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Analysis and Chronology of Glacial Lake Arkona in the Western Lake Erie Basin, USA

by

John R. Dilworth

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the

The Master of Science in Geology Degree

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The University of Toledo

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An Abstract of
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The shoreline of Lake Arkona is characterized by a subtle or “washed” appearance and can be traced around the Lake Erie basin as a discontinuous ridge. The traditional interpretation of Lake Arkona is that lake level dropped approximately 30 m from its previous highest stand to Lake Arkona level, then Lake Arkona was overtopped by the subsequent highstand, Lake Whittlesey. To assess the standard interpretation of Lake Arkona, this study evaluated the Lake Arkona and Lake Whittlesey shorelines in the western Lake Erie basin to evaluate the standard model and compare the geomorphology of the two shorelines. Any overtopping of the Arkona shoreline should be expressed stratigraphically by a truncating erosional surface. Ground penetrating radar was used across the Arkona Shoreline to evaluate the internal stratigraphy and determine the presence of a strong reflection indicative of a ravinement surface. Ground truth at each field site was provided by a combination of hand-dug pits, vibrocore and auger transects. To better constrain the lake sequence between the Lake Whittlesey and Lake Arkona, optically stimulated luminescence dates were taken from each shoreline. The geomorphic differences between the Arkona and Whittlesey shorelines were described from field

observations and a statistical model. The model incorporated topographic profiles taken perpendicular to the long axis of the shoreline features, and extending 5 km into the lake basin. These topographic profiles were obtained using GIS ArcMap and 3 m LiDAR elevations acquired from the U.S. Geological Survey's National Map Viewer. The model was used to support interpretations for field observations of pre-existing topography, paleo-wave direction and sediment supply for the shorelines in the western Lake Erie basin. The results of the study have several implications: 1) Due to the lack of a strong GPR reflection interrupting the internal stratigraphy of the Arkona coastal features, it is unlikely that the shoreline was overtopped by a higher lake stand; 2) These results call into question the traditional interpretation of the proglacial lake sequence in the Lake Erie basin; 3) The traditional description of Lake Arkona being a washed shoreline needs to be re-evaluated.

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Chapter 1

Introduction and Lake Erie Proglacial Lake History

1.1 Problem Overview

During the Port Bruce Stadial approximately 18,700 cal age BP (15,500 ^{14}C yr BP), the Lake Erie and Lake Huron basins experienced a glacial readvance that culminated in the formation of the Wabash Moraine (Barnett, 1985). Recessional moraines that formed during the subsequent recession included the Fort Wayne and Defiance Moraines as the Huron-Erie Lobe withdrew from the Lake Erie basin (Eschman and Karrow, 1985).

The retreating ice accumulated meltwater at the prow of the glacial lobes. The ponding water in front of the glacier formed a succession of proglacial lakes of Ancestral Lake Erie (ALE), controlled by the changing geographic location of the ice margins (Leverett and Taylor, 1915; Lewis, 1969; Dreimanis, 1977; Fullerton, 1980; Chapman and Putnam, 1984; Calkin and Feenstra 1985; Barnett, 1985). The general sequence of glacial retreat is well understood on a regional scale, but the specific timing and ice-margin positions are still being evaluated locally.

The evolution of the proglacial lakes forming in the Lake Erie basin is understood at a fundamental level, but specific elevations and dates for each successive lake are not well constrained (Fisher et al., 2015). This brings into question the lake-level sequences proposed by Leverett and Taylor (1915), Lewis (1969), Fullerton (1980), and Barnett (1985). Standard lake-level curves suggest that the older sequence of the proglacial lakes progress from Maumee (I-III) to Arkona, Ypsilanti, Whittlesey, Warren, Wayne, Grassmere, Lundy, Early Algonquin and Early Lake Erie. However, as more information on lake chronology has become available, the classical model has been called into question (Figure 1.1). Thesis studies by Campbell (2009),

Anderson (2011) and Blockland (2013), summarized by Fisher et al. (2015), have sought to provide dates and elevation analysis of the Maumee through Warren shorelines. Information from these studies has been used to refine the lake sequences and improve the lake-level curve. The purpose of this research is to evaluate the Arkona shoreline, in particular, its geomorphic structure, chronology, and comparison with the Whittlesey shoreline.

1.2 Introduction

The original model for lake succession was first proposed by Leverett (1902) and Leverett and Taylor (1915), then later modified by Barnett (1985). Leverett and Taylor (1915) identified ten major lakes in the Lake Erie basin. The elevation of the shorelines with respect to one another is presented in Figure 1.2. From highest to lowest elevation, the shorelines progress from Lake Maumee, Whittlesey, Arkona, Warren, Wayne, Grassmere, Lundy, Early Algonquin, Early Lake Erie and present day Lake Erie. The early analysis of shoreline location involved looking at outcrops and exposures that reveal shoreline deposits, and looking for the surface expression of strandlines and nearshore features. For the initial chronology, the lakes were not dated directly. Shorelines and nearshore features were related to moraine locations or analysis of lake drainage pathways to give an indirect chronology of the strandlines (Leverett and Taylor, 1915). Later studies began dating features associated with the strandlines such as organic layers that accumulated in drainage channels associated with each lake level.

Lake Maumee

The name Maumee was first used by Dwyer (1888) to describe the highest-elevation lake. Lake Maumee is the first of the sequence of proglacial lakes to be identified by Leverett (1902). Lake Maumee can be divided into stages Maumee I, II, and III (Forsyth, 1959; Lowden and Blake, 1968). The highest-elevation shoreline is Maumee I at 800 ft asl (243 m). Maumee I

formed when the Huron-Erie Lobe began to retreat from the Fort Wayne Moraine, causing water to accumulate between the moraine and retreating ice (Hough, 1958; Calkin and Feenstra, 1985). Dating of the Maumee shoreline is loosely confined. A radiocarbon date of 15,236 to 14,004 cal age BP ($13,700 \pm 210$ ^{14}C yrs BP) is interpreted as the abandonment of the Imlay outlet near Imlay City in Lapeer County, Michigan (Eschman and Karrow, 1985). Maumee I is characterized by well-developed ridges that are particularly well defined in western Ohio. Initial mapping of the strandlines by Leverett and Taylor identified the shorelines 10 km north of Imlay, MI (Calkin and Feenstra, 1985). Lake Maumee I was proposed to drain through either the Imlay River channel or Fort Wayne outlet.

Maumee II is described as being faint and fragmented with a general “washed” appearance. Maumee II is the lowest elevation of the Maumee shorelines and marked at 760 ft asl (231 m), and was first mapped by Russell and Leverett (1908). Lake Maumee II was formed by the retreat of the glacial ice across the Huron basin and Saginaw Bay. This caused lake level to drop rapidly and begin draining through the Grand River Valley (Hough, 1958). Leverett and Taylor (1915) stated that the Imlay and Fort Wayne outlets were too high in elevation to allow water to drain, so the water was forced through a lower outlet (Bleuer and Moore, 1972). In the standard sequence, the subsequent Maumee III shoreline was identified by Leverett as being 780 ft asl (237 m) and is significantly more defined than the Maumee II shoreline. Lake Maumee III marked a transitional period of outlet migration. Leverett and Taylor stated that lake level was too low to utilize the Fort Wayne outlet and instead drained through the lower Imlay outlet.

The sequence of Lake Maumee I-III has two major interpretations. The first sequence proposed by Leverett and Taylor (1915) is the Maumee I, II, III, essentially highest, lowest and middle by elevation. Leverett and Taylor interpreted that Lake Maumee III transgressed over

Maumee II, causing Maumee II to develop a “washed” appearance, and deposited a fine-grained layer on Maumee II beach ridges and deltas. This sequence of Lake Maumee was challenged by Totten (1985), who asserted that this complex sequencing is unlikely. The “washed” appearance could be attributed to shoreline features forming with low relief. Totten proposed that the lake sequence could be simplified to “Highest”-“Middle”-“Lowest” (Totten, 1985). Significant work at the Fort Wayne outlet by the Indiana Geological Survey determined that all levels of Lake Maumee could have drained through this outlet (Bleuer and Moore, 1972). The Totten model of the Lake Maumee lake sequences has been supported by recent dating and evaluation by Fisher et al. (2015).

Lake Arkona

Lake Arkona was named after an Ontario village close to a beach ridge identified by Spencer (1891). Lake Arkona is characterized by a subtle or “washed” appearance and occurs as a discontinuous ridge that can be identified around the Lake Erie and Lake Ontario basins. Additional beach ridges identified by Calkin (1970) close to North Collins, NY show ridges between the Whittlesey and Warren I shorelines that may correlate to Lake Arkona or an unrecognized lake stage (Calkin, 1970). Many of the Arkona ridges in the Ontario area are gravelly and lack form (Chapman and Putnam, 1966; Cooper, 1979). Lake Arkona formed as a result of the Huron-Erie lobe retreating northeastward past the thumb of Michigan, opening the Grand River outlet during the Mackinaw Interstade (Dreimanis and Karrow, 1972; Totten, 1985). This led to the abandonment of the Fort Wayne outlet as water diverted to the lower Grand River outlet (Hough, 1958). It was proposed by Leverett and Taylor (1915) that Lake Arkona can be divided into three major elevations at 710 ft (216 m), 700 ft (213 m) and 695 ft (211 m) asl. However, the cause of these three lake-level stages is uncertain.

Hough (1958) suggested that the first of the three Arkona shorelines was caused when the water became dammed against the eastern border of the Erie basin, where ice was still present in the New York region. To explain the fluctuations of lake level, Bretz (1951) hypothesized that meltwater discharge would increase during times of glacial retreat and the increased flux of meltwater flowing through the Grand River would deepen the channel. This would cause a progressive drop in the outlet, allowing the lake to reach lower levels. In Bretz's model, glacial advances would cause stagnation in lake levels, producing shorelines at the 700 ft (213 m) and 695 ft (211 m) elevations. The lowest Lake Arkona level in Bretz's model is attributed to have formed during the Port Huron advance. Field evidence does not support this assessment; beach ridges were observed to have formed independent of the advancement and retreat of the glaciers and were not entirely dependent on outlet elevation as proposed by Bretz's model (Farrand and Eschman, 1974). In the case of some Arkona ridges, well-developed beach ridges were found near the Port Huron moraine. Several of the ridges were overtopped by outwash associated with the Port Huron Moraine. This indicates that the shorelines were in place prior to the establishment of the Port Huron moraine thus having developed prior to the glacier advance into the area (Calkin and Feenstra, 1985).

From the testing of Bretz's model, a model by Larsen (1985) suggests that water-budget discrepancies caused small lake-level fluctuations. A radiocarbon sample taken from a small lagoon near Cleveland, OH, yielded an age between 14,930 to 17,861 cal yrs BP ($13,600 \pm 500$ ^{14}C yrs BP). To account for the shoreline's washed appearance, it was proposed that Lake Arkona was later overtopped by Lake Whittlesey. Evidence to support the claim comes from analysis of the sediment overlying the lagoonal deposit. The overlying sediment was attributed to sediments associated with Lake Whittlesey deep-water sediments (Goldthwait, 1958). This implies that

beneath the transgressive deposits a ravinement surface truncating the Arkona beach sediments should be observable (Cattaneo and Steel, 2003).

Lake Ypsilanti

Lake Ypsilanti was proposed by Kunkle (1963) as a Lake Erie lowstand that occurred following Lake Arkona but prior to Lake Whittlesey in the Ancestral Lake Erie chronology. Evidence supporting the existence of Lake Ypsilanti comes from Kunkle (1963) who interpreted a gravel unit beneath the Huron River near Ann Arbor, MI. The gravel unit was deposited in a relict river channel that is cut into Port Stanley till then overtopped with oxidized silt and clay believed to be associated with Lake Whittlesey and Lake Warren deposits (Dreimanis, 1977; Fullerton, 1980; Calkin, 1985). If a lowstand had occurred in the Lake Erie basin, the lithologic facies would be present in the sediment record. Anderson's (2011) work in the Wildwood and Oak Openings Metro Parks, and Stranahan Arboretum revealed uninterrupted varve sequences recording approximately 500 years of sedimentation. No evidence was found resembling ravinement surfaces or a large-scale unconformity interrupting the sequence that would be associated with a lake lowstand (Anderson, 2011). The lack of a large-scale unconformity or ravinement surface makes it unlikely that a lowstand occurred prior to Lake Whittlesey. This suggests that the placement of the Ypsilanti lowstand event on the traditional cyclic lake-level curve should be reevaluated. A possible Lake Ypsilanti could be placed as a younger lowstand occurring after the Lake Whittlesey highstand (Fisher et al., 2015). A recent study by the Ontario Geological Survey of the central Norfolk sand plain, in southern Ontario, found evidence of discontinuous, channelized, medium- to coarse-textured sand and gravel deposits overlying Maumee and Arkona sediments. The distribution of these deposits suggested that they may fill channels which extend into the Lake Erie basin. These channelized deposits were attributed to

Ypsilanti low-water phase deposits and suggests evidence for a lowstand in the Lake Erie basin (Marich, 2014). AMS radiocarbon-dated samples were taken from numerous detrital wood and leaves of *Dryas integrifolia* (a colonizing shrub) found in glaciolacustrine deposits overlying Port Stanley Till. Two major age populations resulted from the radiocarbon samples, the older range 29.45 and 50.6 ka ^{14}C BP and the younger population ranged between 14.06 and 14.7 ka ^{14}C BP. The younger age range suggests that deglaciation occurred prior to these dates and it was suggested that deglaciation occurred by 15 ka BP (Marich, 2014).

Lake Whittlesey

Lake Whittlesey was first identified, mapped and named after Charles Whittlesey in 1838. Lake Whittlesey was extensively mapped by Leverett and Taylor (1915), and characterized as well-developed shorelines and spit complexes that formed at 740 ft asl (225 m). The Lake Whittlesey shoreline is discontinuous north of the city of Hamburg, Mi. close to Lake St. Clair (Calkin, 1970), and is best defined as a single continuous ridge extending through Ohio and Pennsylvania to New York (Forsyth, 1959; Calkin, 1970; Schooler, 1974). Lake Whittlesey shorelines are cut into bedrock and glacial drift deposits, creating steep banks along the southern portion of the Erie Basin (Totten, 1982). Lake Whittlesey formed during the Port Huron re-advance, when the Ontario-Erie lobe advanced and blocked any eastward drainage of water. In the standard interpretation, this caused water level to rise and overtop the Arkona shoreline by approximately 30 ft (9 m) (Calkin and Feenstra, 1985). Since eastern drainage was cut off, lake waters began to drain westward through the spillway at Uby, Michigan (Leverett and Taylor, 1915).

Lake Whittlesey is chronologically bracketed by several radiocarbon dates. The first date was taken from wood samples contained in beach sediments that yielded an age between 14,021

to 12,276 cal years BP ($12,800 \pm 250$ ^{14}C yrs BP) (Hough, 1958). Another sample was taken from a peat unit beneath overlying beach sediments. Wood samples taken from the peat unit yielded an age between 14,592 to 12,078 cal years BP ($12,920 \pm 400$ ^{14}C yrs BP) (Rubin and Alexander, 1958). Recent work by Fisher et al. (2015) collected 13 OSL dates from Winameg ridge, Lyle's ridge and the surrounding areas in northwest Ohio. OSL samples taken from hand-dug pits on top of hummocks and on an identified Lake Maumee spit yielded an approximate age of 16.8 ± 1.1 ka. This date was applied to the lowest of the Lake Maumee strandlines. An OSL date of 16.8 ± 1.1 ka was taken from a sand sample beneath a Whittlesey spit. If accurate, this suggests that Lake Whittlesey is not significantly younger than the Maumee shorelines, which it should be if the cyclic model is valid (Fisher et al., 2015). If the sample does not date the Whittlesey but rather a Lake Maumee deposit, then dating of the Whittlesey would need to be obtained (Fisher et al., 2015). The age range of shoreline sediments from 4 OSL samples from Fisher et al. (2015) provides a window of a few thousand years in which Lakes Maumee, Whittlesey, Arkona and the Ypsilanti lowstand formed prior to Lake Warren. This becomes significant with the dates taken from Lake Arkona. An age that has been attributed to the Arkona is 16,400 cal years BP ($13,600 \pm 500$ ^{14}C yrs BP) from tree fragments obtained from lagoonal deposits overlain by Whittlesey sand and silt (Hough 1958). This means lake levels would have to have dropped to the Arkona, then fallen to a lower stage for the Ypsilanti Low and then risen significantly to form the Whittlesey shoreline within a very short interval of time (Fisher et al., 2015).

Lake Warren

Lake Warren shorelines have been traced throughout Ontario, Michigan, Ohio, Pennsylvania, and western New York as three well-defined ridges (Whittlesey, 1850; Leverett

and Taylor, 1915; Leverett, 1939). The successive ridges are Highest Warren at 685 ft (208 m) (Warren I), Middle Warren at 670 ft (204 m) (Warren II), and Lowest Warren at 660 ft (201 m) (Warren III). Lake Warren formed as a result of ice retreating from the Port Huron Moraine allowing the Uby outlet for Lake Whittlesey to drain into Saginaw Bay and drop overall water levels to approximately 685 ft (208 m) corresponding with the highest Warren strandlines (Calkin and Feenstra, 1985). Principle drainage was westward through the Grand River Valley. The outflow of water through the Grand River Valley caused extensive and progressive incision of the river channel, resulting in the successively lower Warren stages (Totten, 1985).

The Warren strandlines are rarely represented geomorphically by wave-cut features, but rather littoral drift features (Leverett, 1902; Forsyth, 1959; Schooler, 1974; Totten, 1982). Across the mapping area, Warren II and Warren III often appear as a single ridge. In areas that are predominantly flat, or lack significant topographic relief, the three Warren shorelines can be easily distinguished; otherwise the lowest Warren strandline tends to blend with the middle Warren due to its low cresting elevation (Totten, 1985). The Warren strandlines have a higher sand volume than older beaches (Whittlesey) and form large barrier island and spit complexes in southern Michigan and northern Ohio (e.g., Calkin and Feenstra, 1985; Totten, 1985; Higley et al., 2014). Lake Warren is constrained from a series of dates that bracket the relative age of the beaches. Totten (1985) collected a wood sample from beach sand between Avon and Sheffield, OH that yielded a radiocarbon age between 14,004 to 13,337 cal years BP ($13,050 \pm 100$ ^{14}C yrs BP) (Totten, 1985). The maximum age for Lake Warren was taken from a silty peat layer representing a recessional sequence between Lake Whittlesey and Lake Warren. The radiocarbon age for that sample was between 13,837 to 12,252 cal years BP ($12,730 \pm 220$ ^{14}C yrs BP) (Calkin, 1970, 1984). A recent study by Campbell (2009) dated wood fragments found

in a littoral drift unit of the Oak Openings Ridge between 14,507 to 13,921 cal years BP (13,430 $\pm$ 90 ^{14}C yrs BP); the reworked wood fragments provide a more reliable maximum age for Lake Warren in the Erie Basin (Campbell, 2009). Recent work from Higley et al. (2014) obtained an OSL age for Lake Warren of 14.1 ± 1.1 ka.

1.3 New Model of Lake Levels

The standard lake-level model or cyclic model introduced by Leverett and Taylor (1915) states that lake-level stages began at Lake Maumee then dropped to Lake Arkona, followed by a drop to an unknown low at Lake Ypsilanti, then transgressed over top of Lake Arkona to Lake Whittlesey, giving Lake Arkona its “washed” look, then dropped to Lake Warren. Recent studies by Campbell (2009), Anderson (2011), Blockland (2013) and Fisher et al. (2015) have better defined the lake-level curve and present evidence that supports a more episodic model proposed by Totten. The episodic model suggests that the lake sequence progressed from Lake Maumee to Whittlesey, then Arkona to Warren, with the omission of a Lake Ypsilanti due to insufficient stratigraphic evidence. The 500 varve couplets observed by Anderson (2011) delineate a possible uninterrupted sedimentation record of Lake Maumee to Lake Warren and provide a window of time for the development of lakes in the Lake Erie basin. Dates obtained for the Maumee and Warren shorelines require a few thousand years during which lake stages can be developed. This supports a simpler episodic lake-level fall than the more complex cyclic model. It is postulated that a complex model, such as the cyclic model would have difficulty accounting for timing of the mechanisms needed to drop lake level below the Arkona to the Ypsilanti, then raising lake level back over the Arkona to the Whittlesey level. A simpler lake-level curve of general lake-level fall from higher-elevation to lower-elevation strandlines with smaller stages of lake-water fluctuations would better explain the ancestral lake sequences. To better confine the

broader picture of lake-level fluctuations, a more in-depth analysis of the different lake stages should be undertaken. While Lake Ypsilanti has been largely displaced from the new model lake-level curve, the interaction between the Whittlesey and Arkona shorelines is still poorly understood.

The Arkona shoreline is characterized by thin discontinuous ridges that are, in general, poorly expressed throughout the Lake Erie basin (Leverett, 1902). The “washed” look of this beach is generally associated with being drowned by waters from Lake Whittlesey. To explain this appearance in congruence with the new lake model, it is hypothesized that Lake Arkona represents a short-lived lake level that on a broad scale represents a step-down stage from Lake Whittlesey as lake levels fell to Lake Warren levels. In comparison with the typically well-developed shoreline features of Lake Whittlesey, Lake Arkona's are weakly expressed in most areas. This is to be expected if lake level only stopped at a specific elevation for a short period of time. It is unlikely that lake-level succession was strictly regressional. Fluctuation in global climate and ice re-advancement could lead to lake-level transgressions (Bretz, 1969). Since it is common for transgressions to remove by shoreface ravinement or bury former shorelines during such oscillations (Kraft, 1971), it is proposed that the shorelines identified as Lake Arkona represent only the youngest recessional ridges that have not been transgressed subsequently. The age that has been attributed to the Arkona is between 15,912-12,981 cal years BP ($13,600 \pm 500$ ^{14}C yrs BP) (Hough, 1958). This date has a wide margin of error that can place the Arkona as being older than the oldest Maumee shoreline or younger than the Warren. The radiocarbon date loosely confines the Arkona shoreline within a few thousand years.

1.4 Objectives and Hypotheses

An objective of this research is to characterize the Arkona shoreline and propose an explanation for its “washed” appearance. A second objective is to directly date the strandline. A third objective is to evaluate the physical conditions of deposition of the Arkona shoreline and that of the Lake Whittlesey and explain the differences and positioning on the lake-level curve. A fourth is to date the Whittlesey shoreline directly in an effort to better confine the sequence of the Lake Maumee, Whittlesey and Arkona highstands with the ages obtained by Campbell (2009) and Higley et al. (2014).

The working hypothesis is that Lake Arkona was a short-lived, immature strandline created during a step-down from Lake Whittlesey to Lake Warren. This implies that the Arkona shoreline was not transgressed by a higher lake stand. Therefore, if the hypothesis is accepted, the traditional interpretation of the Arkona shoreline as a washed shoreline will need to be reevaluated. Dating of the Lake Arkona strandlines is expected to produce ages between 14,300 cal years BP (13,500 ^{14}C yrs BP) and 13,100 cal years BP (12,700 ^{14}C yrs BP). Similarly, the age of the Whittlesey strandline is expected to be directly dated between 15,000 cal years BP (14,000 ^{14}C yrs BP) and 14,300 cal years BP (13,500 ^{14}C yrs BP), which will correspond to the episodic lake curve model.

1.5 Summary and List of Major Objectives

This research will produce a more complete mapping of the Lake Arkona and Whittlesey shorelines than has previously been able to be accomplished due to the limitation of technology and the unparalleled resolution of LiDAR-based digital elevation models (DEMs). Geophysical studies will provide a detailed stratigraphic representation of the currently poorly understood Arkona shoreline. OSL dates of the Lakes Arkona and Whittlesey strandlines will provide

additional chronological data to better constrain the model for lake-level fluctuations during this late-glacial period of general regression. Findings from this research could potentially change the interpretation of the traditional lake-curve (Barnett, 1985). If Lake Arkona does not display a ravinement surface, then the overtopping of the shoreline by rising waters of Lake Whittlesey is not probable. Furthermore, this research states that the term “washed” appearance is a misnomer. The Arkona shoreline’s faint appearance is likely due to Lake Arkona existing as a single stillstand event between Lake Whittlesey and Lake Warren. If Lake Arkona dates in-between the Lake Whittlesey and Lake Warren shorelines, then it gives more credence to the idea that Lake Whittlesey occurred prior to Lake Arkona, and that Lake Arkona represents a single, brief stillstand event prior to Lake Warren. This would revise the standard lake-curve to the more modern lake sequence interpretation championed by Totten (1985). Comparing the data obtained with past research will assist in producing a more accurate model and lake-level curve. The five major points to be addressed in this thesis are as follows:

<u>Specific question or research point</u>	<u>Potential Answers</u>
1. "Washed" appearance of Lake Arkona	Lake Arkona represents an immature shoreline that was produced as a step-down from Lake Whittlesey to Lake Warren
2. Presence of a ravinement surface above the Arkona deposits	No evidence of a ravinement surface above Lake Arkona is found. This suggests that Lake Whittlesey did not overtop Lake Arkona causing the "washed" appearance.
3. Evaluating OSL ages of Lake Arkona	Dating of the Lake Arkona strandlines will likely produce ages between 16.5 ka and 16.1 ka.
4. Evaluating OSL ages of Lake Whittlesey	Dating of the Whittlesey strandline will likely produce ages between 16.8 ka and 16.5 ka.
5. Evaluation of the standard lake-level curve	Based on the evidence of this research, the standard lake-level curve should be interpreted as Maumee to Whittlesey, Arkona to Lake Warren instead of Maumee, Ypsilanti, Arkona, Whittlesey, Warren.

Figure 1.1. The cyclic model of ancestral Lake Erie. The lake levels progress in a generally decreasing elevation from Lake Maumee, Arkona, Ypsilanti, Whittlesey and Warren down to Early Lake Erie. From Barnett (1985).

1.6 Expected GPR Reflections and Stratigraphic Lithofacies

The landforms and stratigraphy of a relict shoreline system are expected to include: foreshore, backshore, dune, upper shoreface, escarpment, and spit complex (Figure 1.2). The foreshore is defined as an intertidal section of the beach which extends to the landward change in slope. The foreshore is also known as the forebeach or beachface (Davis and FitzGerald, 2004). In a marginal marine setting, the backshore is the landward section of the beach from the high-water line to the base of dunes or cliff face. The backshore is also called the backbeach (Davis and FitzGerald, 2004). The back barrier extends from the lee of the barrier island across a mud flat, tidal flat, tidal creek or lagoon.

Understanding the basic GPR reflections and expected lithologies of such features are paramount for geomorphic identification and interpretation of relict coastal features. GPR transects taken along the Cape Henlopen, Delaware, spit complex identified radar facies typical of recurved spits, beach-accretion plains, and spit complex (Kraft, 1971; Daly et al., 2002). Tangential-oblique GPR reflections, were interpreted as representing accretional bedding of a beachface or dune sands. Sigmoidal-oblique reflections were interpreted as spit-platform sand and gravel. Sub-horizontal reflections within these coastal settings were interpreted as aggradation of spit sand and gravel or dune sands. Hummocky reflections were attributed to the internal bedding within dune sands. Daly et al. (2002) observed that on recurved spits on the basinward side of a GPR profile, sigmoidal-oblique reflections would indicate progradation of the ridge. Nearly horizontal reflections that occur in contact with the sigmoidal-oblique reflections are interpreted as vertical accretion of the beachface. In comparison to recurved spit profiles on the basinward side of a transect, a beach-accretion plain can be subdivided into two major sets of reflections. The lowermost reflections tend to be sigmoidal-oblique, and the uppermost surface is tangential-oblique. Dune sediments would typically be sequences of sub-horizontal and hummocky reflections (Daly et al., 2002).

