SL-1 and SL-2, and based on the ^{210}Pb age model were deposited between the years 1830 and 1880. Because the lower two peaks are only separated by a few centimeters, whereas the uppermost peak is ~10 cm or more further up-section, it is possible that the uppermost peak represents deposition from the Gale of 1878, whereas the lower peaks reflect historical storm events in 1830 and 1846, respectively.

The remaining peaks in mean grain size were probably deposited more than 300 years ago, which puts them outside the historical record of storms. However, five additional storm-like signatures are present in the grain size records of SL-1, SL-2, and SL-4, which equates to a minimum of 8 depositional events occurring in Silver Lake during the span of approximately 500 years (Figure 31). A complete list of these storms, interpreted from the mean grain size data, and their associated age estimates can be found in Table 2.

According to the grain size data, Silver Lake has a recurrence interval of approximately one severe storm every 60-70 years. However, the lack of a definitive connection between a historical storm and washover deposit limits the predictive ability of the record with respect to storm intensity. According to NOAA tide gauge records from nearby Lewes, DE, no storm since has produced a higher surge than the 1962 Ash Wednesday storm (Table 3). The absence of a sedimentary signal from this storm implies that storm size and associated surge heights may not be reliable indicators of overwash occurring in Silver Lake. Rather, patterns of overwash are

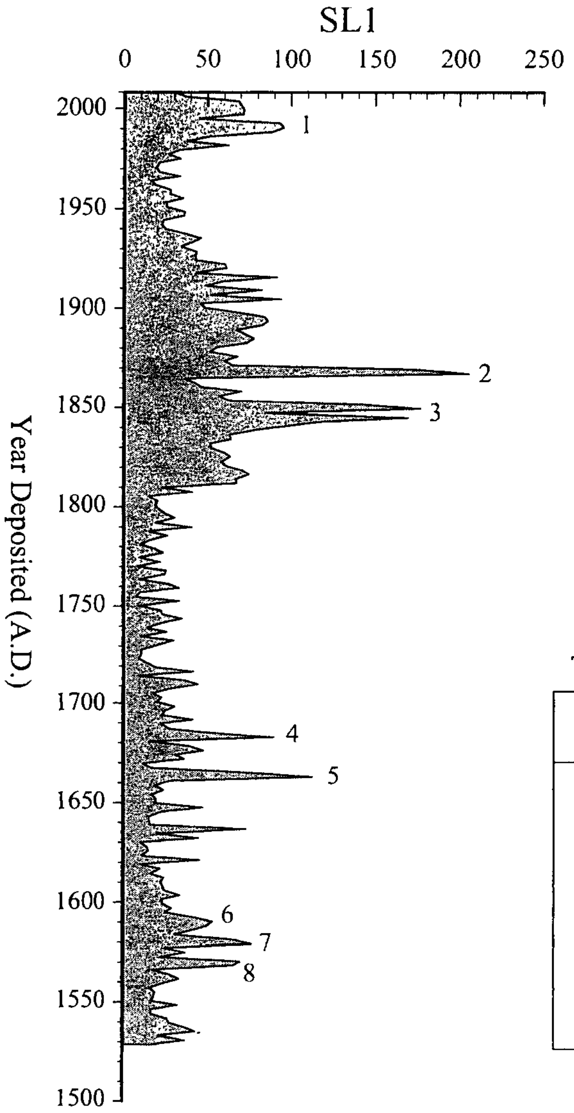


Figure 31. SL-1 mean grain size (μm) versus year deposited. Interpreted storm events are numbered and listed in Table 2.

Table 2. List of storm events interpreted from the sedimentary record of Silver

Event Number	Depth in SL-1 (cm)	Depth in SL-2 (cm)	Depth in SL-4 (cm)	Estimated Date of Deposition
1	3-10	n/a	8-14	1985
2	63-65	25-28	25-27	1878
3	72-74	31-34	32-34	1846
4	148	98	85	1680
5	156-157	103-104	96	1660
6	190-191	131-132	119	1585
7	194-196	134-135	124	1573
8	199-200	140	140	1565

Table 3. Dates and heights of highest recorded tides at Lewes, DE tidal station

Number	Date	Tide Height (m above MSL)	Storm Type
1	March 6, 1962	2.13	Extratropical
2	January 4, 1992	1.99	Extratropical
3	January 28, 1998	1.95	Extratropical
4	February 5, 1998	1.91	Extratropical
5	September 27, 1985	1.77	Tropical (Hurricane)
6	March 3, 1994	1.75	Extratropical
7	October 25, 1980	1.74	Extratropical
8	March 29, 1984	1.73	Extratropical
9	January 8, 1996	1.71	Extratropical
10	December 12, 1992	1.70	Extratropical

likely heavily influenced by the pre-existing beach conditions prior to each individual storm event. The low frequency of washover layers still suggests that only the most severe of storms will deposit sand into Silver Lake, but it appears that the probability of overwash occurring for any storm of this type is closely linked to morphological variables as well.

Previous research indicates that there is a generally positive relationship between the size of a washover deposit and the scale of a storm event (Liu and Fearn, 1993). The majority of sand deposits in the Silver Lake cores are on the order of 1-4 centimeters in thickness, which does not provide much variability for differentiating storm intensities. However, about three of the grain size peaks in the Silver Lake cores are substantially greater in size relative to the remaining peaks also interpreted as overwash deposition. Perhaps these peaks (located at 63 cm, 74 cm, and 156 cm depth in SL-1) reflect storm events of a larger scale than those depositing finer layers of sand. For instance, the peak in mean grain size at 63 cm depth in SL-1 correlates well with possible deposition during the Gale of 1878. Reports on this storm suggest that it may be the hurricane of record for Delaware and provides a model for the worst-case scenario of a modern hurricane potentially impacting the same region (Ramsey and Reilly, 2002). In either instance, the Gale of 1878 seems to have been the last major hurricane to impact Delaware.

