Influence of Lake Levels and Ice Cover on a Modified Shoreline: Ohio's Headland Beaches

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ABSTRACT

Ohio's Lake Erie shoreline, situated along the high-energy south-central Lake Erie coast, is characterized as a sediment-starved, wave-dominated erosional coastal system. Harbor-protecting structures installed in the early 1900s have fragmented the littoral system, which trends from W to E across the area, trapping bluff-derived sediments on their up-drift sides. The studied depositional harbor headlands of Lake County (i.e. Headlands Beach) and Ashtabula County (i.e. Walnut Beach and Conneaut Beach) are located along a ~65 km stretch of the south-central Lake Erie shoreline. Given many shared similarities and similar degrees of exposure to lake-level variations, winter-ice covers, and storm conditions (with associated surge levels, waves, and strong coastal currents), the geologic and anthropogenic distinctions between the sites need to be evaluated as potential drivers of coastal change. Historic shoreline positions, mapped from georeferenced aerial photographs, provide a chronology to evaluate the recent geomorphic evolution of these headlands with respect to these physical forcing parameters. Ground-penetrating radar (GPR) data reveal changes in prograding clinoform (i.e. preserved foreshore deposits) geometry, attesting to the inherent dynamics of headland beaches, which have been impacted by episodic erosion and deposition at decadal timescales. Multiple regression analysis of net beach growth, derived from shoreline positions, versus lake level and ice cover suggest that high lake levels are more strongly associated with beach growth overall; this is surprising given variable sediment sources and beach compositions from site to site. Beach growth during elevated lake levels are likely attributed to increased sediment fluxes from sourcing bluffs. Ice cover appears to play a secondary, yet important role in headland evolution as both an erosional and depositional mechanism capable of entraining course-grained sediments and reshaping shorelines. The design of harbor structures influences sedimentation at the headlands by dictating the bounds of beach form. Changes in the rates of decadal beach progradation are associated with distinct changes in breakwater orientation, which represent an intrinsic control on the distribution of accommodation-space distribution at the shoreline.

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Background

The widespread use of shore protection structures has a profound influence on coastal margins. Nordstrom (2014) reviewed the effects of shore protection structures and their influence on the coastal zone: 1) Traditional shore protection structures include groins, bulkheads, seawalls, revetments, breakwaters, etc.; 2) Groins are shore-perpendicular structures that trap littoral sediment leading to accretion on the up-drift side and increased erosion on the down-drift side; 3) Bulkheads, seawalls, and revetments are shore parallel structures that are built to protect coastal infrastructure when the natural protection (i.e. wide beaches) is lost; and 4) Breakwaters are shore parallel structures, which reduce wave energy and promote deposition along their landward beaches. Much of the current understanding of the effects of shore protection structures comes from oceanic settings. While the Great Lakes region houses many of these traditional shore protection structures (or modified versions), their influence on coastal dynamics here is not fully understood. For the purpose of this paper, shore parallel structures are referred to as breakwaters while shore perpendicular structures are referred to as jetties, although these terms are often used interchangeably.

Ohio’s Lake Erie shoreline, situated along the high-energy south-central Lake Erie coast (Figure 1), is characterized as a sediment-starved, wave-dominated erosional coastal system. Especially vulnerable are this coastal region’s till or till-mantled bluff shorelines, which in some localities tower up to ~20 m above the surf zone below (Carter et al. 1981; Fuller, 1996; Dawson and Evans, 2001; Morang et al., 2011). Beaches historically lined the entire coast (up until the 1800s), protecting bluffs by serving as a natural defense against wave attack and other shoreline processes (e.g. ice-sediment interactions); beaches today, if present at all, are comparatively much narrower and provide little protection as bluff-fronting buffers. The overall erosional tendencies of Ohio's Lake Erie shoreline over the last century are attributed to a relatively high number of shore protection structures (i.e. harbor jetties, sea walls, groins, and breakwaters) along this particular stretch of the lower Great Lakes, in particular, the density of these structures along the shoreline has increased dramatically since the early 20th century and is attributed as the primary cause for much of the erosion intensification noticed since (Carter et al.1981, 1986).

The population statistics for the Ohio lakeshore counties show an overall increase since the 1930s; consequently, many lakefront homes were built, the majority of which in close proximity to the bluff edge (Guy, Jr., 1999). Prior to regulatory oversight, which began with the federal Coastal Management Act of 1972, coastal landowners battled erosion problems with a variety of ingenious and heavily varied (i.e. unregulated) shore-protection methods. As this unregulated practice continued, impacts of local shoreline modification led to attenuated erosion elsewhere (e.g. downdrift), prompting the installment of additional hard structures; this created a positive feedback loop between hard structure installation and coastal erosion as limited sand resources in coastal waters preferentially sequestered against hard structures while failing to replenish other shoreline segments. Subsequently, while the number of protective structures increased along Ohio's Lake Erie shore, beach widths steadily decreased (Carter et al., 1981, 1986).

First-hand accounts of the effects of a poorly understood coastal system (e.g. houses being lost to Lake Erie), likely prompted the surge in research efforts to document coastal erosion and the processes regulating it in an effort to provide guidance to coastal landowners. Today, there is a systematic permitting process conducted by the Ohio Office of Coastal Management (ODNR) to ensure these structures can withstand the environmental variables they are subjected to (i.e. lake levels, ice cover, tides, waves, etc.) while protecting particularly vulnerable and ecologically valuable areas along the coast.

While much past research has been devoted to the study of these region-wide erosional trends (Buckler and Winters, 1983; Guy Jr., 1999; Vallejo and Degroot, 1988; Amin and Davidson-Arnott, 1995; Davidson-Arnott and Ollerhead, 1995; Carter et al., 1981,1986; Dawson and Evans, 2001; Foyle and Naber, 2012; BaMasoud and Byrne, 2012), little work has been devoted to developing a better understanding of the changes in sediment routing along the coast and what sedimentary records created by littoral sediment trapping against hard structures can reveal about sediment supply regimes (e.g. provenance, climatic forcing, etc.). Morang et al. (2011) evaluated sources of sediment input into Lake Erie's southern margin and detailed the fragmentation of the coastal supply engine (i.e. littoral drift) by large harbor jetties that disrupt littoral transport. This fragmentation offers a unique opportunity to compare littoral cells sedimentologically and geomorphologically.

Of all the hard structures emplaced along the U.S. Lake Erie coastline, those designed for protecting harbor mouths are by far the largest and associated with the highest degree of shoreline change (Morang et al., 2011; Mattheus, 2014). Rukavina and Zeman (1987) found that harbor structures are responsible for ~ 40% of sediment accumulation of the north-central Lake Erie shore; however, their south-central analogs remain largely understudied, despite their inferred importance in governing margin-wide erosional trends by enhancing down-drift sediment starvation (Morang et al., 2011). BaMasoud and Byrne (2012) discuss how littoral cell interruption can significantly impact the shoreline with their study on the eastern shore of Point Pelee National Park in Ontario, Canada, where up to 200 m of recession occurred in just four years following structure installment in 1973. These shore-perpendicular to shore-oblique harbor-protecting structures, which extend into Lake Erie by up to 2 km, were constructed as harbor towns evolved for the safe passage of freighters into and out of the harbor. The influence of these extensive structures on coastal sediment routing has been two-fold: 1) low-energy conditions within the confines of breakwaters and jetties have allowed harbor basins to sequester sediment originally bound for the littoral zone; these basins must therefore be routinely dredged to maintain adequate depths for harbor vessels. Most of the dredged materials, which are generally silts and clays, are subsequently placed offshore into confined disposal facilities (CDFs), thus removed from the littoral system; and 2) the south-central littoral system, which transports from W to E (Pincus, 1953; Beletsky et al., 1999; Hubertz et al., 1991; Rao and Schwab, 2007) is obstructed by these protruding hard structures, creating depositional sinks along their western sides (Morang et al., 2011; Mattheus, 2014). The large amount of accommodation space created at the shoreline along the up-drift side of these large harbor jetties has provided depositional settings for evaluating sand accumulations over decadal timescales, referred to as fillet beaches (Rukavina and Zeman, 1987) or headland beaches and harbor headlands in the present study.

Mattheus (2014) attempts to explain differences in rates of sand accumulation at two of Ohio's harbor headlands (at Fairport and Ashtabula harbors), assessed from shoreline positions and bathymetry elucidated from historic nautical charts, as a function of sediment input from bluff environments and transport along the shore to the depositional sinks. As coarse clastic materials are generally lacking in the nearshore environment, which is largely characterized by outcropping Paleozoic rock strata (Figure 1; Fuller, 1996), the coastal system is vulnerable to changes in sediment input from eroding bluffs, representing the primary sediment source (Morang et al., 2011).

While Mattheus (2014) investigates two harbor headlands and evaluates their changes with respect to lake levels and winter-ice covers, which are both shown to differentially influence rates of bluff erosion over time (Dawson and Evans, 2001; Buckler and Winters, 1983; Amin and Davidson-Arnott, 1995; Davidson-Arnott and Ollerhead, 1995; Carter and Guy, Jr., 1988; Foyle and Naber, 2011; BaMasoud and Byrne, 2012; Vallejo and Degroot, 1988), a more detailed reconstruction of headland geomorphologies is needed to more clearly assess complex linkages between physical forcing parameters and coastal change. This project expands upon findings by Mattheus (2014), focusing on Ohio's three largest harbor headlands and evaluating morphologic change at a higher temporal resolution. The purpose of additional investigation here is three-fold: 1) The inclusion of an additional harbor to those studied by Mattheus (2014) provides complete spatial data coverage along Ohio's portion of the central Lake Erie shoreline (Figure 1), where hydrologic conditions (i.e. wave exposure, longshore-current directions, lake levels) are uniform or highly comparable and headland evolution can be evaluated as a function of sediment supply; as this portion of the coast is segmented by the occurrence of these large structures, sedimentologic differences (e.g. grain-size distributions) at each headland may provide information on the dynamics within each respective littoral cell (bound by the breakwaters); 2) breakwater orientations differ among headlands, providing an opportunity to investigate how the design of the hard structures influences the nature of headland growth at each site; and 3) The inclusion of aerial photographs, which exist for the study areas at much higher temporal resolutions than the nautical charts used by Mattheus (2014), provides more detailed information on shoreline change to be used in statistical evaluations against lake-level and ice-cover forcing. The following sections describe the geologic framework of the study area and detail its anthropogenic and hydrologic influences.

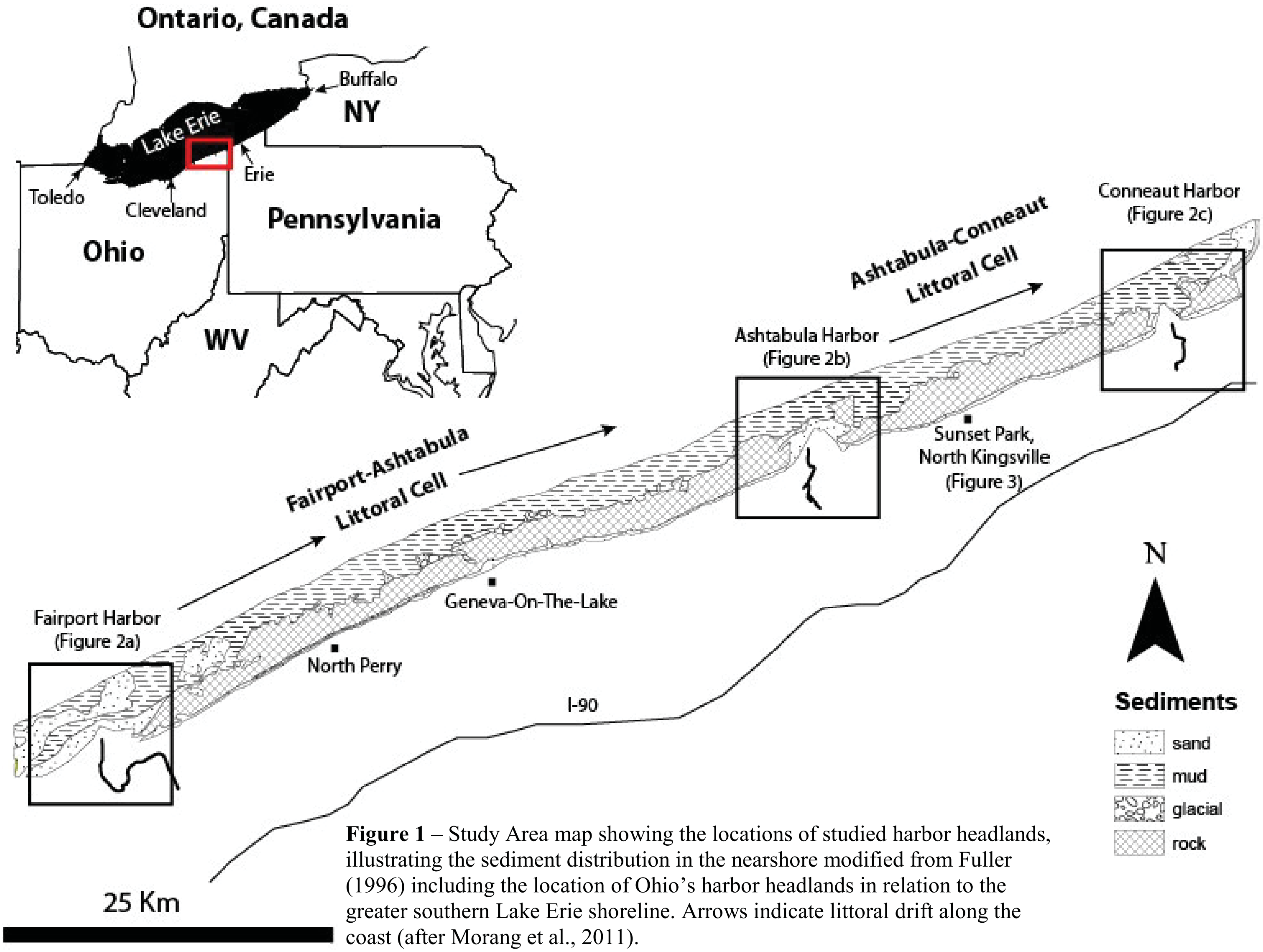


Figure 1 – Study Area map showing the locations of studied harbor headlands, illustrating the sediment distribution in the nearshore modified from Fuller (1996) including the location of Ohio's harbor headlands in relation to the greater southern Lake Erie shoreline. Arrows indicate littoral drift along the coast (after Morang et al., 2011).

