2010

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Journal of Great Lakes Research 37 (2011) 64–77

Contents lists available at ScienceDirect

Journal of Great Lakes Research

journal homepage: www.elsevier.com/locate/jglr

Re-interpreting Great Lakes shorelines as components of wave-influenced deltas: An example from the Portage River delta (Lake Erie)

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ARTICLE INFO

Article history:
Received 12 February 2010
Accepted 21 September 2010
Available online 9 November 2010

Communicated by Gerald Matisoff

Index words:
Lake Erie
Deltas
Lake-level change
Lake history
Beach ridges
Peats

ABSTRACT

Deltas deliver both sediment (bedload sands and suspended load muds) and water to a coastal environment. In the past, deltaic models have emphasized the sandy bedload component constructing a depositional feature that protrudes from the coastline. In contrast, wave-influenced deltas form where river discharge effectively blocks the prevailing longshore drift. The resulting delta is asymmetric, with an extensive strandplain of multiple beach ridges updrift, and fewer beach ridges with wetlands, ponds, and subsidiary bay-head deltas downdrift. In Lake Erie, an analysis of 28 vibracores from the Portage River delta demonstrates significant updrift–downdrift sedimentological differences. Updrift of the delta consists of >3 m thick gravel-rich sands overlying glaciolacustrine sediment. The deposits are organized into coarsening-upward, progradational shoreline sequences showing facies transitions from lower shoreface to upper shoreface to beachface to backbeach. A 1939 aerial photograph suggests >15 prograding shoreline sequences were accreted during present lake levels (highstand systems tract), resulting in re-attachment of a bedrock high (Catawba Island) to the mainland. Downdrift of the delta consists of a one progradational shoreline sequence <1 m thick that overlies peats and glaciolacustrine sediment. The peats have ^{14}C ages between 1616 and 2025 cal YBP, and are interpreted as wetlands that formed during an earlier phase of rising lake levels (lowstand and transgressive systems tracts). The overlying beach ridge was accreted during present lake levels (highstand system tract). The coastal features in this portion of Lake Erie are best understood as components of an evolving wave-influenced delta, the first recognized in the Great Lakes.

Introduction

Deltas form where a river enters a standing body of water such as the ocean or a large lake. The river contributes both sediment (sandy bedload and muddy suspended load) and water to the coastal environment. The sandy bedload is typically deposited near the mouth of the delta. If the river carries a large bedload component, deposition of the bedload can produce a constructional feature that protrudes into the coastal environment as a readily recognizable feature, such as the Mississippi delta. However, not all deltas have this "typical" appearance. Complications can include situations such as (1) the sandy bedload component is small and the sediment contribution of the river is thus a large volume of muddy sediment that can be widely dispersed; (2) the mouth of the river is embayed (estuaries, lagoons, bays) due to recent sea-level or lake-level rise, thus the delta is a bay-head delta; and (3) the delta is strongly affected by waves and/or tides, as will be described next.

Deltas have traditionally been classified using a tripartite approach as "fluvial dominated," "wave dominated," or "tide dominated" despite many practical problems or inconsistencies these categories entail (Coleman and Wright, 1975; Miall, 1979; Bhattacharya and Walker, 1992). The Great Lakes do not exhibit tidal effects, thus tide-dominated deltas are not relevant to this study. Fluvial-dominated deltas and wave-dominated deltas form a continuum, ranging from end members that are strongly fluvial dominated, such as the bird's-foot morphology of the Mississippi River delta, to strongly wave dominated, such as the shoreline-parallel, linear morphology resulting from strong longshore drift in the Senegal River delta.

All of the previous discussion has focused on the sediment load of the river. There is increasing recognition of the effect of the water discharge of the river on the coastal environment. This has stemmed in part from the recognition that many deltas are asymmetric in map view, as a result of the effect of fluvial discharge on the net longshore sediment transport rate (Dominguez, 1996). If the jet of river discharge into the nearshore area of the lake or ocean is sufficient to block the prevailing longshore current (called the "groyne effect"), the result would be sediment accumulation on the updrift side of the delta, creating a strandplain of multiple accreted beachridge complexes. In contrast, the downdrift side of the delta would sand-depleted (deposition dominated by muds and organic matter).

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doi:10.1016/j.jglr.2010.10.002

Episodically, major floods would deposit sands in the delta front, as middle-ground or distributary mouth bars and offshore barrier bars. Subsequent shoreward migration of these bars would result in an accretionary beach ridge complex on the downdrift side of the delta. Such deltas are now referred to as "wave-influenced deltas," and not only can many of the world's modern deltas can be explained in this context, but the resulting facies models are being successfully used in petroleum exploration (Bhattacharya and Giosan, 2003).

In the Laurentian Great Lakes, a wide range of coastal geomorphic features have been recognized including bays, estuaries, barrier islands, spits, strandplains, and coastal marshes. Much of the coastal research in the Great Lakes has focused on beach ridges, as indicators of post-glacial lake stages and in order to understand the evolution of the Great Lakes (e.g., Forsyth, 1973; Coakley and Lewis, 1985; Thompson, 1992; Thompson and Baedke, 1995; Larson and Schaetzl, 2001; Holcombe et al., 2003; Baedke et al., 2004). Other studies have focused on coastal wetlands and freshwater estuaries (e.g., Herdendorf, 1990, 1992; Bowers and Szalay, 2004) because of significant impacts of wetlands loss and ecosystem change. There have been few studies that focus on deltas in the Great Lakes, possibly because these features in the Great Lakes tend to be relatively small bay-head deltas.

This is a surprising contrast to marine coastlines, where deltas are considered the major features that control nearshore sediment budgets and process dynamics. Indeed, the trend in marine geology and sedimentology is to study deltas from a synoptic viewpoint, looking at deltaic processes as the most important drivers of continental-margin-scale evolution (e.g., Liu et al., 2009). This paper re-evaluates a portion of the coastline of Lake Erie to suggest that there has been a significant underestimating of the importance of deltas in the history and evolution of Great Lakes shorelines. The implications are that significant geomorphologic features both updrift and downdrift of the delta mouth are genetically linked as part of the evolution of a deltaic system. This understanding, in turn, has important ramifications for using beach ridges to interpret the history of lake-level changes.

Background

Lake Erie formed at the end of the Wisconsinian Ice Age as a series of pro-glacial lakes primarily affected by the position and elevation of outlets, amount of glacio-isostatic rebound, erosional downcuttting of outlets, overall water budget, lake morphology (surface area to volume ratio), and paleoclimate (Holcombe et al., 2003). The Holocene history of Lake Erie has been reviewed elsewhere (Barnett, 1985; Calkin and Feenstra, 1985; Coakley and Lewis, 1985; Holcombe et al., 2003). Only the most recent part of this history is relevant to this paper. The highest lake levels in the Lake Erie basin were recorded during the Nipissing I (5.5–5.0 ka) and Nipissing II (4.5–3.5 ka) stages (Coakley, 1992; Holcombe et al., 2003; Clotts et al., 2005). Lake levels dropped subsequently. An analysis of submerged features in the vicinity of the Portage River delta suggest lake levels fell 4–7 m below present lake levels at approximately 3.4–2.0 ka (Holcombe et al., 2003). The features discussed in this paper formed during the approximately 4–7 m rise in lake levels during the past approximately 2000 YBP.