O'Neill (1985) conducted research along the coast of New York and discussed basic geomorphic descriptions and properties of several coastal features including: the coastal plain, beach, offshore bars, dunes, barrier islands and bluffs. A characteristic elevation profile including many of these features is presented in Figure 1.2. A typical gently sloping coastal plain is composed of sand and gravel. If the system is close to a river mouth, the river typically provides large amounts of sediment for beach aggradation and progradation. The coastal plain and beach usually reside above the base water plane (O'Neill, 1985). O'Neill, (1985) defined the

portion of the beach that is covered by wave uprush and backrush as the foreshore, and the area only affected by storm waves as the backshore. The shoreface is generally defined as the inner shelf out to water depth equivalent to wave base during moderate storms, which typically is about 20 m along an ocean coast (Davis and FitzGerald, 2004). Offshore bars are formed as sediment eroded from the beach is transported offshore and deposited. Offshore bars can build up as a mound of sediment and act as a break for incoming waves. Offshore bars which receive adequate sediment supply will form ridges beneath the water surface (O'Neill, 1985). Coastal dunes consist primarily of sand and form in the lee of the beach. Dunes that are the closest to the active beach are considered primary dunes and those more landward are secondary dunes. A barrier island is an offshore bar that is oriented parallel to the beach and has accumulated enough sediment to be above the normal water level. Bluffs are positive relief features that typically consist of silt, clay, sand and gravel with a possible bedrock base. The slope of the bluff can vary depending on physical characteristics of the sediments (O'Neill, 1985).

Figure 1.2. A characteristic shoreline profile, from O'Neill (1985).

Work by Kraft (1971), focused on sediment facies of Holocene coastal systems in Delaware. These Holocene sediments showed landward vertical and lateral movement indicative of transgressive sequences. Kraft (1971) made the observations that during the building cycle of berms, the internal bedding is typically horizontal or sub-horizontal well-sorted medium to coarse sand. During storm or erosional events, beach sediment can be washed over the berm into the back-barrier lagoon, and the beachface would be eroded and steepened. A typical transgressive sequence of a baymouth barrier from the surface to base is as follows: 1) an eolian cap with well-sorted fine to medium cross-bedded sand; 2) low-angle laminated beach sediment of medium to very coarse sand with gravel; 3) back-barrier peat; 4) possible tidal-delta deposits; 5) fine to medium well-sorted sand with silt laminae; 6) clay-silt lagoonal deposits; and 7) marsh deposits (Kraft, 1971). Figure 1.3 illustrates the Holocene transgressive sequence of a baymouth barrier in a transgressive shoreline environment.

Figure 1.3. Schematic of the Holocene sequence of a baymouth barrier in a transgressive shoreline environment (Kraft, 1971).

Basic stratigraphic lithofacies associated with the upper Great Lakes coastal features are reported by Baedke et al. (2004). Sand dunes or foredunes in the upper Great Lakes commonly consist of moderately to well-sorted, medium- to upper fine-grained sand. The geomorphic appearance of these dunes is linear or curved to the shoreline, and at a consistent height along their long axis (Baedke et al., 2004). A typical beach ridge in the upper Great Lakes is characterized as a curvilinear ridge of sand that is in similar orientation to modern shorelines. Beach ridges can also exist as cusped plains of sand on the flanks of tombolos (Baedke et al., 2004). The backshore in upper Great Lakes coastal environments typically has minimal

deposition, which slopes landward. The common surficial sediment would be windblown sand and would contain minor wind ripples and small aeolian bedforms (Baedke et al., 2004). The foreshore of a shoreline would commonly contain poorly sorted medium sand with granules, and possibly with gravel and cobbles depending on the local source of sediment. The coarsest-grained sediment would be located at the plunge point at the base of the beachface (Baedke et al., 2004).

Further stratigraphic information regarding the lithofacies of paleo-coastal features at the base of the beachface was documented by Fisher (2005). Lithologies from several paleoshorelines were obtained in the southern Lake Agassiz basin near the convergence of North Dakota, South Dakota and Minnesota. Cores taken into the Herman beach ridge consist of relatively thin silty sand units, which overlie a clayey silt and a diamicton. The silty sand unit appears to be a part of a broad platform and is thickest along the crest of the ridge and begins to thin basinward (Fisher, 2005). Two cores were taken on the Tintah strandline. Cores across the Upham strandlines exhibited stratigraphy similar to the Tintah. The first core from the backshore off the crest of the ridge consisted only of diamicton sediment. The second core consisted of a thin sand and gravel, above a diamicton unit overlying laminated silty sand. The littoral sediment associated with the Upper Campbell strandlines in the southern Agassiz basin are characterized by thin sequences of laminated silty sand and thin gravel beds overlying a diamicton. In contrast, cores across the Norcross strandlines show thick sequences of laminated silty sand and sand units (Fisher, 2005). Three major explanations were proposed: 1) that the Upham spits grew quickly resulting in a short period of deposition; 2) sediment supply to the these strandlines was low because the local diamicton was clay-rich and did not provide a good source of sand, and no streams are located nearby which could have provided a sediment source;

3) wave and current turbulence could have been high enough to keep most silt and clay in suspension. To explain the low amount of littoral sediment with the Upper Campbell strandline, it was proposed that the Upper Campbell was a short-lived highstand resulting in poor sedimentation. The thick littoral deposition seen in the Norcross strandlines was best explained by: 1) a longer time interval during which sedimentation for the strandline could occur; 2) katabatic winds from the ice sheet could have enhanced longshore transport; and 3) a larger overall sediment supply or availability (Fisher, 2005).

Sequence stratigraphy of transgressive sequences was described by Catuneanu (2002). Transgressive sequences occur along a coastline when the rate of base-level rise exceeds the sedimentation rate (Catuneanu, 2002). Catuneanu (2002) described the major forces at work in a coastal setting, predominately wave erosion which produces a ravinement surface and produces an onlap and deposition. If a coastal onlap is observed in a sequence, it indicates a transgression, and topset beds indicate aggradation (Catuneanu, 2002).

The GPR reflections and stratigraphy from the shorelines of other proglacial lakes or similar coastal depositional environments provide useful analogs for expected stratigraphic and lithological facies in the Lake Erie basin.

1.7 Geomorphic Differences between Lake Arkona and Lake Whittlesey

The Arkona and Whittlesey shorelines were described by Spencer (1891) and Leverett and Taylor (1915). Previous researchers (Chapman and Putnam 1966; Calkin 1970; and Totten 1985) have described the Arkona shoreline as a low-relief discontinuous ridge with a characteristic “washed” appearance at elevations of 211, 213 and 216 m asl. Lake Whittlesey shorelines by comparison, can be best classified as well-developed and continuous ridges across much of the Lake Erie basin (Whittlesey, 1838; Chapman and Putnam 1966; Forsyth, 1959;

Calkin, 1970; Schooler, 1974; and Totten, 1985). Based on the geomorphic differences between the shorelines, a testable hypothesis is that the Whittlesey and Arkona shorelines formed under coastal and lake environments with variations of dominant physical factors of wave energy, sediment supply, and pre-existing topography.

Shoreline development is affected by several factors: wave energy and direction, sediment supply and transport, and topography of the shoreface, wind speed and fetch, erosional processes, tidal forces and relative sea level (O'Neill, 1985). The interactions and magnitudes of each of these factors will govern the geomorphic development of a given shoreline. Coastlines are by no means uniform and the shoreline development factors vary between coastal systems to produce regionally distinct coastal features.

Shoreline development factors can be applied not only to marine coastal systems but also to the Great Lakes region, with the exception of tidal forces. Measurements taken by NOAA show that spring tides produce approximately 5 cm of tidal height, which is negligible. When applying these factors to paleoshorelines, several factors can't be measured directly. Wave energy, wind speed, and sedimentation rates are measured directly as the processes are currently affecting the shoreline development. Paleoshorelines are relict systems, and as such the processes are no longer active and direct measurements of them are not possible. However, many of these factors can be inferred based on the resulting geomorphology of the shoreline. Factors such as dominant wave direction, wind direction, topography, and resultant sedimentation thicknesses and erosional features can all be directly evaluated based on the preserved paleoshorelines. This approach was applied to the Lake Arkona and Whittlesey shorelines in the western Lake Erie basin to better classify the differences between the physical environment during these two lake-level events.

Variation in geographic position within a coastal system can result in distinctly different shorelines due to variability in wave energy, tidal range, and sediment supply (Hayes 1975 and Hayes, 1979). Large littoral systems can be broken down into individual compartments (List and Terwindt, 1995, Sanderson, 1999, Bird 2008, and Pucino, 2015). It is proposed that Lake Arkona and Lake Whittlesey formed under different coastal and lake environments. To evaluate these two littoral systems, analysis of independent coastal compartments associated with each lake level was undertaken.

Coastal compartments were selected based on observations of field sites and analysis of geomorphic features observed on LiDAR-based DEMs. The parameters used to separate the individual coastal compartments are: local shoreline profile, sediment supply, and topography. The resultant profile of a relict shoreline can be generically defined as the sum total of all the littoral processes that acted on that shoreline during a given highstand. This holding true, then shorelines of a particular coastal compartment should be differentiable from shorelines of another coastal compartment. The sediment supply parameter evaluated the longshore gradient of sediment transport along individual shorelines, as well as identifying possible sources of sediment. The final parameter, topography, evaluated the local relief to characterize shorelines based on the observed changes in topography.

Shorelines of given highstand events can be quantitatively differentiated from other systems as well as differentiated internally. A statistical model was constructed to evaluate the Arkona and Whittlesey shorelines in the western Lake Erie basin. The primary goals of the model were to show statistically the differences between the Arkona and Whittlesey shorelines, aid in outlining coastal compartments of Lake Arkona and Lake Whittlesey, provide

substantiating data to field observations regarding shoreline geomorphology, and aid in the interpretation of the larger littoral systems of the two proglacial lakes.

Due to the direct sampling limitations imposed by relict shoreline systems, the differences in the shore zone and elevation profiles of the Arkona and Whittlesey shorelines were evaluated. The determination to use the shoreface as the principle factor to base the model on was Bruun (1962). Bruun's major observation was that the entire shoreface would respond to sea-level rise (Bruun, 1962). When defining physical process parameters for the numerical model, littoral processes that affect the entire shoreface were considered.

Chapter 2

Methodology

2.1 Construction of DEMs

Detailed 3-m horizontal resolution LiDAR elevation data has been obtained from the U.S. Geological Survey's *National Map Viewer*. LiDAR-based DEMs were constructed using ESRI's ArcGIS Global Mapper version 10.2. DEMs were used to identify and trace the major Lake Erie shorelines to compare with previous mapping results and evaluate glacio-isostatic adjustment (GIA). LiDAR-based DEMs provide unparalleled vertical and horizontal resolution that allow for the delineation of geomorphically subtle features. In a DEM or overland view, a strandline appears as a scarp that separates two different elevations, whereas a ridge persists as positive relief on a generally lower landscape. To differentiate these features from one another and aid in mapping strandlines and near-shore features, light angle and shading techniques were employed using ArcGIS. Strandlines are illuminated most notably from a sun angle which is oblique to the scarp face. An angle opposite the angle of maximum illumination will cause the strandline to effectively disappear and no shadow will be produced. This is caused by the inherent geometry of the strandline. Ridges will cast a shadow from light angles positioned oblique to the ridge face. Elevations of the ridges were assigned based on the break in slope between the beach and the lower shoreface of the ridge, the estimated location of the water plane.

2.2 Ground Penetrating Radar

Ground penetrating radar (GPR) was collected from six of the ten field sites totaling 3.5 km of profiles over 22 individual transects. The targets for the GPR transects were Lake Arkona and Lake Whittlesey coastal features. The application of GPR was used as a principle

investigation method into the internal stratigraphy of the observed coastal features. For ground truth, hand-auger transects, hand-dug pits and vibracores were employed to verify the GPR profiles and determine lithologic properties of the coastal features. The same GPR procedure was used at all field sites. Transects were taken in sets, with one set of transects oriented perpendicular to the long axis of the feature. Since coastal features in general form normal to the active water plane, a transect perpendicular to the long axis of the ridge is essentially a dip section that should be able to observe the depositional or erosional development of the feature. A second set of transects was also taken along the long axis of the ridge, essentially a strike section. The goal of this transect would be to evaluate the uniformity of the stratigraphy along the feature.

The Sensors and Software Inc. pulseEKKO 100 unit with a 1000V transmitter was used to collect the GPR profile data. The deployment followed the Jol and Bristow (2003) and Jol et al. (2010) method for GPR evaluation of beach ridges and coastal features. Due to the thin nature of Arkona beach deposits, a 100 MHz antenna was used exclusively for GPR data acquisition. The 100 MHz antenna sacrifices depth of penetration for an increase in vertical resolution. The basic setup of the pulseEKKO 100 unit used two operators. One operator used a rig that contained the receiver, transmitter and antennas which could be moved freely along the transect. A second operator moved a field wagon which contained the electronics console, 12V battery and computer. The console connected to the antennas via fiber optic cables. The two operators would then move in tandem along a transect. At each site GPR was deployed along two major transects as described above, with one perpendicular to the long axis of the feature extending from the basin into the backshore, and second parallel to the feature. A handheld Garmin GPS was employed to record geographic locations for the origin and terminal point for

each transect. Topographic corrections for the GPR transects were obtained using a TopCon rotating laser with a stadia rod to measure elevation every 20 m and at topographic breaks.

Processing of the GPR data was done using the Sensors and Software Inc. EKKOview Deluxe and pulseEKKO version 4.22 software. The data were dewowed, then a vertical time filter of 5 samples and a horizontal spatial filter of 3 traces were applied. Traces were time-chopped to -10 to 250 ns time chop. Topographic corrections were applied to the traces as a table of elevation vs distance data acquired from the TopCon rotating laser.

Identification of geophysical facies boundaries for this study was done using the characterization outlined by Mitchum (1977). A figure outlining the basic Mitchum facies and the comparable field facies is presented in Figure 2.1. Interpretation of the identified facies was done using the methods of Wilkins and Clement (2007), who had conducted GPR across paleo-shorelines of Lake Alvord, Oregon. Furthermore, interpretations were aided by the results and conclusions drawn from Curray (1964), Thompson and Baedke (1996) and Higley et al. (2014) who developed models for shoreline development and basic shoreline stratigraphic facies.

Figure 2.1. Common stratigraphic boundary contacts that can be observed within depositional sequences from Mitchum (1977).

2.3 Radar Facies

Five major facies were observed in the GPR profiles of this study. Radar facies are presented as RF1, RF2, RF3, RF4 and RF5 as seen in Figure 2.2. These facies relate to beach-ridge aggradational deposits or the upper ridge surface, backshore or back-barrier deposits, foreshore deposits, or lake plain. The stratigraphic features typically observed as part of the backshore or back-barrier deposits are cross bedding, planar bedding, and top-lap deposits (Mitchum, 1977). Expected beach-ridge stratigraphies are planar bedding with possible cross bedding on the upper surface if a dune cap is present. Foreshore stratigraphy is related to sequences of sigmoidal beds deposited sequentially on top of one another with possible berm-migration beds deposited on top of the sigmoidal beds. Lake plain or lagoonal deposits are expected to exhibit essentially horizontal planar bedding (Mitchum, 1977). Detailed analysis of GPR transects and a facies description of each field site is discussed below.

Figure 2.2. Radar facies with basic facies description and a lithologic interpretation.

Radar Facies 1 (RF1)

Radar Facies 1 is defined as tangential or oblique reflections with top-lap and down-lap terminations. As mentioned by Mitchell (1977), top-lap beds indicate the upper termination of an initially dipping depositional sequence. The down-lap termination is the lower termination boundary for a dipping depositional sequence and is commonly observed dipping away from the source of sediment supply (Mitchum, 1977). In a GPR profile, RF1 can be observed as

sigmoidal and dipping slightly basinward. RF1 is always found on the lakeward side of the coastal features observed in this study. The individual sigmoids tend to be strong reflections that can be easily traced in the profiles.

A common interpretation for tangential or oblique reflections in a coastal environment is related to progradation or accretion of beach or shoreface deposits, such as spit platform deposits, or in foreshore deposits (Daly et al., 2002; Jol et al., 2010 and Higley et al., 2014). The top-lap and down-lap termination points are indicators of a non-depositional hiatus (Mitchum, 1977). In the GPR transects taken during this study, RF1 is found on the lakeward side of the coastal features.

Radar Facies 2 (RF2)

Radar Facies 2 is defined as parallel lines of strong reflection. They are observed as being horizontal to dipping slightly. The reflections are generally continuous over tens of meters. These facies are commonly found beneath tangential or oblique reflections and in close proximity to hummocky reflections (Daly et al., 2002).

In a coastal setting, the interpretation of horizontally deposited beds can have several definitions. The first comes from Jol et al. (2010), a GPR profile taken across Jekyll Island, Georgia showed horizontal bedding inside the core of the island. This was interpreted as being related to vertical accretion without progradation in any specific direction. Another interpretation from Daly et al. (2002) is that parallel reflections also show aggradation of sands in prograding spits or as part of the internal structure of dune caps along coastal features. A third interpretation is that these planar beds represent basinal deposition sequences.

Radar Facies 3 (RF3)

Radar Facies 3 is defined by short discontinuous sequences of strong reflections that often overlap with variable dip directions. These surfaces are often observed as the upper surface of the highest portion of a beach ridge and are common in the backshore. These deposits are often thin and attenuate rapidly off the top of the upper surface of a beach ridge.

Hummocky reflections have been attributed to cross bedding that occurs within coastal dune structures (Daly et al., 2002). If the dune deposit on a coastal feature is thin or discontinuous, the reflection may not produce clear cross bedding. Often the reflections are discontinuous and short, with only one or two major dip directions or mound being recorded (Daly et al., 2002). GPR analysis of the Lake Warren shoreline produced similar radar facies that also were attributed to dune deposits overlying littoral sediment (Campbell, 2009 and Higley et al., 2014). Due to the lack of sediment thickness in many of the field sites, the RF3 may be represented by a single reflection. The interpretation that a reflection is a RF3 is related to ground truth at that location.

Radar Facies 4 (RF4)

Radar Facies 4 typically is a strong reflecting surface that has no strong reflections below it. Those reflections that are observed are severely attenuated and produce a weak reflection. RF4 is typically present beneath a relatively strong reflector associated with RF1, RF2, or RF3. RF4 is observed in the lake plain beneath RF2, or as the base of backshore deposits and lagoonal deposits.

A surface that commonly produces a weak or poor reflection in a coastal environment is often attributed to saline water infiltrated into sediment or as silt/clay depositional unit (Daly et al., 2002; Jol et al., 2010). As mentioned by Jol et al. (2010), GPR signals can be rapidly

attenuated by silt and clay-rich sediments which would result in a poor reflection. The cause of the attenuated GPR signal in this study is not attributed to the infiltration of saline water since these are coastal systems of a fresh water lake. Instead, the presence of RF4 will generally indicate the contact with the stiff clay/silt diamicton present in the region. The unevenness of the upper surface of the diamicton can be attributed to erosional processes related to transgressing waters or possibly uneven surface deposition of the diamicton.

Radar Facies 5 (RF5)

Radar Facies 5 is characterized by short, discontinuous, sub-horizontal, strong reflections. RF5 is often in close proximity to sigmoidal or tangential/oblique reflections. The individual reflections within this unit typically overlap and produce a layered appearance. This facies is interpreted geomorphologically as vertical accretion of littoral sediments produced from the landward migration of a shoreline or the progradation of a spit platform. In another study conducted in the Lake Erie basin, Campbell (2009) and Higley et al., (2014) identified a similar radar facies that was attributed to littoral deposition of the Lake Warren shoreline. When observed on the upper surface of a coastal feature, RF5 becomes extremely difficult to distinguish from RF3 due to the shallow nature of many of the Arkona shoreline deposits.

2.4 Hand-Auger Transects

Hand-auger transects were employed when possible along the GPR transects to provide ground truth for the GPR reflections. Auger transects were used to evaluate grain size, sediment color, clast characteristics, thickness of deposits, and any sedimentary contacts. This information was used to aid in the interpretation of the GPR transects. Where auger transects were unable to be taken, hand-dug pits or isolated auger holes were dug to provide complementary data to the geophysical data.

2.5 Vibracores

Vibracores were employed when the sedimentary resolution of a hand auger was insufficient to evaluate the internal stratigraphy of a shoreline deposit. Vibracores are targeted instruments that allow for the evaluation of the sedimentary structures. To maximize the efficiency of the research, the vibracores were employed after geophysical data acquisition. The geophysical data provided locations and targets for the vibracore. The basic set-up and operation of the vibracore are shown in Figure 2.3. Sediment samples were extracted from the vibracore to obtain the Wentworth sedimentary class size (Fisher, 2004). The naming convention is as follows: the first two letters represent the field site ID number (corresponding to field notes), first number is core number, the next sequence of numbers represents the one-number month, two-number day and two-number year when the core was taken (e.g., 41016 equates to April 10, 2016).

Figure 2.3. Vibracore basic setup and operation. A: Basic setup for the vibracore operation. B: Shows JP Finnegan assisting with the operation of the vibracore on the agricultural field at Field Site 6.

2.6 Wentworth Sediment-Size Analysis

The Malvern Mastersizer 2000 laser diffraction system and Hydro 2000UM dispersion unit were used to determine the Wentworth sedimentary grain sizes. Sample preparation followed the method outlined by Bobak (2010). Samples were placed in capped tubes and mixed with 5 mL of 4% sodium hexametaphosphate (Calgon) which served as a deflocculant. Samples were then spun in a centrifuge to ensure adequate mixing of the sample and deflocculant, and allowed to sit for 12 hours. The prepared samples were added into the Hydro2000UM for final dispersion and introduction to the Malvern Mastersizer 2000 diffraction laser for grain-size analysis. Wentworth sedimentary grain sizes for all acquired samples are listed in the Appendix.

2.7 Optically Stimulated Luminescence

The method for optically stimulated luminescence (OSL) sample collection and testing follows the process detailed by Aitken (1998). OSL measures the last time a sediment sample was exposed to sunlight by measuring the amount of energy stored in the defects of the crystalline lattice of quartz or feldspar. This energy is released and measured in the laboratory by stimulating the sample with laser light. Pits were dug through the Arkona and Whittlesey beach ridges to observe the stratigraphy (Figure 2.4). Based on the observed stratigraphy, OSL targets were selected from sand units associated with the plunge point of the beach ridge (Thompson and Baedke, 1995). OSL ages from Arkona and Whittlesey beach ridges will help to better constrain the overall lake-level curve. The best targets for the OSL samples are fine-grained sand beneath the shoreline scarp or spit complex.

Figure 2.4. OSL pit examples. A: Brian Samsen digging the OSL pit along the crest of the Arkona barrier island at Field Site 2. B: Mitchell Dziekan and Jonathon Luczak digging a pit into the crest of the Arkona shoreline along Richfield Center Road, Sylvania, OH at Field Site 4.

Beneath the shorelines should be a unit of predominately sand which could provide as a suitable OSL sample. Potential errors that could occur from OSL dating can be related to errors in sampling procedures. To avoid potential errors, samples were taken from the middle of the desired sand unit. This reduced the likelihood that the sample would include sediment that had been reworked (partial bleaching) at a transition surface. Sand stratigraphic units associated with the body of the barrier island or spit complex were evaluated. Sampling the incorrect unit or a portion of the incorrect unit may result in the OSL ages derived from those samples being either too old or too young to accurately date the desired feature.

Chapter 3

Results from Field Sites

3.1 Introduction for Field Sites 1 & 2

The Arkona strandlines as defined by past research are low-relief, discontinuous ridges, often with poorly defined geomorphology (Spencer, 1891; Leverett and Taylor, 1915). A traditional example of the appearance of the Arkona strandline can be observed in the southwestern Lake Erie basin. Approximately seven low-relief discontinuous ridges can be observed between the cities of Napoleon and Bowling Green, OH. Preliminary analysis of the ridges began with DEM observations and geomorphic descriptions of the individual ridges. Two field sites were selected and labeled Site 1 and Site 2 on Figure 3.1. Field site investigations include hand-auger transects, vibracores, hand-dug pits, OSL collection, and GPR profiles. The elevation legend for Figure 3.1 is shown in Figure 3.1b, and the elevation legend for all field-site DEMs is shown in Figure 3.2.

Geomorphology from DEMs

The entire sequence of discontinuous ridges occurs over approximately 21 km between the cities of Napoleon and Bowling Green, OH. On average the ridges rise 1-2 m in height and are between 1.2 km and 2.7 km in length along the long axis of the ridge. The elevations of the ridges are 211 m asl, which is consistent with the lowest-elevation Arkona shoreline (Spencer, 1891). Approximately 10 km to the south of the ridges is the Whittlesey shoreline, and approximately 12 km to the north of the ridges is the valley of the Maumee River. These two features establish a geographic boundary for the region. From the Whittlesey shoreline to the Arkona ridges is a change of approximately 10 m in elevation, which produces a gently sloping

surface between the two lake levels. A change of 9 to 10 m in elevation is observed between the Arkona ridges and the current Maumee River valley, and produces a more gradual elevation change than the Whittlesey to the Arkona. The area north of the ridges is defined as the Arkona lake plain or lake basin, and the region to the south of the ridges is defined as the back barrier or back shore. Two tributary streams to the Maumee River cut through the ridge sequence, South Turkey Foot Creek and Beaver Creek. Between the tributaries are the locations of the largest of the seven ridges.

In the expanse between the Whittlesey and Arkona shorelines, there are linear ridges ranging from 0.5 km to 3.5 km in length and 0.25 m to 1 m in height. The ridges have a northeastern orientation. Similar lineations can be observed north of the Arkona ridges. These lineations are 0.2 km to 0.75 km in length and 0.25 m to 1 m in height with a northeastern orientation.

Figure 3.1. A regional DEM of the western Lake Erie basin was constructed using 3-m resolution LiDAR data from the USGS National Mapviewer. Mapped Whittlesey shorelines are denoted by the violet lines and Arkona shorelines are denoted by black lines. Field study Sites 1-9 are labeled as white boxes. Study Site 10 was in the central Lake Erie basin near Perry, OH, approximately 55 km northeast of Cleveland, OH.

Figure 3.1b. Elevation classifications for the regional DEM of the western Lake Erie basin.

Figure 3.2. Elevation classifications for all field-site DEMs.

3.2 Field Site 1, Beaver Creek Arkona-Elevation Ridge

The first field site is located 9 km due east of Field Site 2 along County Road J. Field Site 2 is located on an agricultural field south of County Road J and to the west of Beaver Creek (Figure 3.3). The principle feature of this field site is a 2.4 km long semi-sinuuous ridge oriented in a west-east direction with a height of 2.1 m. The base of the ridge is located at 211 m asl, which is consistent with the elevation of the lowest Arkona shoreline. The ends of the ridge bend to the south with the steepest gradient being the northwestern face of the ridge. The crest of the ridge is not at a consistent elevation, it varies from 211 m asl in the west to close to 216 m asl at its highest point. To provide a better visualization of the low-relief ridge that shows its geomorphology, a 3D shaded rendering is presented in Figure 3.4.

Figure 3.3. DEM of an Arkona shoreline southeast of Malinta, OH near Beaver Creek. Proposed dominant wave direction denoted by white arrows. Locations of GPR and auger transects denoted by the dotted and solid light and medium gray lines. The number 1 denotes the vibracore BV141016 and 2 represents BV241016. P1 represents the hand dug pit. The dashed red line denotes a small platform of fine-grained sand wrapping around the distal end of the ridge. The violet dashed line denotes one of the many linear ridges present throughout the area with a general orientation of ENE to WSW.

Figure 3.4. Three-dimensional shaded rendering of the Arkona-elevation ridge near Beaver Creek. Dominant wave direction is indicated by the white dashed lines.

3.3 Field Site 1 GPR

Four GPR transects were taken over the ridge in Field Site 1. The first transect labeled BV-01 started at the plunge point at the base of the foreshore deposits over the top of the ridge onto the lower surface south of the ridge. Two transects were taken from the base of the ridge and extend north into the lake plain. These transects are referred as BV-03 and BV-04. These two transects ran parallel and were laterally offset by approximately 40 m. The final transect, referred to as BV-02, was taken along the long axis of the ridge and crossed transect BV-01.