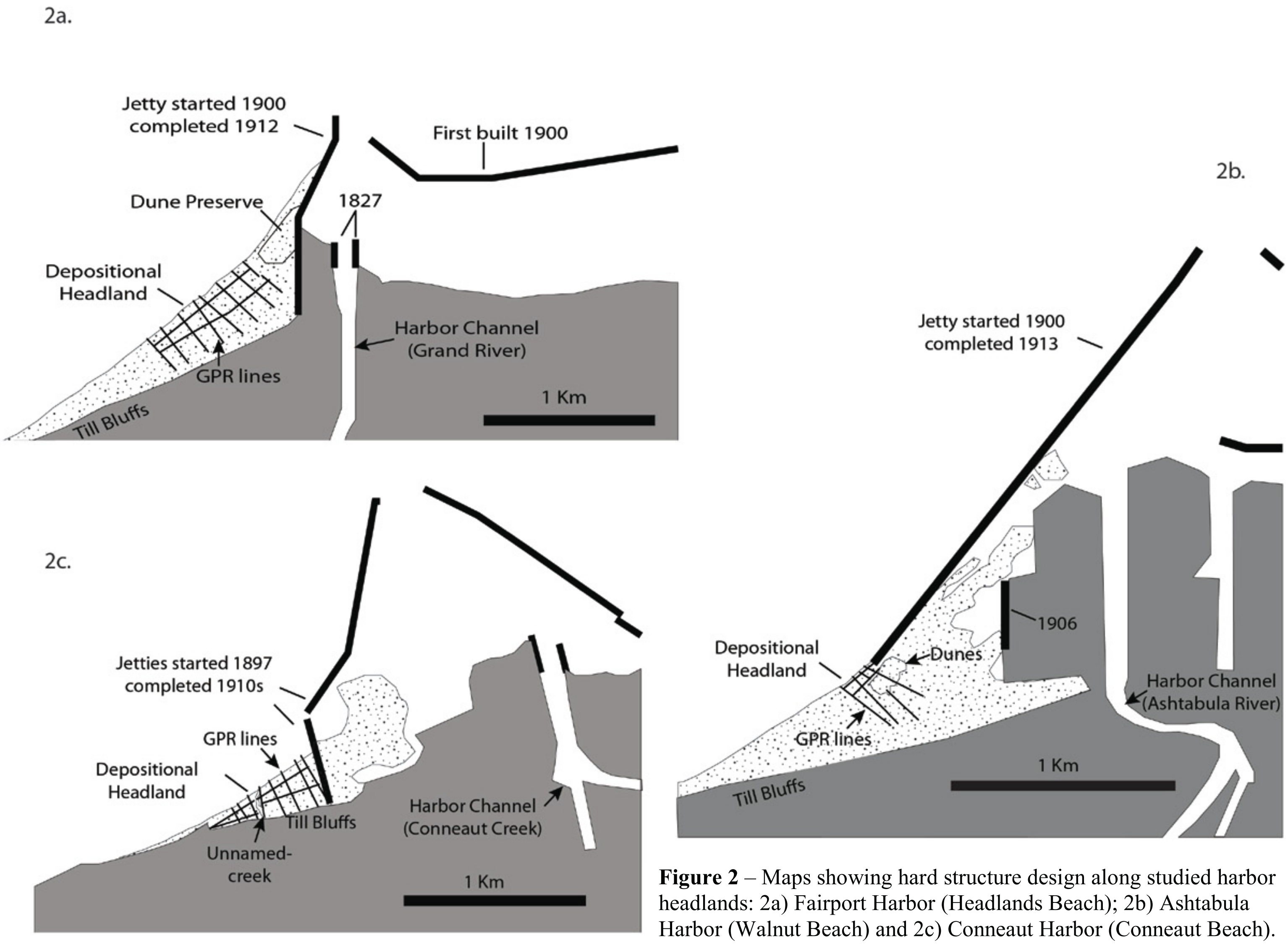


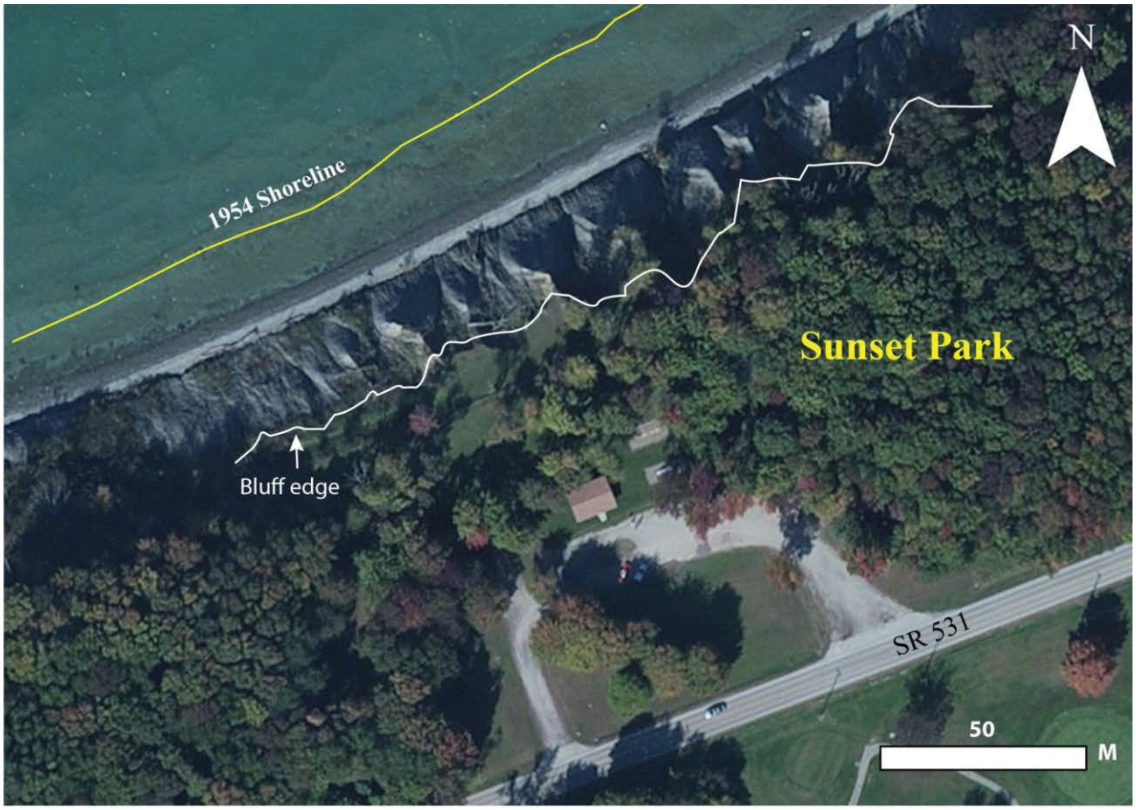
Figure 2 – Maps showing hard structure design along studied harbor headlands: 2a) Fairport Harbor (Headlands Beach); 2b) Ashtabula Harbor (Walnut Beach) and 2c) Conneaut Harbor (Conneaut Beach).

Study Area

The studied harbor headlands of Lake County (i.e. Headlands Beach) and Ashtabula County (i.e. Walnut Beach and Conneaut Beach) are located along a ~65 km stretch of the south-central Lake Erie shoreline (Figure 1). All sites share the following characteristics: 1) location along the sediment-starved south-central basin coastline (Fuller, 1996), thus reliant on bluff erosion and littoral transport to facilitate sedimentation and headland growth (Figure 1; Morang et al., 2011); 2) similar influence of lake fetch and headland orientation on hydrologic conditions (e.g. wave and current exposures; Kang et al., 1982; Figure 1); and 3) documented histories of net progradation over the past century (Mattheus, 2014). The close proximity of the sites along the central basin is a particularly important factor that helps normalize sites by wind fetch across the lake; this, in combination with the orientation of the headlands along the southwest-to-northeast trending coastline, implies that prevailing W-E coastal currents (Pincus, 1953; Beletsky et al., 1999; Hubertz et al., 1991; Rao and Schwab, 2007) and wave refraction patterns during high-energy storms impact these analogous settings similarly. Sites are hence differentiated solely based on the nature of their sourcing bluffs (to their west, respectively; Figure 1) and individual hard structure designs (Figure 2). Each headland has exhibited a relatively long history of progradation (Mattheus, 2014), which is essential for developing a conceptual understanding of sedimentary processes and evolution as a function of physical forcings impacting bluffs and influencing the sediment-routing engine to the headlands. Given the similarities between sites and equal degrees of exposure to lake-level variations, winter-ice covers, and storm conditions (with associated surge levels, waves, and strong coastal currents), geomorphic changes at the sites can be evaluated based on sedimentologic and anthropogenic differences.

Geologic Setting

The geology of the coastal region extending from the Grand River to the Ohio-Pennsylvania state line, which spans the entire coastal area of interest in this study (Figure 1), is dominated by Devonian-aged sedimentary bedrock (e.g. shale), which extends into the nearshore to depths between 10-15 m (Holcombe et al., 2003; Fuller, 1996). Aside from sporadic, relict lag deposits of sand and gravel, the nearshore system contains little coarse clastic sediment, emphasizing the importance of bluff erosion as a mechanism for supplying the littoral system along this heavily sediment-deprived coastal margin (Figure 1; Fuller, 1996; Morang et al., 2011). The southern Lake Erie shore is also heavily shaped by the region's glacial history and is bounded by till or till-mantled bluffs and outwash plains (Morang et al. 2011). Bedrock bluffs are generally comprised of friable shale that is draped by till sediments; these easily erodible materials, which comprise bluffs ranging from 3 to 20 m in height, are especially vulnerable to erosion as beaches fronting them are largely absent and waves are able to attack bluffs directly (Carter et al. 1981; Dawson and Evans, 2001). Evidence of high bluff erosion rates along this margin is hence observed; for example, bluffs at Sunset Park of North Kingsville, located between Ashtabula and Conneaut, have recessed ~ 30 m between 1954 and 2011 (Figure 3). Upon entering the nearshore system these eroded materials favor an eastward movement with littoral drift until encountering the flow obstruction presented by the Conneaut Harbor jetty (Figure 1). The evidence of this conceptual coastal sediment route lies in the depositional headland that has formed here since jetty construction (i.e. Conneaut headland).



A: View to the West

B: View to the East

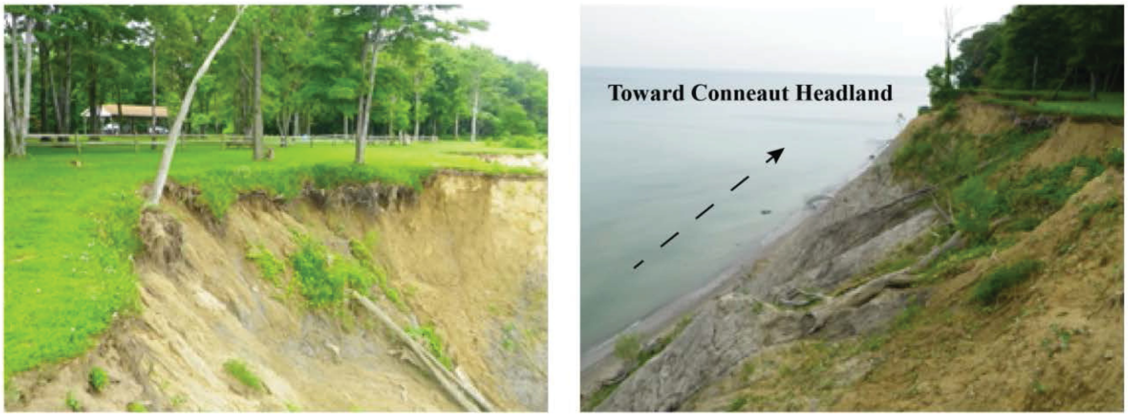


Figure 3 – Map showing the slumping bluffs of Sunset Park, North Kingsville: a) view to the west and b) view to the east. The 1954 shoreline position is based on the 1954 beach.

Hydrodynamics of the Littoral Zone

A conveyor-belt model best explains the nature of the littoral engine along each cell within the heavily compartmentalized south-central Lake Erie coast (Figure 1): 1) bluff erosion introduces a variety of sediments into the nearshore; 2) wave and current action within nearshore regions separates out materials based on grain size; 3) coarse clastics (i.e. sand and gravel) remain close to shore while fines are dispersed, predominantly into deeper water offshore; and 4) littoral drift routes coarse sediments along shore in an eastward direction until hitting a massive obstruction (i.e. a harbor headland). Given this conceptualization of the coastal sediment dynamics of the study area based on our understanding of historic bluff-erosion trends and historic shoreline changes (Guy, Jr., 1999; Foyle and Naber, 2011), patterns of littoral drift (Pincus, 1953; Morang et al. 2011), and headland growth (Mattheus, 2014), a detailed characterization of the headlands is needed to help better understand the linkages and degrees of sediment connectivity across this coastal zone. A description of each studied headland from W to E and its associated hard structures follows (Figure 2): 1) Fairport Harbor (Headlands Beach), 2) Ashtabula Harbor (Walnut Beach) and 3) Conneaut Harbor (Conneaut Beach).

Headlands Beach

The Grand River enters Lake Erie at Fairport Harbor, where the river mouth is modified with over 3.5 km of protective structures (Figure 2a). Construction of two parallel piers at the river mouth first began in 1827; located to the E and W of the harbor channel, these structures were originally constructed in 1900 and finished in the 1910s while the ~1.5 km-long shore-oblique harbor jetty to the W of the harbor was finished by

1912 (Mattheus, 2014). The jetty is continuous, but segmented into sections of slightly different orientation (Figure 2a). Sediments are sequestered in the harbor channel as this is the new baselevel for the Grand River. These sediments, which otherwise would have been bound for the nearshore, are removed and placed in confined disposal facilities (CDFs); approximately 115,000 m^3 of material has to be subsequently dredged every 1-2 years from the harbor channel (Morang et al., 2011; US Army Corps of Engineers, 2014).

Part of Headlands Beach State Park, Headlands Beach, Ohio's longest strand (at ~1.8 km in length), formed updrift of the western jetty (Mattheus, 2014; Figure 2a). The sediment-sourcing area to this beach encompasses ~50 km of the southern Lake Erie shore, extending from just west of Cleveland, where the net littoral direction changes to E-W, to the Fairport Headland depositional headland (Morang et al., 2011; Figure 1). Modern beach width (measured from the present shoreline to a parking lot now occupying the bluff-fronting portion of the depositional headland) ranges from ~0.10 km to ~0.215 km and decreases in a westward direction from the hard structure (i.e. is wedge-shaped). This exceptionally expansive beach (by Lake Erie standards) coupled with prevailing onshore winds and relatively high supply of sandy sediments along a substantial source region (Figure 1; in comparison to Walnut Beach and Conneaut Beach) has allowed for dune formation via aeolian transport. While much of the modern strand is groomed during the summers for tourism, a vegetated dune field under state protection situated along the breakwater in the eastern part of the headland is most reflective of the recent sediment sequestration and headland growth.

Walnut Beach

Located to the east of Fairport Harbor, Walnut Beach is supplied by ~44 km of the south-central bluff shoreline, the region to the west of Fairport Harbor (Fairport-Ashtabula littoral cell, Figure 1). Shoreline sediments here are noticeably coarser (predominantly gravel-sized) compared to those along the sandy Headlands Beach shoreline. Measured from the present shoreline to the dune ridge, the average beach width is ~0.05 km; the headland's sedimentary wedge thins to the west (Figure 2c). The Ashtabula River enters Lake Erie at Ashtabula Harbor (Figure 2c). More than 4 km of protective structures here include a 2.2 km western jetty, two parallel piers at river mouth (constructed in 1826), inner jetties, and breakwaters. Jetties and breakwaters were first built in 1897 and modified thereafter. Walnut Beach (~0.22 km in length) has formed updrift of the western jetty, which is strongly shore-oblique, since the 1910s (Figure 2b; Mattheus, 2014). Approximately 76,000 m^3 of material must be dredged from the river and harbor every 2-3 years on account of harbor-protecting structures, representing a loss to the nearshore system (Morang et al. 2011; US Army Corps of Engineers 2014).