The Portage River delta is located along the Ohio shoreline in the western part of Lake Erie (Fig. 1). The Portage River watershed is elongate in a SW–NE direction, approximately 97 km in length, and covering an area of about 1580 km^2. The drainage basin has a very low gradient (average slope of 6×10^{-4}) over the Lake Erie coastal plain, which consists of glaciolacustrine sediments, glacial till, glacial outwash, and exposures of Paleozoic sedimentary rocks. The present land-use is 78% agricultural, 11% urban, 8% woodland, and 3% other (USACE, 2008). While smaller tributaries of the Portage River have been ditched and channelized (as part of the draining of the pre-settlement Great Black Swamp region of NW Ohio), the downstream main channel of the Portage River retains its natural meandering geometry with minor modification (Finkbeiner et al., 2002) with the exception of harbor mouth dredging (USACE, 2008). Harbor dredging has been about 12,000 $m^3\,yr^{-1}$ (Bernhagen, 1976), which is very minor (about 1%) compared to adjacent rivers and harbors, such as the Maumee River (Toledo) or Cuyahoga River (Cleveland). The mean annual discharge for the Portage River is approximately 10 $m^3\,s^{-1}$. Flood stage height is variable, because of ice jams and because the mouth of the Portage River is strongly influenced by the level of Lake Erie, with local flooding attributed to coastal setup during storms. The largest flood of record, which occurred in March 1913, was approximately 500 $m^3\,s^{-1}$ and is interpreted as a 500-year event (USGS, 2010). The mouth of the Portage River has shifted at least once in recorded history, as maps recorded in 1754 show the mouth of the river at the west end of the existing sand spit (USACE, 2008).

The Portage River delta is highly asymmetric. An aerial photograph from 1939, before significant land development in the area, shows that the east side of the delta is a strandplain formed from a series of >15 accreted beach ridges and intervening small wetlands and lakes (Fig. 2). In contrast, the west side of the delta consists of many fewer accreted beach ridges and more extensive development of wetlands and lakes. This paper focuses on the sedimentary history of the Portage River delta, and attempts to show it is better understood as a wave-influenced delta.

Methodology

Field work for this study was conducted along a 15-km stretch of the Lake Erie coast both east and west of the mouth of the Portage River. A total of 28 vibracores were collected in 1995 and 2007 (Fig. 1). The vibracorer utilizes a vibrating head, powered by a portable generator, which is attached to aluminum pipe with a 7.5 cm diameter. Vibracoring causes minimal sediment disturbance, and penetrates most sediment easily. In this case, core recovery was up to 4.5 m in length, and penetrated through beach sands and related deposits until reaching denser, glaciolacustrine sediments. The location of each core was recorded using a Garmin GPS unit.

In the lab, each core was split lengthwise and one half was archived for future work. The working half was cleaned, photographed, and the color described using a Munsell Color Chart while still damp. Compaction corrections were calculated using previously described methods (Evans et al., 2002; Clark, 2008). Due to the overall sandy content of the cores, compaction corrections were minimal (<5%). As part of stratigraphic evaluation of the cores, selected samples were taken for grain size analysis. A total of 77 sand samples were dried and sieved following standard practices. A total of 7 muddy samples were dispersed to appropriate sediment particle concentrations, and then the grain size distribution was determined using a Spectrex PC-2300 laser particle size analyzer. Grain size statistics were calculated using the method of Folk and Ward (1957).

A succession of peats from core 07-PC-14, located west of the Portage River delta (Fig. 1) was evaluated for age using ^{14}C geochronology. Sample collection and preparation protocol is described elsewhere (Clark, 2008). Conventional ^{14}C age determinations, including $\delta^{13}C$ correction, were performed at Geochron® Laboratories. Based on the Libby half-life (5570 years), the ^{14}C age determinations were converted to calibrated years (cal YBP) using the radiocarbon calibration program Calib Revision 5.0.2® (Stuiver and Reamer, 1993). This program produces a probability distribution, and from this the mean and standard deviation (1σ) values are herein reported. In this study, the three peat samples, when plotted against compaction corrected depth, produce a linear sediment accumulation curve with an $r^2 = 0.9923$.

To evaluate historical changes in the Portage River delta, aerial photograph sets were obtained from the Ohio Geological Survey (OGS) for 1957 and 1980 and from the United States Department of

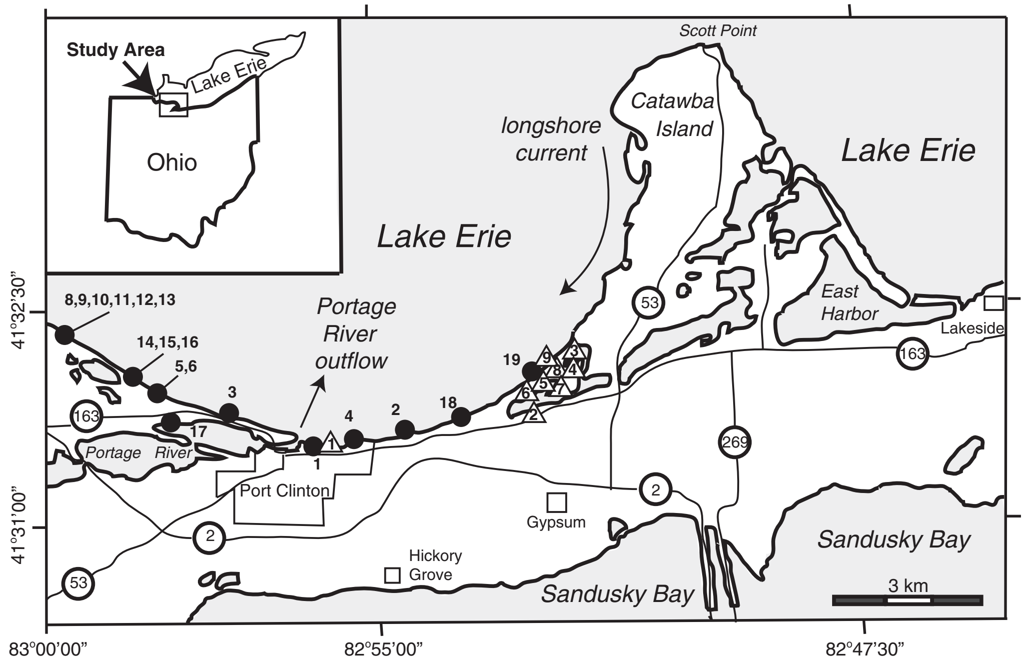

Fig. 1. Location map showing the study area along the Ohio shoreline of the western basin of Lake Erie. White triangles are sediment cores from 1995, solid circles are sediment cores from 2007, and the numbers refer to the respective core numbers. Larger white circles indicate roads.