Transect BV-01

GPR transect BV-01 was taken across 265 meters of the ridge perpendicular to the long axis of the ridge. With the working hypothesis that this geomorphic feature is a barrier island, the target of BV-01 was to investigate the internal stratigraphy of the main ridge and back-barrier structure. The first 20 m of the profile produces parallel planar reflections attributed to RF2. This section of the ridge is attributed to a shallow-water environment on top of a thin sand body that wraps around the eastern end of the feature. Progressing onto the front of the ridge (the north side) tangential-oblique reflections of RF1 are observed extending up to the upper surface of the ridge. Overlapping discontinuous reflections can be observed beneath RF1. These facies are attributed to shoreface depositional processes and classified as sub-horizontal RF5. Based on ground truthing, these sediments are medium- to fine-grained sands, which is consistent with beach sediments. Exposed on all the surficial quadrants of the ridge there are coarse granules, pebbles with the occasional cobble. The planar beds near the crest of the ridge represent the aggradation of the barrier island. The central section of the ridge, moving into the back-barrier (landward, toward the south) exhibits RF5. This is interpreted as aggradation of medium-grained sand deposited by overwash as the barrier island was formed. This surficial layer of sediment

has a significant component of coarse sand, and common granules and pebbles; a few small cobbles are also exposed at the surface. Underlying all the observed radar facies is the abrupt attenuation associated to RF4. Based on contact depth between the other radar facies and RF4 and the ground truthing of the site, the sediment most likely attributed with RF4 is the glacially derived diamicton unit. No strong reflection was observed within this GPR profile that truncated and interrupted the structure of the sequence interpreted as a barrier island. This leads to the conclusion based on ground truthing and GPR reflections that no ravinement surface is present indicating the barrier island was overtopped by a higher lake stand. The GPR profile and facies classification are presented in Figure 3.5.

Transect BV-02

GPR transect BV-02 was taken along 110 meters of the long axis of the ridge. The first major reflection is related to the air wave and the ground surface reflection (Jol et al., 2010). Planar bedding is observed throughout this unit that is indicative of observing a strike section across the dipping sigmoidal beds of the shoreface. The reflecting surfaces observed from this profile are RF1 with RF5 below. The reflections are strong and continuous across the profile. The planar beds dip slightly to the west and east following the contour of the ridge. Small troughs are observed within the reflections; these troughs can be the result of uneven deposition or erosional channels produced by overwash flow from storm events. The lowest reflections are attributed to RF4. The crucial evidence provided by this profile is that the internal stratigraphy of the ridge is continuous over a distance and is not disturbed or interrupted by a large erosional event. The GPR profile and facies classification are presented in Figure 3.5. As with the profiles perpendicular to the long axis of the ridge, these axis-parallel profiles are consistent with the expected structure of a low-relief barrier island.

Figure 3.5. GPR profiles and the interpretation for transects BV-01 and BV-02. Location of hand-augers are noted by black arrows, black boxes indicate locations of hand-dug pits and vibracores. OSL sample was collected from the hand-dug pit, indicated by the white circle. A lithologic description and facies interpretation (dashed box, I) is presented in Figure 3.5b.

Figure 3.5b. Basic lithology and facies classification for the GPR profile represented in the dashed box I on BV-01 (Figure 3.5).

Transect BV-03

GPR transect BV-03 was taken perpendicular to the water plane and extends 170 m across the ridge, beginning on the lake plain to the north and continuing across the face of the ridge and a platform of fine-grained sand that wraps around the eastern edge of the barrier island. The first major facies observed in the GPR profile is RF1 (Figure 3.6). RF1 structures lap onto the underlying reflections on the upper section of the sand platform. Based on the ground truth, the sediment associated with the RF1 surface is fine-grained sand. The sand becomes progressively finer grained with closer proximity to the basin. The RF1 reflections across the platform of fine-grained sand is finer than the sand obtained from the crest of the ridge with less coarse grained sand granules. Underlying the other reflections is RF4, which is attributed to an erosional surface at the top of the diamicton. No ravinement surface is present that truncates any of the above facies. The GPR profile and facies are presented in Figure 3.6.

Figure 3.6. The GPR profile and the interpretation for transect BV-03. Arrows indicate hand-auger holes. A lithologic description and facies interpretation (dashed box, J) is presented in Figure 3.6b.

Figure 3.6b. Basic lithology and facies classification for the GPR profile represented in the dashed box J in Figure 3.6. Hand-auger holes denoted by black arrows.

Transect BV-04

GPR transect BV-04 was taken parallel to BV-03 and offset 40 m to the east. BV-04 is approximately 135 m long and in comparison to BV-03, it begins closer to the north edge of the

sand platform surrounding the eastern portion of the barrier island. In profile BV-04, the beginning 20 m to 30 m exhibits planar bedding associated with RF2. The RF2 structure is interpreted as lake plain depositional stratigraphy. Beneath the planar reflections are tangential oblique beds that extend onto the upper face of the sand platform where the reflections begin to attenuate. The sigmoidal beds are attributed to RF1. The sediment associated with the tangential oblique is fine-grained sand with interspersed 1 - 3 mm coarse grained sand grains. Consistent with the other three transects, the erosional surface at the top of diamicton represented by RF4 underlies the entire sequence. As with BV-03, no ravinement surface or strong reflection indicative of an erosional surface is present that truncates the radar facies. The GPR profile and facies classification are presented in Figure 3.7.

Figure 3.7. GPR profile and the interpretation for transect BV-04. Arrows indicate the locations of hand-auger holes. A lithologic description and facies interpretation (dashed box, K) is presented in Figure 3.7b.

Figure 3.7b. Basic lithology and facies classification for the GPR profile represented in the dashed box K in Figure 3.7. Hand-auger holes denoted by black arrows.

Discussion of the GPR Profiles from Field Site 1

Based on the observed radar facies and ground truth obtained at this field site, it is determined that this barrier island was not transgressed by a subsequent higher lake stand. No prominent ravinement surface is present that truncates the depositional sequence or the internal stratigraphy of the barrier island. It is proposed that the barrier island was formed during a single lake highstand. The sand platform that wraps around the eastern end of the barrier island was deposited by both longshore transport and direct wave transport. Fine-grained sand is commonly found in longshore drift and based on the geomorphology of the platform, the sand was most likely being worked into a prograding spit off the eastern edge of the barrier island. The barrier island itself consists of landward aggradational deposits of medium- to fine-grained sand from overwash building from a diamicton base. The north face of the barrier island has sigmoidal beds that prograde basinward, which is interpreted as the foreshore.

3.4 Field Site 1 Hand-Auger Transect and Hand-Dug Pit

The initial investigation into the stratigraphy of the ridge at Site 1 was done along a 500-m long hand-auger transect with auger hole spacing at approximately 60 m. Due to the limitations of augering to preserve internal bedding of lithologic units, several vibracores and a single hand-dug pit, and GPR transects were employed across the ridge. The location of the hand-auger transect is shown on Figure 3.3.

Four major lithostratigraphic units were observed based on the results of the hand-auger transect. The uppermost, Unit A is an approximately 30-40 cm thick soil with a dark brown or black completion. Unit A is rich in organics (roots and plant fibers abundant throughout) and is consistent with the Holocene agricultural soil found in the region. Unit A and the upper 4 cm of Unit B are within the plow zone. On the sandy surface of Unit A are coarse granules and pebbles, and sparse cobbles, of varied lithology. The coarse gravel and pebbles are found on the surface of all sides of the ridge with no exception. The second, Unit B is found beneath Unit A, and is characterized as a medium- to fine-grained, well-rounded, oxidized sand unit with a mottled appearance and a thickness ranging from 8 to 35 cm. Unit B is thickest along the crest of the ridge and becomes progressively thinner with distance from the crest of the ridge. The third, Unit C is found beneath Unit B and is characterized by a medium- to fine-grained, well-rounded, and oxidized sand unit. Unit C is thickest at the crest of the ridge at 60 cm and thins with distance from the ridge. The fourth, Unit D is the bottom lithologic unit and is characterized by a stiff, medium sand/silt unit with a significant clay matrix, and 1 mm to 2 mm sand grains are present in the auger samples. The water table is commonly found at the depth of Unit D so the thickness of Unit D is presently unknown.

Hand-Dug Pit

A 1.52-m deep hand-dug pit was dug on the crest of the ridge. Four major lithologic units were identified, based on the stratigraphy observed in the pit, Units A, B, C and D (Figure 3.8a). Unit A is a dark brown, organic rich soil with in-situ roots present. Unit A is consistent with the agricultural soil of the area (Figure 3.8b). Unit B is 56 cm thick and characterized by a mottled general appearance. Unit B's lithology is an oxidized, well-rounded, fine- to medium-grained sand with a silt matrix. Unit C is 58 cm thick and consists of a well-rounded, gray, near-pure fine- to medium-grained sand unit (90% fine-grained sand). Planar laminations are observed within Unit C, which would be consistent with the stratigraphic features expected in the lower section of a low-relief barrier island (Daly et al., 2002). OSL sample UT1601JD was taken from Unit C at a depth of 1 m in an effort to date the Arkona shoreline in this region. The resultant age of that sample is 10.9 ± 0.4 ka. The fourth lithologic unit is Unit D, the thickness of which is unknown. The transition between Unit C and D is abrupt, leading to the interpretation as an erosional contact. Unit D is lithologically characterized as a stiff medium sand/silt unit with a significant clay matrix, with randomly distributed, varied lithology, 1 mm to 2 mm sand. At the time the pit was dug, the local water table was found at the depth of Unit D. A characterization of the hand-dug pit and pit images are presented in Figure 3.8.

Figure 3.8. Hand-dug pit description, characterization and designations of lithologic units. The OSL sample JDUT16-1 was taken just below the C horizon transition to the medium- to fine-grained sand unit. Panels A, B, C and D presented in Figure 3.8b correspond with the locations of images I through IV respectively, shown in this figure.

Figure 3.8b. Panels A, B, C and D represent images taken from the hand-dug pit in Figure 3.8. The letters of the panels correspond to the roman numerals I - IV in Figure 3.8. Note that the sands in panels B and C show a mottled character.

3.5 Field Site 1 Vibracores

To investigate the internal stratigraphy of the ridge and provide additional ground truth for the GPR, two vibracores were collected along the crest of the ridge in tandem with the GPR transects. The two cores are named BV141016 and BV241016.

Description of core BV141016

The first 33 cm of core BV141016 is an organic-rich soil with in situ organics (roots, plant fibers). The coloration is dark brown to black, and corresponds to the auger Unit A as the Holocene agricultural soil. At 33 to 41 cm there is a gradual transition to oxidized sand. Within

this gradual transition zone, leaching and root bioturbation are observed. Unit B occurs between depth 41 to 56.5 cm. Grain size analysis of Unit B from particle samples BV1-8 indicates the lithology is 82% fine sand, 8% medium sand and 10% silt/clay sized grains. Unit B can be described as an oxidized, well-rounded sand unit with a mottled appearance. Unit B represents the lithologic facies for GPR facies RF1. Unit C occurs from 56.5 to 148 cm and is characterized by particle samples BV1-2, 3, 5 and 6; particle size data are presented in the Appendix. The grain size distribution from the particle samples showed that on average the lithology of this unit is approximately 90% fine-grained sand with a small percentage of medium to coarse sand, and approximately 10% silt and clay sized particles. Unit C is oxidized, well-rounded, fine-grained sand with a silt matrix. The bottom 36 cm of this unit has interbedded silt laminae. Unit C represents the lithologic facies for GPR facies RF5. Unit D occurs from 148 to 149 cm; there is an abrupt wavy erosional surface separating the two lithologic units C and D. From 149 cm to the bottom of the core, the lithologic unit is characterized by medium sand/silt with a significant clay matrix, and 1 to 2 mm grains present in the core. This lithologic unit best corresponds to Unit D in the hand-dug pit. Unit D represents the lithologic facies associated with GPR facies RF4. The lithologic facies observed in this core is comparable to the lithology observed in the hand-dug pit. Core image and characterization are presented in Figure 3.9.

Figure 3.9. Image and description of core BV141016. Sediment samples taken from the core and descriptions of each sample are listed in the Appendix. Basic core lithologic characterization and a brief description are adjacent to the core image. Panels I, II and III display close up views of the core presented in Figure 3.9b.

Figure 3.9b. Close-up views of the main body of core BV141016. Panels I, II and III correlate to the same numerals in Figure 3.9. Panel I shows the oxidized, mottled fine- to medium-grained sand which makes up the bulk of the core. Panel II shows the same sand unit as panel I with near horizontally bedded silt bands. Panel III shows the contact between the fine- to medium-grained sand and a diamicton at the base.

Description of core BV241016

The first 29.75 cm of the core is a dark brown to black, organic-rich soil with in situ organics (roots, plant fibers) and corresponds to the auger Unit A as the agricultural soil of the area. At 30 to 52 cm there is a gradual transition boundary with root bioturbation present. Unit B is observed from 52 cm to 94 cm. Unit B is characterized by five particle samples BV2-9, 8, 7, 6 and 5; particle size data are presented in the Appendix. Sample depths are as follows: BV2-9 was taken at 58 cm; BV2-8 at 71cm; BV2-7 at 86 cm, and BV2-6 at 104 cm. Unit B's grain size distributions from these samples average 80% fine-grained sand, 14% silt and 6% clay-sized particles for this unit. Unit B is described as an oxidized, well-rounded, sand with a mottled appearance. This unit corresponds to the auger Unit B. The upper 30 cm represents the lithologic facies for GPR facies RF1 and the lower portion of Unit B represents the GPR facies RF5. A gradual transition to the next unit occurs at an approximate depth of 94 to 99 cm. From

99 to 160 cm, an additional lithologic Unit C is observed. Particle analysis of this unit was done from samples BV2-3, 2, 1 for the body of the unit, and BV2-4 was taken from a fine-grained lamina. Based on the particle analysis, the body of this unit is approximately 85% fine-sand, 5% medium sand, and 5% silt/clay grains. BV2-4 taken from the fine-grained lamina resulted in the grain distribution of 85% fine sand to coarse silt, 10% silt and 5% clay grains. Unit B is described as being predominantly well-rounded, oxidized fine-grained sand with interbedded silt laminae. The convex bend is a deformation of the silt laminae due to the mechanics of the vibrocore operation. It is presumed that the silt laminae were originally deposited in horizontal bands. Unit C is the lithologic facies that correlates with the GPR facies RF5. Core image and characterization are presented in Figure 3.10.

Figure 3.10. Image and description of core BV241016. Sediment samples taken from the core and descriptions of each sample are listed in the Appendix. Basic core lithologic characterization and a brief description are shown adjacent to the core image. Panels I, II and III display close-up views of the core presented in Figure 3.10b.

Figure 3.10b. Close up views of the main body of core BV241016. Panels I, II and III correlate to the same numerals in Figure 3.10. Panel I shows the oxidized, mottled fine- to medium-grained sand which makes up the bulk of the core. Panel II shows the same sand unit as panel I with convexly bent silt bands. Panel III shows fine- to medium-grained sand with silt planar beds.

3.6 Discussion of Field Site 1

The first site is located to the southeast of Malinta, OH, near Beaver Creek. The primary geographic feature on this field site was an east-west trending ridge at the elevation of the Arkona shoreline. Before a final conclusion as to the genesis of the ridge, basic lithologic facies attributed with a shoreline or beach (if sand dominated) will be discussed. There are four major components of a shoreline or beach ridge which should have lithologic signatures observable in ground truth exploration. The dune unit is often a “cap” of well-sorted fine-grained sand, typically with a frosted appearance indicating aeolian transport. It is also possible for a shoreline to form without dune caps when energy and sediment supply are low (Otvos, 1999). The foreshore is defined as the region in the front of the crest of the ridge that extends into the basin. The base of the foreshore indicates a break point for wave action (Davidson-Arnott, 2010). Foreshore deposits from relict shorelines in the Lake Michigan and Lake Huron basins indicate that the sediment is generally fine- to medium-grained sand that fines toward the lake plain from the crest of the ridge (Baedke and Thompson, 2004). Pockets of coarse-grained sediment also may occur at the inflection point of the foreshore, dubbed the plunge point. The backshore is

defined as the relatively flat area behind the crest of the ridge, and often contains finer-grained sediments than what is found in the foreshore. This is directly related to the depletion of wave energy at the foreshore to the backshore and the drop of suspension competency of the moving water as the waves flow over the barrier during storms.

The lithology and stratigraphic information obtained from geophysical methods and ground truth will now be discussed. Lithologic Unit A can be largely discounted from the stratigraphic sequence since it is a modern agricultural soil that postdates the ridge formation. However, coarse gravel and pebbles with sparse cobbles are observed on all surfaces of the ridge. These larger grains are significant for interpreting the formation of the ridge. The first surface encountered in the GPR facies is RF1 that is defined as tangential or oblique reflections commonly associated with progradation or accretion of beach or upper shoreface deposits (Mitchum, 1977; Daly et al., 2002; Jol et al., 2010). RF1 can be traced from the basinward side of the ridge to the base of the ridge. The next unit that begins in the basinward side of the ridge and continues into the main body of the ridge is RF2. RF2 is defined as horizontal beds associated with vertical aggradation of the base of a barrier island (Daly et al., 2002; Jol et al., 2010). The next facies is RF5, and it is found in the central section of the ridge and extends into the backshore. RF5 is indicative of vertical accretion of the main body of a barrier (Mitchum, 1977; Campbell, 2009). The lithology of these facies is oxidized, well-sorted, fine-grained sand with a silt/clay component and, significantly, the individual sand grains do not exhibit frosting. The lithology observed in Units B and C, as correlated with the GPR facies, is best interpreted as vertical aggradation of sand in a littoral setting to create the base of a barrier island. Distributed regularly throughout the fine grained sand unit are 1 - 2 mm coarse sand to granules. Prior to grain size analysis of these coarser grains were removed using a fine sieve. Pebbles of varied

lithology and occasionally cobbles can be found on the surface of the proposed barrier island with no side of the feature being excluded. Neither the lithology nor stratigraphy is consistent with what should be expected within a dune deposit. The lithologic facies are not homogeneously fine-grained, well-sorted, frosted sand grains. The coarse gravel and pebbles, with occasional cobbles, that appear across the entire surface of the ridge is inconsistent with the lithology of a dune. However, they are consistent with a coarse lag produced by eolian deflation of barrier-island deposits. Also, the GPR facies do not show hummocky reflections which are indicative of dunes (Kraft, 1971; O'Neill, 1985; Daly et al., 2002; Baedke et al., 2004). Further, the land surface on the ridge does not have mounds and swales that might indicate a dune field or even isolated, low dunes.

Taking together the geomorphology, GPR stratigraphy, and lithology, the most consistent interpretation of the ridge at Site 1 is a barrier island associated with Lake Arkona. The GPR facies and the lithology on the crest of the ridge are consistent with the vertical aggradation of sand that is associated with the development of a barrier island or set of beach ridges (Beaumont, 1845; Otvos, 1980; Smith et al., 2010). Fine-grained sand with a silt matrix recovered from the foreshore of the ridge is consistent with the sediment facies expected from the foreshore on the basinward side of the barrier island, with a sharp contact between the foreshore deposits and beach ridge deposits (Smith et al., 2010). The silt laminae found at the base of Unit B on the lee side (landward side) of the ridge are interpreted as storm overwash deposits. During periods of high-energy wave action, such as during storms, water could overtop the ridge to deposit sand on the lee of the ridge defined as the backshore. The energy loss by waves flowing over the barrier island would result in the loss of suspension and deposition of coarser sediments such as sand grains. As the water flow velocities decrease in the backshore, fine-grained sediments such as

silt and clay would settle out of suspension and be deposited. Although thin, the silt units appear mostly homogeneous with a slightly coarsening upward trend. The result of periodic overwash events would result in sequences of fine-grained laminated sediments being deposited in the backshore. Both Unit B and Unit C are predominantly well-sorted, fine- to medium-grained sand, and are consistent with the expected lithology of beach sands. This sand unit becomes progressively finer in grain size on the lower elevation platform that wraps around the eastern edge of the ridge. This very low-relief platform extends east of the main ridge into an incised valley presently occupied by Beaver Creek. The platform then spreads as a wider apron that wraps around into the shallow back-barrier. Longshore transport along the basin side of the barrier island exposed to wave action could cause sediment to wrap around the distal ends of the ridge, resulting in a localized spit platform to form off either end of the barrier island (O'Neill, 1985; Daly et al., 2002). Silt laminae and thin sand couplets are also observed on the back crest of the ridge and in the sand units on the lee side of the ridge, which is consistent with a subaqueous overwash platform.

The only unit that does not fit the typical depositional model of a barrier island is the deepest unit observed in the ground truth. The contact between the ridge sediments and the lowest unit, Unit D, is a sharp and abrupt contact, which implies an erosional surface between units. The lithologic description of Unit D is synonymous with a diamicton. As defined by Bennett and Glasser (2009), a diamicton is a non-sorted or poorly sorted unconsolidated but commonly densely compacted, sediment that contains a wide range of particle sizes for which no genesis is presumed. It is beyond the scope of this research to assign genesis to the diamicton unit. However, diamictons are generally formed under few conditions, one being glacial processes. It can be assumed based on the glacial origin of the Lake Erie basin that this

diamicton is most probably related to glacial deposition or compacted glacial-lacustrine sediment. It can be assumed that the processes that would have been required to form the diamicton would have preceded deposition of any proglacial sediment in the Lake Erie basin. Since there are no erosional contacts within the sediment above the diamicton, then the sedimentation sequence of the barrier island can be considered uninterrupted and complete. The diamicton would have predated any proglacial lake sediments therefore, no lake sediment associated with the proglacial lake sequence illustrated in the traditional lake-level model of Lake Erie would be found beneath the diamicton units. This implies that a complete sedimentation sequence has been observed in the sediments preserved in the barrier island at Field Site 1.

3.7 Field Site 2, Malinta, OH, Arkona-Elevation Ridge

The second site is located to the southeast of Malinta, OH, on an agricultural field northeast of the intersection of Country Road 8 and County Road J (Figure 3.11). The principle feature of this field site is a 1.2-km long, semi-sinuuous, 2-m high ridge oriented in a west-east direction. The ridge persists at an elevation of 211 m asl, which is consistent with the elevation of the lowest Arkona shoreline. The edges of the ridge curve slightly to the south and the northwestern face of the ridge exhibits the steepest gradient and highest elevation points.

Figure 3.11. A: DEM of an Arkona shoreline southeast of Malinta, OH. Proposed dominant wave direction denoted by white arrows. Locations of GPR transect is denoted by a solid black line, and hand-auger transect is denoted by a dotted line. B: Aerial image of the field site was acquired from Google Earth. Shoreline is denoted by the dashed black line.

3.8 Field Site 2 GPR

A single GPR transect RA-01 was collected at Field Site 1. RA-01 is 350 m long and was taken perpendicular to the long axis of the ridge, starting in the lake plain and progressing over the crest of the ridge into the backshore. The principle objective of this GPR profile was to observe the internal stratigraphy of the ridge and investigate for a strong reflection indicative of a transgression.

Transect RA-1

GPR transect RA-1 began on the basin side (north) of the ridge and progressed southward over the top of the ridge into the lower area south of the ridge. The uppermost reflection (not associated with the surface waves) is identified as the horizontal beds of RF2. This radar facies

is congruent with stratigraphic features that would be found in the back-shore environment of a barrier island. The RF2 found on the upper surface of the ridge is consistent with landward aggradation of the ridge, as a barrier island. The tangential-oblique reflections of RF1 are observed to pinch out into the lake plain. RF1 is observed in the shoreface of the ridge and is interpreted as a basinward progradation of the foreshore in a sediment-poor environment. RF5 is also observed within the core of the ridge as subhorizontal reflections directly beneath and lateral to RF1 surfaces. Underlying the radar facies of the body of the ridge is a sharp termination associated with RF4, which is determined to be the contact with the diamicton observed in the ground truth. As with the interpretation of the internal geometry of the ridge at Site 1, the radar facies from Site 2 are consistent with the interpretation of this feature as a barrier island. Based on the radar facies, no ravinement surface is observed that truncates the deposits of the barrier island. Based on the ground truth and the GPR, the central ridge is mainly fine- to medium-grained sand, with uninterrupted landward and vertical accretion. Although the overall sequence is considerably thinner than the ridge at Site 1, this feature also has internal bedding that is consistent with that expected in a low-relief barrier island. No evidence is found that supports the interpretation of transgression and overtopping by a higher lake stand. The 350 m GPR profile and facies classification are presented in Figures 3.12 and 3.12b.

Figure 3.12. GPR profile and interpretation for transect Ra-1a. Arrows indicate the locations of hand-auger holes.

Figure 3.12b. GPR profile and interpretation for transect Ra-1b. Arrows indicate the locations of hand-auger holes.

Hand-Auger Transect

The stratigraphy of the ridge was investigated using a hand-auger transect across the long axis of the ridge. The transect was 360 m in length with a hole spacing of 60 m. The auger transect ran parallel to the ground penetrating radar survey.

Three main lithostratigraphic units were observed based on the results of the auger transect. The uppermost, Unit A is a 60-cm thick soil unit with a dark brown to black completion with in-situ organics and roots. Found on the top of Unit A is a granules with varied lithology. Unit A is consistent with the agricultural soil present throughout the area. Unit A is

within the plow zone for this area. The second, Unit B is a medium- to fine-grained, well-sorted, oxidized sand unit, which is consistently beneath Unit A. Unit B is below the plow zone, so the internal lithology is not considered compromised by anthropogenic disturbance. Unit B is thickest (120 cm) on the crest of the ridge and is thinnest on the south side of the ridge (30 cm). Based on the auger transect, it is apparent that Unit B pinches out on the south and north sides of the ridge. Small silt laminae are observed in the lower 20-30 cm of Unit B on the south (landward) side of the ridge. The third, Unit C is found throughout the auger transect beneath Unit B. Unit C is a stiff, medium sand/silt unit with a significant clay matrix, 2-mm grains are present. This unit shares the same lithologic description as the diamicton at Field Site 1. Commonly the regional water table is found at the depth of Unit C, so the thickness of Unit C is unknown. Due to the limitations of hand augering, the internal stratigraphy of the individual units is not well preserved.

3.9 Discussion of Field Site 2

The second site is located to the southeast of Malinta, OH, on an agricultural field with the principle feature being a low-relief ridge at the elevation of the Arkona shoreline. The general geomorphic description of the ridge in Field Site 2 is similar to the description of the ridge in Field Site 1 in both lithology and GPR facies. Again, the geomorphology, lithology and stratigraphy are consistent with the interpretation of the ridge at Site 1. Even though the barrier island at Beaver Creek was thin, this ridge is thinner, indicating an even more limited sediment supply.

3.10 Discussion of Field Sites 1 and 2

In a mixed-energy coastal environment, chains of low-relief ridges can be formed as a result of wave action and vertical aggradation of sand. These ridges in the chain will form at the

same time and at the same elevation if they are associated with the same water level. It is the assertion of this research that the sequences of seven low-relief ridges at 211 m asl in Henry County, in the southwest portion of the Lake Erie basin, are a barrier island chain associated with glacial Lake Arkona. It can be assumed that the underlying stratigraphy and the general lithologic sequencing should be similar for each successive ridge.

In order to complete the classification of the barrier island chain, a probable source of sediment for the barrier islands must be discussed. At the Arkona elevation, no large paleo-deltas associated with major rivers or smaller streams in the local area have been identified by this study or previous research to suggest a likely source of coarse sediment. The only major river in the region is the Maumee River, but no deltas are associated with this river at the Arkona lake level. Further, these barriers are at least 10 to 20 km from the closest sandy valley-fill sediments associated with earlier courses of the Maumee River. It is deemed unlikely that river systems were supplying the sand that makes up the bulk of the barrier island sediment. The energy regime of the Arkona barrier islands was probably a low-energy wave-dominated environment. Wave energy was substantial enough to form ridges, but was probably too low to transport sand from other parts of the basin to provide a viable sand source. The only other source of sediment available to create the barrier island chains would have had to be derived locally. Within the region, the only other significant topographic features are the previously mentioned northeast-oriented, narrow, 1-m relief lineations. These ridges persist in the lake plain and in the back barrier, and in some instances intersect the Arkona barrier islands. It is proposed by this research that the lineations were created prior to the formation of the Arkona barrier islands, most likely as sub-glacial ridges. The general pattern in the plain north and northeast of the study area is consistent with flow directions of glacial ice bounded by the

Defiance Moraine. During the Arkona highstand, wave action eroded and reworked the sediment contained in the lineations to be the primary source of sand and coarse grains for the barrier islands. The lineations persist at various elevations but all retain approximately the same orientation.