Conneaut Beach

Conneaut Beach is situated ~ 20 km to the east of Walnut Beach, sourced by the Ashtabula-Conneaut littoral cell, (Figure 1). Conneaut Creek enters the lake at Conneaut Harbor, where over 3.5 km of harbor-protecting structures exist. Two parallel piers at the river mouth were constructed by 1829 while the first jetties were built in 1897 with many modifications following (Morang et al. 2011; US Army Corps of Engineers, 2013; Figure 2c). An unnamed creek channel dissects Conneaut Beach (Figure 2c). Approximately

92,000 m^3 must be dredged from the river and harbor every 2-3 years (Morang et al. 2011; US Army Corps of Engineers, 2013). Conneaut Beach (~ 0.64 km in length) has prograded against the western jetty, which totals ~2 km in length; similar to Fairport Harbor's western jetty, it is segmented into sections of different orientation (Figure 2c). Conneaut Beach has prograded lakeward from coastal bluffs and thins in a westerly direction; the widest section (~0.33 km) occurs proximal to the jetty, measured from the present shoreline to the bluff (Figure 2c).

Spatial and Temporal Scales for Studying Coastal Change

The evolution of Lake Erie's coastal morphology, as pertaining to harbor headlands, can be explained in varying spatial and temporal terms. The study design must follow certain guidelines set by the spatiotemporal parameters of data availability and known coastal process-landform interactions. Spatial scales of interest to the coastal scientist can range from micro (changes at a specific point), to meso (changes of a beach profile) and macro (changes along entire coastlines); temporal scales range from micro (individual wave events), to meso (individual storm events) and macro (beach evolution at yearly to decadal and century to millennia scales; Reeve et al. 2004). Evaluating coastal change against highly complex and convoluted forcing parameters thus presents many challenges and care must therefore be taken when dealing with multiple independent variables that change spatiotemporally. This is especially true when integrating datasets and interpreting data trends as certain variables should only correlate at specific scales; furthermore, coarser scales could fail to resolve effects or may lead to incorrect correlations between variables. While Mattheus (2014) investigates the morphologic changes at Headlands Beach and Walnut Beach at a near-decadal timescale, this study is geared at resolving coastal changes at a higher temporal resolution and includes an additional headland (Conneaut; Figure 1) to better evaluate the impacts of fluctuating lake levels and winter-ice covers on depositional headland evolution. The following sections outline the forcing parameters (i.e. physical variables) of interest to this study in elucidating the controls on coastal change and the nature of the sediment-routing engine.

Physical Variables

Lake Levels

The influence of lake levels on coastal change is generally considered two-fold: 1) Rates of bluff erosion are linked to lake levels – higher lake levels supply more bluff-derived sediments; while, low lake levels limit sediment supply; and 2) lake-level changes lead to the creation or reduction of accommodation space, or the space available for sediment accumulation (Jackson and Cooper, 2009), at the beach shoreline (e.g. increased lake level, increased accommodation space). Littoral material occupies this available space in the nearshore and the loss of that space by lake-level lowering, for example, has implications for nearshore and shoreline evolution, such as reduced rates of beach building. Higher lake levels increase accommodation space and shift the shoreline landward while lower lake levels decrease accommodation space and force shoreline regression. The evolution of coastal environments along other Great Lakes has been evaluated as a function of these shifts in accommodation-space distribution (Lichter, 1995; Thompson, 1992; Thompson and Baedke, 1995). Mean Lake Erie water levels have fluctuated over time (Hamblin, 1987; Lenters, 2001; Morang et al., 2011). Long term (i.e. past century) trends in annual water level means between record highs and lows shows a difference of ~1.4 m while a superimposed seasonal signature shows an annual variation of ~0.23 m (Hamblin, 1987). Monthly mean water levels tend to be highest in July and lowest in January. These fluctuations can be explained by the lake's water budget largely controlled through the inflows (the upper lakes, via the Detroit River) and outflows (the Welland Canal and the Niagara River; Quinn, 2002; Hamblin, 1987; Lenters, 2001). The Great Lakes have negligible astronomical tides, however, surface seiches (i.e. wind- and pressure-controlled oscillations of the lake surface) are common during strong and lasting wind events. Areas such as Buffalo, NY, have, for example, reported fluctuations ~3.2 m above and ~1.4 m below LWD in association with wind-driven seiche events (U.S. Department of Commerce, 2009).

Winter-ice Cover

The shallowest of the Great Lakes, Lake Erie is subjected to ice formation in most winters; coastal ice generally begins to form in December and recedes in March along the Lake Erie shore (Assel, 1990; 2003; 2004). Ice cover across the Great Lakes during winter time is a complex variable that can be evaluated in different ways; total ice cover and ice-cover duration are yearly metrics that characterize lake conditions at the largest scale and offer data on year-to-year variances (Assel, 2003). However, these metrics may have varying implications of coastal evolution as shore ice and its duration (for which total ice-cover duration serves as a proxy in lieu of historical data on just shore ice) directly impact shoreline processes while the extent of ice cover has implications for open-water fetch conditions and winter wave/current generation (Barnes et al. 1993; Wang et al., 2012). It is suggested that nearshore-ice cover armors the shore preventing wave erosion (BaMasoud and Byrne, 2012; Mattheus, 2014). Other work suggests that shoreline ice cover redirects wave erosion to the shoreface, where sand losses are potentially felt by the shoreline later in time (Barnes et al., 1993). Regardless, ice as a direct erosional or depositional mechanism is often overlooked along the Great Lakes, despite high wind and wave energy coinciding with winter periods, which providing the energy for the ice to influence nearshore and shoreline sedimentation patterns (Barnes et al. 1993). Coarse clastic materials (exceeding gravel in size) are often found littering the beach following the winter months; this is due to pressure ridges migrating landward and excavating the nearshore bottom, producing sediment-laden ice mounds that cover the beach environment during the winter. When the ice retreats, these sediments are deposited across the beaches, rafted lakeward, or reoccupy the nearshore system. The influences of winter ice on coastal processes should be of high importance given a lack of other mechanisms by which large quantities of coarse clastic material can be deposited at the shoreline.

Study Objectives

While previous studies have focused largely on quantifying rates of till-bluff erosion along the predominantly erosive coasts of Lake Erie and Lake Michigan (Dawson and Evans, 2001; BaMasoud and Byrne 2012; Buckler and Winters 1983; Amin and Davidson-Arnott 1995), few address the deposition of sediments against harbor jetties and associated geomorphic changes (Mattheus, 2014); the latter represents an important puzzle piece for a better understanding of the littoral system and overall Lake Erie coastal evolution. Assessing a century-long depositional record at these headlands may not only provide insight into the controls (i.e. fluctuating lake levels, ice cover conditions and structure design) that drive the evolution of these headland beaches, but also reveal information on bluff erosion trends along a sediment-starved coast. The impact of these environmental variables is hypothesized to be independent and their influence can be determined spatially and temporally. The following sections detail the methods involved in assessing and evaluating these morphologic changes at the surface and in the subsurface.

Data and Methods

GIS-based Shoreline Mapping

GIS analyses are popular tools utilized by coastal geomorphologists to evaluate coastal change and have been implemented in several studies addressing the U.S. Lake Erie shoreline. Foyle and Naber (2012), for example, employed GIS tools to observe the spatial variability of coastal bluff retreat along the Pennsylvania coast of Lake Erie. Just as their analogues along the coastal section of Ohio, bluffs here are comprised of or capped by glacial till (i.e. sand and gravel) and are hence highly erosive, supplying the nearshore with clastic materials. Foyle and Naber (2012) utilize this erosion susceptibility to study the accuracy of assessing shoreline changes using different methodologies. Coastal bluff retreat has traditionally been assessed using historical aerial photos (Guy, Jr., 1999); this method introduces orthorectification and digitizing errors that tend to compromise the accuracy of determining shoreline positions, particularly when defining the crest of a bluff from aerial photos (Foyle and Naber, 2011). The difficulty with recognizing surface features in aerial photographic datasets is not encountered in airborne-derived LiDAR data, which reveals the subtlest morphologies at high resolution and can be employed to evaluate coastal change at the cm-scale; however, such datasets are expensive and available coverage is limited (spatially and temporally). Foyle and Naber (2012) use two LiDAR datasets (from 1998 and 2007) to evaluate bluff retreat and its linkages to subsurface hydrology. Many of their features of interest were not recognizable in aerial photos and USGS quadrangles and the linkage between surface and subsurface hydrology and bluff evolution went unrecognized before GIS analyses of LiDAR data provided the resolution needed. Although LIDAR datasets would provide a high-resolution (cm-scale) look at beach morphology, the limited number of timesteps omits these data types from this analysis. Historic aerial photographs were used as studied headland beaches display little morphologic variance in profile along strike and are flat to gently lakeward-dipping, thus are unaffiliated with distortion and relief displacement errors that generally occur when tall bluff shorelines are evaluated from aerial photographs (Foyle and Naber, 2012).

In order to assess beach changes over time (in terms of shoreline position and/or area), the shoreline must be defined. Farris and List (2007) explain that there is no standard datum when defining shoreline position; however, they statistically show that the choice of datum (i.e. high water, mean sea level, mean higher high water, mean high water, or wet/dry boundary) does not significantly affect results along beach environments if there are no significant changes in lake level or beach profile. This should be especially applicable along Lake Erie’s beaches as documented year-to-year lake level fluctuations only occur within a 1.4 m range (Hamblin, 1987) and seasonal variances occur over a range of 0.23-0.46 m (Hamblin, 1987 and Quinn, 2002). Given the shape of the shoreface, which, given the coarseness of shoreline sediments (e.g. gravel), is relatively steeply lakeward-sloping over short distances (e.g. several m), changes in the position of the break in slope from near-horizontal backshore environment to the sloping foreshore environment should relate primarily to trends in sedimentation or erosion as opposed to patterns of inundation versus exposure. This shoreline definition was employed along Lake Erie by BaMasoud and Byrne (2012), for example, who used GIS to investigate the impact of ice cover on recession rates during the winter of 2005-2006 along the western shore of Point Pelee National Park in Ontario, Canada; this particular sandy coastal environment along the north-central shores of Lake Erie represents the closest analogue to Ohio's depositional harbor headlands as few other places have sequestered much sand to accurately track beach shoreline positions over time. BaMasoud and Byrne (2012) used to the wet/dry boundaries for digitizing relatively small changes (on the order of 0.30-0.50 m) in shoreline position for 2004 and 2006 with high accuracy. Recession and accretion rates measured along shore-perpendicular transects were established at a resolution high enough to allow evaluation of the effects of reduced winter ice-cover conditions, which were found to induce erosion by making the shoreline vulnerable to winter storm attack (BaMasoud and Byrne, 2012). The study of Ohio's headland beaches applies a similar methodology to elucidate affects along strike from shore-perpendicular transects measuring distances between successive shoreline positions. The following section describes the dataset from which shorelines, defined as the wet/dry boundary, were mapped.

Aerial Photograph Dataset

A geochronology was established for each site from high-resolution (<1 m) aerial photographs that were downloaded from the USGS EarthExplorer data webpage, Google Earth, and local Soil and Water Conservation Districts (SWCDs; Table 1). Imagery lacking spatial referencing was georeferenced in ArcGIS Version 10.1 using fixed control points (i.e. road intersections, corners of buildings, hard structures, etc.) common to time-successive images and ArcGIS basemaps. Shorelines were subsequently digitized for each aerial image based on the wet/dry boundary, easily discerned as a pronounced color change typically coincidental or proximal to the backshore-foreshore transition, and transformed into shapefiles for further analysis. Shapefiles were used to quantify beach area changes over time and derive rate of change metrics between successive timesteps. Since volume changes at beaches are very difficult to quantify in absence of highly-detailed topographic information, the areas of beach gain calculated between successive shoreline positions were used as a proxy for sediment-volume changes, an approach previously employed by Farris and List (2007) and Mattheus (2014) based on strong correlations resolved between these two metrics at beaches lacking much structural (i.e. topographic) complexity along strike and across profile. As Mattheus (2014) suggests, the low degree of topographic complexity along Ohio's headland beaches is likely attributed to the absence of tidal forcing and limited beach length. Shore-perpendicular transects provided a framework for measuring relative shoreline changes over time in an effort to access variability in shoreline behavior along strike. The selection of the spacing interval between transects was site specific given different shoreline lengths between headlands and in-field surveying, which provided a sense of resolution needed to resolve slight along-shore variances in shoreline position. At Headlands Beach this interval was very coarse (~200 m) while an internal of ~50 m was selected for Walnut Beach. The transect interval was roughly 150 m for Conneaut Beach as an unnamed channel dissecting the modern beach was taken into consideration and erosional versus accretion trends needed to be evaluated for the shorelines to either side of this feature, which bisects the beach (Figure 2c).

Table 1. Table showing aerial photograph dataset.

	Year	Month	Source
HB	1952	April	USGS
	1960	June	USGS
	1970	April	USGS
	1973	n/a	Lake County GIS
	1977	April	USGS
	1982	April	USGS
	1991	May	USGS
	1994	April	USGS
	2000	September	Google Earth
	2002	n/a	USGS
	2004	August	Google Earth
	2009	June	Google Earth
	2012	April	Google Earth
WB	1952	April	USGS
	1960	June	USGS
	1970	April	USGS
	1973	n/a	USGS
	1974	May	USGS
	1977	April	USGS
	1982	April	USGS
	1989	April	USGS
	1991	April	USGS
	1994	April	Google Earth
	2000	Actober	USGS
	2006	April	Google Earth
	2010	December	Google Earth
	2012	April	Google Earth
CB	1952	April	USGS
	1960	June	USGS
	1969	March	USGS
	1974	May	USGS
	1977	April	USGS
	1982	April	USGS
	1988	June	USGS
	1994	April	USGS
	2000	October	USGS
	2002	May	USGS
	2006	June	Google Earth
	2008	September	USGS
	2009	June	Google Earth
	2012	April	Google Earth

Sedimentologic Data

Shoreline sediments were collected in April of 2014, to evaluate sedimentologic (i.e. grain-size) differences between the three headland sites (Appendix 1). The timing of sampling was specifically chosen to evaluate the impact of a particularly heavy (long duration of ice cover with pressure ridge formation and migration) winter season and ice-shoreline interactions on sediment distribution. Twenty five grab samples were collected just after the shore ice had receded (and before summer reworking by waves and currents) along shore perpendicular transects from backshore to lower foreshore (the water's edge) at Walnut Beach and Conneaut Beach. Headlands beach was omitted from this analysis given a relatively low variance in grain size along the beach; while this beach is entirely sandy, Walnut and Conneaut beaches contain a substantial coarse clastic constituency (gravel), which is most prevalently noticed after winters and the effects of ice on the foreshore and nearshore regions. Only the surficial sediment fraction (~1-2cm depth) was collected and transported to the Sedimentology Lab at Youngstown State University. Samples were dried at ~100° C in a sediment oven to remove all water content; grain-size analysis was then conducted using standard 12" diameter sieves to separate different gravel (63 mm, 31.5 mm, 16 mm, 8 mm, 4 mm and 2mm) and sand (1 mm, 500 µm, 250 µm, 125 µm and 63 µm) fractions (Appendix 1). Attribute data per sample (individual weight percentages, gravel fractions, sand fractions, and mud fractions and associated phi sizes) were tabulated in an Excel spreadsheet from raw data. These datasets were plotted spatially based on XYZ locations for individual samples (Z serving as % gravel and sand, respectively). Sediment-distribution maps were created for each headland-beach site by interpolation in ArcGIS using a Natural Neighbor algorithm.