Agriculture-National Resources Conservation Service (USDA-NCRS) for 2006. The 1957 and 1980 images were in paper format, and were scanned at 600 dpi and imported into Adobe Illustrator CS2. The 2006 image is in electronic format and had previously been orthorectified and cut into Digital Orthophoto Quarter Quadrangle (DOQQ) tiles to produce Compressed County Mosaic (CCM) images. These images were imported into Environmental Systems Research Institute (ESRI) Arc GIS version 9.2®. To compare images, the older images were georeferenced to the 2006 image using a 1st order polynomial transformation based upon three ground control points. The RMS error was calculated to be less than 0.0003 pixels.

Results

Lithofacies analysis

Lithofacies are distinctive combinations of composition, textures, sedimentary structures, and fossils. Lithofacies analysis is a method of interpreting depositional environments, and it proceeds in distinct steps of recognizing, describing, and interpreting individual lithofacies (this section) and then determining the order and sequence of associations of lithofacies (next section). Individual lithofacies represent certain depositional processes, and the order and sequence of lithofacies represents changing environmental conditions in response to shoreline progradation, storms, flood events, or shifting positions of deltaic distributary channels. The lithofacies are summarized in Table 1 and in Clark (2008), and are briefly reviewed here.

Glaciolacustrine sediment (Facies A1)

These deposits are distinctively cohesive, plastic, and indurated, gray silty clays that weather brown in color. Similar deposits have been recognized as glaciolacustrine sediments (Coakley and Lewis, 1985). Cores penetrated up to 65 cm into the glaciolacustrine sediments but did not reach a bottom contact, so the thickness is unknown. The upper contact is an unconformity with micro-topographic relief (typically <1 cm) and the upper part of the unit can be burrowed and burrow-mottled. Facies A1 is typically overlain by beachface sands (Fig. 3A), offshore sandy silts (Fig. 3B) or peats (Fig. 3C).

Offshore deposits (Facies A2)

These post-glacial sediments are repetitive, thinly bedded sequences of non-cohesive gray silts or sandy silts that frequently contain intact gastropod shells (mostly *Elimia livescens*) and occasional bivalve shell hash (Fig. 3D). Each bed overlies a scoured surface and consists of combinations of massive, normally graded sandy silts, laminated sandy silts, and massive silty muds. The combination of silty grain size, position in the stratigraphic succession, and lack of hummocky stratification or cross bedding suggests these deposits formed below wave base in offshore settings. The repetitions of small-scale scouring, normal grading, and muddy drapes suggests that Facies A2 represents prodelta turbidites or hyperpycnites associated with river flood events. Turbidites are frequently subdivided into five lithofacies (Bouma divisions), but in this case the beds are typically so thin (<3 cm) that for practical reasons they have not been subdivided. The gastropod *Elimia livescens* is terrestrial, found in moist riparian habitats including floodplains and river banks, and the presence of intact shells in these offshore deposits is consistent with the origin of the material as re-deposited sediment from river flood events.

Lower shoreface storm deposits (Facies B and C)

Hummocky stratified, moderately sorted medium-grained sands (Facies C) and planar laminated, moderately sorted, fine-grained sands (Facies B) are frequently found together in fining-upward sequences (Fig. 3E). The base of the hummocky stratified sands shows erosional scour with relief in the cores of up to 3 cm. These sequences are interpreted as tempestites representing storm wave erosion above wave base followed by fallout from suspension and combined flow conditions (Harms et al., 1975; Walker and Plint, 1992). A typical trend in cores is an upward transition from individual tempestites (Facies C and B couplets) to amalgamated hummocky stratified sands (Facies C), typical of prograding shoreline successions (Leckie and Walker, 1982).

Upper shoreface cross-bedded sands (Facies D)

Trough cross-bedded, moderately sorted, medium-grained sands typically overlie amalgamated hummocky stratified sands (Facies C). Individual cross-laminae are less than 1-cm thick, and are combined in wedge-shaped cross-bed sets up to 10-cm thick (Fig. 3F). Rare

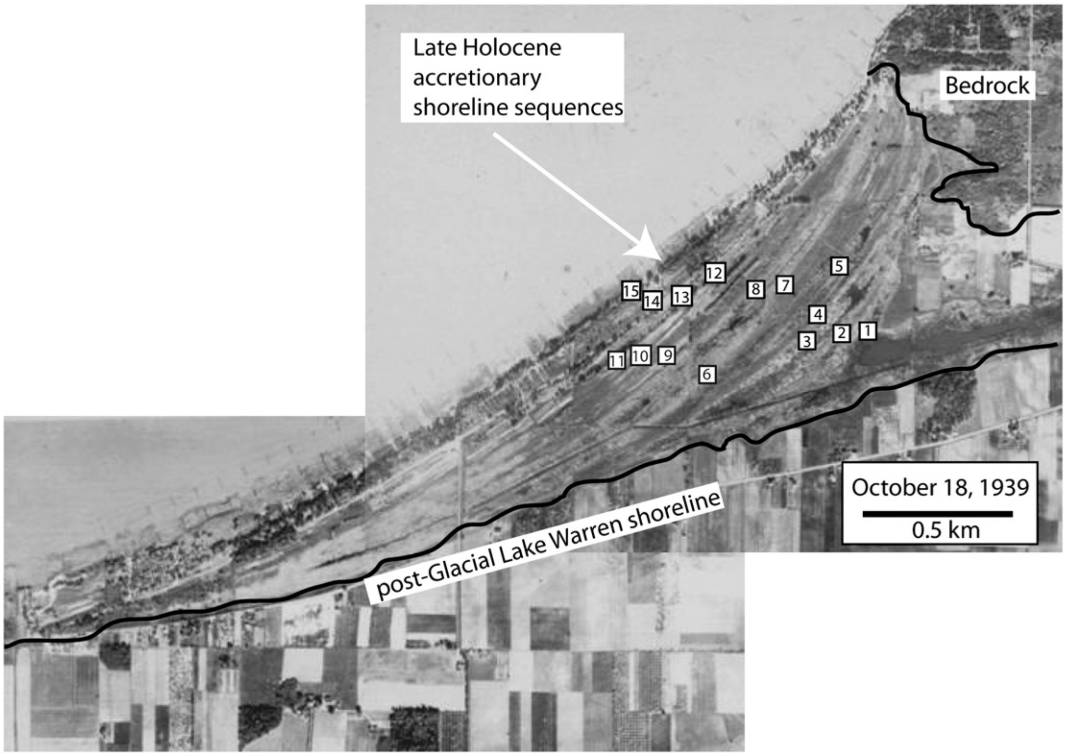

Fig. 2. Aerial photograph from October 18, 1939, prior to significant land development in the area east (updrift) of the Portage River delta. A minimum of 15 beach ridges can be identified in the strandplain that connects the bedrock high (Catawba Island) to the mainland. Today the area is covered with houses, a golf course, and wetlands between the original beach ridges have been deepened to create shallow lakes.

outsized clasts and shell debris can be incorporated into the cross-bed sets. These deposits are interpreted as breaker bar deposits in a high-energy coastline setting (Olsen et al., 1999; Nouidar and Chellai, 2002).