3.6 Sea-level changes

The age-model established for core SL-1 suggests that the record contained in the core reflects a period of approximately 500 years. Due to sea level fluctuations throughout the last millennium, perceived storm events near the base of the core must be interpreted with respect to relative sea level at the time of deposition. Estimates of local sea level rise range from 0.8 to 1.3 mm/yr for the past 1000 years, indicating that sea level was between 40 and 65 cm lower 500 years ago (Kraft, 1976; Nikitina et al., 2000). The most recent age calibrations for the history of Delaware sea level rise suggest a rate of ~1 mm/yr, so this is the value used in this study (Nikitina et al., 2000). A rate of 1 mm/yr corresponds to a sea level 50 cm (0.5 m) lower than present, which is significant in interpreting older storm deposits. Because sea level was lower, the storm surge required to deposit sand in the Silver Lake environment was probably higher (assuming the water level in Silver Lake has been constant throughout time), and so the deposits lower in the core may indicate storms of a greater magnitude than those creating washover in more recent times. However, due to the dynamic nature of barrier environments (i.e. variability in dune height) and the generally unpredictable nature of overwash, there is still some inherent uncertainty in this assumption.

3.7 Reliability of the storm record in Silver Lake

It is generally understood that the sedimentary record of storm activity in any coastal environment is an underestimate (Donnelly et al., 2001). As the primary agents of erosion along the coast, storms are capable of removing traces of previous storms while leaving a record of their own deposition. Also, storms that impact an area in rapid succession may leave overlapping deposits, which can often be indistinguishable from one another in the sedimentary record. The size and shape of washover deposits depend on the intensity of the storm, the orientation of the beach with respect to the approach of storm waves, and the general morphological characteristics and erodibility of the shoreface (Ritter et al., 2002). Thus, the scale of washover after one storm is an unreliable indicator of the amount of washover that may result from a future storm of similar strength. For instance, the lack of sedimentary evidence of the 1962 Ash Wednesday Storm in Silver Lake sediments does not necessarily imply that nor'easters are unlikely to transport sand over the adjacent dune and into the lake. A variety of factors influence the overwash potential of a certain area, so landfall of an intense storm alone is no guarantee that overwash will occur along a certain stretch of coastline. Dune heights and beach width are variable throughout time, which can change the barrier's immediate susceptibility to overwash relative to a specific storm surge. The interpreted storm deposits found in the sediments of Silver Lake reflect the impact of storms characterized by the appropriate combination of pre-existing shoreline morphology, tidal cycle, wind direction, and wave height that lead to the transport of sand across the barrier dune and into the lake.

Despite the lack of sedimentary evidence for the 1962 storm, Table 3 reveals that 9 of the 10 highest tides recorded in nearby Lewes, DE were the result of extratropical storms. The table incorporates tidal data from 1919, and the only tropical storm on the list is Hurricane Gloria, which passed through Delaware in September 1985. Table 3 provides further indication that, at least during the past century, extratropical storms have been just as likely to cause appreciable storm surge as hurricanes, if not more so. There is not enough evidence to prove definitively whether or not the record of overwash within Silver Lake reflects only hurricanes or a combination of hurricanes, lesser tropical storms, and nor'easters. Although the most recent peaks in grain size match up fairly well with historic hurricanes, the lack of a peak from 1962 seems to be an anomaly rather than proof that nor'easters lack the power to deposit washover sand into Silver Lake. Despite the uncertainties of the sedimentary record, Silver Lake still preserves considerable evidence of storm events throughout the ~500 year history contained in the cores.

3.8 Magnetic Stratigraphy

From about 150 cm depth through the base of SL-1, all measurements of magnetic mineral concentration show consistent low values (Figure 32). These low values are most likely the result of reducing conditions within the sediment. The corresponding sediment is composed of organic-rich material that was probably deposited in a salt marsh environment. Anoxic conditions created by decaying organic matter in the marsh sediment, combined with the presence of sulfate from ocean water, likely reduced the iron-bearing minerals to non-magnetic states such as FeS_2 (pyrite).

Throughout the remainder of the core, K, ARM, SIRM, and HIRM parameters are in general agreement. Each parameter has a peak in value just above the interval in which reduction is believed to have taken place. This increase in magnetic mineral concentration corresponds to the sedimentary transition between organic-rich sediment and a denser, very-fine grained unit of lighter-colored mud and silt. As discussed previously, the accumulation of mud and silt probably signals the transition to a closed lake environment, which maintained more favorable conditions for the preservation of