Ground-penetrating Radar

Ground-penetrating radar (GPR) was collected along multiple dip-oriented (i.e. shore-perpendicular) and strike-oriented transects across each headland beach to provide insight into the architectural framework of the subsurface (Figure 2). GPR data were obtained with a pulseEkkoPro system from Sensors and Software, Inc., utilizing 200 MHz antennae. Comprised of a transmitter, receiver, and two precisely spaced antennae, GPR can produce an image of the subsurface based on subsurface reflection and two-way travel time. This method transmits high-frequency electromagnetic signals into the subsurface whereupon the unit receives energy that is reflected back (Baker and Jol, 2007; Bristow and Jol, 2003); GPR traces record changes in dielectric properties of sediments, which are a function of water saturation, grain size, porosity, and mineralogical changes (Jol, 2008). Different antennae penetrate various depths and reveal subsurface architectures at varying resolutions; the choice in antenna was made as prior coastal studies have utilized 200 MHz antennae to image shallow coastal sedimentary architectures with great success (Jol et al., 1996; Moore et al., 2004). Historic shoreline positions, derived from georeferenced aerial images, serve as a chronologic control along GPR transects while auger holes supplied sedimentologic information to ground-truth GPR interpretations.

Statistical Analyses

SPSS statistical software was used to ascertain whether differences between the studied headlands could be explained by lake-level and ice-cover data between 1973 and 2002. Given the lack of data points at individual sites, beach change metrics were considered collectively. Although temporal scales varied slightly between the sites (i.e. aerial photograph coverage varied between sites), the number of data points and the robustness of the planned statistical tests coped with this variance.

Principal Components Analysis (PCA) was performed on beach change (beach area gained or lost between successive timesteps); this approach yielded weak relationships, suggesting little covariance between the lake-level and ice-cover variables. As such, this method was abandoned for the use of multiple regression analysis as the suggestively most inclusive and appropriate test. Since the multiple regression was significant, individual variables were then regressed against beach change. Accommodation space was considered as a categorical variable (confined by the orientation of the structure or unconfined by the structure) to address how the structures themselves influence beach evolution over the long term (i.e. decades to centuries).

Lake-level Data

Lake levels are a more significant variable compared to wave- and storm-climate: A study conducted along the Ohio shore of Lake Erie found greater erosion rates during a quiescent period (1957-1963) compared to an active period (1968-1973); varying erosion rates were subsequently explained by lake-level differences between 173.7 m and 174.2 m, respectively (Carter et al. 1986). This study thus assumes wave and storm climate to remain relatively consistent.

Monthly lake-level data for the period of shoreline information was acquired from NOAA's Great Lakes Water Level Dashboard and daily ice-cover data from NOAA's Great Lakes Ice Atlas. These lake-level data can be analyzed in several ways, depending on context and other data resolutions and availability; we subsequently have several metrics to work with: 1) yearly averages, 2) months of low lake levels (below a determined datum), and 3) months of high lake levels (above a determined datum). Each of these datasets is a representation of the true lake-level conditions, but may reveal different relationships if evaluated against other environmental metrics (e.g. beach change). An example is presented by the effects of lake level on coastal erosion processes: Higher lake level months represent greater sediment potential to the nearshore and could provide a stronger relationship to beach change, given that bluffs are more susceptible to wave erosion (Vallejo and Degroot, 1988; Amin and Davidson-Arnott., 1995); on the other hand, lower lake level months represent periods of reduced sediment supply (Dawson and Evans, 2001). Sediment-supply potential should therefore be considered on a finer temporal scale than the yearly lake-level curve. As such, lake level conditions were looked at on a monthly scale (i.e. months of low lake level, months of high lake level determined from the 25th percentile above and below the mean of the dataset).

Ice Cover Data

Ice-cover data can also be evaluated across different spatiotemporal scales; the following ice-cover data exists: 1) average annual duration of ice cover, 2) daily percentage of ice cover, and 3) dates of first and last ice. Due to data-availability constraints, temporal resolution of information on ice cover was restricted to monthly data from 1973-2002 for statistical analysis and evaluation against beach change (Assel, 2003). Ice cover is considered a transport mechanism when conditions are favorable for pressure-ridge formation (Barnes et al., 1993); however, there is nothing in the published literature that indicates what exactly these conditions are. Ice cover is also considered a natural buffer, which can limit sediment supply by protecting the bluffs (BaMasoud and Byrne, 2012). Thus, it is necessary to comment on the processes associated with ice cover and ice cover duration is included in a statistical evaluation of beach change over time.

Results

Historic Shoreline Positions

Georeferenced aerial photographs reveal the progradational nature of each headland since the 1950s (Figure 4). Although each headland exhibits overall net progradation, each site exhibits different shoreline behavior, manifested as spatiotemporal variances in rates of erosion and deposition (Figure 5). The following sections detail the morphologic changes to each of the studied headland beaches over the timeframe of study.

Headlands Beach

Headlands Beach has gained ~55, 764.95 m^2 of beach area from1973-2002. Within this timeframe, beach growth of up to 87 m was measured, which translates into a maximum annual growth rate of up to 3 m/year. When this temporal window is expanded to include the 1952 timestep, Headlands Beach has progaded ~156 m at a rate of 3.12 m/year in places, consistent with 1973-2002 measurements. The largest gains are jetty proximal (i.e. to the east or in the direction of littoral drift; Figure 4). This growth has been very dynamic with preferential erosion and accretion zones along strike (Figure 5), which appear to coincide with trends in along-shore cusp migration. A single pronounced beach cusp (i.e. large bulge or protuberance of the beach) is currently situated at transect location T2 (Figure 4; Stewart, Davidson-Arnott, 1988); similar features are seen migrating eastward in aerial photographs over time, explaining spatial trends of erosion and deposition (Figure 5). One of these formerly migrating cusps now occupies the space alongside the harbor jetty (Figure 4). Cusp migration is resolvable on a decadal timescale and suggests a wavelength in excess of 0.5 km; Figure 6 shows a conceptual model of cusp migration.

Walnut Beach

Beach-shoreline evolution at Walnut Beach was very irregular between 1973 and 2000, characterized beach gains and losses with a net beach gain for the period of ~14,856.53 m^2. From 1973-2000 Walnut Beach has prograded on average (i.e. along its entire strike) ~49 m at a rate of ~1.80 m/year; however, 98 m of progradation were measured at a rate of ~1.96 m/year when considering the 1952 timestep. The largest gain (~12333.51 m^2) occurred between 1974-1977; while, subsequent change has been at least one order of magnitude less (Table 2). Walnut Beach's non-linear evolution reveals periods of overall beach loss: 1977-1982, 1989-1991 and 1991-1994; conversely, 1982-1989 and 1994-2000 exhibit substantial net growth on the order of 4885.52 m^2 and 3319.99 m^2, respectively (Table 2). Unlike preferential erosion and accretion zones experienced at Headlands Beach, Walnut Beach either accreted or eroded along the entire beach length (Figures 4 and 5).

Conneaut Beach

Conneaut Beach gained ~54,579.99 m^2 of beach area from 1973 to 2002 (Figure 4). Progradation was measured up to ~99 m between 1973 and 2002 (3.4 m/year; Table 2). When considering the earliest timestep (1952) this gain results in 205 m at a rate of 4.1 m/year. Similar to Headlands Beach the largest gains are measured jetty proximal. Progradation has been fairly uniform compared to the other headlands (i.e. for each timestep net growth was exhibited, Figures 4 and 5).

Table 2. Table showing beach change metrics, lake level and ice duration.

	Time interval	Beach Area Change (m^2)	Low Lake Months	High Lake Months	Ice Days
HB	73-77	46149.99	2.00	18.00	81.00
	77-82	-9958.14	5.00	0.00	164.00
	82-91	10979.25	12.00	25.00	263.00
	91-94	-9392.60	4.00	0.00	94.00
	94-00	10097.27	19.00	11.00	179.00
	00-02	7889.18	28.00	0.00	86.00
WB	74-77	12333.51	2.00	12.00	70.00
	77-82	-1265.19	5.00	0.00	164.00
	82-89	4885.52	8.00	25.00	250.00
	89-91	-1847.64	9.00	0.00	32.00
	91-94	-2569.66	4.00	0.00	94.00
	94-00	3319.99	19.00	11.00	179.00
CB	74-77	12848.11	2.00	12.00	70.00
	77-82	11137.03	5.00	0.00	164.00
	82-88	11384.30	3.00	25.00	231.00
	88-94	2544.00	13.00	0.00	173.00
	94-00	9497.99	19.00	11.00	179.00
	00-02	7168.56	28.00	0.00	86.00

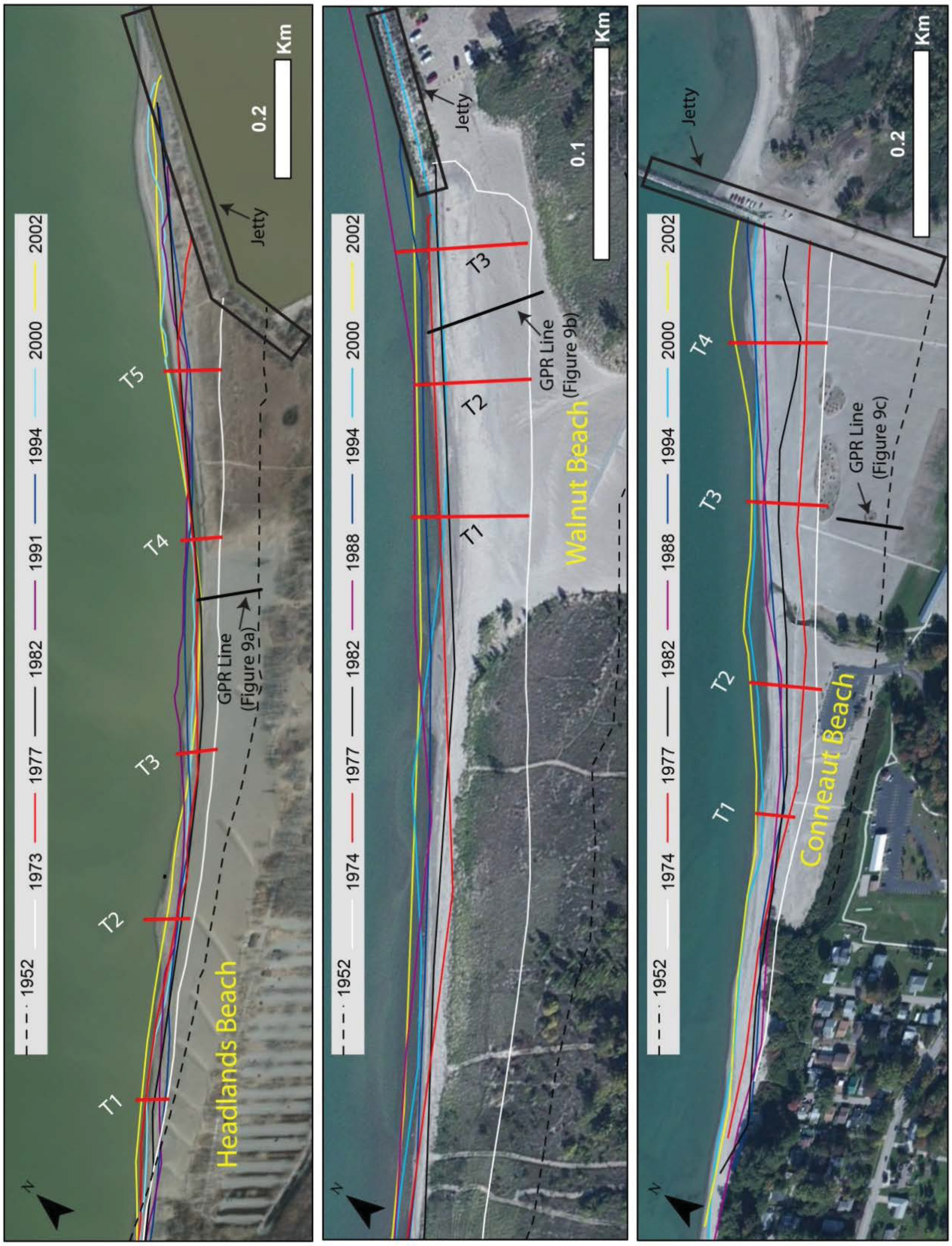


Figure 4. Shoreline reconstructions for Headlands Beach, Walnut Beach and Conneaut Beach.

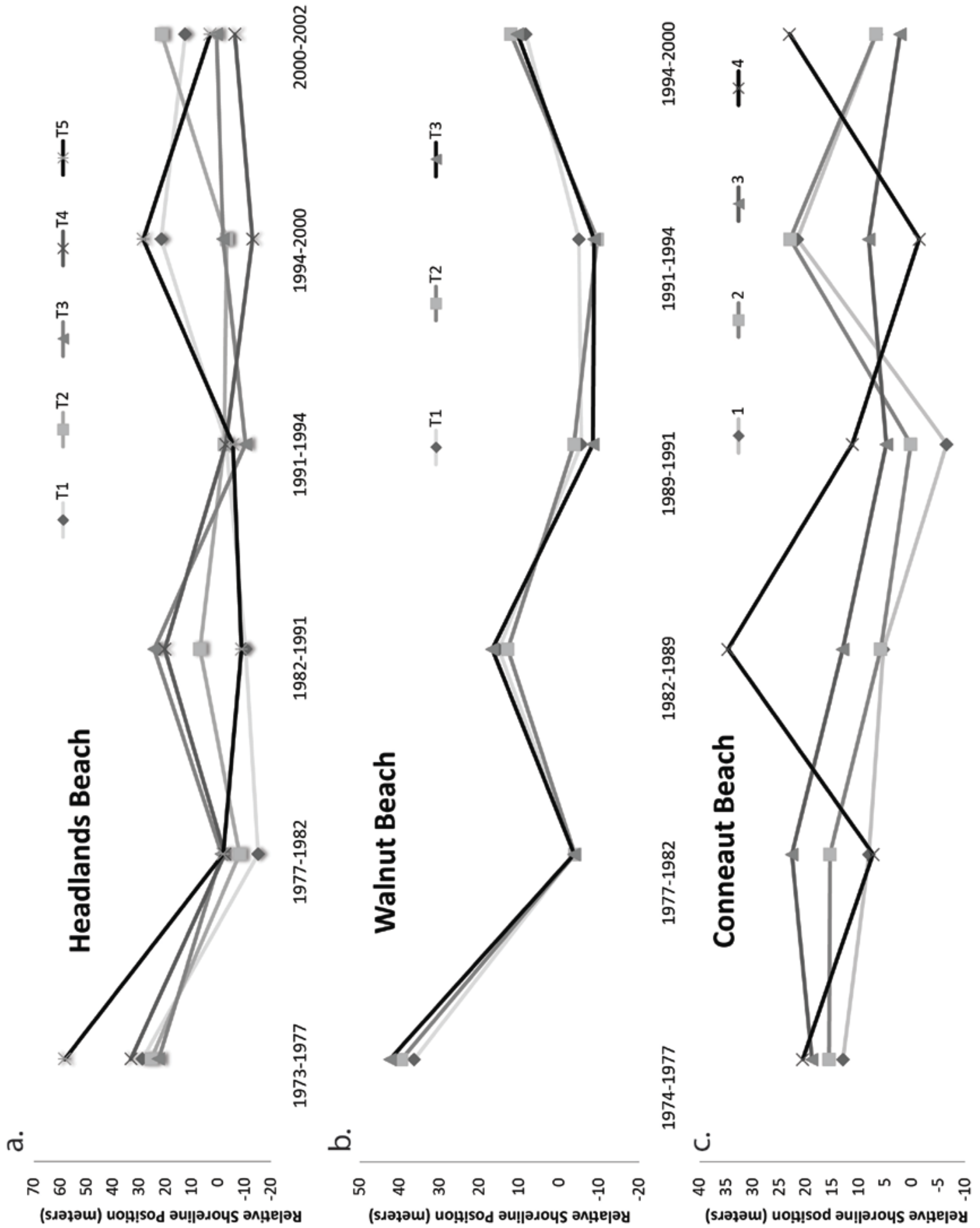


Figure 5. Relative shoreline change illustrating variances of beach profile along strike: a) Headlands Beach, b) Walnut Beach and c) Conneaut Beach.