Several possible origins for the lineations are as follows: coastal features associated with a prior lake stand, aeolian, and glacial. The lineations do not appear to be coastal in origin. The orientation of the ridges does not coincide with the longshore gradient observed on the barrier islands, and the long axes of the ridges are oriented in the opposite direction to where they should be if these were coastal features forming along the water plane. This leaves two major possibilities as to the origin of these features. They could be aeolian or glacial. If these are aeolian in origin, they could fit the description of limbs of parabolic dunes that have been readily identified locally in areas of the Lake Erie basin (Campbell, 2010). Aeolian origin is difficult to explain for these ridges. Field evidence suggests that the barrier islands are positioned on top of or cut into these lineations. Either scenario suggests an interaction between the linear ridges and the shoreline. In order for dunes to be present on a former lake plain, the water would have to have receded from the area to expose the plain to erosion. It is possible that a portion of the lake plain could have been exposed behind the barrier islands, allowing for the formation of parabolic dunes, but this does not fit the timing of the lineations in the lake basin in front of the barrier islands or provide an explanation for the lineations that are beneath the barrier islands themselves. Further, soil surveys of Henry County show that the broad plain is dominated by silt-clay sediment, with essentially no surficial sand.

The most likely process to create the lineations is that they formed prior to the establishment of the glacial lake sequence in the Lake Erie basin. However, it is highly unlikely

that the Erie Basin would have been exposed sub-aerially prior to the establishment of proglacial Lake Maumee, which formed as the ice was retreating across the landscape, leaving no time for dune migration in the basin to occur. It is therefore proposed that a glacial origin for the lineations coincides best with the timing constraints of the basin (as they can be formed as the glacier either retreated or advanced through the region), and can provide the best explanation between the lineations and barrier islands. Furthermore, the lineations are oriented in a direction that's consistent with known ice-flow directions.

A further implication of the findings at Field Sites 1 and 2 relates to the traditional lake-level model for the Lake Erie basin. The relationship between glacial Lake Whittlesey and Lake Arkona in the traditional model would suggest an erosional surface should exist between the sediments of Lake Arkona and overtopping Lake Whittlesey sediments. This erosional surface should be observable as interrupting deposition of Lake Arkona coastal features. The results from Field Sites 1 and 2 show two sites with a complete depositional sequence for a Lake Arkona shoreline. No erosional surface is present that interrupts the vertical aggradation of the barrier islands in either field site. Planar bedding was observed as being uninterrupted in sedimentary sequences exposed in both a hand-dug pit and vibracores. This evidence suggests that the Arkona shorelines in this region were not overtopped by a higher lake stand.

3.11 Field Site 3, Napoleon, OH, Arkona-Elevation Shoreline

The Arkona shoreline is often described as having a “washed” appearance. Geomorphically, the “washed” appearance is describing a wide short axis resulting in a relatively flat-topped low-relief ridge. An Arkona shoreline that matches this general description can be observed in the southwestern Lake Erie Basin. The ridge in question is just north of Napoleon, OH, and extends approximately 10 km to the northeast (Figure 3.13). One field site along this

ridge was selected based on geographic location within the arc of the basin and its representation of geomorphic character. Investigations on this site include: auger transect, vibracores, and GPR survey. To produce a better visualization of the low-relief ridge and display the characteristic geomorphology of Lake Arkona shorelines, a 3D shaded rendering was produced and is presented in Figure 3.14.

Geomorphology

The ridge in question is located 2.5 km north of the city of Napoleon, OH. The ridge is 10 km long and has an average axis width of 150 to 200 m, with relief averaging 2 m along the ridge. The ridge is at 211 m asl, which is consistent with the elevation of the lowest Arkona shoreline. The ridge's continuity is interrupted five times along its 10 km length by streams cross cutting it. The two main geographic boundaries for the Arkona shoreline in this area are the Whittlesey shoreline approximately 6.5 km northwest from the ridge, and the current Maumee River valley 4.5 km to the southeast. The Whittlesey shoreline is approximately 13 m higher in elevation than the Arkona shoreline. The topography between the Whittlesey and Arkona shorelines in this region slopes at an inclination to the southeast. The current fluvial terrace in the Maumee River is 6 m lower than the Arkona shoreline, and produces a gentler sloping surface than the surface between the Whittlesey and Arkona shorelines. Based on the orientation of the geographic constraints, the area to the northwest of the ridge is defined as the back barrier and the region to the southeast of the ridge is defined as the Arkona lake plain.

Figure 3.13. A DEM of an Arkona shoreline northeast of Napoleon, OH. Proposed dominant wave direction denoted by white arrows. Locations of GPR transects and auger transects denoted by the dotted and solid black lines. The three major GPR transects in this field site are denoted by P1, P2 and P3. The number 1 denotes the vibracore M131916, 2 represents M231916a/b, and 3 represents M331916.

Figure 3.14. Three dimensional shaded rendering of the Arkona shoreline near Napoleon, OH. Dominant wave direction is indicated by the white dashed lines.

Location of Field Site 3, Napoleon, OH, Arkona Shoreline

Field Site 3 is located 2.5 km northwest of Napoleon, OH on an agricultural field northwest of the intersection of County Road 14C and County Road S, and east of the Van

Hyning Creek (Figure 3.13). The principle feature is a 1-km long, 210-m wide section of the 10 km ridge. The elevation of the ridge is 211 m asl and is consistent with the lowest of the Arkona shorelines. The ridge exhibits a wide distal axis and is a low-relief flat-topped ridge. This field site location was selected due to the ridge exhibiting the traditional “washed” appearance and proximity to a cross-cutting stream valley.

3.12 Field Site 3 GPR Transects

Seven major GPR transects were conducted over this field site. Three transects were taken northward from the lake plain across the ridge and into the lower area northwest of the ridge. The designations for these transects are P1, P2, and P3 (Position 1, Position 2, and Position 3). The goal of the perpendicular transects was to evaluate the internal stratigraphy of the ridge and inquire for evidence of a regional erosional surface. These three transects each consist of several lines of GPR that are discussed below. The other four transects were taken parallel to the long axis of the ridge. Two of the parallel transects run along the back shore, and two run across the ridge crest. The main goal of the parallel transects was to evaluate the internal stratigraphy of the ridge and observe if the stratigraphy was continuous or internally discontinuous or disturbed.

Position 1 Transects

Transect Mi-1

GPR transect Mi-01 (label P1 on Figure 3.13) extends 60 m from the base of the ridge slope onto the lower portion of the foreshore. The first observation on the profile is that the GPR signal attenuates rapidly in the subsurface (Figure 3.15). Multiple repeated wave reflections are observed in the top of the GPR profile. This indicates that the GPR waves were being attenuated rapidly at a shallow depth. The result is that there are multiple returns of the same surface resulting in repetitions of that reflection surface. Faint discontinuous sigmoidal beds are

observed related to RF1. Directly underlying the RF1 is a faint discontinuous facies related to RF4. Based on the ground truthing, there is a thin veneer of sand approximately 0.5 m thick overlying the glacially derived diamicton.

Figure 3.15. The GPR profile and interpretation for transect Mi-1. Arrows indicate the locations of hand-auger holes.

Transect Mi-2

Transect Mi-2 extends approximately 190 m from the lower portion of the foreshore onto the crest of the beach ridge (label P2 on Figure 3.15). Similar to Mi-1, there are multiple repetitious reflections on the top of the ridge. A single strong sigmoidal reflection is observed beneath the repeated waves. This reflection is interpreted as RF1 and represents the thin sand veneer that comprises the upper surface of the ridge. Beneath the RF1 surface is a faint

discontinuous surface with no overall reflection pattern indicative of RF4. The components of the foreshore of the ridge are defined by a thin sigmoidal veneer of medium- to fine-grained sand with diamicton shallow in the subsurface. The GPR profile and facies classification are presented in Figure 3.16.

Figure 3.16. The GPR profile and interpretation for transect Mi-2. Arrows indicate the locations of hand-auger holes.

Transect Mi-3

GPR transect Mi-3 continues from the end of Mi-2 and extends 40 m over the top of the beach ridge (Figure 3.13). As with the previous two transects in Position 1, multiple repetitions of reflections are present at the top of the profile. Beneath the repetitions are thin planar beds associated with RF2. Based on the ground truth, the planar beds are a thin medium- to fine-grained sand. Underlying the RF2 surface is faint reflective facies attributed to RF4. The signal attenuates rapidly in the RF4 surface, and with the ground truth it is interpreted as the glacially derived diamicton. The GPR profile and facies classification are presented in Figure 3.17.

All GPR profiles and hand-auger holes from Field Site 3 near Napoleon, Ohio, have an extremely thin veneer of sand approximately 0.5 m thick that forms the shoreline ridge. This ridge is deposited directly on an erosional surface at the top of the diamicton. Based on transects taken along Position 1, there is no evidence either lithologically or stratigraphically that a large regional ravinement truncated the depositional sequence of the ridge.

Figure 3.17. GPR profiles for transects Mi-3, Mi-4 and Mi-4b. The interpretation for each transect is found below its respective GPR profile.

Position 2 Transects

Transect Mi-5

GPR transect Mi-5 is approximately 170 m long and was taken from the upper foreshore of the lake plain across the top of the ridge crest into the low behind the ridge. Like the other transects taken across the shoreline ridge, the upper portion of the GPR profile has several reflection repetitions. Beneath the repetitions there is a thin series of sigmoidal beds representative of RF1. A RF2 surface is identified as thin planar beds in the back barrier. Underlying the other radar facies is the RF4 surface. The general interpretation of the shoreline is that the core of the ridge is glacially derived diamicton with very thin laminae of medium- to fine-grained sand. No erosional surface is observed interrupting the deposition of the thin sand deposits. The GPR profile and facies classification are presented in Mi-5 in Figure 3.18.

Figure 3.18. GPR profile and interpretation for transect Mi-5. Arrows indicate the locations of hand-auger holes.

Position 3 Transects

Transect Mi-6

GPR transect Mi-6 is approximately 110 m long and extends from the lake plain across the crest of the ridge and ends on the upper surface of the ridge (label P3 on Figure 3.13). In common with the other transects taken on the shoreline, the upper portion of the GPR is dominated by repetitious reflections. A very faint reflection matching tangential bedding could be interpreted as a RF1. The tangential reflection extends from the lake basin on top of the beach ridge. At the crest of the ridge a short sequence with hummocky reflections is observed (RF3). The unit with the hummocky reflections is best interpreted as a thin deposit on the crest of the beach ridge. Below the RF1 and RF3, there is an uneven discontinuous faint reflective surface, interpreted as RF4. Based on the ground truth, it is interpreted that this thin veneer of medium- to fine-grained sand was deposited directly on top of the diamicton. No evidence for an erosional surface interrupting the depositional beds is observed on this profile. The GPR profile and facies classification are presented for Mi-6 in Figure 3.19.

Figure 3.19. GPR profile and the interpretation for transect Mi-6. Arrows indicate the locations of hand-auger holes.

Transect Mi-7

GPR transect Mi-7 extends northwest approximately 160 m from the upper surface of the beach ridge into the back shore. Multiple repeating reflections appear in the upper portion of the GPR profile. The facies on the upper surface of the ridge are tangential and dip slightly landward, these are classified as RF1. A single planar bed matching the RF2 can be traced from the ridge crest to the back barrier. In the back shore, the facies exhibit an undulating surface that is slightly discontinuous. The planar surface is interpreted as a horizontally deposited unit that is reflecting the unevenness of the underlying diamicton. The RF2 in the back barrier suggests lagoonal or overwash deposits. The uneven surface of these reflections are on the magnitude of

10 – 15 cm which could be attributed to an undulating overwash sheet. Underlying the before mentioned facies is the uneven, discontinuous, faint RF4 surface. Based on ground truth and GPR profiles, no evidence is observed for a ravinement that truncates the depositional beds. The GPR profile and facies classification are presented in Figure 3.20.

Figure 3.20. GPR profile and the interpretation for transect Mi-7. Arrows indicate the locations of hand-auger holes.

Transect Mi-4a

GPR transect Mi-4a is oriented parallel to the shoreline and extends 40 m between Positions 3 and 2 in the backshore (Figure 3.13). The main target for this transect was to evaluate if the stratigraphy between Positions 2 and 3 is continuous. Multiple repeated reflections are observed in the top of the GPR profile. Two facies can be discerned beneath the repeated reflections. The first facies is a horizontal reflection classified as an RF2 surface. Underlying RF2 is a faint, uneven, reflection associated with the diamicton RF4. Based on the

observed facies, it is proposed that the stratigraphy between Positions 2 and 3 in the back barrier is continuous and exhibits no evidence of internal depositional disturbances.

Transect Mi-4b

GPR transect Mi-4b is a westward continuation of Mi-4a. Mi-4b extends 30 m between Positions 2 and 1. The main goal of this transect was to evaluate if the stratigraphy between Positions 2 and 1 is continuous and void of any internal structural disturbances. Multiple repeated reflections are observed in the top of the GPR profile, similar to the other profiles taken in this field site. Two major facies can be observed in this profile. The first major facies is a planar bedded surface, classified as RF2. The second major facies is a faint, uneven reflection interpreted as the diamicton of RF4. The facies between Position 2 and Position 1 is continuous and visibly undisturbed.

Transect Mi-8a

GPR transect Mi-8a is oriented parallel to the water plane and extends 40 m across the long axis of the crest of the ridge. Mi-8a is set between Position 1 and Position 3 with a goal of observing the internal stratigraphy between the two transect lines. Two major facies are observed within this transect. The first major facies is a discontinuous, undulating surface similar to RF5. Based on ground truth obtained at the site, the discontinuous surface is interpreted as a thin deposit of littoral sediment. The littoral deposit is classified as RF5. Underlying the RF5 is an uneven, faint reflector interpreted as the diamicton RF4. The reflections appear continuous from Position 1 to Position 2. The GPR profile and facies classification are presented in Figure 3.21.

Transect Mi-8b

GPR transect Mi-8b was taken as an eastward continuation of transect Mi-8a. Mi-8b extends 40 m across the crest of the ridge between Position 1 and Position 3. The main goal of this transect was to evaluate if the stratigraphy between Position 2 and Position 3 is continuous. Two major facies are observed in this transect. The first facies is a discontinuous, undulating surface. This surface is interpreted as RF5. The second major facies is the diamicton RF4. Both the RF5 and RF4 are continuous from Position 2 to Position 3, suggesting no internal stratigraphic disturbances. The GPR profile and facies classification are presented in Figure 3.21.

Figure 3.21. GPR profile and the interpretation for transects Mi-8a and Mi-8b.

Field Site 3 GPR Discussion

The GPR penetration along all the transects at Site 3 was approximately 0.9 to 1.5 m (3 to 5 feet). This produced very shallow profiles across the entire site. Based on the thickness of

sediment observed on the GPR profiles, the interpretation is that the shoreline sediments are incredibly thin. Ground truthing at the site identified that the depth penetrated by the GPR was consistent with the identified barrier-island and littoral deposits. Wave energy was sufficient to form a coherent shoreline but a lack of sediment supply limited the thickness of the constructed shoreline. It is proposed that the shoreline was principally formed from the direct erosion and reworking of the underlying diamicton unit forming the basis for the beach ridge. The thin veneer of medium-grained sand is probably related to littoral drift or direct wave-deposited sediment. There also was no evidence for ravinement surface indicative of a subsequent transgression by a high water stand.

3.13 Hand-Auger Transect

The initial investigation into the lithostratigraphy was a 360-m hand-auger transect running southeast to northwest perpendicular to the long axis of the ridge. The auger hole spacing was 60 m. The hand-auger transect provided ground truthing for the ground penetrating radar survey conducted across the ridge.

Three main lithologic units were identified in the hand auger transect. The first, Unit A is a dark brown to black 35-cm to 40-cm thick soil with in-situ organics as well as non-situ organics (corn stubble, roots, plant fibers). Unit A is consistent with the regional Holocene agricultural soil common in the area. Cobbles are found on the surface of Unit A, and are of varied lithologies (granites, diorites, etc.). Most grains are semi- to well-rounded and 3 to 5 cm in diameter. The second, Unit B is only clearly identified on the crest of the ridge and is approximately 60 cm thick. Unit B is characterized by a stiff, medium- to fine-grained, oxidized sand with a significant silt/clay matrix (20% silt and clay sized grains). Within Unit B, sub-rounded grains of 1 to 2 mm sand with varied lithologies are present. The third, Unit C is a stiff,

oxidized, silt/clay-dominated unit with very few sand grains. Within Unit C, sub-rounded coarse sand 1 to 2 mm in diameter, varied lithology, are observed with a non-uniform distribution. Unit C is observed below Unit B. The main limitation with the auger transect was the stiffness of the sediment, which made it difficult to obtain depth. The deepest hand-augured hole of approximately 1 m was at the crest of the ridge. The back barrier and lake basin had hand augured depths from 0.5 m to 0.75 m due to the sediment being a stiff silt/clay unit which caused difficulty in digging.

3.14 Field Site 3 Vibracores

Three vibracores were taken in an effort to investigate the internal stratigraphy of the ridge as well as provide additional ground truth for the GPR surveys. The first vibracore M131916 was taken on the southeastern side of the ridge in the lake basin. The second vibracore M231916a and M231916b (a and b denote the upper and lower portions of the core respectively) was taken in line with M131916 but on the crest of the ridge. The third vibracore, M331916 was taken in the back barrier on the same transect as the other two cores.

Description of core M131916

Pebbles and occasionally cobbles can be found blanketing the surface of the ridge and were removed with a hand auger before the vibrocore was applied. The hand-auger hole of 30 cm was dug prior to the insertion of the core. The upper 30 cm represented the overlying Holocene agricultural soil and is named Unit A. The total length of the core is 46 cm. There are no clear lithologic divisions or transitions throughout the core. Coarse sand that ranges in size from 1 to 2 mm of varied lithology is observed non-uniformly distributed throughout the core. Three samples were taken from the core for grain size analysis, samples M1-3, 2 and 1; particle size data are presented in the Appendix. M1- 3 was taken at 26 cm in the core and analysis of

this sample showed the lithology was 1% sand, 63% silt and 36% clay. M1-2 was taken at 36 cm and showed a grain-size distribution of 11% medium sand, 18% fine sand, 47% silt and 24% clay. M1-1 was taken at 46 cm and showed a grain-size distribution of 12% medium sand, 4% fine sand, 54% silt and 30% clay. The sediment within M1-1 shows no obvious bedding and cannot be segregated into individual units or subunits. Based on the grain-size analysis, it appears that the upper portions of the core have higher sand content but it does not appear to be systematically distributed. The lower portions of the core have a higher percentage of silt and clay particles. The core lithology most closely represents Unit C from the hand auger transect. The GPR facies represented by this lithology would be RF1. Core image and characterization are shown in Figure 3.22.

Figure 3.22b. A close up view of the main body of core M131916. Panel I correlates to I in Figure 3.22.

Description of core M231916a/b

The core was taken after the top 20 cm of Holocene agricultural soil was removed by hand auger. The total length of the core M231916a is 33 cm. Two particle analysis samples were taken from the core; sample M2a-2 was taken at 13 cm and sample M2a-1 was taken at 31 cm. Grain-size distribution of sample M2a-2 is 50% medium sand, 12% fine sand, 26% silt and 12% clay. Grain-size distribution of sample M2a-1 is 21% medium sand, 20% fine sand, 39% silt and 20% clay. The upper half of the core consists of a medium- to fine-grained, oxidized sand with a silt and clay matrix. The individual sand grains are sub- to well-rounded with 1 - 2

mm grains of coarse sand are randomly distributed throughout. There is no clear transition between the upper half of the core to the bottom half of the core. The bottom half consists of a unit with nearly equal parts, sand, silt, and clay sized particles. The individual grains are well- to sub-rounded. Coarse sand grains are distributed randomly throughout this unit with the occasional 1 cm sub-angular clast of varied lithology. The core is shown in Figure 3.23 b/c. The GPR facies represented by this lithology would be RF1. The sediment distribution and lithology of this core is similar to core M131916.

Figure 3.23. Image and description of core M231916a. No clear transition is observed between the sediment units. Pockets of higher concentrations of sand can be observed within the core (M2a-2). The predominant unit that makes up the bulk of the core is a clay/silt unit with a sandy matrix. Panel I displays a close up view of the core which is presented in Figure 3.23c.

To acquire greater depth, core M231916b was taken in the same hole once core M231916a was removed. The total length for core M231916b is 17 cm. Two particle-size samples were taken from this unit, sample M2b-2 was taken at 10 cm and sample M2b-1 was

taken at 17 cm. Sample M2b-2 grain-size distribution is 78% medium sand, 16% fine sand, 6% silt and clay. Sample M2b-1 grain-size distribution is 18% medium sand, 7% fine sand, 39% silt and 36% clay. The upper portions of the core have significantly higher sand content than the lower portions of the core, which is rich in silt and clay. The grains appear oxidized and well-rounded but with uneven grain distribution. Coarse sand grains are present throughout the core with the occasional 2 to 3 mm grains (Figure 3.23b). The GPR facies represented by this lithology would be RF1. The core image and characterization are presented in Figure 3.23c. This core is similar in lithology and sediment distribution to core M131916 and M231916a.

Figure 3.23b. A close up view of the main body of core M231916a. Panel I correlates to I in Figure 3.23. Note the 1 mm and 2 mm grains that are distributed throughout the main sand body of the core.

Figure 3.23c. Image and description of core M231916b. No clear transition is observed between the sediment units. Cracks within the core were caused by post extraction desiccation. The body of the core is principally a clay/silt unit with a sand matrix.

Description of core M331916

The first 26 cm of the corehole was Holocene agricultural soil that was removed prior to insertion of the vibracore. The total length of the core is 28 cm. There are no apparent lithologic transitions throughout the core. Grain size analysis sample M3-1 was taken at a depth of 27 cm (Figure 3.24). The grain distribution of M3-1 is 13% medium sand, 9% fine sand, 46% silt and 32% clay. The grains were oxidized and semi- to well-rounded 1 - 2 mm grains are sparsely distributed throughout the core. The core is shown in Figure 3.24. The GPR facies represented by this lithology would be RF1. This core is similar in lithology and sediment distribution to core M131916, M231916a and M231916b.

Figure 3.24. Image and description of core M331916. No clear transition is observed between the sediment units. The primary sedimentary unit is a clay/silt unit with a sand supported matrix. 1 mm sand grains are observed throughout the core with random distribution. Panel I displays a close-up view of the core which is presented in Figure 3.24b.

Figure 3.24b. A close-up view of the main body of core M331916. Panel I correlates to I in Figure 3.24. Note the 1 mm grains that are observed throughout the main body of the core.

3.15 Discussion of Field Site 3

The field site is located to the northwest of Napoleon, OH. The principle feature is a low-relief ridge at the elevation of the Lake Arkona shoreline. Based on the lithology and GPR facies of the ridge, it is proposed that the Field Site 3 ridge is a shoreline. A traditional shoreline is defined geomorphically as a sinuous, often continuous ridge that marks the boundary between a terrestrial and aqueous environment (O'Neill, 1985). Shorelines indicate the high-water mark or swash-zone of the body of water, and mark the location of the terrestrial topographic high or berm. The ridge's elevation is 211 m asl, which is consistent with the lowest of the Arkona shorelines. Unlike the Arkona shorelines in Ontario (Chapman and Putnam, 1966; Cooper, 1979), which commonly occur in three separate ridges, in the southwestern portion of the Lake Erie basin only one Arkona shoreline is observed.

The sediment in Field Site 3 will be evaluated using the description of typical shoreline lithologies. The uppermost sedimentary unit, Unit A, can be disregarded due to its age as an agricultural soil. The contact between the agricultural soil and the lower lithological unit is gradational. This gives the impression that the soil formed directly on top of the underlying sedimentary unit. On the crest of the shoreline beneath the soil is a fine- to medium-grained sand with a dominant silt and clay matrix. Within this unit there are 1 to 2 mm grains of varied lithology. The grains themselves appear to be moderately sorted and sub-rounded and do not appear to be frosted. This unit does not appear to be aeolian in nature based on the lithology based on a lack of frosting of the individual sand grains, the presence of granules and coarse grained sand grains with pebbles and the occasional cobbles blanketing the surface of the ridge. This unit is visibly thinner in the backshore and is not present or not discernible from the sedimentary unit below it. Isolated portions of this unit in the foreshore have concentrations of near-pure medium-grained sands, which could be evidence of transport by longshore drift south along the ridge. A possible origin for the sand is from Bad Creek to the northeast of the field site. The underlying sedimentary unit, Unit C, is a stiff oxidized, silt/clay with 2 - 3 mm grains. The transition between Units B and C is uncertain as there are no sedimentary structures that indicate a change in facies, however there is a gradual lithologic shift from a sand dominated unit (Unit B) to a unit with nearly equal parts silt and clay. Unit C has similar lithologic properties with the diamicton unit observed in Field Site 1. This unit is most likely to be glacial in origin based on the reasons outlined in the discussion of Field Sites 1 and 2. Unit B constitutes the core of the shoreline and most likely formed as a combination of sand originating from longshore drift and wave energy eroding and reworking Unit C. This would best explain the lithologic similarity between Units B and C, and explain the pockets of pure sand contained within Unit B.

In contrast with the paleo-shorelines found in the Lake Michigan and Lake Huron basins, this shoreline is much thinner, and lacks the traditional shoreline lithologic signatures. The shoreline appears to be constructed from relatively low wave energy reworking the local diamicton, with very little sand being added to the system through longshore transport. Furthermore, the lack of an erosional surface implies that the sedimentation sequence from the Holocene soil to the bottom unit is a single complete sedimentation sequence. The lack of ravinement surface also implies that a regional erosional surface indicative of a high stand transgression is not preserved in the stratigraphic sequence contained within the shoreline.

3.16 Field Site 4, Richfield Center Road, Arkona Shoreline

Field Site 4 is located west of the city of Sylvania, OH at the location of a sequence of discontinuous ridges, as shown in Figure 3.25. These ridges had been identified previously as a Lake Arkona shoreline by Campbell (2011). The geomorphology of the shoreline is a discontinuous ridges that extend approximately 8 km with a northeastern orientation. The crests of the ridges appear flattened and elongated. These characteristics are consistent with the traditional “washed” description of Arkona shorelines. The portion of the ridge that was the primary focus was located along Richfield Center Road between Brint Road and Sylvania Avenue. On this field site, a hand-dug pit was used on the crest of the ridge to obtain stratigraphic and lithologic control for the Lake Arkona shoreline in this area.

Figure 3.25. A DEM of an Arkona shoreline west of Sylvania, OH. Proposed dominant wave direction denoted by white arrows. B: The ridge of the Arkona shoreline is denoted by the black dashed lines. The hand-dug pit is denoted by the black box nearest the tree line.

3.17 Field Site 4 Hand-Dug Pit

The hand-dug pit at Site 4 measured approximately 1.5 m by 1 m with a depth of approximately 1 m. The first unit observed is a 31-cm thick unit of black to dark brown sediment with high amounts of organic material (plant fiber and in-situ roots). This unit is consistent with the agricultural soil found in this region. The next 42 cm is an oxidized, medium- to fine-grained sand with a silt/clay matrix. Coarse sand grains of varied lithology were observed throughout the unit. In situ roots were also observed in the walls of the pit. Below this unit is a gradational contact with a 20-cm thick fine-grained, oxidized sand unit with a silt/clay matrix. Coarse sand grains of varied lithology are distributed throughout the unit. A 7-cm, calcareous, and semi-rounded clast was observed within this unit. The base of the pit contains a silt/clay unit with a medium- to fine-grained sand matrix. The base unit is stiff silt/clay with a sand matrix that contains coarse sand grains of varied lithologies. The thickness of this base unit is unknown.