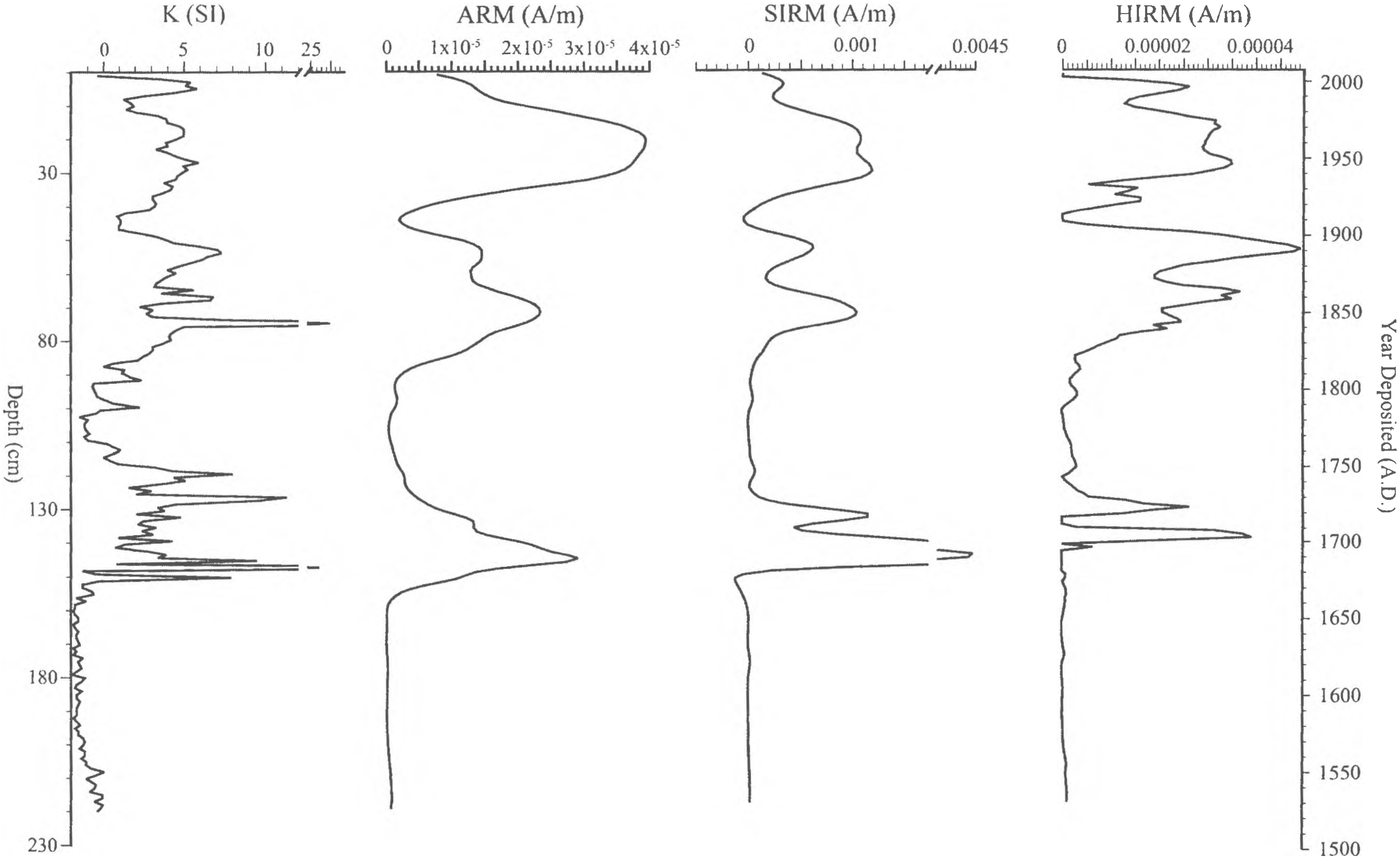


Figure 32. Mineral magnetic parameters plotted versus depth and year deposited for core SL-1.

magnetic minerals. However, this interval was short-lived, and another interval with very low ARM, SIRM, and HIRM values persists from approximately 85-125 cm depth. This section of core is characterized by another segment of organic-rich muddy sediment where reducing conditions are likely present. While also low from 85-115 cm depth, K shows two peaks between 120 and 130 cm depth, which indicates a possible presence of coarse magnetite, or paramagnetic minerals that only show positive magnetism while under the influence of an applied magnetic field (i.e. measurement of magnetic susceptibility). This may reflect input to Silver Lake from an additional sedimentary source throughout this interval. Deciphering this additional source of paramagnetic material, if present, is beyond the scope of this project.

The increase in magnetic material at ~80 cm depth is attributed to human settlement of the surrounding area. According to the ^{210}Pb age model, the sediment at this depth was deposited around the early 1800s. Although a definitive record of local land use was unattainable, the initial rise in Ambrosia also occurs at this depth, suggesting that land clearance and agricultural practices are responsible for the increase in magnetic mineral concentration. In addition, mean grain size shifts to an interval characterized by coarser grains, and total organic material drops to values below 10% (Figure 33). Together, these parameters reflect changes that would be expected from land clearing and increased soil erosion as a result of European settlement.

Since the town of Rehoboth Beach has experienced continual growth after it was first settled, the input of magnetic material is presumed to have remained fairly constant, if not increasing. However, K, ARM, and IRM values oscillate from 0-80