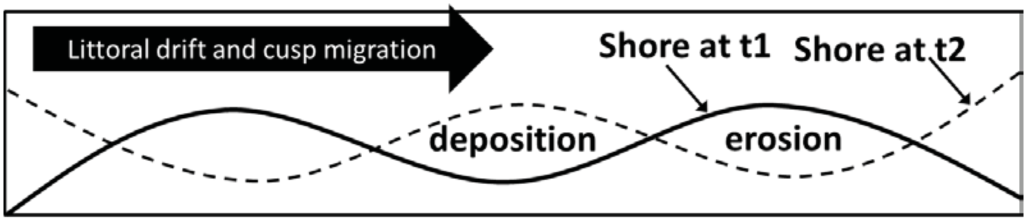


Figure 6. Conceptual model showing cusp formation (pronounced after change in structure orientation in ~1960) controlled by longshore current direction, beach length, and high sediment supply (Stewart and Davidson-Arnott, 1988). Shore erodes at t1 and deposits at t2 as cusps migrate eastward in direction of the prevailing longshore-current direction.

Sedimentologic Data

The sites vary sedimentologically; Headlands Beach is the finest of the three sites in terms of beach-sand composition, largely in the sand-sized class; Walnut Beach and Conneaut Beach, on the other hand, are noticeably coarser, containing abundant sand- and gravel-sized clasts along the shoreline. Sediment distribution maps were generated from samples collected in April of 2014 (following ice retreat) to show these variances and offer insight into the nature of influence by ice processes on sediment distribution (Figure 7). Walnut Beach and Conneaut Beach appear very similar in terms of surface sedimentology as sediment distribution profiles at both sites were similarly skewed toward the coarse end of the size spectrum (Figure 8). At Walnut Beach percent gravel decreased landward as a distinct gravel bar occurred in the swash zone (Figure 7); Conneaut Beach followed this pattern except that the percent gravel increased in the direction of littoral drift.

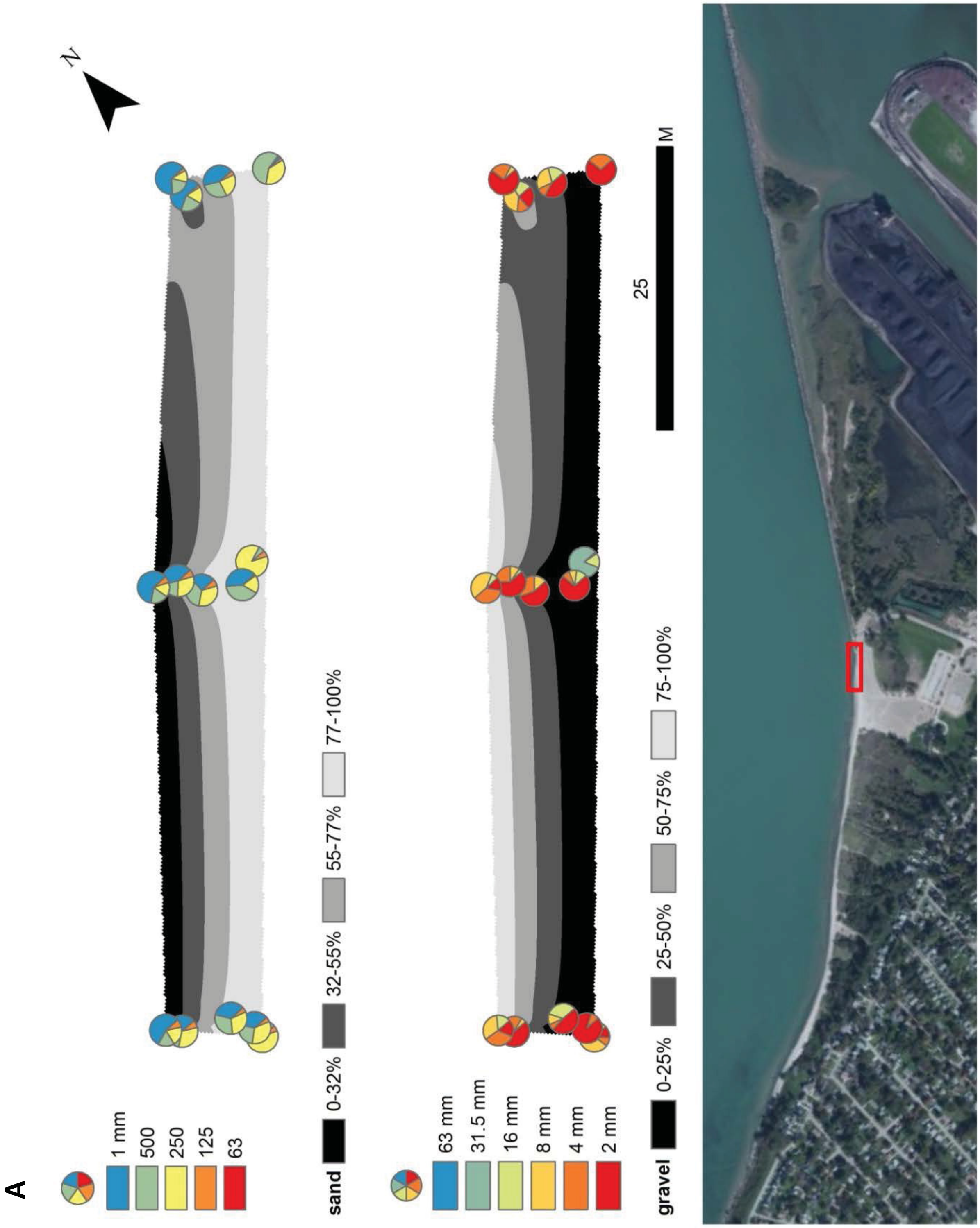
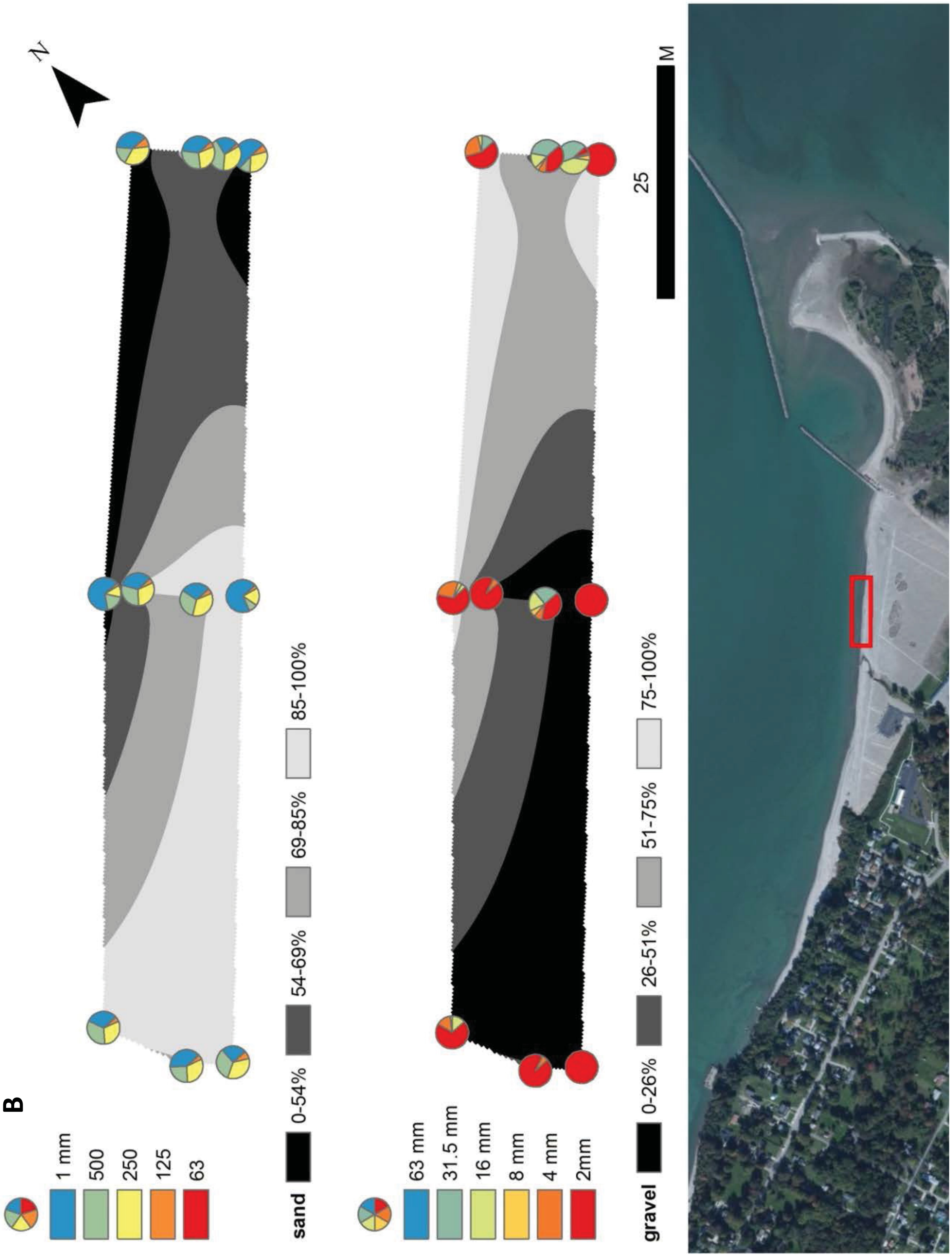
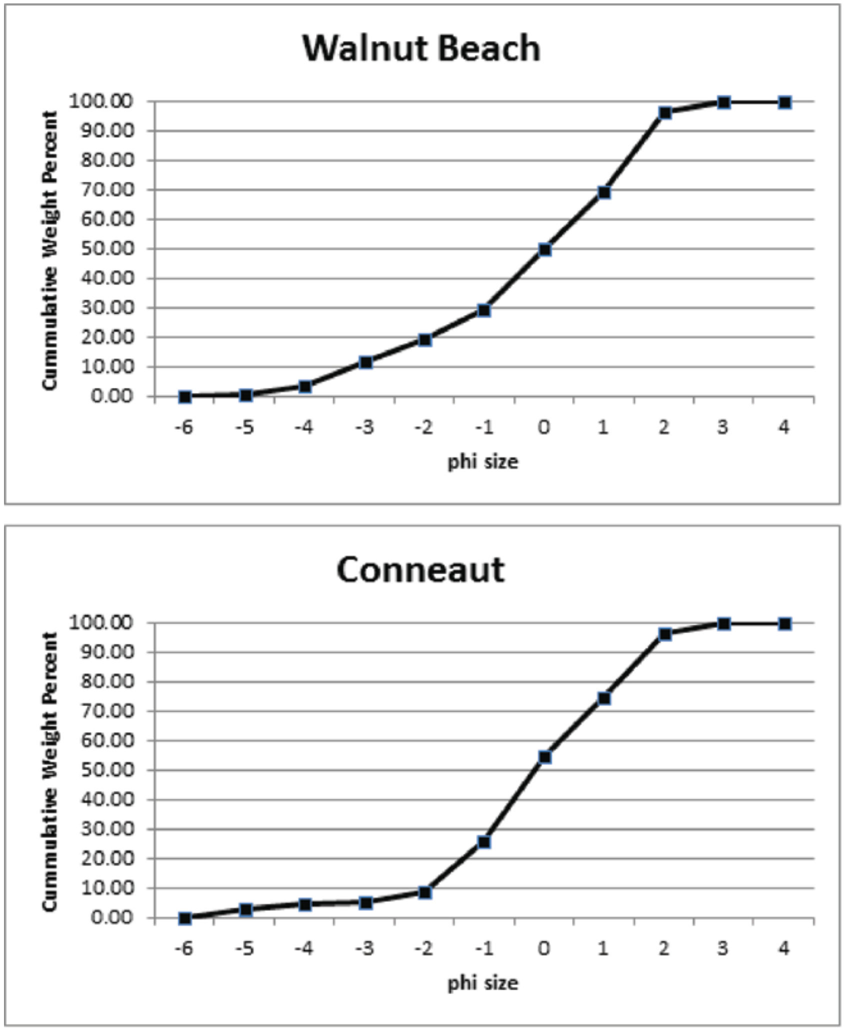
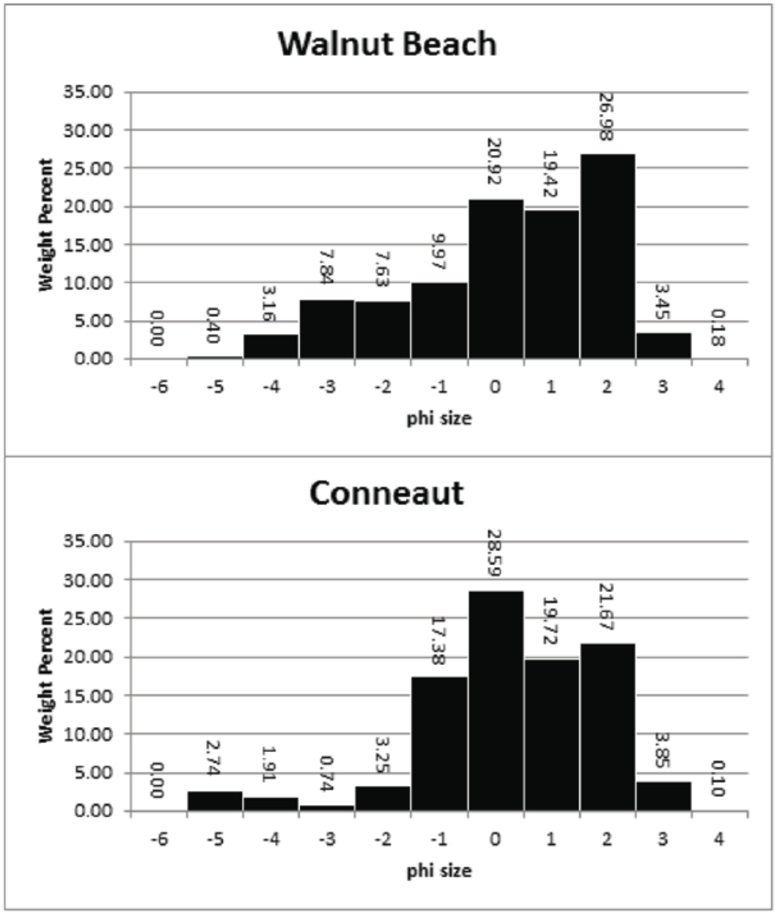


Figure 7. Sediment-Ice interaction maps: a) Walnut Beach and b) Conneaut Beach.