Beachface deposits (Facies E, F1, and F2)

A suite of lithofacies comprise the beachface environment. Planar stratified, poorly sorted, normally graded, shelly granule- to pebble-gravels (Facies E) are interbedded with inclined planar stratified, well sorted, normally graded, medium-grained sands with heavy mineral laminae (Facies F1) and poorly sorted coquinas made of shell hash (Facies F2). The gravels consist of limestone, dolostone, granite, and vein quartz clasts (Fig. 3G). These could have been derived from adjacent bedrock exposures (limestone and dolostone lake bottom and shoreline exposures) or from glacial tills. Heavy mineral laminae in the sands represent alteration of coarser-grained, lower density minerals such as quartz and feldspar with fine-grained, higher density minerals such as magnetite, hematite, hornblende, and garnet (Fig. 3H). Beachface sands are well sorted, while the poor sorting of the gravels is due to secondary infiltration of sand into a gravel matrix, and the poor sorting of the coquinas is due to random shell breakage (Fig. 3I). The younger (stratigraphically higher) coquinas contain zebra mussel (*Dreissena polymorpha*) shells. These exotics invaded Lake Erie in the late-1980s (USGS, 2000). Because the coquina layers have abrupt bottom and top contacts, there is no evidence that the zebra mussel shell layers have been redistributed by post-depositional processes. In summary, the suite of deposits and sedimentary structures are consistent with upper-flow regime sheetflow conditions during wave swash and backswash landward of the surf zone (Clifton et al., 1971; Olsen et al., 1999).

Table 1
Description of lithofacies.

Facies code	Lithology	Sedimentary structures	Interpretation
A1	Silty clay, dark gray, plastic	Massive or laminated	Glacial-lacustrine sediment
A2	Silt to sandy silt, gray, shelly	Planar laminated	Offshore deposits
B	Sand, very fine- to fine-grained, moderately to well sorted	Planar laminated, interbedded with C	Lower shoreface
C	Sand, medium- to coarse-grained, moderately to poorly sorted	Hummocky stratified, interbedded with B	Lower shoreface
D	Sand, fine- to medium-grained, moderately to well sorted	Trough cross-bedded	Upper shoreface
E	Gravel, granule to pebble sized, very poorly to poorly sorted, normally graded, shelly	Planar stratified, alternates with F1 and F2	Beachface gravels
F1	Sand, medium- to coarse-grained, moderately to well sorted, normally graded, shelly, heavy mineral laminae	Inclined planar bedded, gradational with F2	Beachface sands
F2	Coquina, granule to pebble sized, very poorly sorted, sand matrix.	Massive, gradational with F1	Beachface shell deposit
G1	Peat interbedded with muds (G2) and rare sandy storm layers (H)	Massive, rooted, thin clastic interbeds	Hydromorphic paleosol
G2	Carbonaceous silty mud	Massive, rooted	Hydromorphic paleosol
H1	Sand, fine- to medium-grained, moderately to well sorted	Massive to laminated, rooted	Back beach and soils, or storm overwash deposit
H2	Sand, medium-grained, well sorted	Trough cross-bedded	Eolian dune
I	Silt to clayey silt, brown	Massive to laminated, shelly, rooted	Lagoon or estuary

Hydromorphic Paleosols (Facies G1 and G2)

Paleosols are buried soils, and hydromorphic soils develop in wetland or water-saturated conditions. The development of a hydromorphic soil depends on the relative contribution of organic constituents (both allochthonous and autochthonous organic matter) and mineral constituents, the latter caused by physical processes such as storms or floods transporting minerals into the wetland environment. At one extreme, hydromorphic soils are virtually 100% organic matter (peats), at the other extreme are carbonaceous mudstones containing only a few percent organic matter. Both types are recognized in cores from the Portage River delta. Facies G1 consists of massive and rooted peats interbedded with carbonaceous mudstones or thin sand layers (Fig. 3J). Facies G2 are massive and rooted carbonaceous silty muds. Both Facies G1 and G2 are found on either side of the Portage River delta, but with significant differences. On the updrift (eastern) side of the delta, hydromorphic paleosols are thin and formed in swales between accreted beach ridges in a strandplain. On the downdrift (western) side of the delta, a much thicker peat overlies glaciolacustrine deposits and is in turn overlain by a single accreted beach ridge sequence.

Backbeach deposits (Facies H1 and H2)

Well sorted, fine- to medium-grained sands that overlie beachface deposits and are often interbedded with thin hydromorphic paleosols are interpreted as backbeach deposits (Tamura et al., 2003). Facies H2 consists of well sorted, cross-bedded sands and is interpreted as