3.18 Discussion of Field Site 4

This field site is located west of the city of Sylvania, OH. The principle feature is a section of the Arkona ridge. The ridge exhibits the same geomorphic and lithologic facies expected in a shoreline (O'Neill, 1985). The ridge at Field Site 4 in the western Lake Erie basin is consistent with the geomorphology expected for an Arkona shoreline or beach ridge. The ridge's elevation is 211 m asl, which is consistent with the lowest Arkona shoreline (Leverett and Taylor, 1915). The shorelines in Field Sites 3 and 4 are geomorphically similar and at the same elevation. It can then be inferred that all of these shorelines were formed during the same time and during the same highstand event. However, each shoreline formed in different positions

within the Lake Erie basin, so the source of sand for each ridge could vary and possibly be limited to local sources.

Three units were identified in the hand-dug pit. The upper unit is defined as an agricultural soil common to the area. The transition between the soil and the next lower unit is gradational. This implies that the soil was formed directly on top of the lower sedimentary unit. The middle unit consists of a medium- to fine-grained sand with coarse sand grains distributed throughout. Planar bedding structures were observed, which is consistent with foreshore deposits (Baedke and Thompson, 2004). Cobbles are found within the unit; a 7-cm calcareous pebble was observed in the lower portion of the middle unit. The origin of this pebble was most likely from an exposure of the Greenfield Limestone present in the shallow subsurface throughout the local region. The clast was most likely derived locally, eroded by the glacier but not transported from Canada. The contact with the lowest unit is abrupt and interpreted as erosional in nature. The lowest unit is interpreted as a stiff silt/clay with intermixed coarse sand grains of varied lithology. This unit is interpreted as a diamicton of similar glacial origin to the diamicton observed in the other field sites.

The sand core of the shoreline most likely originated from sediment sources north of the field site and was carried to the location via littoral processes. Some possible origins of sediment could be from Ten Mile Creek or the River Raisin. The dominant wave direction was most likely from the northeast and resulted in a longshore drift gradient to the southwest along the shoreline. Evidence for this can be seen in the bulbous distal southern ends of the ridges. The basic development of the shoreline occurred similar to the ridge at Field Site 3, which began as the reworking of the diamicton unit. In Field Site 4, this can be seen by the erosional contact

between the middle and lower unit and the 1-2 mm grains within the middle unit which are lithologically similar to the grains in the lower unit.

Major differences are observed in the lithology between the two shorelines. The shoreline in Field Site 3 is considerably thinner than the Field Site 4 shoreline. The amount of pure sand contained within the ridge is also less than found in the ridge at Field Site 4. These characteristics provide evidence that sediment supply was different for each section of the shoreline system. This could potentially be a function of two primary variables: wave energy and sediment supply. Wave energy could be too low to adequately transport the needed sediment to support the aggradational growth of a sand-rich core of a barrier. This could imply that the sediment supply was either insufficient or inconsequential due to wave energy being unable to transport the sediment regardless of availability. It is probable that the wave energy in the embayed southwestern portion of the Lake Arkona basin is lower than in the more exposed northern portions. This is due to dominant wave direction for Lake Arkona being generally from the northeast quadrant and the southwestern basin is the furthest removed geographically. Another scenario is that the sediment supply was simply insufficient for the area to support the growth of a sand ridge. Yet beds of near-pure sand can be found within the ridge that could easily represent longshore drift deposits. This research proposes that the formation of the ridge was a more moderate function between the two variables. A beach ridge persists on the landscape, so wave energy would have had to be strong enough to rework a diamicton and form the core of a beach ridge out of that sediment. Moreover, the waves had enough energy to transport sand along the length of that section of the shoreline. So it would be reasonable to assume that if sediment was available in greater quantities, then the wave energy would be

sufficient to utilize it. The shoreline in Field Site 3 could be defined as a wave-dominated, sediment-starved system in comparison to the shoreline in Field Site 4.

3.19 Field Site 5, Ottawa Lake, MI, Arkona Shoreline

Field Site 5 is located approximately 0.5 km south of the town of Ottawa Lake, MI. The principle feature of this field site is a 3.7-km long chevron-shaped ridge with elongated ridges extending landward from the backshore of the ridge (Figure 3.26). This ridge has a steep eastern-facing slope and a more gradual western slope. This ridge had been previously mapped and identified as an Arkona shoreline by Campbell (2011). Two sections of the shoreline were investigated. The first area is located on an agricultural field to the northeast of the corner of Clark Road and Lynch Road. The second area is on an agricultural field to the southeast of the corner of Clark Road and Lynch Road. GPR transects were conducted on both areas with a hand-auger transect on the northeast field to provide ground truth. To visually represent the chevron-shaped shoreline and emphasize the steep basinward slope, a 3D shaded rendering was produced and is presented in Figure 3.27.

Figure 3.26. A DEM of the chevron-shaped Arkona shoreline north of Sylvania, OH, and south of Ottawa Lake, MI. Proposed dominant wave direction denoted by white arrows. GPR transects are shown by the thin white dashed lines. The diamicton ridges located in the lee of the shoreline crest are marked by the dashed polyline. Approximately 1.5 to 2 km west of the shoreline there is elevated topography that exhibits the same geomorphic characteristics as the chevron and diamicton ridges observed in the Arkona shoreline.

Figure 3.27. Three-dimensional shaded rendering of the chevron-shaped Arkona shoreline near Ottawa Lake, MI. Dominant wave direction is indicated by the white dashed lines.

3.20 Field Site 5 GPR Transects

Four GPR transects were used to investigate this field site. Three transects were employed on the northeastern field and one transect was taken on the southeastern field. The two transects Re-1 and Re-3 were taken on the northeastern field and oriented from west to east. Re-1 and Re-3 were taken from the backshore to the crest of the ridge perpendicular to the long axis of the ridge. The goal of these transects was to evaluate the internal stratigraphy of the backshore of the crescent-shaped shoreline and evaluate the ridge. A single transect Re-2 was taken parallel to the long axis of the ridge and was run along the crest of the ridge to evaluate the continuity of the stratigraphy. The single transect Al-1a/Al-1b taken on the southeast field, ran from south to north from the shoreface of the lake plain onto the upper surface of the beach ridge.

Re-1 a/b

GPR transect Re-1 was oriented perpendicular to the long axis of the ridge and extends 310 m from the backshore onto the crest of the ridge. Planar bedding is observed in the back shore for the first 60 m of transect Re-1. The planar bedding best reflects the RF2 surface. Based on the ground truth obtained for transect Re-1, the back shore sediment is fine-grained sand with a silt matrix. This is consistent with overwash and lagoonal deposits (Daly et al., 2002; Jol et al., 2010). Tangential/oblique bedding is observed dipping basinward and present in the lee of the beach ridge. These beds are best classified as RF1. On the upper surface and crest of the ridge, there are alternating cross-bedded and continuous planar beds. The surface is classified as RF5, thus representing the vertical aggradation of littoral sediments, but a thin coastal dune deposit similar to RF3 is likely the uppermost surface of the profile. The ground truth for this area shows that medium- to fine-grained sand was deposited in this region of the ridge. The interpretation is that the bedding represents the landward aggradation of beach ridge sediment. No evidence was observed for a ravinement surface interrupting the deposition of these facies. Re-1 is continuous over the 310 meters but was broken into segment part Re-1a and Re-1b to better fit the report. Figure 3.28 displays the GPR facies and interpretations for transect Re-1 a/b.

Figure 3.28. GPR profiles and interpretations for transects Re-1a and Re-1b. Black arrows indicate the locations of hand-auger holes.

Transect Re-2

Transect Re-2 is oriented parallel to Re-1 with a 60-m offset to the north. Re-2 extends 270 m from the backshore to the basinward side of the beach ridge. The major facies of the first 200 m is continuous horizontal reflections. This facies is best described as RF2. Ground truth in the back shore suggests that the planar bedding is caused by laminar beds of fine-grained sand with a silt matrix. Starting at approximately 210 m to 230 m, sigmoidal reflections are observed interbedded with RF2 and dipping basinward from the front of the ridge. The sigmoidal beds are identified as RF1. Directly beneath the sigmoids is a sequence of discontinuous, overlapping reflections classified as RF5. The sigmoidal beds are interpreted as being formed from storm overwash deposits. The discontinuous bands are littoral deposits. The GPR transect and interpretation are presented in Figure 3.29.

Transect Re-3

GPR transect Re-3 is oriented parallel along the crest of the beach ridge between Re-1 and Re-2. The goal of Re-3 was to evaluate the internal stratigraphy of the ridge and determine if the stratigraphy is continuous between Re-1 and Re-2. The main facies observed in Re-3 is overlapping sequences of planar bedding. The sequential deposition of sigmoidal beds and littoral deposits would produce a series of continuous and overlapping beds. Therefore, the planar beds are interpreted as RF1 and the lower RF5 surfaces. A faint, discontinuous reflection is observed at the base of the profile and is interpreted as RF4. Ground truth places the diamicton unit at the depth of the faint reflection and would account for the attenuation of the GPR signal at that depth. GPR transect and interpretations are presented in Figure 3.29.

Figure 3.29. GPR profile and interpretation for transects Re-2 and Re-3. Black arrows indicate the locations of hand-auger holes.

Transects Al-1a/b

The primary objective of transect Al-1 is to provide stratigraphic control of the foreshore of the shoreline that could not be obtained by the Re1 & 2 transects. Two major facies can be observed in Al-1. The first major facies is planar reflections that occur in the first 60 m of the transect. These planar beds are indicative of RF2. Gently dipping sigmoidal reflections are first observed at 65 m and many can be traced continuously across the crest of the beach ridge. The sigmoids are observed to be dipping away from the lake plain toward the backshore. The sigmoidal reflections are interpreted as RF1. Beneath the RF1 and dipping landward is a sequence of sub-horizontal reflections interpreted as RF5. GPR profile and classification are presented in Figure 3.30 and Figure 3.31.

Figure 3.30. GPR profiles and the interpretation for transect AI-1a.

Figure 3.31. GPR profile and interpretation for transect AI-1b.

Discussion of GPR Profiles from Field Site 5

Radar facies in the foreshore produced continuous sigmoidal reflections, interpreted as basinward progradation of littoral sediments associated with the shoreline. Sigmoidal beds are relatively continuous over the crest of the beach ridge and the internal structure of the shoreline does not show evidence of significant disturbances. No strong reflection indicative of a subsequent ravinement surface is observed truncating the RF1 or RF5 surfaces in any profile. It can therefore be stated that it is improbable that the shoreline was overtopped by a higher lake stand.

3.21 Field Site 5 Hand-Auger Transect

A 250-m long transect was used to provide ground truth and stratigraphic control for the Re-1a/b, Re-2 and Re3 GPR transects. The auger transect was oriented perpendicular to the long axis of the ridge. The spacing of the hand auger holes is 60 m. Three major lithologic units were identified by the hand-auger transect. The first major unit, Unit A is a 55- to 60-cm thick, black to dark brown soil unit with a significant organic content (plant fibers). Unit A appears as the

upper unit throughout the auger transect and its appearance is consistent with the agricultural soil present in this area. On the surface of Unit A and within the first 5 cm depth, large grains ranging from 5 to 12 cm in size are observed. These grains are of varied lithologies (granite, diorites and some fossiliferous limestone). The second unit in the sequence is Unit B, which is an oxidized, well-rounded, medium- to fine-grained sand with a silt/clay matrix. The thickest portion of this unit is 3 m and located at the crest of the ridge, and has a significantly lower silt and clay percentage than the portions of this unit that lay off the ridge. Unit B begins to thin off the west side of the ridge to an approximate thickness of 1.1 to 1.3 m. Unit B represents the lithology for GPR facies RF2. The third unit in the sequence is Unit C. Unit C is observed on the two hand-auger holes that were located in the back basin of the ridge. Unit C's thickness is unknown. The contact between Unit B and Unit C appears to be abrupt and suggests an erosional contact. Unit C is characterized as a stiff silt/clay with a sand matrix. 1 - 3 mm grains of varied lithology are present in this unit but the distribution of grains does not appear to be bedded or structured. Unit C is the principle unit within the ridges extending into the backshore of the ridge. Unit C is the lithology of GPR facies RF4.

3.22 Discussion of Field Site 5

This field site is located south of Ottawa Lake, MI. The principle feature is a ridge at the elevation of the Arkona shoreline. As mentioned in the site description, the ridge in Field Site 5 has been previously mapped by Campbell (2011) as a Lake Arkona shoreline. The ridge is at an elevation of 212 m asl, which is in the range for the lowest of the Arkona shorelines. The shoreline wraps around a regional topographic high that protrudes from west to east into the Lake Arkona basin. As a result, the shoreline that was formed in this area was responding to the topographic high as a headland and forms a shoreline along the outer contour of the headland.

The general geomorphology suggests that this shoreline experienced direct wave impacts from the northeast and east, which resulted in a steep foreshore and shoreface profile. In contrast to other Arkona shorelines, the ridge in Field Site 5 is much better defined and does not exhibit the “washed” appearance typical of other Lake Arkona coastal features. Previously not seen in any other Arkona field site is the presence of large grains on the surface of the soil. Resting on the surface of the ridge in the foreshore and on the ridge crest are large 5 to 12 cm grains of granite, diorite, and some fossiliferous limestones and calcareous sandstones. In the backshore, the grains reduce to 5 to 6 cm in size but are still well distributed in the field. The fossiliferous limestone grains were identified as a Middle Devonian fossiliferous limestone units commonly exposed in the Michigan Basin. The calcareous sandstones are identified as the Marshall Sandstone, a Mississippian unit present in the Michigan basin (Bedrock Geology of Michigan, Michigan Department of Environmental Quality, 1987). The igneous grains would have originated from the Canadian Shield and were transported to the area via glacier processes. It is probable that a sub-lobe of the main Huron Lobe would be responsible for transporting the grains. Beneath the soil is a 3-m thick fine to medium sand unit with same 1 - 2 mm grains. The distribution of grain size of this unit is similar to beach deposits found in the Lake Michigan basin (Baedke et al., 2004). Beneath the beach-deposit sand is a stiff silt/clay unit with a sand matrix and randomly distributed 1 - 2 mm grains.

The lowest unit at Field Site 5 is a diamicton by lithology and character. The contact between the beach sand and diamicton is abrupt and is interpreted as an erosional contact created by shoreface ravinement. The diamicton is present beneath the beach ridge sediments and in the ridges that protrude southwestward from the backshore of the ridge. Interpreting the possible origin of the diamicton is critical to developing a depositional model for the shoreline. Based on

the geologic history of the region it is proposed here that the diamicton in this field site is of glacial in origin. Further investigation using a 3-m resolution DEM reveals a similar topography to the elongated ridges observed in the lee of the shoreline repeated two more times on the landscape (Figure 3.12). The additional ridges appear to be washed and are low relief on the landscape. The elevations of these ridges are 214 m and 212 m respectively. While no field data was collected from these two sites, the question can be asked, was the diamicton unit deposited during different intervals?

The deposition model of this shoreline is discussed below. The topographic high that extends into the Lake Arkona basin is at its base. The lithology of this topographic high is believed to be a combination of bedrock and diamicton but the exact lithologic make-up is at presently unknown. Energetic waves from the northeast and east would have eroded and reworked some of the diamicton, resulting in an erosional contact between the beach sand unit and the diamicton. Another possible source of the sand could have come from the deltas in the northwestern portion of the River Raisin basin (Figure 3.1). However, no field evidence linking the sand supply to the deltas was collected. It is therefore proposed that the sand was derived locally and would have been worked in with the sediment eroded from the diamicton. The resultant sedimentary unit would be the fine to medium sand with 1 - 2 mm grains that match the lithology of the 1 - 2 mm grains in the diamicton unit. The steep foreshore implies strong relatively constant wave action, which could have eroded into the underlying diamicton or till. The large grains present on the surface of the shoreline could be explained as overwash from wave action in the foreshore, probably from major storm events. Soil then formed after the shoreline and the plowing of the field could have resulted in the large grains being exposed on the surface of the soil. Frost heaving could also have played a role in exposing the grains sub-

aerially. Based on the lithology of the ridge, there is no evidence of a regional ravinement surface interrupting the bedding of the beach ridge sand unit. This does not support the interpretation that Lake Arkona was overtopped by a higher lake stand.

3.23 Field Site 6, Whittlesey Shoreline in Assumption, OH

Field Site 6 is located approximately 1.5 km due west of the city of Assumption, OH. The principle feature of this field site is a ridge complex at the elevation of the Lake Whittlesey shoreline. The ridge is 4.2 km long with a north-south orientation. The west side of the shoreline is defined as the back barrier, while the eastern side is defined as the lake plain. The north and south distal ends of the ridge show progradation of sediment, and have the geomorphic character of spits. The ridge is well defined and has a steep scarp on the eastern face. These characteristics are consistent with the previous geomorphic descriptions of Lake Whittlesey (Forsyth, 1959; Calkin, 1970; Schooler, 1974). The field site itself is contained to the agricultural fields to the east of County Road 3-3 and bracketed on the north and south by County Road S and Central Ave, respectively (Figure 3.32). To produce a visual display of the characteristic geomorphology of this Whittlesey shoreline, a 3D rendering was produced and is presented in Figure 3.33. GPR was attempted on the field site, but the GPR reflections attenuated within the upper 50 cm, so it was not included in this report.

Figure 3.32. Whittlesey shoreline west of Assumption, OH. Proposed dominant wave direction denoted by white arrows. A: The Whittlesey shoreline's ridge is marked by the black dashed lines. The auger transect is denoted by the black line. The numbers 1, 2 and 3 show the locations of vibracores CE121163, CE121162 and CE121164.

Figure 3.33. Three dimensional shaded rendering of a Whittlesey shoreline near Assumption, OH. Dominant wave direction is indicated by the white dashed lines.

3.24 Field Site 6 Hand-Auger Transect

The hand-auger and vibracore data were used to provide the stratigraphic and lithologic control for this shoreline. The auger transect was oriented west to east, perpendicular to the long axis of the ridge. The locations of hand auger holes and GPR transects are shown in Figure 3.30. Granules are observed on the surface of this ridge. Cobbles ranging in size from 6 - 8 cm and 4 - 6 mm pebbles are found predominantly on the eastern (basinward) side of the ridge, fewer cobbles around 6 cm and 4 - 6 mm pebbles can be found on the western side of the ridge.

Five major sedimentary units were identified based on the results of the hand auger survey. The first unit, Unit A, is characterized as an agricultural soil, rich in organics and dark in complexion with a significant silt/clay component. Unit A is present throughout the auger transect and is the uppermost unit. The thickness of Unit A varies, with the thinnest beds in the back basin and in the lake plain (15 to 23 cm). The thickest portion of Unit A is on the crest of the ridge at 48 cm. 6 - 8 cm cobbles are found on the surface of Unit A; the pebbles range in size

from 4 mm to 6 mm in diameter. The cobbles are varied lithologies (granite, diorite, etc.) and sub-rounded. Below Unit A is the next sedimentary unit, Unit B which is a medium- to fine-grained, oxidized sand with a silt/clay matrix. 1 to 3 mm grains of varied lithologies are observed throughout Unit B. Unit B is the thickest at the crest of the ridge at 30 cm and the thinnest in the lake plain at 18 cm. The third major sedimentary unit, Unit C is characterized as a well-sorted, well-rounded, oxidized fine sand. Unit C is the thickest at the crest of the ridge at 22 to 26 cm. In the back basin Unit C is approximately 8 cm thick. Unit C was not found to the east of the ridge in the lake plain. The deposition of Unit C terminates abruptly at the contact with the fourth lithostratigraphic unit, Unit D. Unit D is a grey, coarse to fine sand that contains many 1 - 2 mm grains of varied lithologies. The abrupt change in litho facies between Unit C and Unit D suggests that the contact between the two units is an unconformity. Unit D is approximately 20 cm thick at the crest of the ridge and 5 cm in thickness in the lake plain. Unit D was not identified in hand-augers in the back barrier. The fifth lithostratigraphic unit, Unit E is the lowest unit and found throughout the auger transect. Unit E is characterized as a stiff silt/clay unit with a sandy matrix equivalent to the diamicton found at other sites. Unit E contains 1 to 2 mm, varied lithology grains with no discernible distribution pattern. The contact between Unit D and Unit E is abrupt. The auger transect was unable to resolve the thickness of Unit E.

3.25 Field Site 6 Vibracores

Three vibracores were taken and used to evaluate the internal stratigraphy of the Lake Whittlesey shoreline. The first vibracore, CE121163 was taken on western side of the shoreline in the back barrier. The second vibracore, CE121162 was taken along the crest of the ridge approximately 240 m to the east of CE121163. The third vibracore, CE1210164 was taken

approximately 86 m to the southeast of CE121162 on the crest of the ridge. No vibracore was taken east of the ridge due to the hardness of the sediment.

Description of core CE121163

30 cm of agricultural soil was removed prior to the insertion of the vibracore. The total length of core CE121163 is 64.5 cm. The first 10.5 cm is a dark brown to black, organic rich agricultural soil. Unit B is observed between 11.25 cm to 53 cm with particle samples CE3-3 and 2 to characterize the grain distribution. CE3-3 was taken at 26.5 cm and has a grain-size distribution of 23% medium sand, 68% fine sand, 7% silt and 2% clay. CE3-2 was taken at 42.75 cm and has a grain-size distribution of 26% medium sand, 70% fine sand, 4% silt and clay. The grains in Unit B can be described as near-pure, medium- to fine-grained, well-rounded sand with convex bands of silt/clay laminae throughout this layer with 2 - 4 mm spacing. The bands are inferred to have been horizontal and deformed by the action of the vibracore pipe, resulting in the convex appearance. Grains of 2 to 3 mm were observed in the lower 13 cm of the unit. Lithologic Unit C is from 53 cm to the base of the core. Unit C is characterized by particle sample CE3-1 that was taken at 59.5 cm. CE3-1 grain-size distribution is 28% medium sand, 16% fine sand, 45% silt and 11% clay. Unit C is described as a stiff, fine-grained silt unit with significant sand and clay component and silt/clay laminae. The silt laminae are approximately 0.5 to 1 mm in thickness and define this lithologic unit. Grains of 1 to 3 mm, with varied lithology are seen in this unit. The core image and description are presented in Figure 3.34.

Figure 3.34. Image and description of core CE121163. Parabolic shaped silt/clay bands were originally horizontal but were deformed by the pressure induced by the vibracore. Sedimentary samples CE-1, 2, 3 are shown with a brief description; particle-size data are presented in the Appendix. Panels I and II outline the borders of close-up images of the core presented in Figure 3.34b.

Figure 3.34b. Panels I and II show a close-up view of the main body of core CE121163. Panels I and II correlate to the I and II in Figure 3.34. Panel I shows the medium- to fine-grained sand with convexly bent silt layers. Panel II shows the laminated silt layer.

Description of core CE121162

The total length of core CE121162 is 91 cm. The first 48 cm of the core is a dark brown to black agricultural soil unit common to the area. The second lithologic unit is Unit B between 48 cm to 61 cm. Unit B is characterized by particle sample CE2-3, which was taken at 57.5 cm. CE2-3 grain-size distribution is 11% medium sand, 62% fine sand, 14% silt and 13% clay. Unit

B is described as an oxidized, well-sorted and well-rounded medium- to fine-grained sand with a silt/clay matrix. The third lithologic unit between the depths of 61 cm to 78.5 cm is labeled Unit C, which is characterized by particle sample CE2-2 taken at 69 cm. CE2-2 grain-size distribution is 28% medium sand, 15% fine sand, 46% silt and 11% clay. Unit C is described as an oxidized near equal parts silt and sand unit with a mottled appearance. The fourth lithologic unit is Unit D, which is found between 78.5 cm and the bottom of the core. Unit D is characterized by particle sample CE2-1 taken at 86 cm. CE2-1 grain-size distribution is 73% medium sand, 19% fine sand, and 8% silt and clay. Unit D is described as a well-rounded medium sand, with few 1 mm grains present. The core image and description are shown in Figure 3.35.

Figure 3.35. Image and description of core CE121162. The core was taken from the Whittlesey shoreline to the north and west of Assumption, OH. Sediment samples were taken throughout the core and are labeled CE2-1, 2, and 3. A brief sample description is listed in the Core Description. Panels I and II outline the borders of close-up images of the core presented in Figure 3.35b.

Figure 3.35b. Panels I and II show a close-up view of the main body of core CE121162. Panels I and II correlate to the I and II in Figure 3.35. Panel I shows the medium- to fine-grained sand with 1-mm grains. Panel II shows a silt with a medium-grained sand matrix with bioturbation.

CE1210164 Description

The total length of core CE1210164 is 64 cm. The first 41 cm of sediment was removed by a hand-auger prior to the insertion of the vibracore. The first 11 cm of the core is termed Unit A, which is the agricultural soil present throughout the area. The second lithologic unit, Unit B is found from 11 to 48.75 cm. Unit B is characterized by two particle-size samples CE4-3 and

CE4-2. Sample CE4-3 was taken at 27 cm and has a grain-size distribution of 52% medium sand, 40% fine sand, 6% silt and 2% clay. CE4-2 has a grain-size distribution of 43% medium sand, 51% fine sand, 4% silt and 2% clay. Unit B is described as an oxidized, well-rounded sand with a minor silt/clay matrix. 2 to 3 cm diameter grains are found within this unit. The third lithologic unit, Unit C is found between 48.75 cm to 53 cm. Unit C is characterized by particle sample CE4-1 taken at 63 cm. CE4-1 grain-size distribution is 14% medium sand, 72% fine sand, 12% silt and 2% clay. Unit C is described as a gray fine sand unit with a silt-clay matrix. A few grains of 1 to 3 mm with varied lithology are found within the unit. The fourth lithologic unit, Unit D is between 53 cm and the base of the core. Unit D is a medium- to fine-grained, oxidized, well-rounded sand with a silt matrix.

To obtain greater depth information, a hand-auger was inserted in the bottom of the vibracore hole after the core was removed. The next 16 cm of sediment was a continuation of Unit D down to a depth of 41 cm. From the depth of 41 cm to 45 cm, the lithology abruptly changes to a grey medium to coarse sand, 1 to 1.5 mm grains are also observed. This unit is identified as Unit E. At a depth of 45 to 59 cm, the lithology makes a second abrupt change named Unit F. Unit F is a gray, stiff, clay/silt unit with a sandy matrix which is being interpreted as a diamicton. 1 - 3 mm grains are present in this unit. The exact thickness of Unit F is unknown. The core image and description are presented in Figure 3.36.

Figure 3.36. Core CE121164 is represented in the above image. The core was taken from the Whittlesey shoreline to the north and west of Assumption, OH. Sediment samples were taken throughout the core and are labeled CE4-1, 2, and 3. A characterization of the hand-auger samples taken below the core is presented in Figure 3.36b. A brief sample description is listed in the Core Description. Panels I and II outline the borders of close-up images of the core presented in Figure 3.36c.

Figure 3.36b. A Characterization of the hand-auger samples taken below vibrocore CE121164.

Figure 3.36c. Panels I and II show a close-up view of the main body of core CE121164. Panels I and II correlate to the I and II in Figure 3.36. Panel I shows the medium- to fine-grained sand with 1 mm grains. Panel II shows a stiff clay overlying a medium-grained sand with 1 - 3 mm grains.

3.26 Discussion of Field Site 6

This field site is located north and west of the town of Assumption, OH. The principle feature is a Whittlesey shoreline. The ridge in Field Site 6 has all the geomorphic characteristics of a Whittlesey shoreline as discussed by Leverett and Taylor (1915), Forsyth, (1959), Calkin, (1970), and Schooler (1974). The shoreline is at an elevation of 223 m asl, which is consistent

with the elevation of the Lake Whittlesey shoreline. Therefore, this research concludes that the ridge in Field Site 6 is a Lake Whittlesey shoreline. Unlike the Arkona shorelines, Lake Whittlesey coastal forms are well defined and easily traceable over long distances. The Whittlesey shoreline is positioned on top of a regional topographic high in close proximity to the Defiance Moraine. There is an apparent progradation of sediment to the southern end of the shoreline where a spit formed. This indicates that dominant wave direction would have been from the northeast and east, similar to the wave direction of Lake Arkona. Another similarity to the Arkona shoreline in Field Site 5 is the presence of elongated ridges in the backshore.