B
1 mm
500
250
125
63
sand
0-54%
54-69%
69-85%
85-100%
63 mm
31.5 mm
16 mm
8 mm
4 mm
2mm
gravel
0-26%
26-51%
51-75%
75-100%
N
25
M





Statistic	Walnut Beach	Conneaut
Graphic Mean	-0.33	0.33
Standard Deviation	1.00	0.75
Graphic Skewness	0.70	0.49

Figure 8 – Grain-size analysis of surface sediments collected after ice retreat.

Subsurface data

Ground-penetrating radar collected along dip-oriented transects (i.e. perpendicular to the beach) reveal the inner architecture of respective strandplains (Figure 9). Only the steeply inclined modern foreshore environments would have necessitated topographic correction as GPR surveys mainly imaged beneath the flat backshore environment, thus avoiding non-vertical radar beam orientations; given the interest of the paleo-shoreline records to this study, which are buried beneath the backshore environments, profiles were not corrected for topography.

Prograding clinoform geometries are recognized in the subsurface across the modern backshore, resolved within the upper ~4.5 m of the sediment column along each transect (Figure 9). These profiles mimic their modern foreshore analogs in size and shape; however, only a few are fully intact as lakeward-dipping clinoform shapes are truncated by horizontal reflectors extending continuously across the upper ~1 m of the subsurface. Foresets (i.e. the swash zone of the shoreface profile) are preferentially preserved while the bottomsets are not resolved due to signal attenuation; the topsets (transition from the foreshore to and including the backshore) are likely acted upon by aeolian processes, as suggested by observations of surficial processes here today and sedimentologic distinctions, assessed from auger samples collected for GPR ground-truthing (Figure 9). The following sections provide site-specific results from the GPR surveys.

Headlands Beach

Prograding clinoforms (i.e. complex layered configurations, which are steepest in the middle, terminate at low angles at the bottom and are nearly horizontal on top; Baker and Jol, 2007) are recognized in the subsurface as lakeward-dipping reflectors. The oldest clinoforms (~1950s, based on aerial shoreline reconstructions; Figure 4) appear to occupy relatively high elevations or shallower depths in the subsurface (with forests identified in the upper 2 m of the profile; Figure 7) while younger clinoforms (formed between 1973 and 2013) occupy lower elevations are found at deeper depths (with foresets identified at 3 m depths; Figure 9). A period of rapid progration was revealed from the shoreline reconstructions, during the 1950s, and is recognized in the subsurface, indicated by a 20 m-wide extent of progradational clinoform geometries with little change in shape or vertical profile position (Figure 9). Some topsets are preserved, truncating earlier deposits of the 1960s; these clinoforms geometries are situated at lower elevations than truncated profiles and are capped by horizontal reflections (Figure 9).

Walnut Beach

The GPR profiles at Walnut Beach reveal prograding clinoform shapes occupying the areas between the 1974 and 1994 shoreline positions (based on aerial photographic reconstructions; Figure 4); a near planar GPR reflection reaching to a maximum of ~1.75 m in depth extends across the subsurface of the modern backshore region (Figure 9).

Conneaut Beach

GPR profiles at Conneaut Beach image subsurface morphologies that are very similar to those imaged beneath the other two headland beaches. Clinoform shapes, suggestive of lakeward shoreline migration vary little in vertical position; these structures are truncated by parallel and horizontal reflections that define the upper ~1 m and extend across the backshore (Figure 9). Shoreline reconstructions based on aerial photographs (Figure 4) suggest rapid progradation here during the 1950s, consistent with prograding clinoform geometries in the backshore's subsurface that vary little in shape and vertical position (Figure 9).

Statistical Analysis

Multiple regression analysis of beach change versus low lake levels, high lake levels and ice-cover duration yielded statistically-significant results (P= .030, R^2 = 0.361). Thus, influence of each variable could be determined individually (Figure 10): Beach change versus high lake-level conditions explains the most variance (R^2= 0.2960). Multiple regression analysis of net beach growth versus lake level and ice cover revealed that high lake levels are more strongly associated with beach growth compared to ice cover, as suggested by R^2 values.

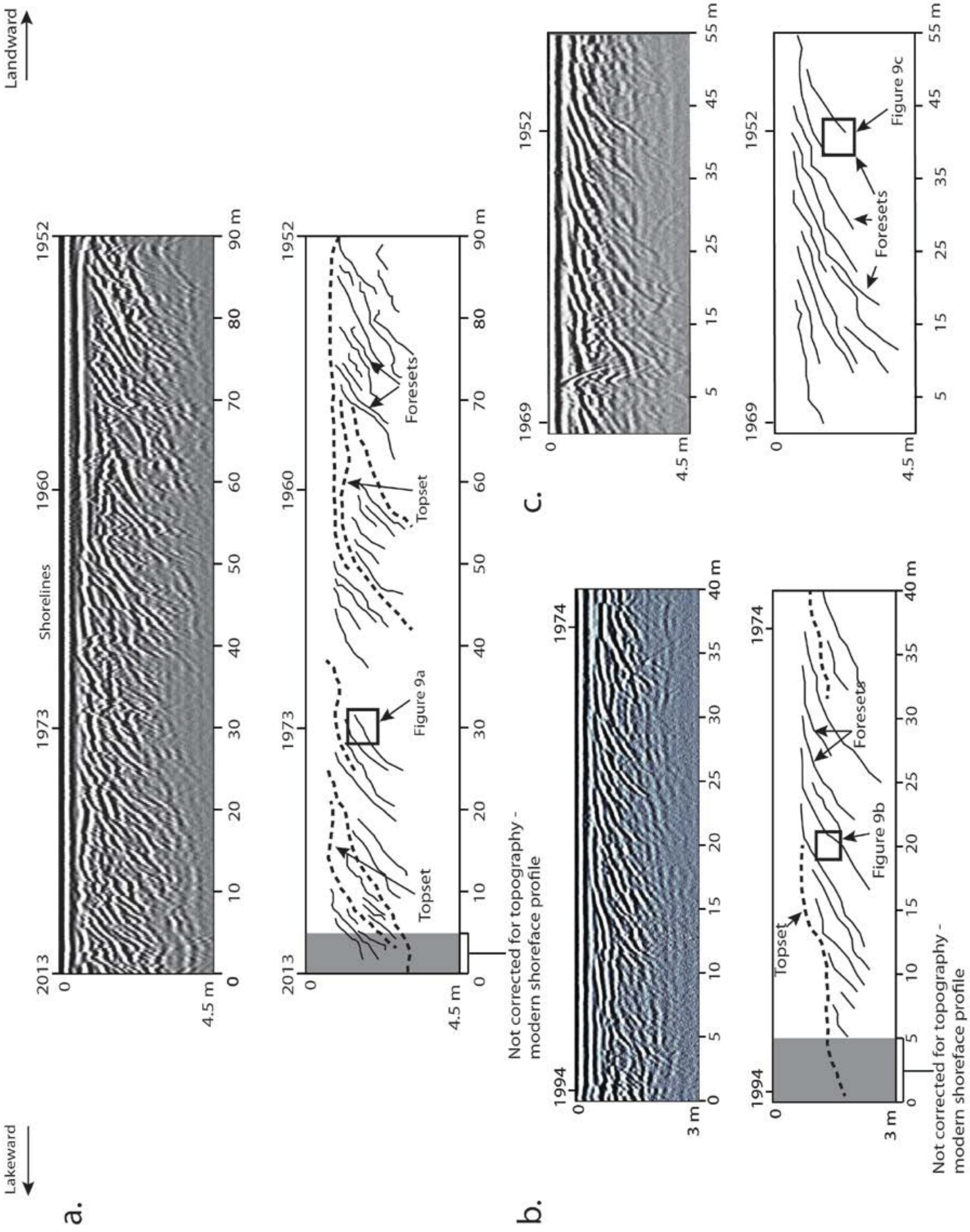
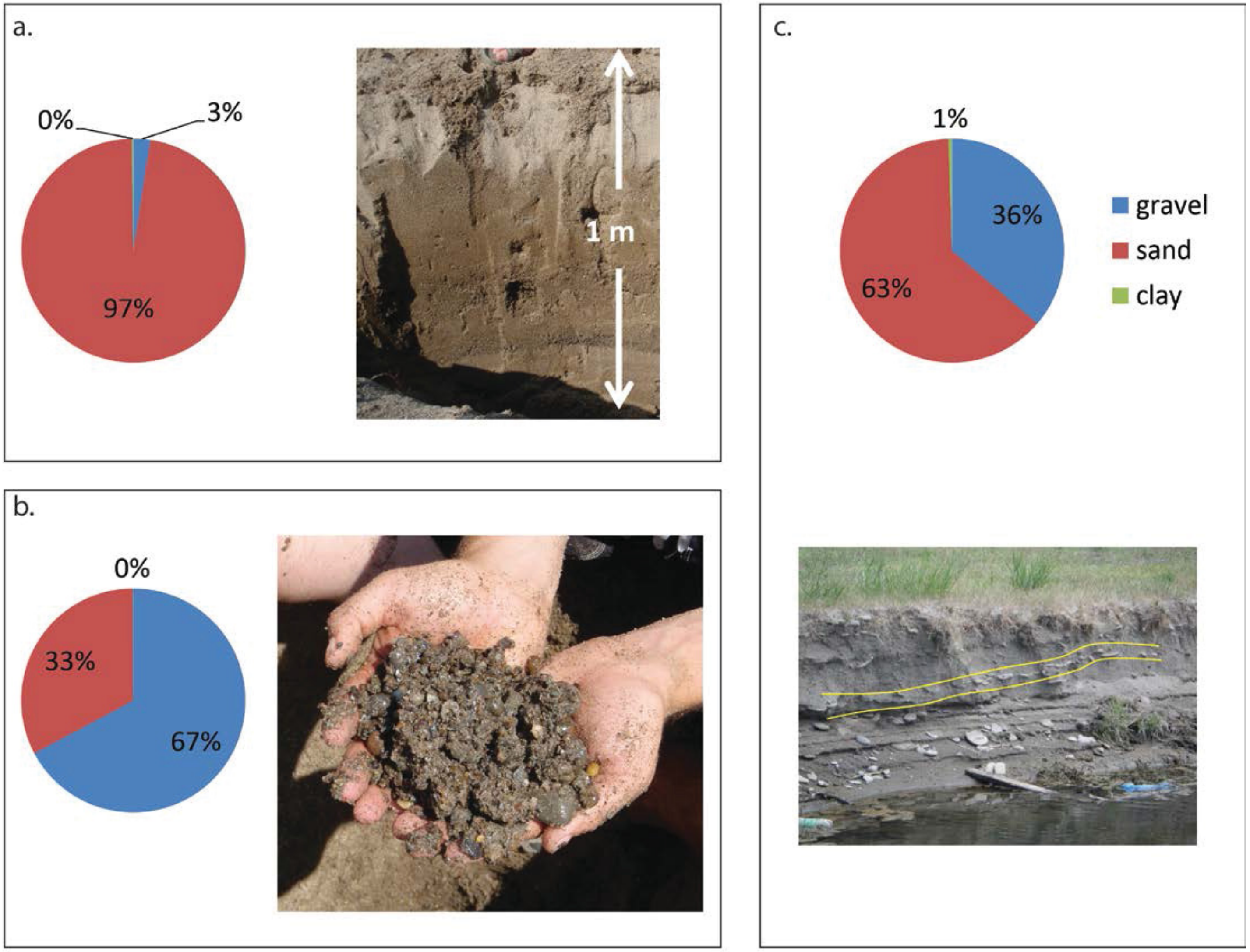


Figure 9. GPR interpretations with description of reflectors: a) Headlands Beach, b) Walnut Beach and c) Conneaut Beach.


a.
0%
3%
97%
1 m
b.
0%
33%
67%
c.
1%
36%
63%
gravel
sand
clay

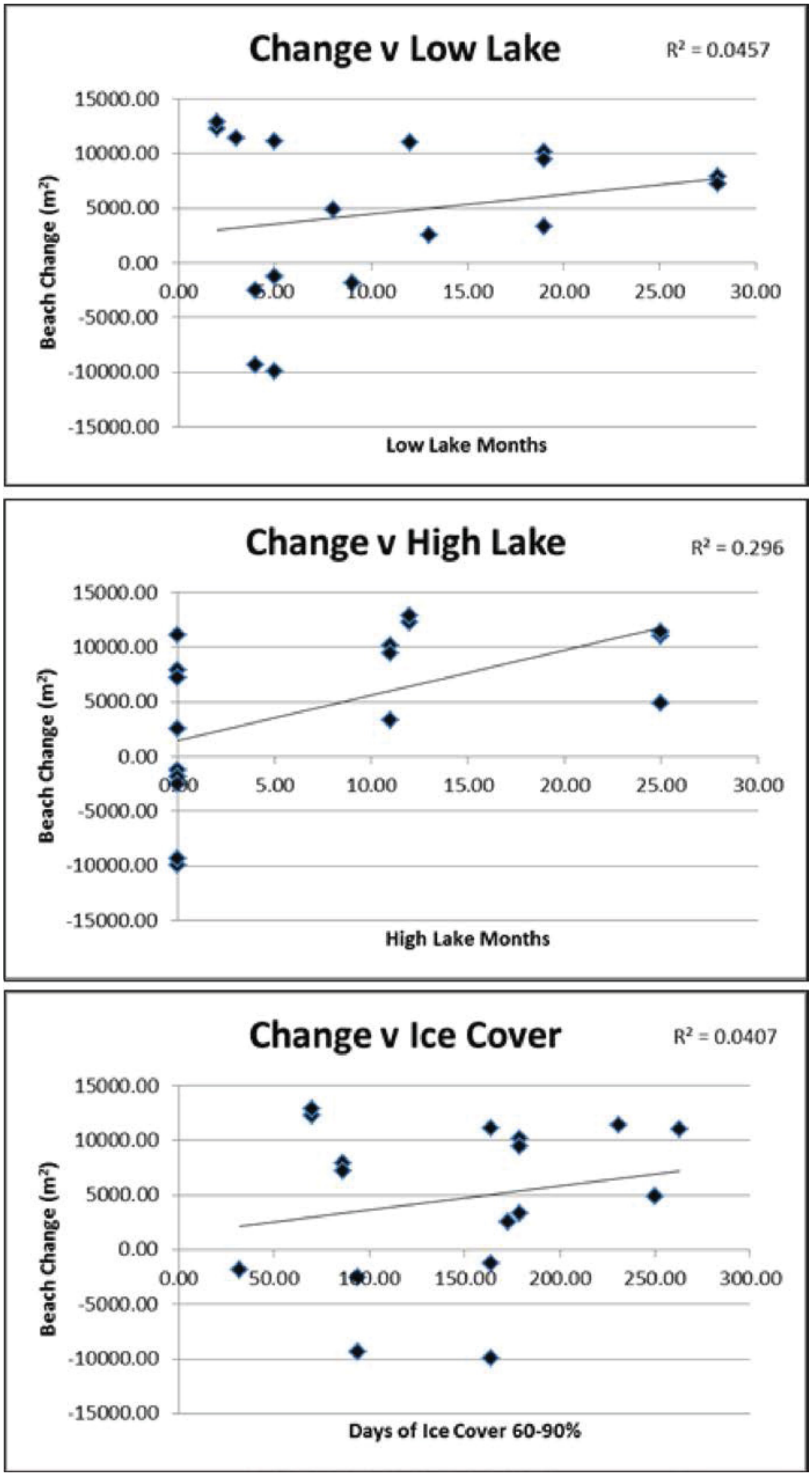


Figure 10. Statistical Analysis

Discussion

Mattheus (2014) addresses the long term evolution of two of the depositional headlands currently under investigation (Fairport and Ashtabula) by evaluating beach change from shoreline positions inferred from published nautical charts, which provide a dataset of decadal-scale temporal resolution. He recognizes a period of stunted beach growth, coincidental with low lake-level conditions, low ice-cover durations, and drought, which existed during the late 1930s and early 1950s. As the stunted headland growth continued into a subsequent period of rising lake level, he suggests a poor buffering capacity of the sediment-deprived littoral system to counteract reduced sediment input from bluffs; while investigating depositional headland geomorphology at a decadal timescale has revealed insight into the long-term evolution of the systems in response to climate extremes (i.e. high versus low lake levels), a more precise model of the spatiotemporal sediment-supply dynamics require a higher temporal resolution for a more process-response-based analysis. This study seeks to explain how shoreline dynamics are driven by lake-level and ice cover variances over time using a statistical approach. The following discussion subsequently focuses on two aspects of headland-beach morphodynamics: 1) Climate forcing as the sum of extrinsic control parameters (i.e. independent variables) evaluated using a statistical approach incorporating lake-level and ice-cover data to explain shoreline change, the dependent variable, over time, and 2) An intrinsic control on beach evolution imposed by breakwater orientation/design, evaluated directly from shoreline behavior constrained from surficial (i.e. shoreline positions) and sub-surface (GPR) datasets.