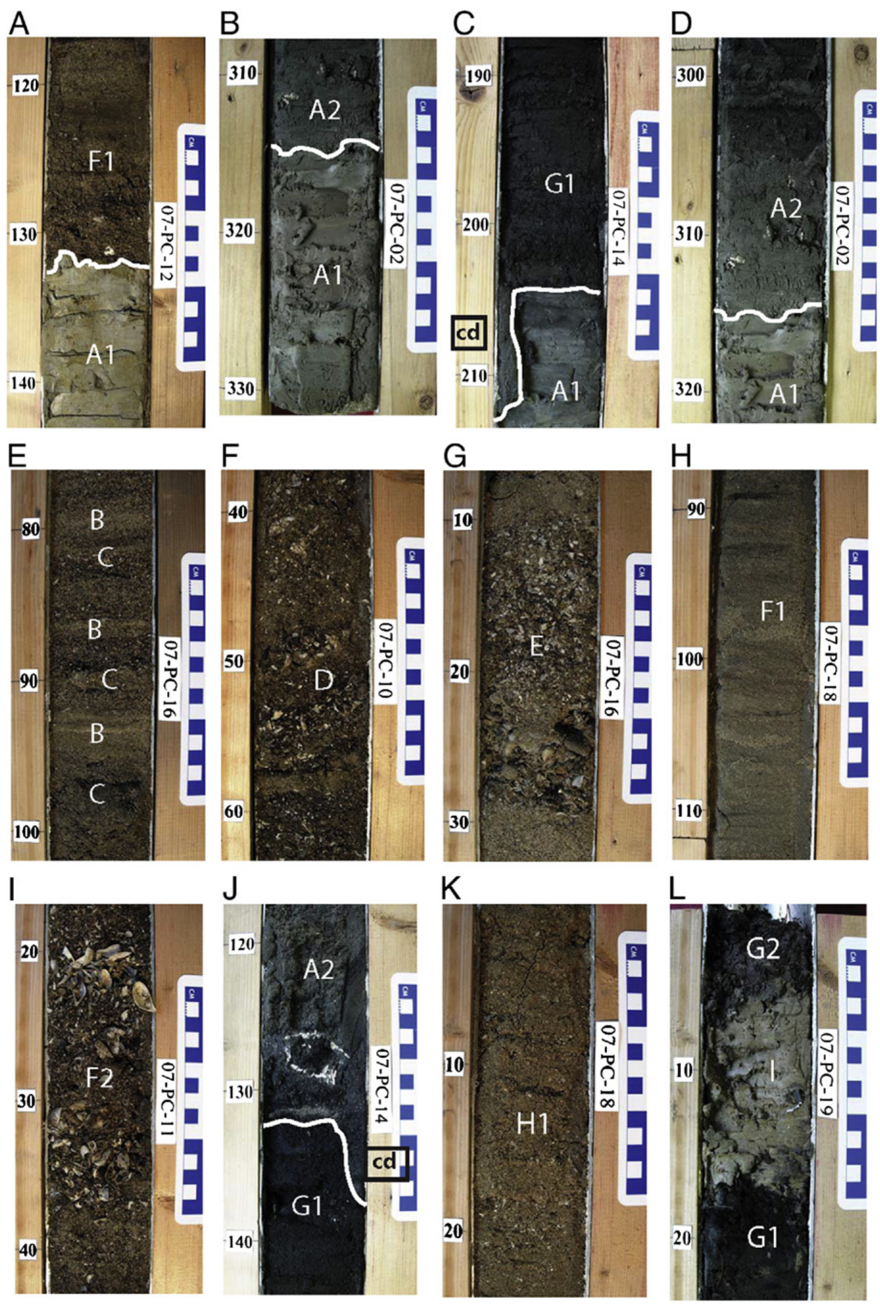

Fig. 3. Core photographs to show examples of lithofacies. A: glaciolacustrine sediment (Facies A1) overlain by beachface sands (facies F1). B: Facies A1 overlain by deepwater silts and silty sands (Facies A2). C: Facies A1 overlain by peats (Facies G1). D: Erosional contact (transgressive surface/surface of erosion) between deepwater silts and silty sands (Facies A2) over older glaciolacustrine deposits (Facies A1). E: Tempestites consisting of hummocky bedded sands (Facies C) and planar laminated sands (Facies B). F: Breaker zone cross-bedded sands (Facies D). G: Beachface gravels (Facies E). H: beachface laminated sands (Facies F1). I: Beachface coquinas (Facies F2). J: Peats (Facies G1) drown by deepwater silts and silty sands (Facies A2). K: Planar bedded storm overwash deposits (Facies H1) with modern soils superimposed. L: Mottled estuarine muds (Facies I) interbedded with peats (Facies G1) and carbonaceous muds (Facies G2). Notation cd refers to evidence for core disturbance.

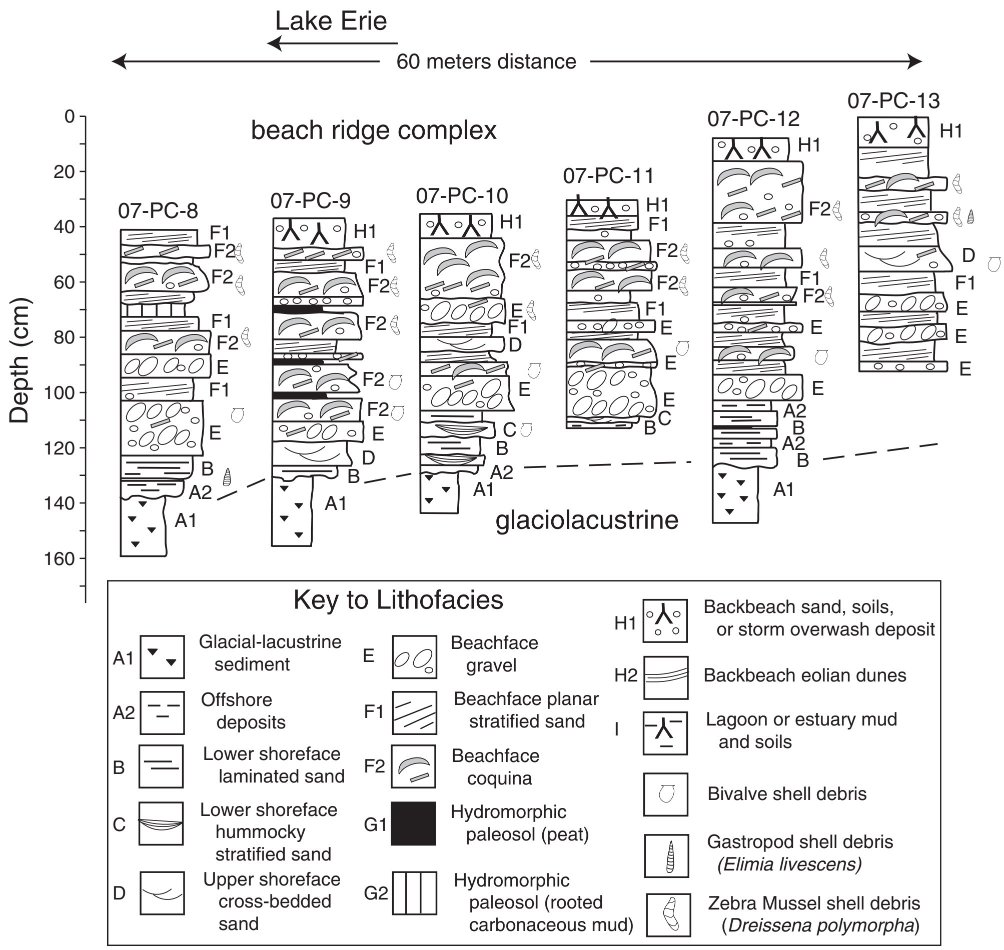

Fig. 4. Core transect through a single beach ridge located west (downdrift) of the Portage River delta, cores closely spaced as shown. Key to symbols shown below.

eolian (Baedke et al., 2004). Facies H1 sands are massive to laminated and often rooted (Fig. 3K). These may be storm overwash sands or rooted and destratified eolian deposits.

Lagoon or estuary deposits (Facies I)

Massive or laminated, rooted, shelly brown clayey silts are found near the Portage River. The sediments are often mottled brown versus blue-gray in appearance (Fig. 3L), suggesting alternating water saturation and dry conditions. These deposits are interpreted as lagoon or estuary deposits. These deposits are typically overlain by backbeach deposits (Facies H1 and H2), suggesting that the lagoon or estuary was partially infilled by the landward migration of the outlying beach ridge complex.