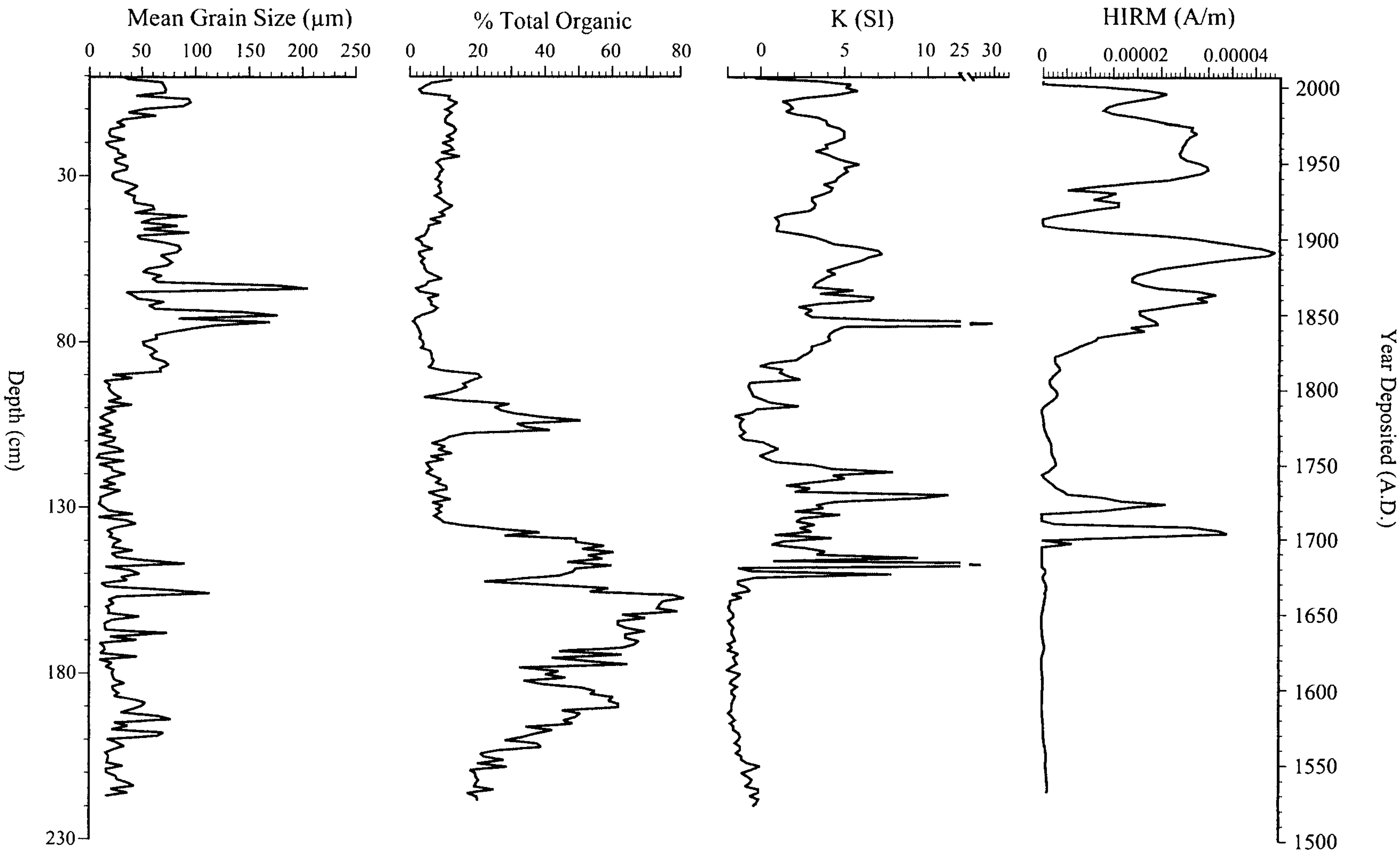


Figure 33. SL-1 plots of mean grain size, percent total organic content, magnetic susceptibility, and HIRM for the purpose of comparison. Note that magnetic concentrations are generally low during intervals of high organic content, and higher during intervals of low organic content.

well with mean grain size or total organic content, so it is doubtful that the magnetic signature reflects changes in these parameters. An alternate explanation is that the fluctuations in the magnetic data reflect varying degrees of surface soil erosion. Peaks in the data may correspond to intervals of increased precipitation, which lead to increased runoff of surface soil and subsequent deposition of high-coercivity magnetic minerals in Silver Lake. High-coercivity magnetic minerals, such as hematite and goethite, are commonly formed during the process of weathering in soils (Oldfield et al., 1985).

To test this hypothesis, yearly rainfall data for Sussex County was compiled from the National Climatic Data Center spanning 113 years from 1896-2008 AD. Compared against magnetic susceptibility and the HIRM parameter, there appears to be a significant correlation, at least visually, between yearly rainfall and the abundance of magnetic material deposited in the sediment of Silver Lake (Figure 34). Magnetic susceptibility (K) and HIRM tend to increase (decrease) as yearly rainfall increases (decreases), indicating that the runoff of surface soils is likely controlling the magnetic signature of the upper ~80 cm of sediment in SL-1. Although careful analysis of Figure 32 shows that the relationship is not perfect, there is substantial correlation to suggest that a relationship does indeed exist.

3.9 Spectral Analysis

Results from kSpectra analysis of SL-1 and SL-2 showed power at varying depth intervals for mean grain size and percent sand. Both SL-1 and SL-2 had strong signals at a frequency less than 0.01, but this is just a signal of the total core length. In