Physical Forcing: External Control Mechanisms on Headland Geomorphology

It is likely that, while site-specific geomorphic trends should be attributed to intrinsic control mechanisms, regional trends in headland-beach evolution are dictated by extrinsic control parameters such as lake level and ice cover, which influence the headland sites similarly (Mattheus, 2014). There should not be any significant hydrologic or climatic variances across the relatively small study region of the south-central Lake Erie coast; furthermore, beach orientations are comparable and the timing of hard structure installation followed co-evolving harbor-development trends (Figure 1). The idea that the three studied beaches respond to climatic forces in unison is easily demonstrated over the short-term as sediment distributions across these studied headlands and their nearshore regions change seasonally as a function of wave/current climate and ice influence: Summer sediment distributions are influenced predominantly by littoral drift (Pincus, 1953) while winter distributions are largely influenced by processes related to ice cover (Barnes et al., 1993); these influences are felt by all headlands equally as they co-evolve in response to these physical forcing parameters. Slight differences in beach profiles from headland to headland associated with these seasonal fluctuations in hydrology are merely a function of local sedimentology; these sedimentologic differences are best evaluated following the winter period, during which ice effects and strong storms are capable of transporting the coarsest nearshore materials against the shorelines (Figures 7 and 8).

The role of ice cover on shoreline evolution is described from in-field observations: Ice cover noticeably affected sediment patterns at both Walnut Beach and Conneaut Beach due to ice cover and pressure ridge dynamics during the winter season of

2013/2014. Upon ice retreat the sediment distribution profile at both sites was very coarse skewed (Figure 8). At Walnut Beach percent gravel decreased landward with a distinct gravel bar occurring in the swash zone; Conneaut followed this pattern except that the percent gravel increased in the direction of littoral drift (Figure 7). This may be the result of littoral drift reaching closer to shore at Conneaut but was pushed further lakeward at Walnut Beach due to ice cover. Sand distributions at both sites inversed gravel distributions; other size classes were more or less non-existent along the shoreline. Field reconnaissance at both sites in March revealed that Walnut Beach was very much affected by subaerial processes. Ice tunnels and other features were present on the beach. It can be assumed that these sediment profiles are directly correlated with the nearshore sand and gravel bars when the ice scours the lakebed and deposits these materials when the ice retreats. These ice processes likely act as the focal point of beach progradation as summer wave and current activity cannot easily remove sequestered gravel at the shoreline; it is highly probable that the interbedding of gravel-sized particles during winter conditions and sand-sized particles during summer conditions at the sites are responsible for much of the reflection configurations imaged using GPR (Figure 9).

While it is suggested from seasonal observations and other studies (Barnes et al., 1993) that ice plays a strong role in moving coarse clastic material against shorelines during winter, creating a setting for continued in-filling and progradation thereafter, the longer-term evolution of beaches can be evaluated from imaging the sub-surface. GPR investigations reveal some long-term influences of climate forcing on headland beach evolution, as these are reflected in the subsurface beneath the modern strand, where the evidence of a century of near-continuous progradation is archived (Figure 9). Imaged lakeward-inclined clinoform geometries, representing preserved beach-shoreline profiles, were mapped across all headland beaches underneath modern backshore deposits; these features reveal changes in accommodation-space distribution at the shore as lake levels influence the vertical position of clinoform profiles as they are generated by continuous or near-continuous progradation (Figure 9). This is most evident when one considers that the only topsets preserved are associated with known shoreline locations (from aerial reconstructions) from period of low lake level; unlike the top ~1 m of the entire backshore region, which is subjected to aeolian and anthropogenic reworking on a seasonal basis, these topsets are buried and intact, extending beneath a continuous surface of erosional truncation (Figure 9). This is clearly seen in the GPR line from Headlands Beach, where the early 1960s shoreline sediments are preserved in their entirety beneath more recent aeolian deposits; clinoform shapes preceding and following this low lake-level period are truncated as clinoform geometries are situated at higher elevations (Figure 9). Additionally, periods of rapid progradation, as suggested by Mattheus (2014) and constrained by aerial photographs (Figure 4), are recognized in the subsurface lakeward of the late 1950s shoreline; prograding clinoform shapes imaged with GPR here change little in elevation and shape between known historic shoreline positions (Figure 9), suggesting rapid lateral accretion (i.e. progradation) of shoreline environments, consistent with historic aerial interpretations (Figure 4).

Foresets and bottomsets are generally preserved while the bottomsets are unresolved in the GPR data due to signal attenuation at depth (~4 m) and water saturation; topsets, on the other hand, which are acted upon by aeolian and/or anthropogenic processes, are absent in most cases (Figure 9). Given the chronological constraints from knowledge of surficial shoreline positions (i.e. aerial photographs), low lake-level conditions preferentially preserve newly formed clinoform geometries, largely because they occupy lower elevations, respectively, allowing them to be buried and go unaffected by subsequent reworking by aeolian processes when lake levels are high (Figure 9). This process may be facilitated by rapid burial as elevated lake levels are suggested to supply the nearshore with more bluff derived sediments (Dawson and Evans, 2001; BaMasoud and Byrne 2012; Buckler and Winters 1983; Amin and Davidson-Arnott 1995; Morang et al., 2011). Interactions between lake levels, accommodation-space distribution, and shoreline response have previously been described by Lichter (1995), Thompson (1992), and Thompson and Baedke (1995) along Lake Michigan. However, it must be noted that lake-level fluctuations are not necessarily linked to ravinement or erosion at the studied Lake Erie headland beaches given continuous, albeit occasionally reduced, sediment supply facilitating continuous growth (Mattheus, 2014). Erosional trends at the shoreline, as elucidated from both surficial and subsurface datasets have less to do with lake levels, but seem to relate more to intrinsic controls on accommodation-space distribution, a topic discussed in a later section.

Statistical Evaluation of Physical Parameters against Beach Change

Multiple regression analysis of beach change versus low lake levels, high lake levels and ice-cover duration yielded statistically-significant results (P= .030, R^2 = 0.361). Thus, influence of each variable could be determined individually (Figure 10): Beach change versus high lake-level conditions explains the most variance (R^2= 0.2960). Multiple regression analysis of net beach growth versus lake level and ice cover revealed that high lake levels are more strongly associated with beach growth compared to ice cover, as suggested by R^2 values. It is already suggested that high lake levels supply more bluff-derived sediments to the beaches (Dawson and Evans, 2001; BaMasoud and Byrne 2012; Buckler and Winters 1983; Amin and Davidson-Arnott 1995; Morang et al., 2011); the statistical evaluations suggest that, along the sediment-starved southern Lake Erie shoreline, reductions in bluff-derived sediment input influence headland-beach morphodynamics, which has already been alluded to by Mattheus (2014). An increased temporal data resolution coupled with this statistical evaluation has allowed an evaluation of the significance levels of different climatic forcing parameters. It is not unreasonable to speculate that rates of headland-beach progradation could be inversely proportional to bluff retreat, given that sediment supply to the littoral system is mainly a product of bluff retreat (Morang et al., 2011); however, these data do not yet exist for the individualized coastal cells of interest to this study (Figure 1).

While regional trends in shoreline behavior along studied headlands , elucidated using statistical methods, are considered a function of extrinsic controls (i.e. lake level and climate), local trends appear to be more heavily affected by intrinsic controls (i.e. hard structures, beach length, grain-size, sediment supply, littoral drift). On a grand scale this is evident when considering that while the regional coastal trend along Ohio's Lake Erie coast is erosion, net progradation occurs locally against harbor breakwaters (Mattheus, 2014). The same concept applies to shoreline evolution at each of these headland sites, given that they represent the termini of three different littoral cells (Figure 1) and differ in terms of hard-structure design (Figure 2). The following section describes the morphologic evolution of the three depositional harbor headlands as a function of these intrinsic variances.

Jetty Orientation as an Intrinsic Control Mechanism on Headland Geomorphology

While lake-level and ice-cover variances may drive common geomorphic trends among headland-beach sites, headland-specific parameters should influence beach geomorphology differentially. Differences between the sites, including grain size, beach length, and accommodation-space distribution, offer explanation for the variability along depositional strike (at each beach) and from beach to beach.

Headlands Beach gained in area by ~55, 764.95 m^2 between 1973 and 2002 area (Figure 4; Table 2); the corresponding rate of shoreline progradation over this timespan (of ~3 m/year average) is less that the rate measured for the preceding period of progradation (at ~3.12 m/year average). Mattheus (2014) notices a similar reduction in rate of headland-beach growth using a different dataset (Figure 11). This abrupt change in rate of beach growth ~1960 coincides with the shoreline approaching a change in breakwater orientation, which likely affected the spatial distribution of accommodation space enough to cause a beach-wide reduction in growth rate. Accommodation-space distribution prior to this time point was confined by a more shore-perpendicular jetty structure; around 1960, the shoreline had approached a change in the orientation of the segmented jetty to more shore-oblique, abruptly increasing accommodation space by lengthening the shoreline (Figures 1 and 4). Interestingly, this lengthening of the shoreline (by ~0.56 km) was also affiliated with cusp formation and migration from west to east; this process, explained by a simple conceptual diagram (Figure 6) is noticeable in aerial photographs post-dating 1960 (Figure 4) and explains the spatiotemporal variances in local shoreline erosion and deposition along a headland beach that is growing overall (Figure 5). While this beach continues to build at a reduced rate, localized sections erode or deposit over the short-term as a function of cusp migration on a decadal timescale (Figure 6); similar processes have been observed along Long Point, Lake Erie Canada, where the migration of these features is controlled by longshore current direction, beach length, and high sediment supply (Stewart and Davidson-Arnott 1988; Davidson-Arnott and Van Heyningen, 2003). It is therefore highly likely that the absence of cusps along Headlands Beach prior to 1960, inferred from nautical charts (Mattheus, 2014) and aerial photographs (Figure 4), was due to an insufficient beach length to promote their formation.

Walnut Beach gained ~14,856.53 m^2 of beach area from 1973 to 2000 (Figure 4; Table 2); the rate of shoreline progradation over this timespan (~1.80 m/year average) was less that the rate of during the earlier period of progradation (1.96 m/year average). This rate of growth was significantly less than that measured for Headlands Beach; this is probably largely due to is the characteristics of the littoral cell supplying this headland (e.g. cell length and sedimentology); the sedimentologic distinctions of the headland beaches are hence illustrated by the differences in shoreline materials sampled in spring (Figure 7). Nonetheless, similarly to the Headlands Beach analogue, beach evolution here has been greatly affected by the hard structure design: A period of rapid progradation prior to ~1960 filled up two depositional basins, Walnut Beach presently occupying the western one (Figure 4). Once this accommodation threshold was reached Walnut Beach responded uniformly along strike (Figure 5). A second accommodation threshold was reached ~1991, when the Walnut Beach shoreline became flush with the jetty, abruptly shifting the system from a confined accommodation space sheltered by the structure to unconfined accommodation space along the jetty (Figure 4). Mattheus (2014) suggests a more variable shoreline evolution after 1960 at Walnut Beach; however, this study is based on a different data set and the growth curve subsequently hinges on different data nodes produced by varying data resolutions. Nonetheless, both datasets and studies agree that during times of decreased sediment supply the beach erodes and progradation occurs when bluff-derived sediment is introduced to the nearshore system during elevated lake level conditions. A period of rapid progradation (1974-1994) as a result of renewed sediment supply following a low lake level cycle was indicated by a 30 m-wide extent of progradational clinoform geometries with little change in shape or profile position in the GPR profile (Figures 9 and Figure 11).

Conneaut Beach gained ~54,579.99 m^2 of beach area between 1973 and 2002, suggesting emplacement of sand volumes comparable to those emplaced at Headlands Beach (Figure 4). Timesteps of beach growth show nothing but net accretion as sand supply sequesters within the confined accommodation space created by the shore-perpendicular jetty (Figure 4). Some variations in rate of beach growth are noted: A period of rapid progradation (1952-1969), revealed from aerial reconstructions (Figure 4) was recognized in the GPR data; this period of exceptionally high growth rates could be explained by a renewal of high sediment supply following a low lake-level period (Figures 9 and 11). The smallest beach area gain 1988 to 1994 (2,544 m^2) can be explained by lower lake level conditions and an increase in ice cover duration, limiting sediment supply; while, the largest gain between 74-77 (12,848.11 m^2) correspond with a combination of higher lake conditions and lower ice cover duration.

The design of hard structures (i.e. harbor jetties) clearly influences long-term sedimentation patterns as these structures provide the bounds of beach form. Instead of a geological constraint as explained by Jackson and Cooper (2009), accommodation at these headlands is a function of hard structure design, which varies from headland to headland. Each beach is unique in the fact that each is in a different stage of evolution based on available accommodation space provided by enclosure. Walnut Beach has reached an end to the confined accommodation space once its shoreline amalgamated with the rock wall, which has restricted long-term beach progradation since 1960 (Figure 4). There is no more confined accommodation space and the long beach length, which now extends along the entire jetty (~2.40 km; Figure 4), allow for short periods of erosion or deposition at the shoreline, depending on seasonality; however, headland progradation has effectively ceased and the shoreline should continue to move above a temporally fixed position determined by the breakwater location and orientation. In contrast to Walnut Beach, Conneaut Beach should continue to prograde as it has yet to reach a threshold in accommodation-space distribution; this beach has continuously built since the 1950s without any resolvable net loss between observed timesteps (Figure 4; Figure 6). The influence of breakwater design is furthermore noted in the statistical evaluation of beach change: When accommodation space is categorized (confined by the orientation of the structure or unconfined by the structure) more of the variance is explained. When accommodation-space distribution is confined, regressions of low lake level, high lake level and ice cover duration yielded R^2 values of 0.0603, 0.3727, and 0.0703, respectively. When accommodation space is unconfined, these values were 0.4995, 0.4194, and 0.2320, respectively.