Lithofacies sequences

As previously discussed, the order and sequence of the individual facies are indicative of depositional processes associated with deltaic depositional environments and related adjacent environments. Several discrete lithofacies sequences are demonstrated in the transects of cores shown in Figs. 4–8.

Prodelta turbidites

Although Facies A2 was previously described as a single lithofacies, as discussed previously this was done for practical reasons because these are actually multiple beds of thin-bedded turbidites or hyperpycnites. Each turbidite is 1–3 cm thick, and typically composed of massive, normally graded sandy silts (Bouma division A), overlain by planar laminated sandy silts (Bouma division B) and massive silt (Bouma division D). These deposits match descriptions for low-density turbidites (Lowe, 1982) from prodelta environments (Pattison, 2005). At the Portage River delta, successions of prodelta turbidites pinch-out in the shoreward direction (Figs. 4–6) and range from a few centimeters thick to about 80 cm thick (Figs. 7 and 8).

Tempestites

Sequences consisting of hummocky stratified sands (Facies C) overlain by planar laminated sands (Facies B) are recognized as tempestites. These storm deposits are created by wave erosion and remolding of bottom topography during a storm, followed by fallout from suspension and combined flow conditions (Harms et al., 1975). At the Portage River delta, tempestites tend to overlie or be thinly interbedded with prodelta turbidites at the base, and are typically overlain by cross-bedded sands (facies D) from the surf zone. The data suggests these tempestites are found in shoaling water just lakeward of the surf zone, or in the lower shoreface. Similar settings for tempestites have been reported elsewhere (Greenwood and Sherman, 1986).

Prograding shoreline sequence

The majority of each of the 28 vibracores shows a prograding shoreline sequence consisting of (from bottom to top) upper shoreface cross-bedded sands representing the breaker zone (Facies D), overlain by beachface gravels (Facies E), sands with heavy mineral laminae (Facies F1) or shell-hash coquinas (Facies F2). The cores reveal a stratigraphic change from older beachface gravels with a small amount of bivalve shells, to more recent beachface coquinas

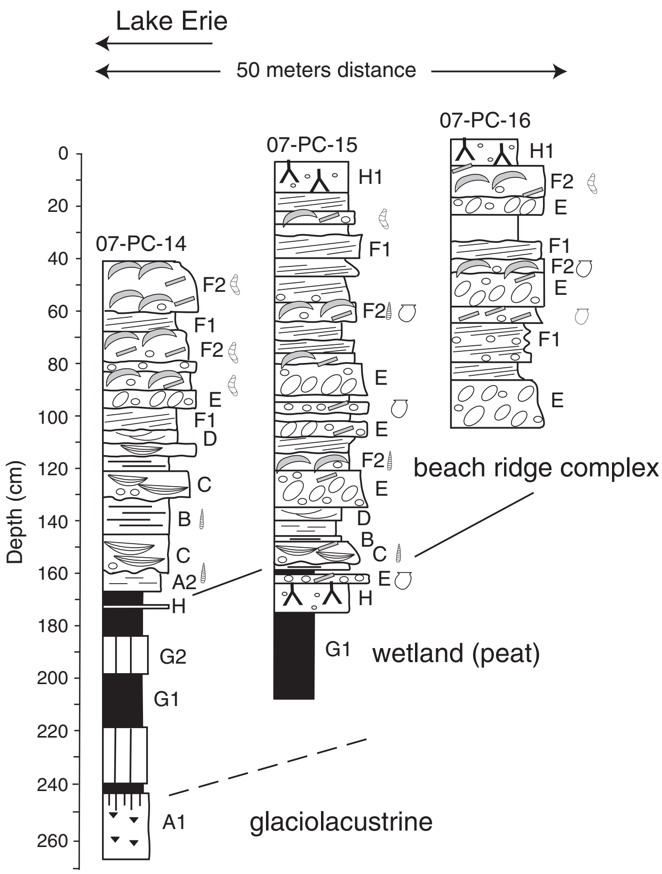

Fig. 5. Core transect through a single beach ridge located west (downdrift) of the Portage River delta, cores closely spaced as shown. Note that a wetland sequence directly overlies glaciolacustrine deposits. Key to symbols given in Fig. 4.

dominated by zebra mussel shells (Figs. 4, 5, and 7). The thickest of these individual prograding shoreline sequences are found east (updrift) of the Portage River delta and are typically >3 m thick. Thinner prograding shoreline sequences are found west (downdrift) of the delta and are typically <1 m thick.

Coastal wetlands sequence

An evaluation of the cores shows that organic sediments fall into two different categories. East (updrift) of the Portage River delta, peats (Facies G1) and carbonaceous muds (Facies G2) are thin (<20 cm thick) and interbedded with backbeach deposits (discussed below). These deposits are interpreted as wetland soils (hydromorphic paleosols) that formed in swales between accreted beach ridge complexes or between eolian dunes (Figs. 7 and 8). In contrast, west (downdrift) of the Portage River delta, peats and carbonaceous muds are up to 90 cm thick and directly overlie glaciolacustrine deposits (Figs. 5 and 6). In one core, roots extend from the basal peat into the underlying glaciolacustrine deposits. In several cores, the upper part of the peats is interbedded with storm overwash deposits (Facies H1).

The peats and carbonaceous muds west (downdrift) of the Portage River delta are interpreted as a coastal wetland sequence. The development of thicker peats in any particular area suggests the following criteria are met: (1) abundant vegetation, (2) minimal clastic input, and (3) rising water table conditions. The necessity for abundant vegetation is obvious. Minimal clastic input is necessary because mineral material dilutes the organic content in peats (producing carbonaceous sediments instead) as well as creates habitat less favorable for accumulating plant material and might cause preservational loss of plant material due to abrasion. Rising water table conditions preserve organic matter and create accommodation space (places favoring deposition and preservation of sediment) that can be filled by peat accumulation. In sequence stratigraphy models, thicker peats or coals are typically interpreted as an indication of slow to moderate rates of sea-level (or in this case, lake-level) rise (Ambrose and Ayers, 2007). Similar interpretations have been made about peat accumulations elsewhere in the Great Lakes (Fraser et al., 1990).