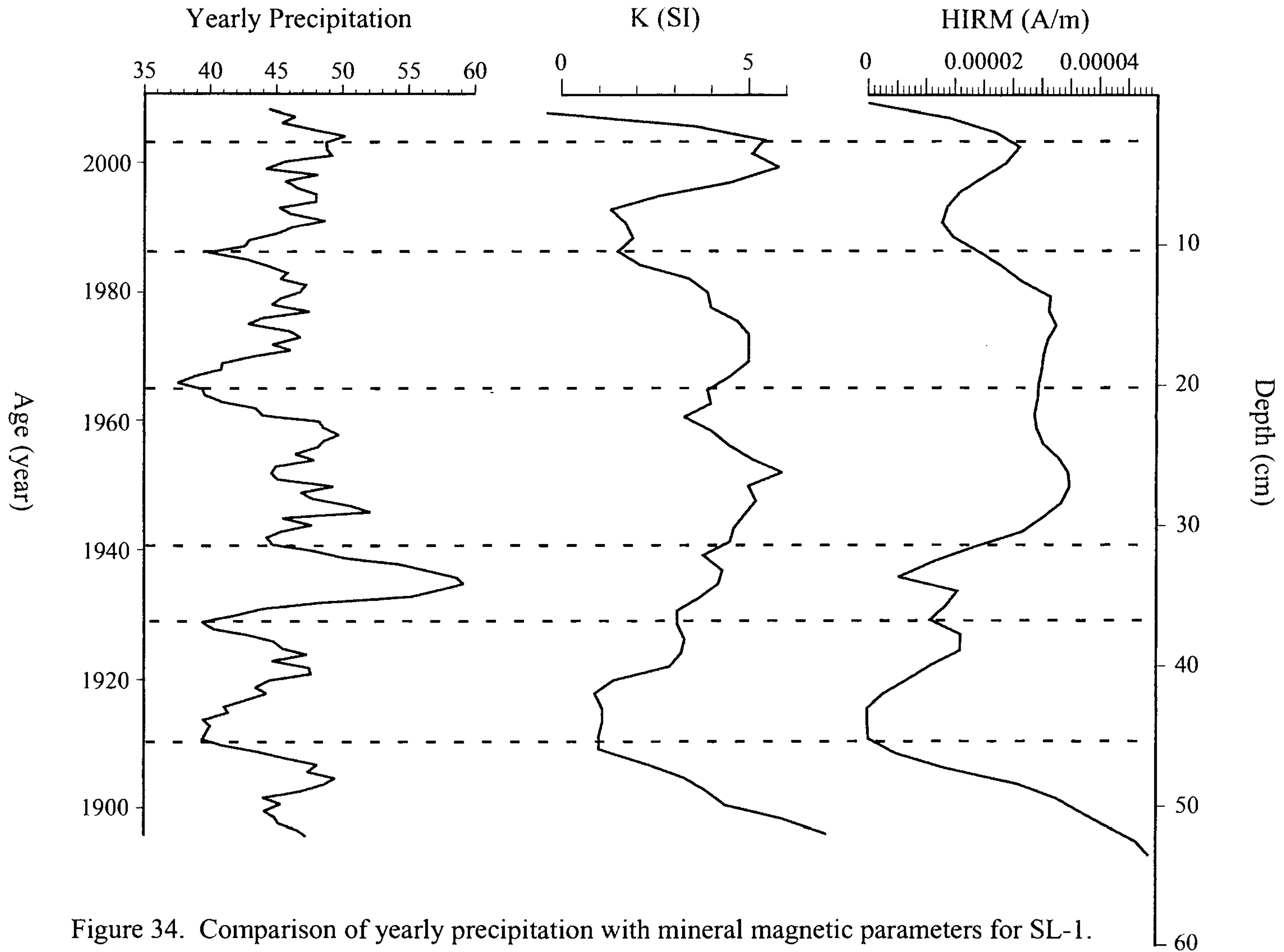
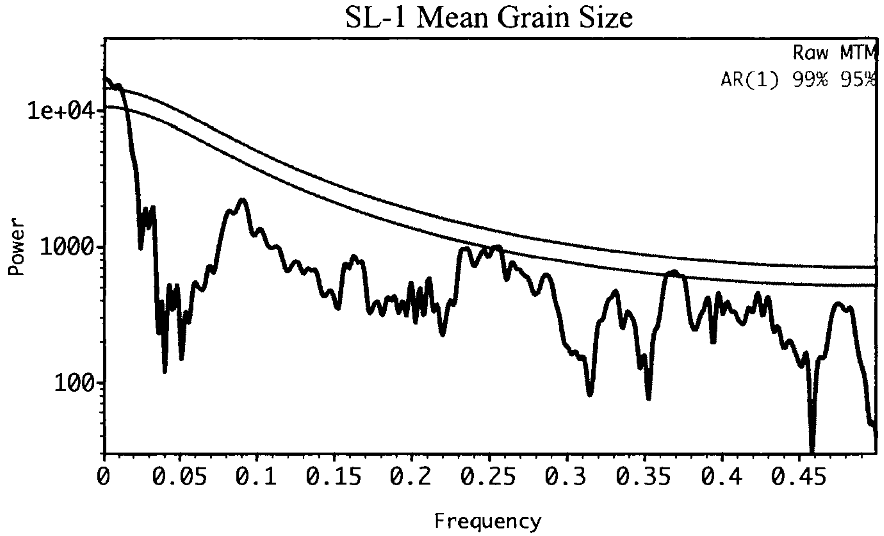


Figure 34. Comparison of yearly precipitation with mineral magnetic parameters for SL-1. Dashed lines delineate intervals of general agreement across datasets.

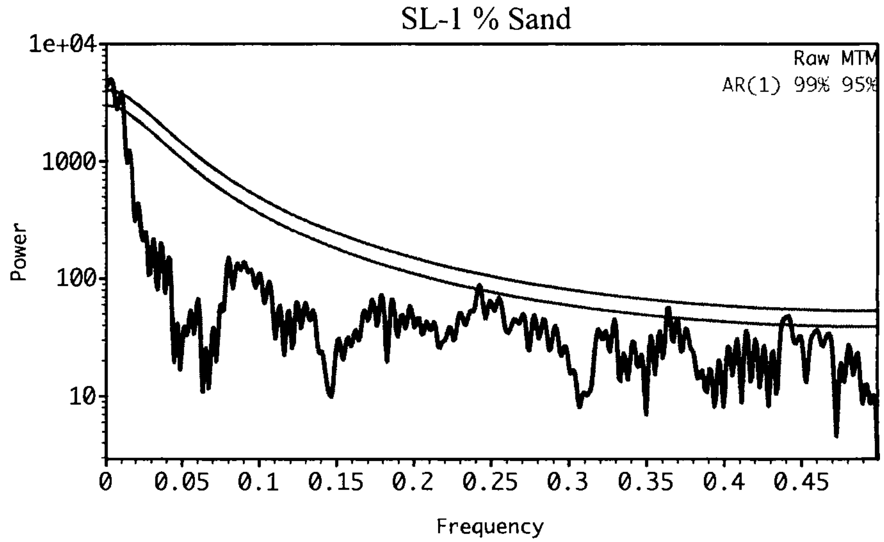
order to obtain the best estimates of power, only peaks with at least a 95% confidence interval were considered. In addition, peaks that were extremely close together were simply averaged and assumed to be representative of the same frequency signal.