Coastal managers must tackle landscape evolution in terms of both natural and human induced change. Coastal erosion is a natural process which constantly seeks to reach equilibrium by redistributing sediments, which changes the profile and form of beaches, dunes and bluffs. Humans exacerbate erosion processes by damaging the natural protective features that protect the shoreface. Thus, engineers design hard structures to mitigate these effects leading to deposition on their up-drift sides and generating sediment starvation on the down-drift. These structures must withstand the environmental variables they are subjected to (i.e. lake levels, ice cover, tides, waves, etc.). It appears that when there is a basin for sediment to be deposited in, these external factors (i.e. lake levels, ice cover) matter less.

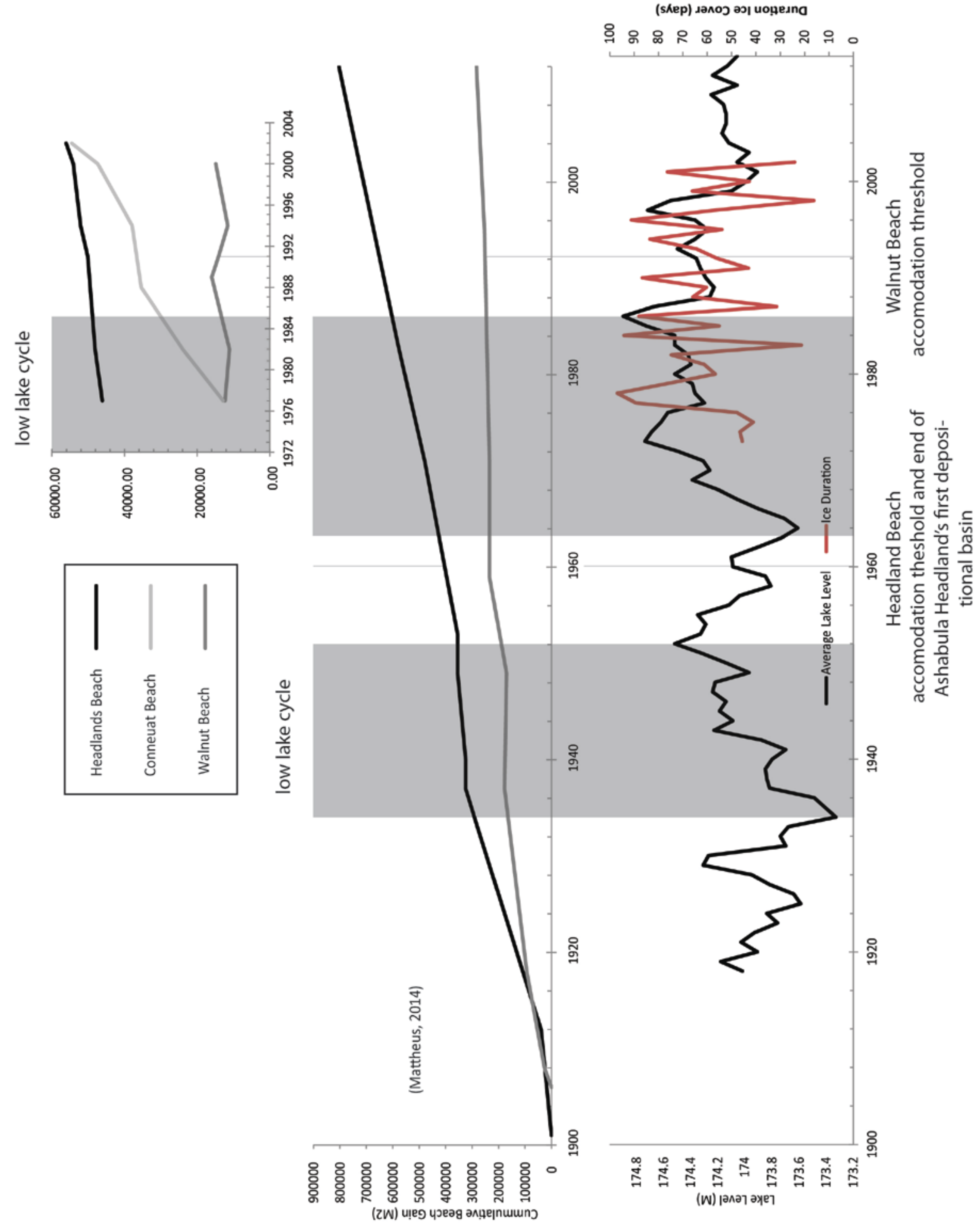


Figure 11. Graph showing differences in the long term progradation trends from Mattheus (2014) in comparison to beach area gain using a different dataset in the present study. Both are compared against lake-levels, ice cover conditions, and respective accommodation thresholds.

Conclusions

In the Great Lakes region, the southern Lake Erie shore is a unique system. However, an understanding of how a modified shoreline responds to environmental variables is useful and certainly has applications elsewhere. Coastal erosion is a natural process which constantly seeks to reach equilibrium by redistributing sediments, which changes the profile and form of beaches, dunes and bluffs. Humans exacerbate erosion processes by damaging the natural protective features (i.e. beaches, dunes and bluffs) that protect the shoreface. Coastal managers must tackle landscape evolution in terms of both natural and human-induced change. However, what can be said is the following: 1) High lake levels are the main drivers of geomorphic change along the southern Lake Erie shore; 2) Ice cover conditions act as a secondary but important variable in beach development; and 3) Hard structure design dictates the form of the beach and provides the necessary accommodation for them to prograde at the headlands. Each site has prograded as a result of the installed hard structures. It appears that the design of these structures impacts the amount of sediment they can accommodate. When the accommodation space is confined, beaches can prograde faster as they have to fill a smaller container; whereas, once this threshold is reached the rates of progradation are reduced. At the same time lake levels affect the accommodation volume. These variables are interpreted as variances in the prograding clinoform geometries in the GPR profiles. In general only the foresets are preserved; the bottomsets are not resolved and the topsets are acted upon by aeolian processes. Additional work on the design and orientation of these structures seems relevant as many tax dollars are spent annually to combat the effects of the dynamic southern Lake Erie shoreline.

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Conneaut Beach Winter-Ice Sedimentologic Data (measured in grams)

Easting	Northing	63000 mm	31.5 mm	16 mm	8 mm	4 mm	pan	2 mm	1 mm	500 µm	250 µm	125 µm	63 µm	pan2	start	end	error
536152	4646010	0	0	0	0	0.5	1072.5	678.7	201.7	43.7	117.5	28.8	0.8	0.1	1073.1	1071.8	1.3
536214	4646058	0	108.2	101.7	12.6	6.4	779	14.9	169.1	304.6	265	25.1	0.4	0.2	1008	1008.2	-0.2
536212	4646060	0	74	32.4	6.8	16.1	907.3	79.2	302.6	237.8	239.5	44.8	1.7	0.6	1036.8	1035.5	1.3
536207	4646065	0	73.7	0	26.7	151.6	770	335.5	161.3	77.3	150.1	41.7	1.9	1.1	1022.3	1020.9	1.4
536184	4646021	0	0	0	0	0	1234.3	92.2	803.7	100.2	196.5	42	1	0.2	1234.3	1235.8	-1.5
536180	4646024	0	51.1	42.9	12.4	17.3	894.4	81	236.9	247.6	284.2	42.1	1	0.4	1017.8	1016.9	0.9
536176	4646029	0	0	0	0	5.7	1016.1	78.2	318.6	282.9	289	44.8	0.9	0.3	1021.8	1020.4	1.4
536173	4646031	0	0	16.8	14.3	91.8	547.1	226.8	210.9	60.8	38.4	8.8	0.3	0.7	670	669.6	0.4
536150	4645984	0	0	0	0	0	886.2	6.4	216.7	294.6	301	67.6	1.3	0.2	886	887.8	-1.8
536146	4645987	0	0	0	1.4	15.5	1014.1	232.3	305.6	194.9	244	34.1	0.6	0.4	1031	1028.8	2.2
536142	4645996	0	0	9.9	1.6	11	912.3	52.7	268.5	286.6	259.5	42.5	1.6	0.7	934.3	934.6	-0.3
Easting	**Northing**	**-6**	**-5**	**-4**	**-3**	**-2**		**-1**	**0**	**1**	**2**	**3**	**4**		**gravel**	**sand**	**mud**
536152	4646010	0.00	0.00	0.00	0.00	0.05		63.32	18.82	4.08	10.96	2.69	0.07		63.37%	36.62%	0.01%
536214	4646058	0.00	10.73	10.09	1.25	0.63		1.48	16.77	30.21	26.28	2.49	0.04		24.18%	75.80%	0.02%
536212	4646060	0.00	7.15	3.13	0.66	1.55		7.65	29.22	22.96	23.13	4.33	0.16		20.14%	79.81%	0.06%
536207	4646065	0.00	7.22	0.00	2.62	14.85		32.86	15.80	7.57	14.70	4.08	0.19		57.55%	42.34%	0.11%
536184	4646021	0.00	0.00	0.00	0.00	0.00		7.46	65.03	8.11	15.90	3.40	0.08		7.46%	92.52%	0.02%
536180	4646024	0.00	5.03	4.22	1.22	1.70		7.97	23.30	24.35	27.95	4.14	0.10		20.13%	79.83%	0.04%
536176	4646029	0.00	0.00	0.00	0.00	0.56		7.66	31.22	27.72	28.32	4.39	0.09		8.22%	91.75%	0.03%
536173	4646031	0.00	0.00	2.51	2.14	13.71		33.87	31.50	9.08	5.73	1.31	0.04		52.23%	47.67%	0.10%
536150	4645984	0.00	0.00	0.00	0.00	0.00		0.72	24.41	33.18	33.90	7.61	0.15		0.72%	99.26%	0.02%
536146	4645987	0.00	0.00	0.00	0.14	1.51		22.58	29.70	18.94	23.72	3.31	0.06		24.22%	75.74%	0.04%
536142	4645996	0.00	0.00	1.06	0.17	1.18		5.64	28.73	30.67	27.77	4.55	0.17		8.05%	91.88%	0.07%

Appendix A

Walnut Beach Winter-Ice Sedimentologic Data (measured in grams)

Easting	Northing	63000 mm	31.5 mm	16 mm	8 mm	4 mm	pan	2 mm	1 mm	500 µm	250 µm	125 µm	63 µm	pan2	start	end	error
515927	4638994	0	0	210	367.8	124.2	824.3	233.7	340.4	132	101.5	14.4	0.8	0.3	1526.4	1525.1	1.3
515930	4638993	0	0	40	64.5	23.9	1060	101.4	404	270.4	235.1	43	1.8	0.9	1189	1185	4
515934	4638991	0	0	0	0	1.2	1181	3.1	39.8	674.5	429.2	33.2	1.4	0.4	1181.2	1182.8	-1.6
515927	4638996	0	0	0	24	93.2	1266	295.9	622.5	189.7	118.8	31.8	1.4	0.8	1383.3	1378.1	5.2
515910	4638966	0	90.3	16.9	0	0	1513	2.1	10.2	91.3	1309.2	96	4.4	0.7	1621.1	1621.1	0
515908	4638965	0	0	14.1	9.7	9.7	1303	87.5	483.3	487.3	222	19.8	0.9	0.3	1331.1	1334.6	-3.5
515905	4638967	0	0	0	23.5	55.3	1265	99.6	284.4	413.3	380.6	80	4.4	1.6	1344.3	1342.7	1.6
515904	4638969	0	0	14.4	39	94.8	1001	227.3	321.4	161	233.4	52.1	2.1	0.6	1150.4	1146.1	4.3
515902	4638970	0	0	75.3	454.6	383.7	248.1	145.8	62.3	18.4	15.1	6.6	0.6	0.4	1161.5	1162.8	-1.3
515883	4638934	0	0	0	4.3	0.5	1400	0.7	12.4	217.1	1083.8	78.5	5.8	0.9	1405.1	1404	1.1
515883	4638935	0	0	0	0.1	1.5	1095	15.3	379.1	279.1	365.1	52.3	2.5	0.5	1096.6	1095.5	1.1
515882	4638937	0	0	36.5	12.4	7	986.1	53	321.9	279.3	280.3	45.8	2.4	0.6	1041.8	1039.2	2.6
515878	4638939	0	0	0	27.4	153.6	1094	310.5	318.2	149.5	250.3	58.4	2.9	1	1274.6	1271.8	2.8
515877	4638940	0	0	104.8	228.1	234.8	194.6	125.8	38.9	11.6	13.6	5.8	0.3	0.1	762.2	763.8	-1.6
Easting	**Northing**	**-6**	**-5**	**-4**	**-3**	**-2**		**-1**	**0**	**1**	**2**	**3**	**4**		**gravel**	**sand**	**mud**
515927	4638994	0	0	13.7696	24.1165	8.1437		15.324	22.3198	8.65517	6.6553	0.9442	0.0525		61.35%	38.63%	0.02%
515930	4638993	0	0	3.37553	5.44304	2.0169		8.557	34.0928	22.8186	19.8397	3.6287	0.1519		19.39%	80.53%	0.08%
515934	4638991	0	0	0	0	0.1015		0.2621	3.3649	57.0257	36.2868	2.8069	0.1184		0.36%	99.60%	0.03%
515927	4638996	0	0	0	1.74153	6.7629		21.472	45.1709	13.7653	8.62056	2.3075	0.1016		29.98%	69.97%	0.06%
515910	4638966	0	5.57029	1.0425	0	0		0.1295	0.6292	5.63198	80.76	5.9219	0.2714		6.74%	93.21%	0.04%
515908	4638965	0	0	1.0565	0.72681	0.7268		6.5563	36.2131	36.5128	16.6342	1.4836	0.0674		9.07%	90.91%	0.02%
515905	4638967	0	0	0	1.7502	4.1186		7.4179	21.1812	30.7813	28.3459	5.9581	0.3277		13.29%	86.59%	0.12%
515904	4638969	0	0	1.25643	3.40284	8.2715		19.832	28.0429	14.0476	20.3647	4.5459	0.1832		32.76%	67.18%	0.05%
515902	4638970	0	0	6.47575	39.0953	32.998		12.539	5.35776	1.58239	1.29859	0.5676	0.0516		91.11%	8.86%	0.03%
515883	4638934	0	0	0	0.30627	0.0356		0.0499	0.88319	15.463	77.1937	5.5912	0.4131		0.39%	99.54%	0.06%
515883	4638935	0	0	0	0.00913	0.1369		1.3966	34.6052	25.477	33.3272	4.7741	0.2282		1.54%	98.41%	0.05%
515882	4638937	0	0	3.51232	1.19323	0.6736		5.1001	30.9758	26.8764	26.9727	4.4072	0.2309		10.48%	89.46%	0.06%
515878	4638939	0	0	0	2.15443	12.077		24.414	25.0197	11.755	19.6808	4.5919	0.228		38.65%	61.28%	0.08%
515877	4638940	0	0	13.7209	29.8638	30.741		16.47	5.09296	1.51872	1.78057	0.7594	0.0393		90.80%	9.19%	0.01%

Appendix B