Coastal wetlands used to be common in the western basin of Lake Erie (Herdendorf, 1992; Reeder and Eisner, 1994). Some, but not all, of these wetlands formed behind barriers and were sensitive to the dynamics of the barrier (Mackey et al., 1994). The presence or absence of a barrier can be assessed by looking at the overlying sediments. In

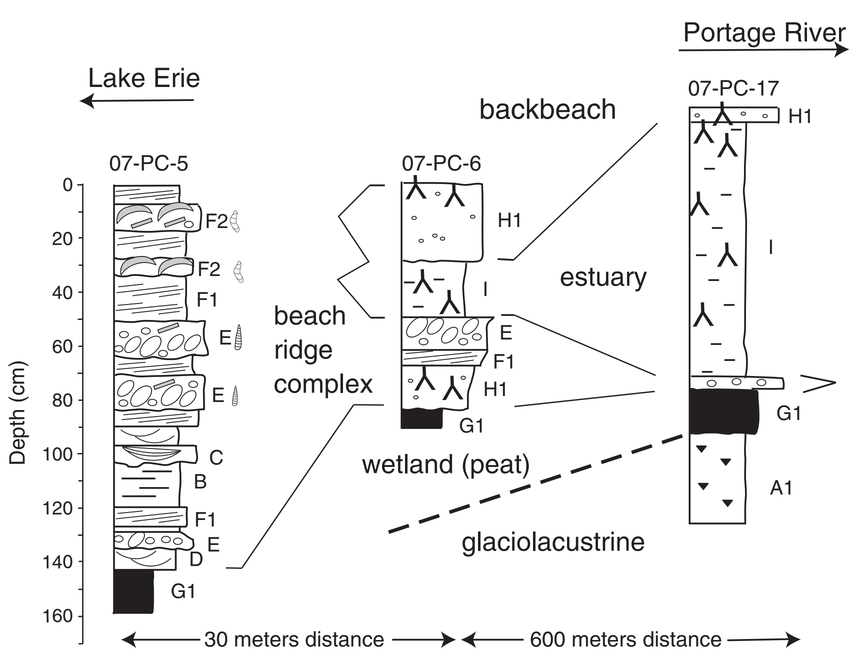

Fig. 6. Core transect through the existing spit of the Portage River delta, located west (downdrift) of the river mouth. Note interstratified beach ridge and estuary which overlie an older coastal wetland sequence. Core separation distances shown. Key to symbols given in Fig. 4.

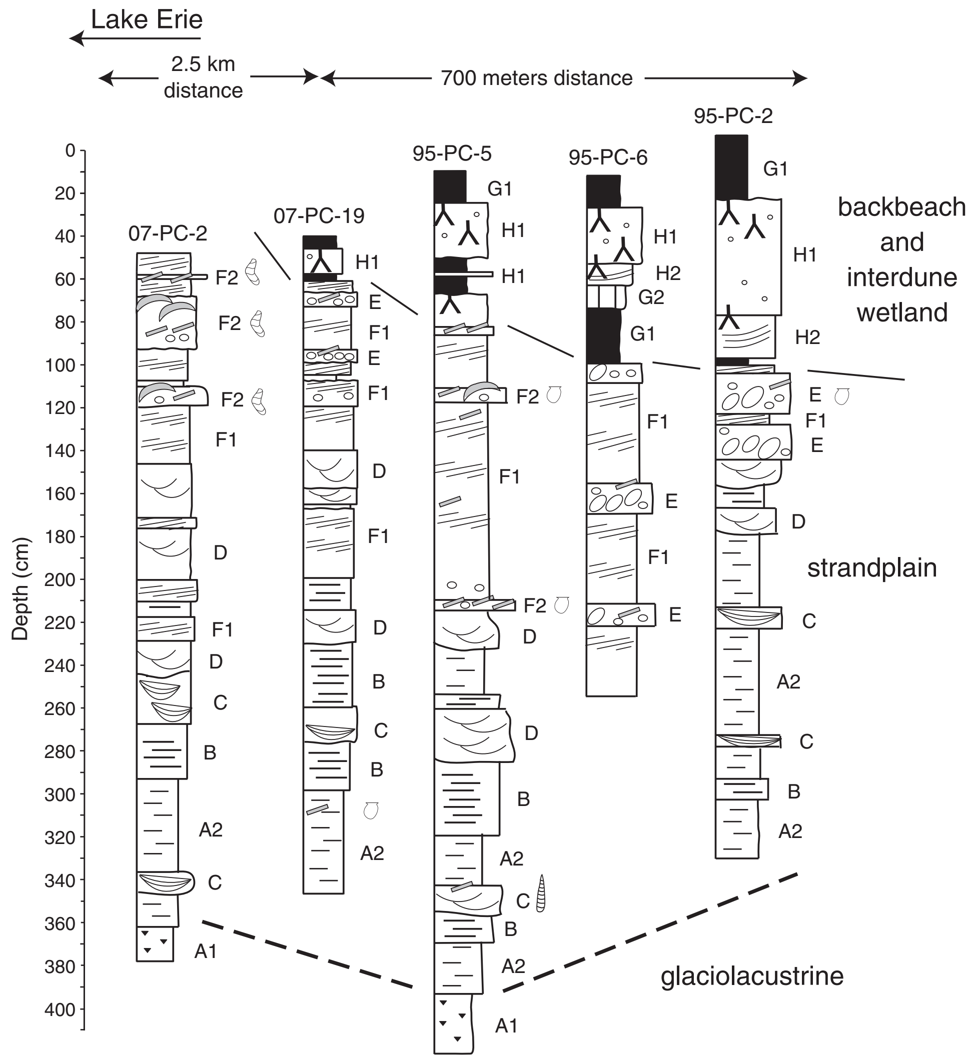

Fig. 7. Core sequence through the strandplain east (updrift) of the Portage River delta. Note the thicker beach ridges which do not correlate laterally because they are a series of accreted individual beach ridge complexes. Also note the increasing thickness and development of backbeach deposits on the older (right side) accreted beach ridges. Key to symbols is given in Fig. 4.

the case of a transgression caused by rising lake levels, an offshore barrier could either continuously migrate landward or else be drown in place (Reinson, 1992). Continuous landward migration of a barrier would produce a sequence where the peats were buried by overwash deposits, eolian dunes, then beachface and shoreface deposits. This sequence is not observed (Fig. 9). Instead, the accumulation of peats in the lowstand systems tract is abruptly overlain by offshore deposits (prodelta turbidites and tempestites) above a transgressive surface/surface of erosion indicating the coastal wetland drown in place. Thus, if these peats formed behind an offshore barrier, the barrier was similarly drown in place (Rampino and Sanders, 1980), and is presently part of the offshore lake bottom. Alternatively, these wetlands were not protected by a barrier.

The timing of these changes has been determined from ^{14}C geochronology. For the Portage River delta, the oldest peats directly overlying glaciolacustrine deposits are 2025 ± 128 cal YBP. A series of ^{14}C ages through the peats indicates a constant sediment accumulation rate of 1.6 mm yr^{-1} ($r^2 = 0.9923$) with a projected youngest peat age of about 1580 YBP, immediately below the transgressive surface (Fig. 9).

Backbeach, wetland, and lagoon/estuary deposits

The upper parts of the strandplain located east (updrift) of the Portage River delta include both facies H1 and H2. These deposits are interpreted as storm overwash deposits (Facies H1) that were later remobilized into eolian dunes and/or stabilized by vegetation. These are interbedded with thin wetland deposits and have modern soils superimposed (Figs. 7 and 8). Backbeach sediments west (downdrift) of the Portage River delta are solely storm overwash sands (Facies H1), interbedded with the coastal wetlands sequence and with modern soils superimposed.