For mean grain size and percent sand, SL-1 has power at 95% confidence for intervals of approximately 2.27, 2.73, and 4.02 cm (Figure 35). Using the ^{210}Pb age model sedimentation rate for conversion (0.45 cm/yr), these values correspond to time intervals of 5.04, 6.07, and 8.94 years. Results for SL-2 are similar, with 95% confidence for power peaks at 2.74 and 6.13 cm, which equate to intervals of approximately 6.1 and 13.6 years (Figure 36).

The main goal of this analysis was to explore any possible linkages between the depositional history of Silver Lake and changing climate conditions controlled by such phenomena as the Atlantic Multidecadal Oscillation (AMO), the North Atlantic Oscillation (NAO), or the El Niño/Southern Oscillation (ENSO). According to recent research, the AMO operates on a cycle of approximately 40-70 years, whereas the NAO is variable day-to-day and month-to-month, but generally stays positive or negative for cycles of 5-15 years (Black et al., 1999; Delworth and Mann, 2000; Hubeny et al., 2006). Conversely, ENSO is quasi-periodic, and El Niño events typically occur every 2–7 years and last anywhere from nine months to two years. Before utilizing power results from kSpectra, grain size was visually compared to proxy records of AMO, NAO, and ENSO. No trends or patterns were apparent, but the results from spectral analysis for SL-1 and SL-2 suggest that Silver Lake grain size has periodicity on the same scale as the NAO. Specifically, SL-1 mean grain size and percent sand indicate power at 6-9 year intervals, whereas SL-2 mean grain size and

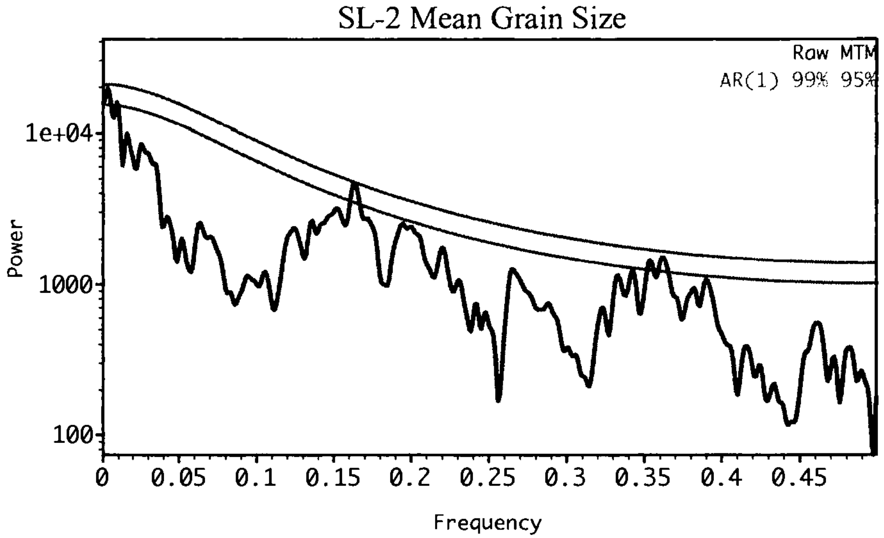


Frequency	Period (cm)	Period (years)	C.I.
0.256	3.91	8.69	95%
0.369	2.71	6.02	95%



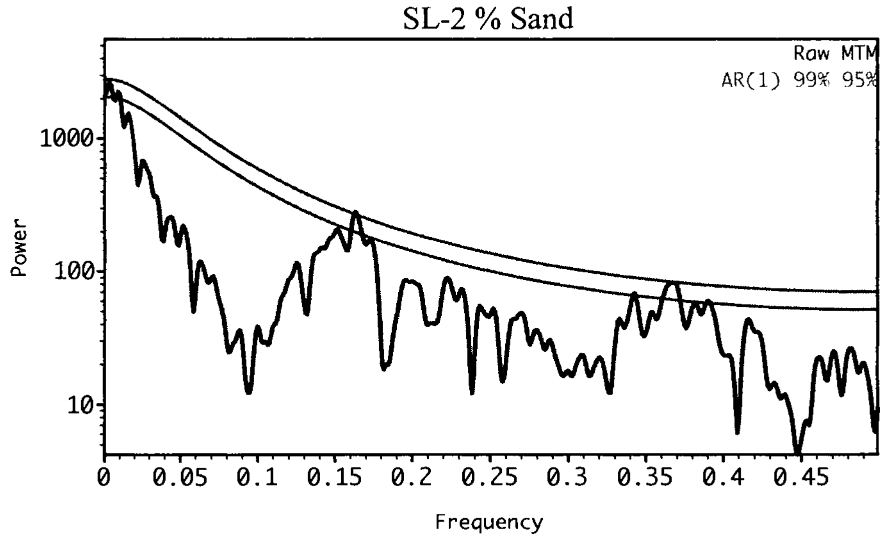
Frequency	Period (cm)	Period (years)	C.I.
0.242	4.13	9.18	95%
0.364	2.75	6.11	95%
0.441	2.27	5.04	95%

Figure 35. Spectral analysis results (multi-taper method) for SL-1 grain size data. Power peaks occur for intervals of approximately 5.04, 6.07, and 8.94 years.