To further investigate the differences and similarities between the Whittlesey shoreline and the Arkona shoreline in the area, interpretations of the Whittlesey sediments will be discussed. Five major lithologic units were identified within this shoreline feature. The first unit was a Holocene agricultural soil. The soil unit will not be discussed in depth because the formation of the soil would post date the formation of the ridge. An important observation that was made is the presence of large grains ranging from 2 to 30 cm in diameter. The grains range in lithologies from granites to diorites, and other igneous rocks common to the Canadian Shield. These grains were originally deposited as diamicton and then eroded and re-deposited in the shoreline features. The presence of these grains is similar to the large grains found at the surface of the Arkona shoreline in Field Site 5, with the exception that no calcareous grains were found on the Whittlesey shoreline. The next unit occurs on the crest of the ridge and in the backshore. The unit is characterized as a well-rounded, oxidized fine to medium, sand, with interbedded planar bands of silt in the backshore. This unit best represents the upper portion of the shoreline's beach deposits. The silt bands in the backshore best represent fine-grained sediment deposition that occurred between episodes of overwash. The silt planar bands observed in the

vibracore from the crest of the ridge are indicative of lagoonal deposits or backshore deposits. Below the silt bands in the crest of the ridge and observed in the backshore is a thinner medium to fine sand that is interpreted as another sequence of beach ridge sediment. Below the second sequence of beach ridge sediments is an abrupt erosional contact with a sub-rounded to well-rounded coarse-grained sand. The coarse-grained sediment unit is observed in both the backshore and beach ridge. This unit would be consistent with an erosional ravinement surface (Cattaneo and Steel, 2003). The unit below that erosional surface is a stiff clay/silt with a sand matrix that matches the basic definition of a diamicton (Bennet and Glasser, 2009).

The basic depositional model for this shoreline is as follows: the underlying diamicton was initially deposited by glacial processes prior to Lake Whittlesey. As the water levels began to stabilize at the elevation of Lake Whittlesey, the upper surface of the diamicton would have been eroded and coarse-grained sediment would have been deposited as a coarse lag, resulting in a ravinement surface on the top of the diamicton. This is evident by the erosional contact between the diamicton and the coarse sand deposited on top. Littoral processes driven by wave energy would have begun to form the core of the beach ridge and create a foreshore and backshore. Sigmoidal bedding of upward-accreting beach ridge sediment would begin to form in the foreshore and prograde basinward (Curry, 1964). The basinward progradation would result in horizontal-bedded (shingled) sand in the upward surface of the beach ridge. A small lagoon or marsh would have formed in the backshore where planar beds of fine-grained silt and sand would have been deposited. The thin silt layers with no trace of organics in the backshore suggest the area would have had very shallow water and any marsh or lagoon would be poorly developed. A poorly developed backshore would be expected in a shoreline that is only 300 to 400 m wide. The silt laminae found in the crest of the beach ridge suggest water-plane

fluctuations. As the water plane moves upward, it would result in a shift landward of the beach ridge deposits. This stratigraphic characteristic of this process is mentioned by and Baedke Thompson (2004), and reflected in cores CE121162 and CE1210164. It is not known how many times or what magnitude the water plane fluctuated, but a result of the varying water plane could help account for the sharpness of the east-facing slope of the beach ridge. As seen in Figure 3.13, the foreshore slope is initially very steep to the plunge point then flattens rapidly into the basin. Sequences of minor lake-level transgressions could have progressively eroded into the foreshore sediments, which would have progressively steepened the foreshore face.

3.27 Field Site 7 Adrian, MI, Whittlesey Shoreline

Field Site 7 is located approximately 7.32 km east of the city of Adrian, MI. and northeast of Palmyra, MI. The principle geomorphic feature is an approximate 1-km section of a steep-sloped ridge previously identified as a shoreline of glacial Lake Whittlesey (Figure 3.37). The field site is an agricultural field located on South Raisin Center Highway between Academy and Demlow Roads. A hand-dug pit, taken on the crest of the ridge was done at this site to investigate the stratigraphy of the ridge. A sample for OSL analysis was taken from this hand-dug pit into the Lake Whittlesey strandline.

Figure 3.37. A: DEM of a Whittlesey shoreline northeast of Palmyra, MI. Proposed dominant wave direction indicated by white arrows. B: The Whittlesey shoreline's ridge is marked by the black dashed lines. The hand-dug pit is denoted by the black box within the tree line.

3.28 Field Site 7 Hand-Dug Pit

A single hand-dug pit was taken at the crest of the ridge in an attempt to locate the beach sand associated with the Lake Whittlesey shoreline, and to identify the overlying stratigraphic units. The pit was approximately 1.8 m deep and allowed the identification of three distinct

sedimentary units. The first unit, designated Unit A, was approximately 45.75 cm thick and consisted of a dark brown agricultural soil with in situ plant material. The second unit, Unit B, is 51.8 cm thick and is an oxidized, homogeneous, brown, medium- to fine-grained sand unit. The third unit, Unit C, is an un-oxidized, light brown, well-sorted, fine- to medium-grained sand with a thickness in excess of 79 cm. An OSL sample was taken from Unit C at a depth of approximately 170.6 cm from the surface of the pit (Figure 3.38). The OSL sample JDUT16-4 (UT1604JD) yielded an age of 15.7 ± 0.7 ka.

Figure 3.38. Description of hand-dug pit for collection of OSL Sample JDUT16-4. Images from the pit are located adjacent to pit characterization and description. The OSL sample JDUT16-4 was taken just below the soil C horizon transition in homogeneous medium- to fine- grained sand (location indicated by a black circle). Labels I-V represent images taken from the hand-dug pit and correspond to panels A – E respectively in Figure 3.38b.

Figure 3.38b. Each panel represents an image taken from the hand-dug pit. Panels A-E correspond to roman numerals I-V in Figure 3.38.

3.29 Discussion of Field Site 7

This field site is located northeast of Palmyra, MI. The principle feature is a Whittlesey shoreline. The field site contains a small portion of a prominent but narrow, near-continuous ridge that can be easily traced over 31 km. The elevation of the ridge is 224 m asl, and based on the description by Leverett and Taylor (1915), the elevation, geomorphology, and mapped location of the ridge is consistent with a Lake Whittlesey shoreline. South of the field site on the distal end of the ridge nearest the River Raisin is geomorphic evidence of progradation of

sediment in a southwestward then westward direction. The sediment appears to have traveled south along the shoreline via longshore transport and deposited at the distal end of the shoreline into the incised valley of the River Raisin. The sediment then appears to have been wrapped around the distal end of the shoreline by waves originating from an east and northeast direction to form a sequence of prograding spits.

The uppermost unit is interpreted as agricultural soil commonly found throughout the area. Therefore, it would have had no bearing on shoreline development and only formed after water receded from this area. Below the soil is an oxidized homogeneous sand unit. This unit could be interpreted as upper beach ridge sediment or possibly a dune cap on the crest of the ridge. The last accessible unit in the pit is an un-oxidized, well-sorted, medium- to fine-grained sand. This unit has a gradational contact with the upper homogeneous finer-grained sand. Similar sedimentation sequences can be observed in the Lake Michigan and Huron basins (Baedke et al., 2004). Based on the observed sedimentation sequences, it is interpreted that the finer-grained sand unit could be a dune cap and the underlying coarser sand is the main sediment associated with the beach ridge. Due to the location of the pit and space constraints, the pit was not dug any deeper, so the exact thickness of the beach-ridge sediment is unknown. Several well logs were analyzed along the length of the shoreline using the well log database maintained by the Department of Environmental Quality of Michigan. Based on those well logs, the thickness of the sand units is between 1.8 to 4.2 m. Possible sources for the sediment supplied to the ridge could have been from the Saline River just 30 km northeast of the field site, or possibly the Huron River located further north.

3.30 Field Site 8, Dundee, MI, Arkona Shoreline

Field Site 8 is located approximately 10.5 km northwest of the town of Dundee, MI. The field site sits on an agricultural field to the northwest of the intersection of Milwaukee Road and

North Couper Road south of the village of Cone (Figure 3.39). The principle feature is a low-relief ridge that is 2 km long, 0.4 km wide and at an elevation of approximately 211 m asl. The elevation of the ridge and the general geomorphology of this ridge are consistent with a Lake Arkona shoreline. A hand-dug pit was done on the crest of the ridge to investigate its internal stratigraphy.

Figure 3.39. A DEM of an Arkona shoreline northwest of Dundee, MI. Proposed dominant wave direction denoted by white arrows. A: The hand-dug pit is the brown patch of soil north of the shed indicated by the black arrow.

3.31 Field Site 8 Hand-Dug Pit

A single hand-dug pit was taken on the crest of the ridge to investigate the internal stratigraphy of the ridge. The pit was approximately 1.5 m deep and exposed three major lithologic units. The first unit, Unit A, is approximately 47.2 cm thick and consists of a dark brown soil, rich with in-situ organics (perennial grass roots). Unit A is consistent with O-horizon and upper A-horizon of the agricultural soil in the area. The second unit, Unit B, is approximately 105 cm thick oxidized brown, well-rounded, fine- to medium-grained sand with planar bedding. The third unit, Unit C is found beneath Unit B and has an unknown thickness. The transition between Unit B and C is abrupt and interpreted as being erosional in nature. Unit C consists of a stiff silt/clay with a sandy matrix, 1 to 3.5 mm grains of varied lithologies appear throughout the unit with no discernible distribution pattern. This unit is being interpreted as a diamicton. The water table coincided with the contact between Unit B and Unit C.

3.32 Discussion of Field Site 8

The field site is located northwest of Dundee, MI, near the village of Cone, MI. The principle feature is an Arkona shoreline. The low-relief Arkona shoreline is in sharp geomorphic contrast to the Whittlesey shoreline just 5 km to the north and northwest. The Arkona ridge has an elongated short axis, giving a washed appearance, and is discontinuous across the landscape. In comparison, the Whittlesey ridge is prominent but narrow, with a steep shoreface that can be traced continuously tens of kilometers. This shoreline is segmented only where it intersects the incised valleys of stream drainage systems. This segment of the Arkona shoreline has an enlarged southern end. This suggests down-drift accumulation with littoral transport of sediment to the south along the shoreline. The implication is that dominant wave direction would have

been from the northeast to north sectors, which in turn is similar to the wave direction observed from Whittlesey coastal features.

The surficial unit covering the Arkona shoreline is an agricultural soil present throughout the area. The unit below the Holocene soil is a well-rounded, oxidized, medium- to fine-grained sand with faint planar bedding. The sand unit is interpreted as beach sand based on its lithological consistencies with beach sediment contained within the core of beach ridges observed in paleo Lake Michigan, Huron and Superior shorelines (Baedke and Thompson, 2004). The lower unit, Unit C is interpreted as a diamicton. As with the discussion of diamicton origin in the Lake Erie basin in several previous sections, it is interpreted that the diamicton in this field site is also derived from glacial processes. The contact between the beach sediment and the diamicton is erosional. This implies that the deposition from the top of the Arkona beach sand to the diamicton is continuous. There is no evidence for a regional erosional surface or ravinement surface interrupting the deposition of the Arkona shoreline that would be expected if the shoreline was overtopped by a higher lake stand.

The deposition model for this ridge is as follows: the glacial diamicton would have been deposited prior to the advancement of water from the proglacial lakes. Whatever sediments were previously deposited on top of the diamicton apparently were removed immediately before deposition of the Arkona shoreline. This sequence implies transgression and ravinement at the start of the Arkona highstand. This area was under water during the occupation of lakes Maumee and Whittlesey, which presumably would have deposited a moderately thin layer of glacial lacustrine silt. The stabilization of water level of Lake Arkona would have created conditions to construct a shoreline. Littoral processes would have supplied the sand for the beach ridge, and wave-shoreface interaction as described by the Curray model would have

resulted in the formation of the preserved Arkona beach ridge. Since geomorphic evidence along the shoreline suggests a dominant north to northeast wave direction, possible sources of sediment for this ridge could be from the Saline or Huron river systems. This sedimentation sequence would have persisted until lake level dropped to a lower lake stand, ultimately abandoning the beach ridge.

3.33 Field Site 9, Bays Road, Arkona Shoreline

Field Site 9 is located approximately 5.5 km southwest of the city of Wayne, OH. The field site is located on an agricultural field to the north side of Bays Road, between Emerson and Portage View Roads (Figure 3.40). The primary features of this site are three discontinuous low-relief ridges with elevations of 211 m, 212 m, and 213 m asl. The field investigation was conducted on the 212 m ridge, which is the best defined of the three ridges. The ridge elevations are congruent with the three shoreline elevations of glacial Lake Arkona as presented by Leverett and Taylor (1915). A hand-dug pit was done on the crest of the ridge to investigate its internal stratigraphy. An OSL sample was collected from the sand unit related to the beach sediment of the Lake Arkona shoreline.

Figure 3.40. A: DEM of an Arkona shoreline southeast of Bowling Green, OH. Proposed dominant wave direction denoted by white arrows. B: The ridge is denoted by the black dashed lines. The OSL pit is indicated by the black box near the tree line.

3.34 Field Site 9 Hand-Dug Pit

A single hand-dug pit was done on the crest of the 212 m Arkona shoreline to evaluate the internal stratigraphy of the ridge. The pit was approximately 1.2 m deep and exposed four lithologic units. The first unit, Unit A, is approximately 55 cm thick and consists of a dark brown, organic rich soil unit. Unit A is consistent with the agricultural soil present in the area. The second unit, Unit B is approximately 24.4 cm thick and consists of an oxidized, fine to medium, well-rounded sand with a silt-clay component. In-situ roots and other organics are found in the upper 10 cm of Unit B. The third unit, Unit C, is 36.5 cm thick and consists of a grayed, un-oxidized well-rounded, near-pure fine- to medium-grained sand (96% fine- to medium-sand). Planar bedding of the sand is observed within the entirety of Unit C. It is interpreted that the planar bedding and the fine to medium sand grains is indicative of Lake Arkona un-oxidized beach sand. An OSL sample was taken from Unit C at a depth of 91.4 cm from the surface of the pit, to date the Lake Arkona shoreline. The fourth unit, Unit D, lies

beneath Unit C at the floor of the pit and has an unknown thickness. The transition between Unit C and D is very sharp and is interpreted as being erosional in nature. Unit D is defined by a stiff silt/clay unit with a sand matrix. Randomly distributed within Unit D are 1 to 2 mm grains with varied lithology, most grains are sub-rounded. Unit D is being interpreted as a diamicton. A characterization of the hand-dug pit and locations of pit images are presented in Figure 3.41. The OSL sample JDUT16-2 (UT1602JD) was taken at a depth of 3 ft (91.4 cm) and yielded an age of 12.4 ± 0.5 ka.

Figure 3.41. Hand-dug pit for OSL sample JDUT16-2 with lithologic description. The OSL sample JDUT16-2 was taken just below the C horizon transition in homogeneous, well sorted, medium- to fine-grained sand (location denoted by a black circle). I-IV represent images of the pit that correspond to panels A-D in Figure 3.41b respectively.

Figure 3.41b. Each panel A, B, C and D represents an image from the hand-dug pit, the letters correspond to the roman numerals in Figure 3.41.

3.35 Discussion of Field Site 9

This field site is located southwest of Wayne, OH. The principle feature is an Arkona shoreline, in the southern portion of the western Lake Erie basin. The Arkona shorelines in this region are geomorphically distinct from the Arkona shorelines in the southwestern portion (Field

Sites 1 and 2). The Arkona shorelines form a small strandplain at elevations of 211 m, 212 m and 213 m. The northeastern section of the ridge seems to be building off a local topographic headland. The definition of individual ridges in the northeastern section of the strandplain is poor. Typically only a single wide ridge can be observed. In contrast, individual ridges are much better defined to the south of the Portage River. This section of the strandplain produces continuous, narrow but distinct ridges similar to shorelines formed in wave-dominated coastal zones.

As stated by Baedke and Thompson (2004) and Curray (1964), a shoreline can develop as long as there is sufficient wave energy and sediment supply to allow the construction of a beach ridge. Based on other sites in the region, it is clear that the dominant wave direction is from the north and northeast. Wave energy was sufficient at Site 9 to erode enough sand from the headland to produce the strandplain ridges. Approximately 30 km farther west at Sites 1 and 2, wave energy was lower but still sufficient to create barrier islands. However, the resultant geomorphic features are distinctly different. The only other applicable factor based on the Curray model that could play a significant part in shoreline development is sediment availability or supply. The dominant longshore transport gradient is interpreted to be to the west along the ridge. The southwestern portion of the strandplain was most likely directly supplied by the Portage River. The dominant supply of sediment for the northern portion of the strandplain is most likely associated with wave-induced erosion of the headland. Based on the bulbous appearance of the northeastern end of the strandplain, and the loss of definition of individual ridges, it is inferred that the sediment supply into the system was near the saturation point. This resulted in a series of thick, nearly indistinguishable ridges to form. As the sediment was

transported southwest along the longshore gradient, the sediment load would decline resulting in individual ridges.

The stratigraphy of the 212-m Arkona ridge also bears similarity to the stratigraphy observed in other field sites. The lithologic unit beneath the agricultural soil is a well-rounded medium- to fine-grained sand. This lithologic unit is interpreted as the upper surface of the core of the beach ridge. There is a gradational transition to an un-oxidized near-pure sand. Planar bedding is observed, which reinforces the interpretation that these units are related to beach ridge aggradation. The contact with the base unit is sharp and abrupt; this contact is interpreted as being erosional. The lithology of the base unit is a stiff, silt/clay, with 1 to 2 mm grains with varied lithologies. The lithology of the bottom sedimentary unit best matches a diamicton. As with the determinations of the diamicton in other field sites, it is interpreted that this diamicton is probably glacially derived. Based on the stratigraphy of the ridge, it is determined that the depositional sequence between the base unit and the soil is continuous. Due to the processes by which a glacier would deposit a diamicton, it is unlikely that any lake sediment would or be found beneath. With no evidence of an erosional contact interrupting the planar bedding of the ridge or the possibility of additional sediment below the diamicton, it is determined that there is no stratigraphic evidence to suggest the shoreline was overtopped by a higher stand lake level.

3.36 Field Site 10 Perry, OH, Arkona Shoreline

Field Site 10 is located approximately 1.3 km northeast from the city of Perry, OH. The field site is on an agricultural field northwest of the intersection of Manchester Avenue and Call Road (Figure 3.42). The principle feature is a low-relief ridge that is 1.3 km long, with an elevation of 214 m asl located near the middle of the southern portion of the Lake Erie basin. The elevation of the ridge is consistent with the known elevation of the highest Lake Arkona

shoreline. Ground penetrating radar was used to investigate the internal stratigraphy of the ridge and a single hand-dug pit was used for ground truth and collection of an OSL sample.

Figure 3.42. DEM of an Arkona shoreline east of Perry, OH. The Arkona shorelines form several discontinuous ridges in stark contrast to the single continuous shorelines formed by Lake Warren and Lake Whittlesey. A: Locations of GPR transects are denoted by the white dashed lines. The location of the OSL Pit is denoted by the white box.

3.37 Field Site 10 GPR Transects

Three GPR transects were taken across the prograding spit to investigate the internal stratigraphy of the ridge. The first profile Ca-01 was taken parallel to the long axis of the ridge to evaluate if the stratigraphy was continuous along the ridge. Profile Ca-02 was run from the crest of the ridge to the beginning of the foreshore. Profile Ca-03 was run from just below the crest of the ridge and down the foreshore.

Transect Ca-01

One major facies is observed in the GPR profile Ca-01. Multiple strong reflections are observed throughout this profile. The reflections are discontinuous, commonly overlap, and dip slightly to the east. These reflections are classified as RF5. The entire facies is continuous throughout the profile. The interpretation of this facies based on ground truth is the vertical aggradation of coarse-grained sand and gravel associated with down-drift progradation of the spit platform from an eroding headland. No evidence is observed within this profile to suggest that

the sequence has been interrupted or truncated. Classifications of the GPR transect and visual representation of Ca-01 are presented in Figure 3.43.

Transect Ca-02

The primary goal of GPR transect Ca-02 was to provide stratigraphic control across the crest of the ridge and provide supplemental data for the OSL sampling pit taken adjacent to the transect. One major facies is observed in this profile. The facies is classified as a sequence of tangential/oblique reflections dipping gently landward that can be traced the length of the profile. The facies is classified as RF5. Based on the ground truth obtained, the sequence observed in the GPR profile is a landward migration of coarse-grained sand and gravel associated with the spit platform. No strong reflection surface is observed truncating the tangential beds. Classifications of the GPR transect and visual representation of Ca-02 are presented in Figure 3.43.

Figure 3.43. GPR profile and interpretation for transects Ca-01 and Ca-02. Black rectangle indicates the hand-dug pit and the solid black line notes the intersection of CA-02 with CA-01.

Transect Ca-03

One major facies is identified in GPR transect Ca-03. Along the length of the profile are sequences of continuous sigmoidal reflections that dip slightly basinward. These reflections are classified as RF1. The interpretation of RF1 in this field site is that the sigmoids represent the progradation of sand and littoral deposits associated with the construction of the spit platform. There are no observed erosional surfaces truncating the entire sequence of sigmoidal reflections. GPR profile and classifications are presented in Figure 3.44.

Figure 3.44. GPR profile and interpretation for transect Ca-03.

Field Site 10 GPR Discussion

GPR profiles across the spit near Perry, Ohio, produce sequences of undisturbed semi-continuous reflections. These reflections are interpreted as continuous deposition of sand and gravel associated with spit-platform development in both a basinward and an alongshore direction to the west. These interpretations are supported by the ground truth obtained at the site. Neither the GPR profiles nor ground truth provided evidence of a ravinement or erosional

surface truncating the depositional sequence exposed in the spit. This would suggest that the spit and the overlying ridge were formed during the same lake-level event. All major reflections dip basinward.

3.38 Field Site 10 Hand-Dug Pit

A single hand-dug pit was taken at the crest of the ridge to provide ground truth for the GPR transects and provide access to Lake Arkona datable sand. The pit was 3 m deep and identified 5 major lithologic units. The five units are defined in order of depth, from Unit A to E. Unit A is 12.7 cm thick and consists of a shallow A horizon soil with in-situ perennial grasses. Unit B is 109 cm thick and consists of a well-rounded, oxidized, coarse sand unit with 2 to 8 mm diameter grains present throughout. Concentrated reddish sediment and black-hued sediment is observed randomly distributed throughout the unit. The upper 60 cm of Unit B is moderately compacted due to the area having once been occupied by a greenhouse. Unit C is approximately 85 cm thick and consists of an oxidized, brown, well-rounded, fine- to medium-grained sand with 1 to 2 mm rounded grains. Unit C has a mottled appearance and has a gradual transition to Unit D. Unit D is 76.2 cm thick and consists of an un-oxidized, well-rounded, near-pure 98% fine to medium sand unit. Quartz and feldspar are abundantly present within Unit D, however there is an appreciable amount of shale fragments easily visible (approximately 15 to 20% of the visible grains). This unit represents the lithology for GPR facies RF1. The transition between Unit D and Unit E is sharp and abrupt, and is interpreted as an erosional contact. The total thickness of Unit E is unknown but it extends from the base of Unit D to the bottom of the pit. Unit E is characterized as a stiff silt/clay with a sandy matrix. Unit E contains 1 to 2 mm grains of varied lithology with no discernible distribution pattern. A characterization of the hand-dug pit and pit

images are presented in Figure 3.45. OSL sample JDUT16-3 (UT1603JD) was taken at a depth of 8.8 ft (2.07 m) and yielded an age of 18.2 ± 0.8 ka.

Figure 3.45. Description of hand-dug pit for collection of OSL Sample JDUT16-3. Images from the pit are located adjacent to pit characterization and description. The OSL sample JDUT16-3 was taken just below the C horizon transition in homogeneous medium- to fine-grained sand unit (location denoted by a black circle). Labels I-V represent images of the pit which correspond to panels A-E respectively in Figure 3.45b. VI represents an image of the gravel presented in Figure 3.45c.

Figure 3.45b. Each panel A - E represents an image from the hand-dug pit, the panel letters correspond to the roman numeral I-V in Figure 3.45.

Figure 3.45c. Gravel and coarse sand in the upper portion of the hand-dug pit. Panel Ab corresponds to the roman numeral VI in Figure 3.45.

3.39 Discussion of Field Site 10

This field site is located in the city of Perry, OH. The primary feature is an Arkona shoreline. The Arkona coastal feature in this portion of the basin is a set of prograding spits at elevations of 211 m, 212 m and 214 m between the Lake Warren and Lake Whittlesey shorelines in the central part of the Lake Erie basin. The orientation of the spits suggests dominant wave direction was from the north and northeast, which is the same direction as in the western basin. Many of the spit forms in this region are heavily disturbed by anthropogenic activities, and appear discontinuous. The ridges that are still observable are well defined and produce low-gradient shorefaces. Low-gradient shorefaces are often attributed to deposition-dominated shorelines; examples of this can be seen in pluvial Lake Bonneville in Utah (Schofield, 2004).

The stratigraphic sequence of this field site is similar to other Arkona shorelines observed during this study. The largest exception is the spit in Field Site 10, which yielded the thickest sedimentary sequence of any of the other shorelines observed. The hand-dug pit used for stratigraphic and lithologic description was positioned on the foreshore side of the ridge crest. Beneath the soil is coarse-grained, well-rounded sand with varied lithic grains ranging from 2 to 8 mm distributed throughout. The coarse-sand sized grains and abundance of semi-rounded to rounded grains suggest this sediment was deposited in a high-energy coastal environment. The reddish and black hued sand is consistent with heavy mineral layers that occur within foreshore deposits (Davidson-Arnott, 2010). The contact with the lower unit is gradational. The next major lithologic unit has finer-grained, oxidized sand with 1 to 2 mm grains scattered throughout. This unit suggests a lower-energy environment and best reflects the upper surface of a beach ridge deposit. Beneath the finer-grained sand is a gradational contact with a un-oxidized medium- to fine-grained sand unit. Planar bedding is observed within the un-oxidized sand. This unit is interpreted as the main portion of the beach ridge deposit. Below the beach ridge sediment is an erosional contact with a stiff silt/clay with a significant sandy matrix, 1 to 2 mm grains are observed throughout the unit. The lithology of this unit is interpreted as being a diamicton. Based on the diamicton observed in other field sites, it is inferred that the diamicton is glacial in origin. All the contacts regarding the beach ridge and foreshore deposits are gradational with no erosional contacts interrupting the internal deposition. Several conclusions can be derived based on the lithology. First, the thickness of the sediment associated with the ridge, the shallow-gradient shoreface, and the aggradational sedimentary sequence, suggest that the beach ridge is part of a deposition-dominated shoreline. Second, the lack of an erosional

surface interrupting the deposition of the prograding spit suggests that the ridge was not transgressed by a higher lake stand.

Chapter 4

Discussion of Field Sites

4.1 Implications of data gathered from field sites

As mentioned in the introduction, a transgression of Lake Whittlesey over Lake Arkona has a major stratigraphic implication. The rising water level of Lake Whittlesey would have drowned the Lake Arkona shoreline features by 7 to 14 m, and the coastline would have retreated several kilometers inland. This would have resulted in a rapid shoreface retreat as the transgressive waters would have eroded and truncated the depositional sequence of the Lake Arkona shorelines. This erosion surface, known as a ravinement surface, would be recognizable basin-wide on Arkona coastal features. In GPR profiles this surface would be represented by a strong reflective surface truncating sigmoidal reflections indicative of a prograding shoreface. In a lithologic sense the ravinement surface would be a coarse lag deposited on top of previously deposited littoral sediments along the shoreface. If water rising to the level of Lake Whittlesey overtopped the Arkona shoreline, due to the depth of water over the Arkona coastal forms, a significant thickness of silt and clay planar beds indicative of lake basinal sediments would be expected. At a minimum, a second sequence of sigmoidal littoral sediments would be expected to be deposited on top of the ravinement lag.

Based on ground-truth methods, no ravinement lag was identified in any Arkona coastal features. Furthermore, no strong reflection truncating depositional beds were observed in any of the GPR profiles. No lithologic or stratigraphic data produced by any field method yielded support for the claim that Lake Arkona was transgressed by Lake Whittlesey. It is therefore proposed that the traditional lake-level curve for paleo Lake Erie should be reevaluated. It is the

assertion of this study that the model proposed by Totten (1985) is the lake-level model best supported by the stratigraphic and geomorphic evidence. Based on the data gathered in this study, the appropriate sequence of high lake level stand should be Lake Maumee, Lake Whittlesey, Lake Arkona, and then Lake Warren. This sequence suggests a generally regressive trend between the first four major proglacial lakes. This is not to state that lake level did not fluctuate between the major lake stands. Instead, in all probability lake level oscillated frequently but with an overall longer-term regression. The field observations from this study offers no direct evidence related to the existence or placement of a possible Ypsilanti lowstand in the overall sequence of lake levels. However, in the cases of both the Arkona and Whittlesey shorelines, there is clear evidence of interactions between the shoreline and pre-existing incised valleys, for example, the progradation of spits into those topographic lows. A prominent example of this relationship can be observed with the Whittlesey shoreline near Palmyra, MI, where a spit was prograding into a former river valley of the River Raisin (Figure 5.3). This suggests that paleo lake levels were below Lake Whittlesey water elevations prior to its formation, in order for the River Raisin to have incised the river valley. Lake levels then rose to Lake Whittlesey levels resulting in the formation of a spit prograding into the incised river valley. It is proposed that Lake Whittlesey was the result of a transgression following an unknown lowstand event. The exact elevation of the lowstand is presently unknown and no evidence was collected or observed that could suggest that this lowstand is evidence of the Ypsilanti low.

To better explain the traditional washed appearance of the Arkona shoreline, it is proposed that the Arkona shorelines were produced during a short-lived stillstand event occurring between Lake Whittlesey and Lake Warren. Within the Maumee River and River

Raisin basins, the Arkona shoreline has little geomorphic expression of more than one lake-level elevation as has been reported elsewhere. A short stillstand could also account for the lack of geomorphic definition of the Arkona shorelines and the discontinuous nature. A short-lived stillstand could also help explain the lack of developed littoral facies and the thinness of the internal Arkona stratigraphy. The lack of a ravinement surface in the shoreface in the GPR profiles of Lake Arkona shorelines also provides evidence of either shoreline regression or water-level drop since reworking of previously deposited sediments would result in an overlapping relationship (Wilkins, 2007).

Chapter 5

Statistical Model for Classification of the Shoreface

Shoreline segments of a single highstand event can be quantifiably differentiated and compared with other highstand events. A statistical model was constructed to evaluate the Arkona and Whittlesey shorelines in the western Lake Erie basin. The primary goals of the model were to show statistically the differences between the Arkona and Whittlesey shorelines, aid in outlining coastal compartments of Lake Arkona and Lake Whittlesey, provide substantiating data to field observations regarding shoreline geomorphology, and aid in the interpretation of the larger littoral systems of the two proglacial lakes.

5.1 Description of the Statistical Model

A total of 190 elevation profiles were taken across the Arkona shoreline and 336 profiles were taken from the Whittlesey shoreline. The data for the profiles were produced from 3-m horizontal resolution LiDAR taken from the USGS National Map viewer data archive. The profiles themselves were generated using the ESRI ArcMap 3D Analyst Extension. Each profile extends on average 4.5 km to 5 km from the crest of the shoreline into the lake basin. The profiles start at the crest of the beach ridge and continue into the basin past the edge of the shoreface. The length of each profile ensures that the entire shoreface is represented in the profile. Fewer profiles were taken across the Arkona shorelines due to its discontinuous nature, producing fewer coastal features to evaluate in the basin. Each profile was spaced approximately 60 to 100 m apart, ensuring that multiple profiles were taken across each shoreline feature. Profiles were taken in closer density where a particular section of the shoreline appeared to change rapidly over short distances. Profiles were not taken if in a 4 - 5 km distance away from

the shoreline the profile would intercept fluvial systems or anthropogenically modified areas. The landscape alteration from fluvial systems or anthropogenic activities would have an effect on the overall characteristic of the relict shore zone. The length used for each profile also would help to reduce random error and error caused by small drainage ditches and roadways. Where a profile was taken across a large drainage ditch or road (anthropogenic features), a short elevation profile was taken across the anthropogenic feature and that profile was subtracted from the entire shoreface profile in Excel to remove the anthropogenic feature.

A mathematical model was developed to evaluate the individual profiles. The model's base equation is presented in Equation 1.

$$y = (Hx^{-k})(Mx)$$

Equation 1. Base equation used for the Statistical Model.

The equation is a modified polynomial consisting of a decay function with a linear component. The decay function was used to characterize the crest of the ridge to the foreshore and the top of the shoreface; the linear component function was used to characterize the lower shoreface to the offshore. The variable H is the slope of the best-fit line of the foreshore, with k being the modifying exponent. The slope will increase with increasing k values and will decrease with decreasing k values. Shorelines with smaller k values in general have gently sloping foreshores that geomorphically are expressed as a lower-relief ridge. In contrast, shorelines with higher k values have steeper foreshores with more distinct ridges. The M variable represents the slope of the lower shoreface and a portion of the offshore. The slope of the lower shoreface and offshore is less affected by littoral depositional processes that dominate the foreshore and upper shoreface. Therefore, it is considered that the linear component of the equation represents the broad topographic changes in the profile and acts as a topographic modifier for the entire profile.

The equation presented in Figure 5.1 was applied systematically to the 526 profiles to produce best-fit lines that could be compared for each shoreline across the basin. Figure 5.1 illustrates how variations to each respective variable can affect the best-fit line of the model.

Figure 5.1. Representation of the effect of variables incorporated into the model to create a best-fit trend line. Panel A represents the model's best-fit line output with no exaggerated values for variables. Panel B represents an exaggerated value for variable M. Panel C represents an exaggerated value for variable H. Panel D represents an exaggerated value for variable k. Variations in any of the three variables will produce a response in the model best-fit line.

5.2 Results for the Arkona Coastal Compartments

Five coastal compartments were identified from the DEM analysis of the Arkona shoreline (Figure 5.2). Detailed DEMs of each coastal compartment are presented in Figure 5.3.

Based on DEM observations related to the progradation of spit complexes, it is determined that the dominant wave direction was from the north and northeast. Figure 5.4 presents examples of characteristic shoreline profiles of the different Arkona coastal compartments. The variance between the best-fit line and the actual profile was examined using the coefficient of determination (R^2 value) to test the model's validity. The R^2 was calculated for each profile and plotted on Figure 5.5. A running average was then taken through the data to determine the range that the R^2 fluctuates throughout the model. On average the R^2 values cluster between 0.93 and 0.97, with outliers as low as 0.85 and as high as 0.99. It is therefore determined that the model's results can be considered representative of the observed values. Data for variables k , M and H were recorded from each profile, the data are presented in Figures 5.6, 5.7 and 5.8.

Figure 5.2. Location of the Lake Whittlesey and Arkona coastal compartments. Coastal compartments for the Whittlesey shoreline are represented by segments A through H. Lake Arkona coastal compartments are represented by AA, AB, AC, AD and AE. Lake Whittlesey shorelines are denoted by blue lines and Lake Arkona shorelines are denoted by red lines. Profiles taken across each shoreline are denoted by the black and purple lines respectively.

Figure 5.3. Each of the panels A-F represents a LiDAR DEM showing the coastal compartments of Lake Arkona and Lake Whittlesey. White arrows represent dominant wave direction, dashed black lines represent elevations 210 and 224 m (as labeled on panels) and major cities are outlined and labeled in black.

To evaluate the hypothesis that the coastal compartments for the Whittlesey and Arkona shorelines are quantifiably different, the statistical environment software R (R Core Team, 2016) was used to perform a multivariate analysis of variance or MANOVA on model best-fit profile lines. Several MANOVAs were conducted using the Hotelling-Lawley, Roy, Pillai and Wilks methods (Pillai, 1960; Hand and Taylor, 1987; Krzanowski, 1988; and Krzanowski and Marriott, 1994). The results of the MANOVAs were a p value of 2.2×10^{-16} , which indicates that there is significant variance within the system, or a rejection of a null hypothesis. To evaluate where the variance could be occurring within the system, a partial analysis of variance was taken by comparing the significance of one variable against the others. To finalize the resultant data, a Tukey post hoc test was conducted with the results for each variable. Significant variance between the individual variables was determined when the observed p value was less than 0.03. The results of the Tukey test for the k variable are presented in Figure 5.9.

Based on the k values, Arkona coastal compartment AE is differentiated from the other coastal compartments. This also is illustrated by plotting a running average for k across all the shorelines (Figure 5.6). The running-average trend is fairly linear through the first four coastal compartments, but there is a substantial drop in average k values at the beginning of coastal compartment AE. Moreover, coastal compartment AE also is differentiated from the other coastal compartments by the topographic constant M. A running average through the M measurements of all the Arkona shorelines shows that the first four coastal compartments are relatively the same, but the M values increase at the start of the AE profiles (Figure 5.7). The Tukey plot for M is presented in Figure 5.10.

The Tukey plot for H shows that Arkona compartment AB can be differentiated based on the characteristic slope of foreshore of the shoreline (Figure 5.11). The second major

interpretation from the Tukey plot is that the deviation of AA-AB is significantly different from the interactions of AB with the other coastal compartments. In general, coastal compartment AB and AD are distinctly different from the other coastal compartments as well as from each other. The differences of AA from AC and AD are a bit more subtle. From observing Figure 5.4, AA has a steeper slope for the foreshore and shoreface but is otherwise similar to AC and AD. Therefore, the only way to represent the subtle differences is by analyzing the differences in their responses with the other coastal compartments. The evaluation of the model was unable to distinguish the differences between coastal compartments AC and AD.

Figure 5.4. Representative elevation profiles across the shoreface for each of the respective Arkona coastal compartments.

Figure 5.5. Plot of R^2 values for all measured Arkona shorelines. The original data are represented by the blue line with the moving average denoted by the red line. The moving average period of 20 profiles is represented by the shaded region on the graph, and vertical bars represent the separation of the individual coastal compartments. Shoreline groups are denoted by the letters AA, AB, AC, AD, and AE.

Figure 5.6. Plot of k values for all measured Arkona shorelines. The original data are represented by the blue line with the moving average denoted by the red line. The moving average period of 15 profiles is represented by the shaded region on the graph and vertical bars represent the separation of the individual coastal compartments. Shoreline groups are denoted by the letters AA, AB, AC, AD, and AE.

Figure 5.7. Plot of the M values for all measured Arkona shorelines. The original data are represented by the blue line with the moving average denoted by the red line. The moving average period of 15 profiles is represented by the shaded region on the graph and vertical bars represent the separation of the individual coastal compartments. Shoreline groups are denoted by the letters AA, AB, AC, AD, and AE.

Figure 5.8. Plot of the H values for all measured Arkona shorelines. The original data are represented by the blue line with the moving average denoted by the red line. The moving average period of 10 profiles is represented by the shaded region on the graph and vertical bars represent the separation of the individual coastal compartments. Shoreline groups are denoted by the letters AA, AB, AC, AD, and AE.

Figure 5.9. A visual representation of the Tukey post hoc test for Arkona coastal compartments and variable k. Coastal compartments are aligned along the y axis with average k values plotted along the x axis. Significant variances between the coastal compartments are highlighted in red. All the significant values involve the AE coastal compartment.

Figure 5.10. A visual representation of the Tukey post hoc test for Arkona coastal compartments and variable M. Coastal compartments are aligned along the y axis with average k values plotted along the x axis. Significant variances between the coastal compartments are highlighted in red. All the significant values involve the AE coastal compartment.

Figure 5.11. A visual representation of the Tukey post hoc test for Arkona coastal compartments and variable H. Coastal compartments are aligned along the y axis with average k values plotted along the x axis. Significant variances between the coastal compartments are highlighted in red. All the significant values involve the AB coastal compartment.

5.3 Interpretations of the Model for the Arkona Shoreline

Coastal compartments AB and AE are significantly different from the other major Arkona coastal compartments. This difference is supported by field observations taken at those sites. AB is primarily formed along a topographic high on the edge of a protruding headland in the central section of the study area at the topographic boundary between the River Raisin and

the Maumee River basins (Figure 5.3). The shorelines in this region had a local supply of sediment from erosion of the headland and would have experienced direct wave impacts. AE is in a similar position, but in the southeastern section of the study area. It also was experiencing direct wave attack and formed in the lee of a topographic high. Its source of sediment was from a local eroding headland. The impression given is that AE was formed in a coastal section dominated by wave energy. In contrast, the other Arkona coastal compartments produce discontinuous shorelines because they are in embayed areas with reduced wave energy and minimal sediment supply.

Coastal compartments AA, AC and AD are each very similar with only subtle differences. Dominant wave direction is interpreted as coming from the north and northeast quadrants. AA was formed in the far northern portion of the basin and waves would have approached the coastal compartment obliquely. However, it would have had a relatively local sediment supply coming from the Saline River, and possibly the Huron River. The evidence of this sediment supply is observed in Field Site 8. AC and AD are both in similar parts of the western Lake Erie basin, which is located in the embayment caused by the location of the Defiance Moraine. Both systems would have experienced a significantly lower wave energy, with the lesser being AC. The shorelines in AC run parallel to the dominant wave direction, whereas the shorelines in AD are nearly perpendicular to the dominant wave direction, and would thus received direct exposure to incoming waves. The geographic position of the AC shorelines would have placed the shorelines in a more protected position than the position of the AD shorelines. Sediment supply also was greatly restricted for both systems. This is evident in AC because of the thin littoral deposits at Field Site 3 observed in vibracores and hand-auger transects. The coastal system in AD did not have enough wave energy or sediment supply to

form shorelines like in AC. Coastal compartment AD was only able to form a series of barrier islands out of sediment derived locally, mostly by mining glacial ridges present in the area.

5.4 Discussion of Whittlesey Coastal Compartments

Eight coastal compartments were identified for the Whittlesey shoreline. These compartments are identified as A through H. The geographic locations of the Whittlesey coastal compartments are presented in Figure 5.2 and Figure 5.3. As with the Arkona coastal compartments, the paleo-wind and dominant wave direction are determined to be from the N and NE. This observation was determined based on the dominant progradation direction of spit complexes at the end of Whittlesey coastal features as observed in the LiDAR-based DEMs (Figure 5.3). Characteristic profiles for each coastal compartment are shown in Figure 5.12. The range of R^2 values for the Whittlesey shoreline is between 0.9 and 0.99, with all outliers falling within this range (Figure 5.13). Therefore, the model variance is in an acceptable range to be deemed suitable for further analysis. Data for variables k, H and M were recorded from each profile and displayed in Figures 5.14, 5.15 and 5.16. The resultant value of the MANOVA was $2.2e-16$, showing significant variance among the parameters. A partial ANOVA for each of the variables was done to determine the variance between each variable. The Tukey post hoc test was conducted and plotted on Figures 5.17, 5.18 and 5.19.

The first plot analysis for the Whittlesey shorelines was the Tukey plot for variable k (Figure 5.17). Coastal compartment A was significantly different from the other seven coastal compartments. This also is observed in Figure 5.14, which shows that the trend of k values for coastal compartment A is significantly more negative than the other compartments. Coastal compartments C, D, E, G and H exhibit slightly negative k slopes, but B and F have positive k values. The Tukey plot for H shows that compartment E differs significantly from every other

coastal compartment, and differs only slightly from compartment F. Compartments G and H also vary significantly in respect to compartment E, differently from all other compartments. Figure 5.15 shows that the difference can be related to the slightly positive slope that H and G have with respect to the negative E values. It is also important to note that compartments B and F have entirely strong positive slopes, differentiating them from the all other compartments. The final Tukey plot for the M variable shows that coastal compartment A differs significantly from the other coastal compartments (Figure 5.19). This difference also appears in Figure 5.16 which shows that compartment A has a steep positive slope in comparison to the other compartments.

A brief analysis of the model results shows that the coastal compartments A and E are significantly different from the rest of the coastal compartments. Based on Figure 5.16, the greatest difference between A and E relates to a greater variance between the M values. In general the other six compartments share similar properties and have only subtle differences; this is observed in the characteristic shoreface plots of the Whittlesey shorelines. Coastal compartment C is differentiated from the others based on a negative slope for the H values. Compartments B and F have coinciding slope gradients that are generally in contrast to the other six compartments with respect to the measured variables. The major difference between B and F is that the gradient of B's slope is often a higher magnitude than F's slope. Coastal compartments D, G and H can be differentiated from one another by observing the difference in their responses to the H value. The shorelines within D have a more positive gradient for the model H values than compartments G or H (Figure 5.15). Coastal compartment G has slightly higher gradients of H and M values than coastal compartment H. The end result is a characteristic G profile plotting slightly higher than H shorelines (Figure 5.12).

Figure 5.12. Characteristic shoreface profiles for each of the respective Whittlesey coastal compartments. The dashed black box highlighting the gap in profile E represents the mathematical removal of a large drainage ditch profile.

Figure 5.13. Plot of the R^2 values for all measured Whittlesey shorelines. The original data are represented by the blue line, with the moving average denoted by the red line. The moving average period of 20 profiles is represented by the shaded region on the graph and vertical bars represent the separation of the individual coastal compartments. Shoreline groups are denoted by the letters A through H.

Figure 5.14. Plot of the k values for all measured Whittlesey shorelines. The original data are represented by the blue line, with the moving average denoted by the red line. The moving average period of 20 profiles is represented by the shaded region on the graph and vertical bars represent the separation of the individual coastal compartments. Shoreline groups are denoted by the letters A through H.

Figure 5.15. Plot of the H values for all measured Whittlesey shorelines. The original data are represented by the blue line, with the moving average denoted by the red line. The moving average period of 20 profiles is represented by the shaded region on the graph and vertical bars represent the separation of the individual coastal compartments. Shoreline groups are denoted by the letters A through H.

Figure 5.16. Plot of the M values for all measured Whittlesey shorelines. The original data are represented by the blue line with the moving average denoted by the red line. The moving average period of 20 profiles is represented by the shaded region on the graph and vertical bars represent the separation of the individual coastal compartments. Shoreline groups are denoted by the letters A through H.

Figure 5.17. A visual representation of the Tukey post hoc test for Whittlesey coastal compartments and variable k. Coastal compartments are aligned along the y axis with average k values plotted along the x axis. Significant variances between the coastal compartments are highlighted in red. Coastal Compartment A differs significantly from most other coastal compartments based on variable k.

Figure 5.18. A visual representation of the Tukey post hoc test for Whittlesey coastal compartments and variable H. Coastal compartments are aligned along the y axis with average k values plotted along the x axis. Significant variances between the coastal compartments are highlighted in red. Coastal compartment E differs from most other coastal compartments based on variable H.

Figure 5.19. A visual representation of the Tukey post hoc test for Whittlesey coastal compartments and variable M. Coastal compartments are aligned along the y axis with average k values plotted along the x axis. Significant variances between the coastal compartments are highlighted in red. Coastal compartment A differs from most of the other coastal compartments by variable M.

5.5 Interpretations of the Model for the Whittlesey Shoreline

Coastal compartments A and E are significantly different from the other Whittlesey coastal compartments. Compartment A is the northern-most section in the study area, and has a well-developed, continuous shoreline along the north-west margin of the River Raisin basin.

Coastal compartment E lies along the northern margin of the Maumee River basin just south of a topographic high that separates the Maumee and River Raisin basins. A and E are geographically oriented roughly parallel to the dominant wave and paleo-wind direction. Coastal compartment E is also sheltered from direct wave impacts by the local headland. This would result in the minimization of longshore transport by wave energy. Moreover, coastal compartment A is situated near major fan-delta deposits from the Saline River, River Raisin and Black Creek that can be observed in Figure 5.3. The setting for both A and E would result in an adequate supply of sediment to form distinct ridges. The major difference between coastal compartments A and E is the topographic location in which they were formed. Coastal compartment E was formed along the south flank of a topographic high located in the western section of the basin proximal to the Defiance Moraine (Figure 5.3). The five other coastal compartments are all similar and each has a long axial ridge oriented at an oblique angle to the dominant wave direction. The exception would be coastal compartment H which would have received nearly direct wave attack.

Coastal compartments B, C and D formed on the northwest section of the regional topographic high. Each one of these systems presumably was receiving sediment from longshore transport from the River Raisin and Black Creek. Of the three, compartment B's foreshore slope was the steepest. This could have been a result of the B compartment being oriented approximately parallel to the dominant wave direction. Coastal compartment B is positioned on a steeply sloping land surface just south of Adrian, Michigan. This land surface was relatively close to the ice-margin edge of the southern flank of the Saginaw Lobe and in the vicinity of the Huron Lobe. The dominant longshore transport direction was from the north coming down from

compartment A, and a sub-dominant longshore gradient from the east is evidenced by the spit complex in compartment C showing progradation to the west.

Another change in longshore transport is seen in compartment D. Between the two sets of spits, the northern-most spit shows progradation to the west (Figure 5.3 Panel B) but the spit form on the southern-most shoreline shows progradation to the south (Figure 3.32). This indicates that a nodal zone for longshore transport occurred between these features. This node would be in line with a headland that extends out into the basin that the Lake Arkona shorelines occupy (Figure 5.3, panel B). Two drainage systems also are observed on either side of the headland trending in a west-east direction. It is proposed that those fluvial systems follow the north and south edges of a regional topographic high that is acting as a breaking point for wave direction thus causing a change in local wave environment. The shorelines of coastal compartment D formed steep foreshores but relatively flat shorefaces that extended into the offshore region. Coastal compartment D was differentiated from the other proximal compartments because of the presence of a linear ridge that runs north-south through the town of Assumption, OH (Figure 3.32). This ridge does not have the characteristic morphology of a shoreline. Instead it appears to be a ridge created by glacial processes that was subsequently partially flooded during the Whittlesey highstand. This set of topographic highs may have been offshore islands about 1 km to the east (toward the lake basin) from the actual Whittlesey shoreline, which is west of Assumption. This offshore ridge would have acted as a buffer to the incoming waves providing protection to the D compartment shoreline.

Coastal compartment F formed on the edge of the Defiance Moraine just north of the valley cut by the Maumee River through the Defiance Moraine. Compartment F bore similarities to compartment B, but the slope gradient is greater for F than B because of F's position on the

Defiance Moraine. This resulted in a steeper shoreface and offshore slope for the F compartment. Compartments G and H formed in the southwestern portion of the basin on the Defiance Moraine. Both of these compartments formed sharp continuous shorelines consistent with the observations by Totten (1985). The shorelines were much thinner and narrower in this part of the basin than in the north where shorelines were being supplied with sediment from major river systems (e.g., River Raisin and Saline River). However, enough sediment and wave energy was available to form continuous ridges. The major difference between coastal compartments G and H is that H was formed on the steeper slope of the Defiance Moraine. This resulted in a steeper slope for H shorelines in comparison to G shorelines. As a general observation, coastal compartments A, B, G and H contain narrow, continuous shorelines with few inlets. These are shorelines indicative of wave-dominated coastal regimes. In contrast, coastal compartments C, D, E and F, which occupy the regional topographic high produce larger, semi-discontinuous shorelines with many inlets and prograding spits. This describes a mixed-energy coastal regime. If this is indeed a coastline response to the Defiance Moraine, then the shorelines in compartments C, D, E and F respond differently than any other section of the Whittlesey shoreline that was formed proximal to the Defiance Moraine. It is possible that the regional topographic high that the Whittlesey shorelines are responding to in compartments C, D, E and F is not related to the Defiance Moraine, but is a remnant feature relating to a different process of formation.

5.6 Comparison of Arkona and Whittlesey Coastal Compartments

The model results for variables k , H , and M for both the Arkona and Whittlesey shorelines were compared directly to see if variance could be observed between the two highstands. A comparison of the characteristic shorelines from Arkona and Whittlesey

shorelines is presented in Figure 5.20. The method for the MANOVA was the same as for the Arkona and Whittlesey coastal compartments. The results of the MANOVA showed that there was significant variance between the two highstands. A partial ANOVA was then conducted for each of the variables over the range of both the Arkona and Whittlesey coastal compartments. Results were considered significant if the p value was less than 0.03. A post hoc Tukey test for model variables M, k and H are presented in Figures 5.21, 5.22 and 5.23.

With respect to variable M, there is significant difference between all the coastal compartments of the Arkona and Whittlesey shorelines with the exception of Arkona compartment AE. In respect to variable k, there is not an appreciable difference between the Arkona and Whittlesey coastal compartments with the exception of the Arkona AE coastal compartment (Figure 5.22). The result of the analysis for variable H shows that there are significant differences between the Arkona and Whittlesey coastal compartments with the exception of Arkona coastal compartment AB (Figure 5.23). A note must be made that there is a significant difference between Arkona AB and Whittlesey E with respect to variable H.

Figure 5.20. Characteristic profiles of both the Arkona and Whittlesey shorefaces are plotted on the above figure. The dashed lines correspond to the mean shoreline profile associated with the coastal compartments for each lake. The chart legend is in Figure 5.20b.

Figure 5.20b. The legend for Figure 5.20.

Figure 5.21. A visual representation of the Tukey post hoc test for the Arkona and Whittlesey coastal compartments for variable M. Coastal compartments are aligned along the y axis with average k values plotted along the x axis. Significant variances between the coastal compartments are highlighted in red. Note that Whittlesey compartments are identified with a single letter (e.g., A) and Arkona compartments with two letters (e.g., AA). All of the similar compartments are associated with Arkona AE.

Figure 5.22. A visual representation of the Tukey post hoc test for the Arkona and Whittlesey coastal compartments for variable k. Coastal compartments are aligned along the y axis with average k values plotted along the x axis. Significant variances between the coastal compartments are highlighted in red. Note that Whittlesey compartments are identified with a single letter (e.g., A) and Arkona compartments with two letters (e.g., AA). All of the dissimilar compartments are associated with Arkona AE.

Figure 5.23. A visual representation of the Tukey post hoc test for the Arkona and Whittlesey coastal compartments for variable H. Coastal compartments are aligned along the y axis with average k values plotted along the x axis. Significant variances between the coastal compartments are highlighted in red. Note that Whittlesey compartments are identified with a single letter (e.g., A) and Arkona compartments with two letters (e.g., AA). All of the similar compartments are associated with Arkona AB.

5.7 Interpretation for the Arkona and Whittlesey Coastal Compartments

The Arkona compartment AE was unique within the Arkona coastal compartments as it was the only coastal regime to be interpreted as being wave dominated. AE was primarily differentiated by its variance with variable M. AE formed in the lee of a topographic high and formed a better-developed and steeper shoreface that the other Arkona coastal compartments lacked. The formation of AE on a topographic high resulted in higher (steeper) M values that were most similar to those of Whittlesey coastal components; this geomorphic similarity resulted

in no significant variance for the Tukey post hoc test. The circumstances of AE's development are reflected in observations of Whittlesey shorelines. Whittlesey shorelines formed on the flanks of topographic highs and received sufficient sediment supply to form continuous ridges. The Arkona coastal compartment AB was unique within the Arkona compartments due to its formation in the lee of a major headland and on the edge of a regional topographic high. Within the Arkona coastal compartments, AB varies due to the H variable, which is the same variable that shows no variance with Whittlesey coastal compartments other than compartment E. The major difference between the AB shoreline and the Whittlesey shorelines, and particularly compartment E, is that the AB shoreline is much lower in relief and has much thinner beach sediments. The steepness of the foreshore and shoreface are also less than the Whittlesey shorelines in coastal compartment E (Figure 5.20).

To summarize, overall the Arkona and Whittlesey shorelines are geomorphically distinct (Whittlesey, 1838; Spencer, 1891; Forsyth, 1959; Chapman and Putnam, 1966; Calkin, 1970; Schooler, 1974; Totten, 1982, 1985). Therefore, the two highstands should be differentiable using the statistical shoreface model. Several characteristic differences between the two shorelines are observed in the Tukey plot for variables M and H. For both plots there are significant differences between most of the Whittlesey and Arkona compartments with the exception of compartment AE and compartment AB with respect to variable M. Compartments AE and AB differed from the other Arkona compartments by forming on the lee of topographic headlands which enabled the shorelines to develop steep shorefaces resulting in shorelines more geomorphically similar to Whittlesey shorelines than Arkona shorelines. As a result, compartments AE and AB were not significantly different than Whittlesey coastal compartments for these two tests. The major difference between Arkona compartments AE and AB shorelines

from Whittlesey shoreline compartments is that the Arkona shorelines formed at a lower elevation than the Whittlesey shorelines.