SL-2 Mean Grain Size

Frequency	Period (cm)	Period (years)	C.I.
0.163	6.13	13.6	95%
0.361	2.77	6.16	95%



SL-2 % Sand

Frequency	Period (cm)	Period (years)	C.I.
0.163	6.13	13.6	99%
0.343	2.92	6.49	95%
0.368	2.72	6.04	95%
0.390	2.56	5.69	95%

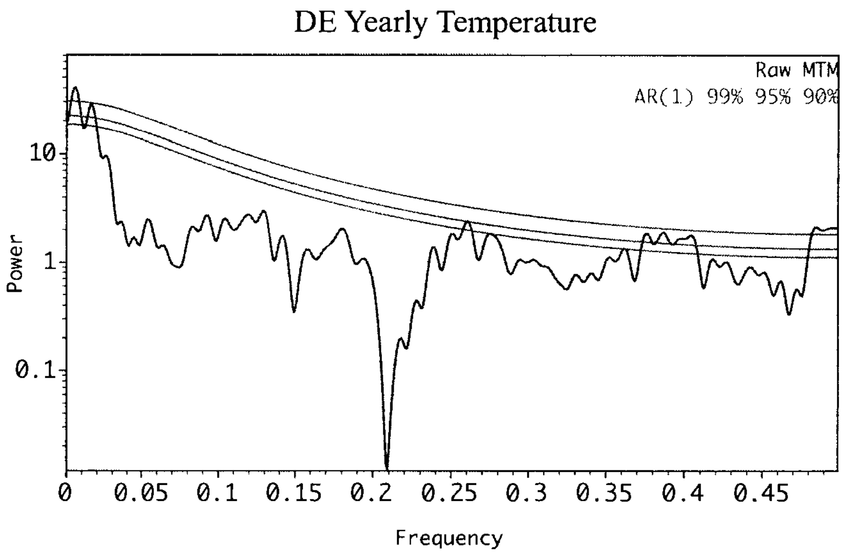
Figure 36. Spectral analysis results (multi-taper method) for SL-2 grain size data. Power peaks occur for intervals of approximately 6.1 and 13.6 years.

percent sand indicate power at intervals of approximately 6 and 13 years – all of which are consistent with previous studies of NAO periodicity.

In order to further test the possible connection between Silver Lake grain size and the NAO, Delaware average yearly temperature and yearly total precipitation spanning the years 1895-2009 were compiled for spectral analysis. Although not identical to the periodicities for grain size, the results for temperature and precipitation indicate power at periodicities between 2-12 years (Figure 37). Since these results, along with Silver Lake grain size spectra, are on the same scale as the NAO, it is likely that the differing phases of the NAO exert some influence on the local climate and grain size record of Silver Lake. During the negative phase of the NAO, storm tracks shift to the south, bringing storm systems to the Mid-Atlantic area that would otherwise track throughout New England and Canada. This increased storminess leads to greater than average precipitation, which increases runoff and results in the deposition of coarser than average material into Silver Lake. Although this hypothesis may explain the similar power spectra for Delaware climate variables, Silver Lake grain size, and varying states of the NAO, deciphering the precise mechanism by which the NAO may influence the sedimentary record of Silver Lake is beyond the scope of this project.

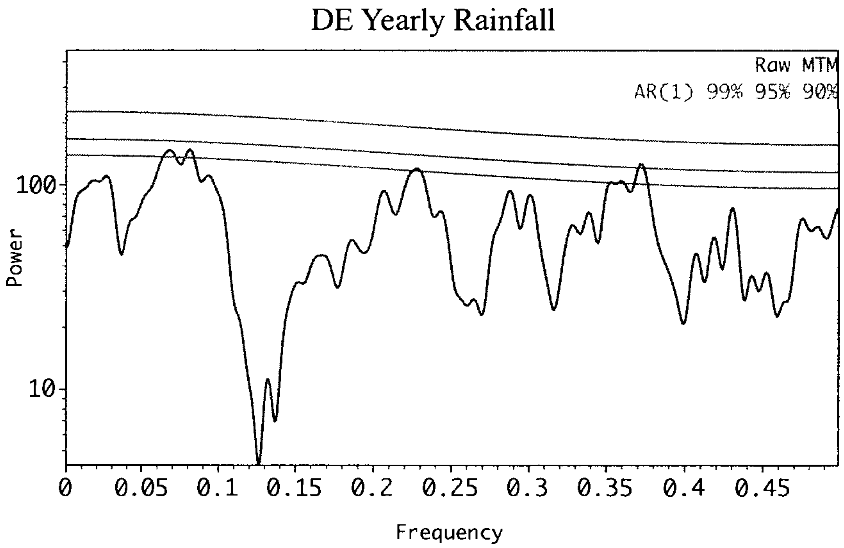
3.10 Regional Comparison

The record of overwash in Silver Lake may correlate to sedimentary evidence of extreme storm events at nearby study sites. Cores from Whale Beach and Brigantine in southern New Jersey preserve sand layers that were likely deposited



DE Yearly Temperature

Frequency	Period (years)	C.I.
0.017	58.8	99%
0.26	3.85	95%
0.387	2.58	95%
0.484	2.07	99%



DE Yearly Rainfall

Frequency	Period (years)	C.I.
0.08	12.5	90%
0.23	4.4	90%
0.37	2.7	95%

Figure 37. Spectral analysis results (multi-taper method) for Delaware yearly average temperature and yearly total precipitation. Power peaks occur at intervals of approximately 2-12 years.

during the Norfolk and Long Island Hurricane of 1821 (Donnelly et al., 2001; Donnelly et al., 2004). Although this hurricane passed over the Delmarva Peninsula and led to reports of widespread destruction throughout the area, reports of damage and flooding specific to the Silver Lake area are scarce. Nevertheless, it is possible that the sand horizon at ~75 cm depth in SL-1 represents deposition from this storm. Although age estimates for the layer suggest that it was deposited closer to the year 1840, uncertainties in this estimate cannot conclusively rule out deposition during the Long Island Hurricane of 1821. If so, this would be the only common event preserved in the records of New Jersey and Delaware. The Whale Beach and Brigantine cores also provide evidence for a hurricane between the 7th and 14th century A.D., but this dates beyond the record preserved in this study.