Chapter 6

Chronological Constraints of Lake Arkona and Lake Whittlesey

6.1 Introduction for Relative Dating of the Arkona and Whittlesey Shorelines

Independent of absolute dates for Lake Whittlesey and Lake Arkona, it is still possible to obtain a relative chronology of lake succession and evaluate the standard cyclic model, using the principle of glacial isostatic rebound and shoreline inflection of proglacial lakes. As an ice sheet moves into an area, it begins to apply a load on the regional crust. In response to the addition of the new load caused by the overriding ice sheet, the crust deforms and causes regional subsidence in proportion to the mass of the overriding ice. When the ice sheet begins to recede from the area, the load on the region is removed (Walcott, 1970; Clark et al., 1978; Andrews, 1989). The removal of this load causes a rebound of the crust, with the fastest vertical response being in the closest proximity to the highest load. It is possible to measure the amount of rebound of a given region with respect to a certain point in time (or event) if a large body of water filled the basin at that time and created shorelines throughout the region (Leverington et al., 2001). Shoreline data from proglacial lakes are valuable in determining the rate of rebound due to the nature of the shoreline deformation. A shoreline would initially form as the water of a glacial lake stabilized at a specific elevation around the basin. However through time the effects of differential ice loading on the basin would result in the shorelines being at different elevations around the basin (Lewis et al., 2012). Therefore, a single paleo-shoreline represents both the elevation of past lake level and an independent short lived chronological event.

As the load of the ice sheet is removed from the region and the crust begins to rebound, this rebound can be observed in paleoshorelines of proglacial lakes. A curve that represents

variations in the rate of rebound across a region can be constructed from the current elevation of a shoreline segment and the distance of the shoreline segment from the contemporaneous ice margin. The inflection of the shoreline with regional rebound is a function of time. The longer the load has been removed from an area, the more the land surface would have been elevated. In the case of multiple shorelines being present in an area, the relative age of each subsequent shoreline can be inferred by comparing the slopes of their individual inflection curves. The oldest shoreline will have the steepest slope since it would have been rebounding for the longest period of time, while the youngest shoreline would have the least slope since isostatic rebound has affected it for the least amount of time. Furthermore, most of the rebound would have occurred prior to the establishment of younger shorelines, resulting in younger shorelines having a lower slope than older shorelines. Regionally, the greatest rate of rebound occurs soon after the ice mass is removed. Consequently, a younger shore will also experience an overall lower rate of rebound than an older shoreline in the same area. This approach of evaluating the deformation of shorelines by rebound provides an accurate relative dating technique that can be used to define lake succession in a region (Leverington et al., 2001).

The inflection curve not only represents the regional rebound but also the inflection of the water plane of the lake. Following the method of Leverington et al. (2001), the water-plane inflection can be used as a baseline to remove the effects of rebound and recreate a paleo-environment prior to rebound. If this data is coupled with OSL or other dating techniques, it would be possible to adjust for glacial isostatic adjustment, or (GIA) (Lewis et al., 2005 and Fisher et al., 2012). Similar attempts at reconstructing the GIA for paleo lakes in the Great Lakes basins were conducted by Johnston et al. (2012) in the Lake Superior basin.

Based on the methods outlined by Leverington et al. (2001) and Breckenridge (2013), an isostatic rebound curve for Lake Whittlesey and Lake Arkona, as well as paleo-environmental reconstruction DEM for the Arkona highstand were produced to evaluate the traditional lake-level model.

6.2 Construction of DEMs

Detailed LiDAR elevation data were obtained from the USGS *National Map Viewer*. LiDAR-based DEMs were constructed using ESRI's ArcGIS Global Mapper version 10.2. LiDAR-based DEMs provide unparalleled vertical and horizontal resolution that allow the identification and digitization of shorelines associated with Lake Whittlesey and Lake Arkona. In a DEM or overland view, strandlines appear as a scarp that separates plains at two different elevations, whereas a ridge persists as positive relief on the landscape. To differentiate these features from one another and aid in mapping strandlines and near-shore features, light angle and shading techniques were employed using ArcGIS. Strandlines were illuminated most noticeably from a sun angle that is oblique to the scarp face. An angle opposite the angle of maximum illumination causes the strandline to effectively disappear and no shadow is produced. This is caused by the inherent geometry of the strandline. Ridges cast a shadow from light angles positioned oblique to the ridge face.

Paleo-Environmental Reconstruction for Lake Arkona

The constructed DEM serves as the modern topographical data that isobase lines must be constructed from. For the purposes of this study, the isobase data were extracted from the digitized shoreline elevations for Lake Arkona. The resolution of the DEM used for the northern portion of the Lake Erie basin (northern Michigan and Ontario, Canada) and in the far eastern basin (New York) was insufficient to accurately delineate any Arkona shorelines from urban

development due to the Arkona shorelines low relief and discontinuous nature. However, over 11,000 data points were compiled to create an elevation/distance dataset. A trend function using a third-degree polynomial was fit to the dataset to form a rebound plane instead of the recommended TIN function as outlined by Leverington et al. (2001). Due to the discontinuous nature of the data and the reliance on a TIN algorithm for sharp geometric faces, it was proposed that a TIN function would produce too coarse of a plane. A third-degree polynomial was selected to produce a smoother fit to the dataset. The constructed plane was then subtracted from the base DEM to produce a DEM that was corrected for isostatic rebound.

Construction of Inflection Curves

In order to construct the inflection curves for Lake Whittlesey and Lake Arkona, a central reference line was first projected through the Lake Erie basin. The line was constructed in a northeast trend running orthogonal to lines of equal uplift that exist across the Lake Erie basin. This central reference line was used to project the shoreline data gathered from the digitization of the Whittlesey and Arkona shorelines (Breckenridge, 2013).

Each shoreline was digitized as a polyline and saved independently from one another. The polylines were then converted to raster datasets using the base DEM as reference using spatial analysis tools. The shoreline rasters were converted to point shapefiles using the “Raster to Point” tool. Attribute extraction (“Extract Values to Points” tool) was then applied to each of shoreline point files and the DEM with the extraction parameter being the elevation value. This produced a final shoreline point file where each data point had spatial and elevation data. Using the “Snap” tool, the shoreline point files were realigned to the central reference line. The “Near” tool was then applied to each shoreline point file to get the linear distance between each pair of points within the point file. The final product was two shoreline point files that had elevation of

each point and distance measurements between each pair of points along the central reference line. The resultant table of these operations was exported as a text file to be imported into Excel. A total of 22,169 data points were collected for Arkona shorelines, 78,165 for the Whittlesey shorelines, 60,154 for the Warren shoreline, and 9892 for the highest Maumee shoreline for a total of 170,380 data points. The positions of major cities also were plotted along the x axis to give geographic reference to the plotted shorelines.

In Excel, the elevation and distance data of each point and each shoreline were extracted into individual columns. A final scatterplot was produced of distance over elevation for each of the shorelines, producing inflection curves for the Whittlesey and Arkona shorelines. This process was then repeated for the highest Maumee shoreline and the Lake Warren shoreline. A trend line was fit to all datasets so comparisons of the datasets could be made (Breckenridge, 2013) (Figure 6.1).

Figure 6.1. Plot of strandline elevation versus distance along a central reference line. Trend lines were fit to each shoreline and the equation of the trend line is displayed above each line. Major cities were included along the horizontal axis as geographic reference points.

Discussion

The reconstructed paleo-environmental DEM for Lake Arkona upon first observation was extremely similar to the modern DEM. Topographic profiles were constructed in the paleo-environmental DEM across Arkona coastal forms throughout the basin. These profiles were compared numerically to the modern LiDAR-based DEM profiles for the same locations for variances in elevation. Based on the DEM, the amount of rebound in this section of the Lake Erie basin was approximately zero. Work by Andrews (1973) shows the zero isoline runs very close to the Central Lake Erie basin, which supports the observation that the calculated rebound rate was close to zero. This is also congruent with the interpretation of the basin being isostatically stable (Sella et al., 2007). Another possibility as to why the DEM did not produce significant rebound is that due to the discontinuous nature of the Arkona shoreline, there may not have been enough data points equally spread around the basin to produce an accurate rebound plane. This would result in a reconstructed DEM underestimating the true value of rebound. Including LiDAR-based DEMs from Ontario would help improve the resolution and accuracy of the paleo-environmental DEM.

The scatter plot of the inflection curve consisted of 170,380 individual data points between all four shorelines analyzed. Basic inferences about the relative age of the shorelines can be made from the lake levels shown in Figure 6.1. The slope of the best-fit line of the Maumee shoreline is the steepest, indicating that it should be considered the relative oldest shoreline in the sequence. Lake Warren's best-fit slope is the lowest, which indicates that it should be the relative youngest. These observations are consistent with both the traditional model of proglacial lake succession proposed by Leverett and Taylor (1915) and the newer succession model proposed by Totten (1985). Lake Whittlesey's slope is steeper than that of

Lake Arkona. In a chronological sense this would indicate that Lake Whittlesey would be relatively older than Lake Arkona, otherwise it could not have developed a steeper slope (Breckenridge, 2013). The best-fit slopes of both Lake Whittlesey and Lake Arkona are similar in magnitude. A possible inference based on the similar slope values is that the two lakes formed in close succession to one another. One final observation that can be made is that the slope of each shoreline close to the southwestern basin is relatively flat. That observation supports the classic interpretation of the southwestern basin being isostatically stable. The slope does increase with linear distance to the northeast, which would indicate a more rapid rebound in the northeastern portion of the basin (Figure 6.1).

The classical model of lake-level succession of Lake Arkona to Lake Whittlesey should be reevaluated. Based on geostatistical analysis of Lake Whittlesey and Lake Arkona using shoreline inflection models, it is unlikely that Lake Arkona is older than Lake Whittlesey. The slope of Lake Whittlesey is steeper than Lake Arkona, indicating that it has experienced greater isostatic rebound. Consequently, Lake Whittlesey must be chronologically older than Lake Arkona. If the Arkona shorelines were older than the Whittlesey shorelines, then the rebound experienced would have been greater and thus produced a steeper slope. This calls into question the classical lake-level model. While the findings of this study do not provide direct dates that appear to meaningfully chronologically date the Arkona, the relative dating techniques does call into question the traditional lake level curve. Again, this suggests a reevaluation of the placement of Lake Whittlesey and Lake Arkona in the traditional lake-level succession model.

6.3 Optically Stimulated Luminescence

Four OSL samples were collected from four different shorelines. Three samples were taken from Arkona shorelines and one sample was taken from a Whittlesey shoreline. The OSL

sample locations are shown on the site maps presented earlier in the report (Figures 3.3, 3.37, 3.40 and 3.42). OSL sample ID and relevant data are presented in Table 1 and 1b. Additional OSL supplemental data can be viewed in Appendices B. The OSL samples were processed and analyzed by Dr. Kenneth Lepper at the North Dakota State University (Lepper 2017).

Sample ID	depth (m)	H ₂ O (%)	K concentration (ppm)	Rb concentration (ppm)	Th concentration (ppm)	U concentration (ppm)
UT1601JD			14295 ± 1269	38.88 ± 5.62	2.172 ± 0.207	1.056 ± 0.088
UT1601JD'			13524 ± 1158	43.37 ± 5.88	1.685 ± 0.161	0.767 ± 0.069
Average	1.00	20 ± 5	13909 ± 1213	41.12 ± 5.75	1.928 ± 0.184	0.911 ± 0.079
UT1602JD			12763 ± 1211	32.76 ± 5.88	2.147 ± 0.203	0.987 ± 0.089
UT1602JD'			12785 ± 1092	38.63 ± 5.79	1.701 ± 0.161	0.993 ± 0.083
Average	0.91	8 ± 3	12774 ± 1151	35.69 ± 5.83	1.924 ± 0.182	0.990 ± 0.086
UT1603JD			12656 ± 1324	53.05 ± 7.56	5.425 ± 0.496	2.224 ± 0.167
UT1603JD'			13940 ± 1193	54.20 ± 8.03	5.654 ± 0.517	2.015 ± 0.156
Average	2.59	12 ± 3	13298 ± 1259	53.63 ± 7.79	5.540 ± 0.506	2.120 ± 0.161
UT1604JD			9746 ± 1079	30.50 ± 5.31	3.586 ± 0.331	0.987 ± 0.083
UT1604JD'			10050 ± 883	31.38 ± 5.05	1.715 ± 0.164	0.946 ± 0.082
Average	1.65	12 ± 3	9898 ± 981	30.94 ± 5.18	2.651 ± 0.247	0.967 ± 0.082

Table 1. Dosimetrically relevant data which includes elemental composition of individual samples. Sample identifiers used in the text of the thesis follow the format UT16-01-JD, which represents University of Toledo, year of collection 2016, sample number 01, collected by John Dilworth. Table and caption modified from Lepper (2017).

Sample ID	N	M/m	U _t	U _d	U _g	dD _c	Equivalent Dose (Gy)	Dose Rate (Gy/ka)	Age (ka)	Uncert. (ka)
UT1601JD	91/96	1.01	0.35	0.27	0.08	0.0%	16.400 ± 0.604	1.507 ± 0.143	10.9 ± 0.4	1.1
UT1602JD	89/96	1.04	0.36	0.23	0.13	4.0%	20.112 ± 0.769	1.627 ± 0.139	12.4 ± 0.5	1.2
UT1603JD	89/95	0.99	0.41	0.16	0.25	1.3%	37.082 ± 1.624	2.039 ± 0.155	18.2 ± 0.8	1.6
UT1604JD	90/96	1.05	0.41	0.23	0.17	3.1%	21.152 ± 0.914	1.346 ± 0.116	15.7 ± 0.7	1.5

Table 1b. OSL ages and supplemental data. Sample identifiers are presented in the format outlined in Table 1. Table and caption modified from Lepper (2017).

Results for Optically Stimulated Luminescence Samples

Several conclusions can be drawn from the preliminary OSL results. Both the UT1601JD (10.9 ± 0.4 ka) and UT1602JD (12.4 ± 0.5 ka) OSL samples taken from Field Site 1 and Field Site 9 respectively produced ages significantly younger than the traditionally recognized age of

the Arkona shoreline around $13,600 \pm 500$ Cal yrs BP. The younger ages are possibly a result of stratigraphic sampling error. In this case, the samples taken from the Beaver Creek barrier island and the Arkona shoreline on Bay Road near Wayne, OH may have been taken from aeolian deposits. However, if the sand was from aeolian deposits associated with coastal dunes then the age of these sands should be equivalent to the age of the barrier island or shoreline. As discussed in Chapter 3, the presence of gravel on top of all aspects of the ridges in both Field Site 1 (Beaver Creek) and Field Site 9, the lack of sand grain frosting and the presence of granules and coarse sand grains within the sampled sand does not support an aeolian interpretation. The evidence at Field Site 1 strongly supports the interpretation that the feature is a barrier island. Furthermore, the GPR transects of Field Site 1 lack a hummocky reflector indicative of an aeolian deposition. The OSL sample (UT1601JD) was collected from deep in the sedimentary sequence from a sand unit approximately 0.45 m above the contact with the underlying diamicton. From the GPR profiles, this sand unit is the base of the barrier island sequence, and is not associated with aeolian reworking at some younger time. Similarly at Field Site 9 (Wayne, OH) the stratigraphy and lithology represent a shoreline, and not a sand dune. Consequently, the younger than expected ages for the Arkona shoreline probably do not represent aeolian reworking several thousand years after the Arkona highstand.

In contrast, OSL sample UT1603JD produced an age of 18.2 ± 0.8 ka that predates any of the known proglacial lakes active in the Lake Erie basin. The sampled sand at Field Site 10 was also considerably coarser than other sampled Arkona sites. There are also many pieces of shale within this sand unit which could have affected the dose rate. The Arkona shoreline at Field Site 10 (Perry, OH) is a series of spits that were created by eroding sediment from a prominent headland composed of till. The flanks of this headland are steep and the transport paths between

erosion and deposition are short, on the order of a few kilometers. The sediment that created the spits was derived locally from older till, and probably did not have sufficient exposure to sunlight to bleach completely. Therefore, the data obtained by the UT1603JD is in effect dating the topographic high that the Arkona spit would eventually occupy during the high stand event. Finally, OSL sample UT1604JD from the Whittlesey shoreline produced an age of 15.7 ± 0.7 ka which is still in general agreement with the ages reported by Barendsen and Deevey (1957), Calkin (1970), and Bucky (1976). These results are considered preliminary and a second round of dosimetric analysis is currently being applied to the samples.

Chapter 7

Summary, Conclusions, and Future Work

7.1 Summary

The shoreline of Lake Arkona in the study area is comprised of a series of low-relief, narrow, barrier islands with the toe of the foreshore scarp at an elevation of 211 m asl. and 212 m asl. Stratigraphic information obtained from vibracore and hand-dug pits provided the best control to characterize the Arkona shoreline. The coastal features associated with the Arkona shoreline typically consist of thin beds of planar, interbedded, well-rounded, fine- to medium-grained sand units. These sand units have a gradational contact with the overlying soil. At the top of sand unit (approximately 1.25 m to 1.5 m thick) interpreted as the body of a barrier-island, there was no evidence of erosional truncation or deposition of an overlying second sand unit that would suggest a transgressive event. The sedimentary sequence continues to the underlying contact with a diamicton unit, which is the base of possible littoral deposits. The upper surface of the diamicton is distinctly erosional, indicating transgressive ravinement prior to deposition of the barrier island sequence. All ground truth obtained at each Arkona field site produces no stratigraphic evidence that the Arkona shorelines were overtopped by a higher lake stand. This interpretation differs from the traditional view of the Arkona shoreline first stated by Leverett and Taylor (1915), which stated that the higher elevation Whittlesey shoreline was younger, and the Whittlesey transgression would have overtopped the Arkona shoreline.

A total of 3.5 km of GPR transects were obtained over 22 individual profiles. Analyzed GPR profiles across Arkona coastal features showed continuous interbedded and sigmoidal reflections that are interpreted as undisturbed aggradation of barrier-island sediments. This

interpretation is supported by the ground truth obtained at each GPR field site. No strong reflection indicative of a ravinement surface of a higher lake stand was observed truncating the Arkona depositional units. The lack of a truncating ravinement surface supports the hypothesis that the Arkona shoreline was not overtopped by the Lake Whittlesey highstand as stated by previous research.

Four OSL dates were obtained from three Arkona shorelines and one Whittlesey shoreline. The results of the OSL dates are still considered preliminary, and the initial dates for two samples from the Arkona shoreline are significantly younger, by 2-3 thousand years, than the radiocarbon age of $13,600 \pm 500$ Cal yrs BP. One possible explanation for the younger than expected OSL dates for the Arkona is that the sediment samples were collected from a younger aeolian deposit that sits on top of the shoreline ridge. This option is not supported by the stratigraphy and lithology of the Arkona ridges that were sampled at Beaver Creek and Wayne, OH.

The third OSL sample from an Arkona shoreline at Perry, OH, yielded a date of 18.2 ± 0.8 ka, which is older than expected by at least 2000 years. In this setting, erosion of a headland composed of till was redistributed to create spits of the Arkona shoreline. It is likely that the sand grains in this sample had not been completely bleached by sunlight prior to burial. Another possibility is the presence of the shale fragments could have increased the dose rate causing a fluctuation in the resultant age.

The OSL date for the Whittlesey is 15.7 ± 0.7 ka, which is younger than the dates produced by Calkin (1970), Barendsen and Deevey (1957) and Bucky (1976) but as previously stated these results are considered preliminary and a second round of dosimetric analysis is being undertaken. Even without direct dates on the Arkona shoreline, the relative age between the

Whittlesey and Arkona shoreline was evaluated using a shoreline-inflection curve. The resultant inflection curve constructed from 100,334 points for the Arkona and Whittlesey shorelines, indicated that the Whittlesey shoreline had experienced a longer period of isostatic rebound due to the slope of the curve being greater than that of the Arkona shoreline. This suggests that Lake Whittlesey is relatively older than Lake Arkona.

A secondary goal of this research was to describe the geomorphological differences between the Whittlesey and Arkona shorelines. A total of 526 topographic profiles were taken across the foreshore and shoreface of the Arkona and Whittlesey shorelines. These profiles were evaluated with a numerical model to quantify the differences in shore-perpendicular geometry of the geomorphology between the Arkona and Whittlesey shorelines and differences within each highstand event. The results of the model suggest that the Whittlesey and Arkona shorefaces are statistically different from one another. This conclusion is supported by field observations and past research. This research concluded that the differences between these shorelines are a result of the Arkona shorelines being primarily sediment starved rendering them unable to produce well-developed strandlines. Further, it is inferred that Lake Arkona was a short-lived highstand. This evaluation also supports the interpretation that the Arkona shoreline was not formed as a result of “drowning” by a higher lake stand.

7.2 Conclusions

The hypothesis that Lake Arkona was not transgressed by Lake Whittlesey is accepted due to no physical evidence existing that would indicate that the depositional sequence of the Arkona was truncated or interrupted by a ravinement associated with a higher lake stand. Based on the new evidence that was collected on Arkona shorelines, the traditional “washed” appearance of Lake Arkona shorelines is reinterpreted. Lake Arkona littoral deposits are

extremely thin, the complete sequence rarely exceeds 1.5 to 2 m in the western Lake Erie Basin, thicker Arkona deposits greater than 2 m can be in the mid to eastern basins an example being Field Site 10 in Perry, OH. The result is a low-relief, discontinuous ridge being formed. It is proposed that the Arkona shoreline in comparison to the Whittlesey shoreline had substantially lower sediment supply, which resulted in the stark geomorphological differences between the two shorelines. The OSL samples taken in this research do not appear to yield ages that are consistent with previous radiocarbon and OSL dates that bracket the Arkona shoreline. Relative dating techniques were employed. An isostatic inflection plot for the Lake Arkona and Whittlesey shorelines was created to evaluate the magnitude of isostatic rebound experienced by the two lake levels. Based on the plot, the Lake Whittlesey shoreline experienced a greater amount of isostatic rebound, and is interpreted as being the older of the two. Based on all the data gathered, it is concluded that Lake Arkona is best interpreted as a step-down from Lake Whittlesey to Lake Warren, which supports the episodic lake-level model proposed by Totten (1985 and Fisher et al., 2015).

7.3 Future Work

To provide a more complete record of the Arkona shoreline and its stratigraphy, field sites in Ontario and in the eastern Lake Erie basin should be strongly considered. Additional field sites from outside the western basin would provide a more cohesive picture of the provenance of Lake Arkona and the magnitude of its littoral processes. In the western Lake Erie basin, the Arkona shoreline just north of Field Site 4 should be evaluated for sediment thickness and would be a possible target for an OSL sample. The diamicton beneath the Arkona shorelines in the western Erie basin should be evaluated for depositional origin. Since this study was unable to acquire a substantial amount of OSL samples for either shoreline, additional OSL

samples from Lake Arkona and Lake Whittlesey beach sand should be collected. In order to better constrain the episodic model, direct dates of the proglacial lakes must be obtained.

More extensive research into Lake Whittlesey could also be undertaken. Lake Whittlesey is a dynamic shoreline that has sharp contrasts to the Lake Arkona and Lake Warren shorelines particularly in the western Lake Erie basin. To better understand the lake sequence in the Lake Erie basin, a more thorough analysis of Lake Whittlesey littoral deposits should be conducted. Evaluating Lake Whittlesey's interaction with the Defiance Moraine could also help explain the differences in geomorphology of the Lake Whittlesey shoreline from the other lake levels in the Erie basin. Furthermore, analysis of the lake basin west of the Defiance Moraine, where only Lake Maumee and Whittlesey shorelines were observed, may provide useful information about the lake-level fluctuation from Lake Whittlesey to Lake Arkona. An important field site in answering that question would be near the town of Defiance, OH, where the Maumee River cuts through the Defiance Moraine and where Lake Whittlesey elevation ridges are observed close this break.

Chapter 8

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Appendices A

Wentworth Sediment Grain Size Plots

Core: BV141016

U.S. Geological Survey
Hydrogeology

Core: BV241016

U-Tahoe hydrogeology

Core: M131916

$U = T_{olag} h_{ydrogeology}$

Core: M231916a and M231916b

U=Total *h* *hydrogeology*

Core: M331916

Core: CE121164

U.S. Geological Survey
Hydrogeology

Core: CE121162

$$U = T_{\text{Toledo}} \nabla h_{\text{hydrogeology}}$$

Appendices B

OSL Supplemental Data

Table 2. Dosimetrically relevant data

Sample ID	depth (m)	H ₂ O (%)	K concentration (ppm)	Rb concentration (ppm)	Th concentration (ppm)	U concentration (ppm)
UT1601JD			14295 ± 1269	38.88 ± 5.62	2.172 ± 0.207	1.056 ± 0.088
UT1601JD'			13524 ± 1158	43.37 ± 5.88	1.685 ± 0.161	0.767 ± 0.069
Average	1.00	20 ± 5	13909 ± 1213	41.12 ± 5.75	1.928 ± 0.184	0.911 ± 0.079
UT1602JD			12763 ± 1211	32.76 ± 5.88	2.147 ± 0.203	0.987 ± 0.089
UT1602JD'			12785 ± 1092	38.63 ± 5.79	1.701 ± 0.161	0.993 ± 0.083
Average	0.91	8 ± 3	12774 ± 1151	35.69 ± 5.83	1.924 ± 0.182	0.990 ± 0.086
UT1603JD			12656 ± 1324	53.05 ± 7.56	5.425 ± 0.496	2.224 ± 0.167
UT1603JD'			13940 ± 1193	54.20 ± 8.03	5.654 ± 0.517	2.015 ± 0.156
Average	2.59	12 ± 3	13298 ± 1259	53.63 ± 7.79	5.540 ± 0.506	2.120 ± 0.161
UT1604JD			9746 ± 1079	30.50 ± 5.31	3.586 ± 0.331	0.987 ± 0.083
UT1604JD'			10050 ± 883	31.38 ± 5.05	1.715 ± 0.164	0.946 ± 0.082
Average	1.65	12 ± 3	9898 ± 981	30.94 ± 5.18	2.651 ± 0.247	0.967 ± 0.082

Table 2. [1] No. of aliquots used for OSL De calculation / no. of aliquots from which OSL data was collected (filtering criteria given in Lepper et al., 2003). [2] Mean/median ratio: a measure of dose distribution symmetry/asymmetry (see supplement to Lepper et al., 2007). [3] Total dose distribution data dispersion (Std. dev./Mean). [4] Dosimetric dispersion. Percentage of total data dispersion that can be attributed to radiation dosimetric properties of the sample. [5] Geologic process dispersion. Percentage of total data dispersion that cannot be directly attributed to radiation dosimetric properties of the sample. Interpreted to reflect variations in resetting during sediment transport. [6] Dose recovery fidelity (refer to "check dose" in Lepper et al., 2000 and supplement to Lepper et al., 2007). [7] Equivalent doses are based on the mean and std. err. of the OSL De distribution. [8] Dose rates calculated following the methods described in Aitken (1985; 1998) and Prescott and Hutton (1988; 1994). [9] Fully-propagated age uncertainty (Append. B, Aitken, 1985). Table and caption taken from Lepper (2017).

Table 2b. OSL ages and supplemental data

Sample ID	N	M/m	U _t	U _d	U _g	dD _c	Equivalent Dose (Gy)	Dose Rate (Gy/ka)	Age (ka)	Uncert. (ka)
UT1601JD	91/96	1.01	0.35	0.27	0.08	0.0%	16.400 ± 0.604	1.507 ± 0.143	10.9 ± 0.4	1.1
UT1602JD	89/96	1.04	0.36	0.23	0.13	4.0%	20.112 ± 0.769	1.627 ± 0.139	12.4 ± 0.5	1.2
UT1603JD	89/95	0.99	0.41	0.16	0.25	1.3%	37.082 ± 1.624	2.039 ± 0.155	18.2 ± 0.8	1.6
UT1604JD	90/96	1.05	0.41	0.23	0.17	3.1%	21.152 ± 0.914	1.346 ± 0.116	15.7 ± 0.7	1.5

Table 2b. Irradiations for INAA were performed at the Ohio State University Research reactor. INAA data reduction was carried out by Scientific Consulting Services, Dublin, OH. Table and caption taken from Lepper (2017).