Cores from western Long Island, N.Y., preserve washover deposits that correlate with hurricane strikes in 1893, 1821, 1788, and 1693. Due to the substantial distance between the southern Delaware coast and Long Island, as well as differences in the orientation of the associated shorelines, comparable records of storm events are unlikely. Thus, it is not surprising that there are no storm events clearly preserved at both sites. However, the record of storm events from Long Island and Delaware both indicate a sequence of hurricanes or other extreme storm events occurring during the Little Ice Age (~1550-1850 A.D.). This connection was first explored by Scileppi and Donnelly (2007), and indicated that despite the cooler sea surface temperatures (SSTs) during this time, hurricanes were still prevalent. This is contrary to recent research suggesting that hurricanes have a positive relationship with increasing SSTs throughout the past few decades (Emanuel, 2005; Goldenberg et al., 2001). During the Little Ice Age, SSTs were 1-2°C cooler than present throughout the southern Atlantic Ocean, suggesting that hurricane frequencies would be lower for that period of time (Scileppi and Donnelly, 2007). However, no pattern emerges from the storm record within Silver Lake, implying that SSTs have little control over the frequency of extreme storm events in this area. In fact, the record from Delaware is fairly consistent and shows little evidence for any periods of high or low storm activity. A longer record of storms would be necessary for further exploration into these types of patterns.

CONCLUSIONS

Sedimentological and geochronological analyses of multiple cores from Silver Lake in Rehoboth Beach, DE provide a ~500 year environmental history of the lake basin. Facies changes and variability in total organic content indicate shifts between closed freshwater, open saltwater and transitional environments. Peaks in grain size data represent overwash deposition as a result of historic and prehistoric storm events that tracked over or in close proximity to the Silver Lake area. Eight total storm events were identified, corresponding to deposition in 1985, 1878, 1846, 1680, 1660, 1585, 1573, and 1565 based on a ^{210}Pb age model with additional age constraints from ^{137}Cs, lead and copper trace metal, and pollen abundance. Historical records indicate that no storm has made landfall in the state of Delaware while maintaining hurricane intensity, but events such as the Gale of 1878 tracked very close to the coastline and resulted in hurricane-force onshore winds that likely caused widespread flooding and overwash throughout most coastal areas of the state. Coupled with the damage chronicled from the Ash Wednesday Storm of 1962, the results of this study imply that Delaware is vulnerable to both tropical and extratropical storm systems tracking along the Mid-Atlantic Coast of the United States.

The frequency of storm events throughout the ~500 years represented by SL-1 do not correlate with changes in SST or differing phases of atmospheric phenomena such as the AMO, NAO, or ENSO. However, results from spectral analysis of mean grain size and Delaware temperature and precipitation records indicate that cycles of mean grain size may be controlled by changing states of the NAO. Specifically, the negative phase of the NAO may increase storminess over the Silver Lake area, resulting in the deposition of coarser-grained sediment. In addition, magnetic data suggest that a relationship may exist between the concentration of magnetic minerals in Silver Lake sediments and patterns of yearly rainfall. Increased rainfall leads to increased runoff, which may erode surface soils and subsequently deposit higher concentrations of high-coercivity magnetic minerals into the lake.

The geologic setting of Silver Lake, characterized by its location on the Scotts Corners Formation of the Rehoboth Headland, has remained relatively stable throughout the past 500 years. Low rates of shoreline erosion, along with historical maps and photographs indicating little to no morphological change over the past ~130 years, agree with the sedimentary record of low-energy lake deposition for this period. Despite interpreted transitions to and from a tidally influenced marsh environment, cores SL-1, SL-2, and SL-4 have reliable grain size records that preserve signals of past storms.

Eliminating the most recent grain size peak, a history of seven storms in 500 years equates to a recurrence interval of one extreme storm event every 71 years. Although the Ash Wednesday Storm of 1962 is considered by some to be the storm of the century for the Mid-Atlantic Coast, it failed to leave a record of overwash in Silver Lake. Patterns of overwash are highly dependent upon pre-existing beach conditions, tidal cycle, and individual storm characteristics. Prior to the Ash Wednesday Storm of 1962, the Silver Lake barrier may have been characterized by a high dune and large sand volume that acted as a substantial buffer to overwash. Nevertheless, the storm created abundant overwash throughout the rest of the Delaware coast, and the lack of a washover layer in Silver Lake suggests that only larger, stronger tropical storms or those storms with a more direct track over the Rehoboth Beach area will create a signal in the grain size of Silver Lake.

Although a minor peak in grain size suggests that a storm may have deposited washover sand into Silver Lake sometime in the past 20-30 years, the deposition of a much coarser, laterally continuous layer of sand at ~65 cm depth in SL-1 implies that the Gale of 1878 was perhaps the most severe storm to impact Rehoboth Beach in the last 200+ years. A smaller population and less infrastructure during this time likely skewed reports of flooding and damage throughout Delaware's southern coast, and a similar storm impacting the area in the near future would undoubtedly result in widespread washover deposition along this stretch of coast as well as significant damage throughout the community surrounding Silver Lake. Assuming that half of the interpreted storm events in the sedimentary record of Silver Lake were on a similar scale of magnitude, such an event has occurred once every 125 years throughout the last half-century.

Coastal storms, especially rare intense events such as the Ash Wednesday Storm of 1962 and the Gale of 1878, are the biggest threat to beach communities situated along the U.S. East Coast. Strong winds, powerful waves, and the overwash of sand and saltwater are capable of destroying homes and buildings, downing trees and power lines, and rendering roadways impassable. Due to these threats, it is crucial that the frequency and nature of intense storms are thoroughly understood. Sedimentary proxies of storms on longer timescales, such as the record preserved in Silver Lake, will hopefully aid in predictions of future storm activity as well as proposed framework for erosion and hazard mitigation.

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