Fig. 6 demonstrates the relationship of cores across the existing Portage River spit on the west side of the delta. Again, coastal wetland deposits (peats) overlie glaciolacustrine deposits at the base of the section. There are storm overwash deposits above the peats representing flooding of the coastal wetlands when the rate of lake-level rise exceeded the rate of wetland plant growth and accumulation. The modern barrier (prograding shoreline sequence) is intertongued laterally with deposits from the Portage River estuary (Facies I).

Discussion

Sequence stratigraphy

The sediment successions observed in the Portage River delta cores represent nearshore environments such as prodelta turbidites, tempestites, prograding shoreline sequences (such as lower shoreface, upper

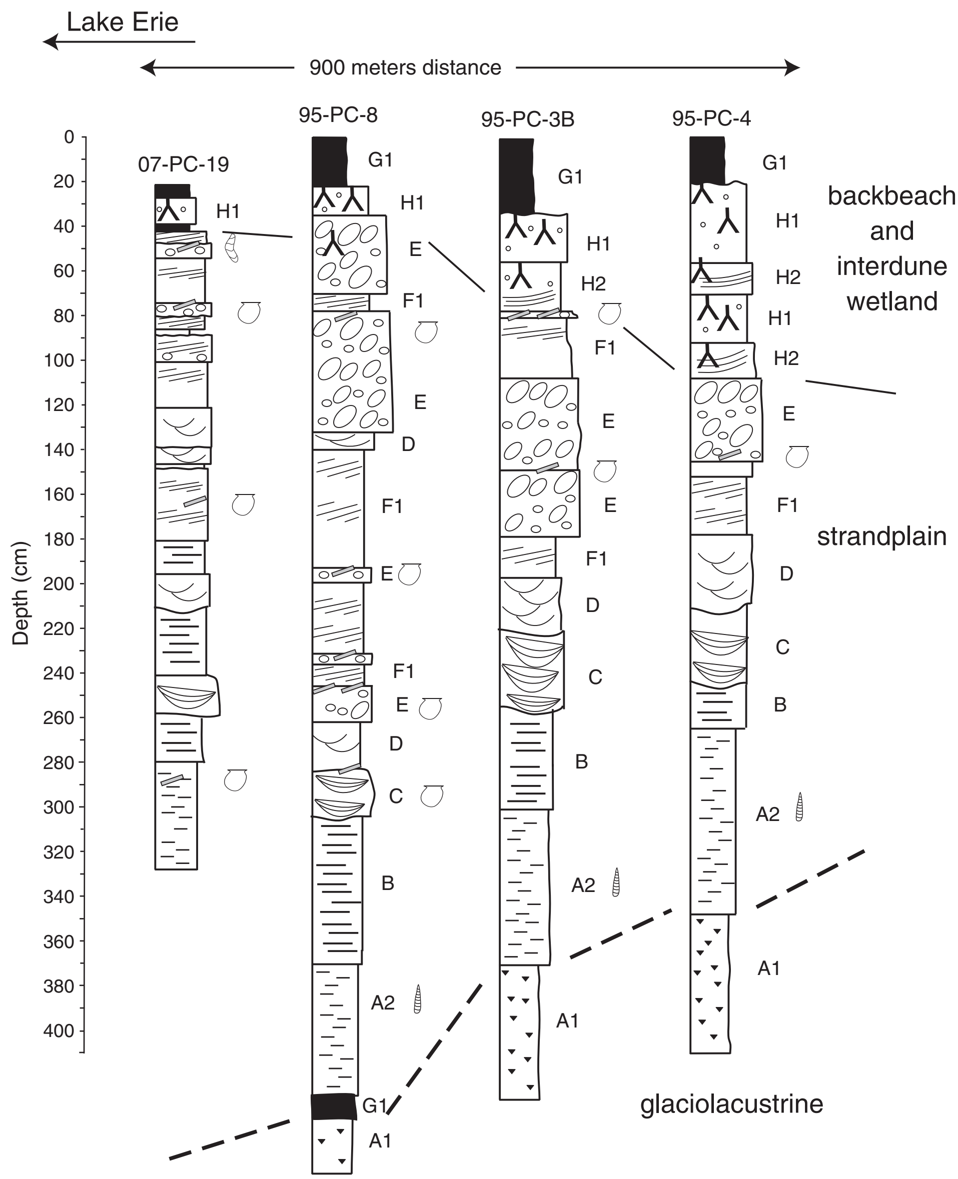

Fig. 8. Core transect through the strandplain east (updrift) of the Portage River delta, again showing lack of lateral correlation between individual accreted beach ridge complexes. Key to symbols is given in Fig. 4.

shoreface, and beachface deposits), coastal wetland sequences, backbeach, and estuarine or lagoonal deposits. These deposits have predictable spatial and temporal relationships. For example, the coastal peats are abruptly overlain by prodelta turbidites representing deposits from below wave base, indicating lake-level rise and shoreline retreat, accordingly the contact between the peats and overlying turbidites is interpreted as a transgressive surface/surface of erosion (Fig. 9). Overlying the turbidites is a repetitive succession of tempestites interpreted to represent passage of wave base across each core location. The overlying deposits represent a prograding shoreline sequence, thus the upper part of each core is mostly a highstand system tract. The lowest contact between the tempestites and turbidites can be identified as a maximum flooding surface, and a relatively thin transgressive systems tract can be interpreted between the transgressive surface/surface of erosion and maximum flooding surface, as shown in Fig. 9. Thus, the deposits found in the vicinity of the Portage River delta follow orderly facies transitions in response to rising lake-level and changes in accommodation space, similar to many examples in the geological literature (Reinson, 1992; Ambrose and Ayers, 2007).

Delta facies asymmetry

Updrift portion of the delta

Updrift (east) of the Portage River delta, a series of at least 15 accreted beach ridges form a strandplain. In each sediment core, there is a predictable sequence of prograding shoreline deposits above older glaciolacustrine sediments. Each core demonstrates the succession from offshore deposits to lower shoreface to upper shoreface to beachface to backbeach deposits. However, core transects (Figs. 7 and 8) show a juxtaposition of environments and ages from one beach ridge to the next, showing that each of these beach ridges was independently formed and accreted to the shoreline, as the strandplain evolved and widened. The beach ridge sequences range from 3 to 4.5 m thick. The overlying backbeach deposits thicken landward (Figs. 7 and 8) in response to multiple episodes of overwash and breaching, and these deposits are later remobilized into eolian dunes or stabilized by vegetation and soils. Studies at Long Point, Lake Erie interpret similar backbeach sequences as a response to long-term higher lake levels (Davidson-Arnott and Reid, 1994).

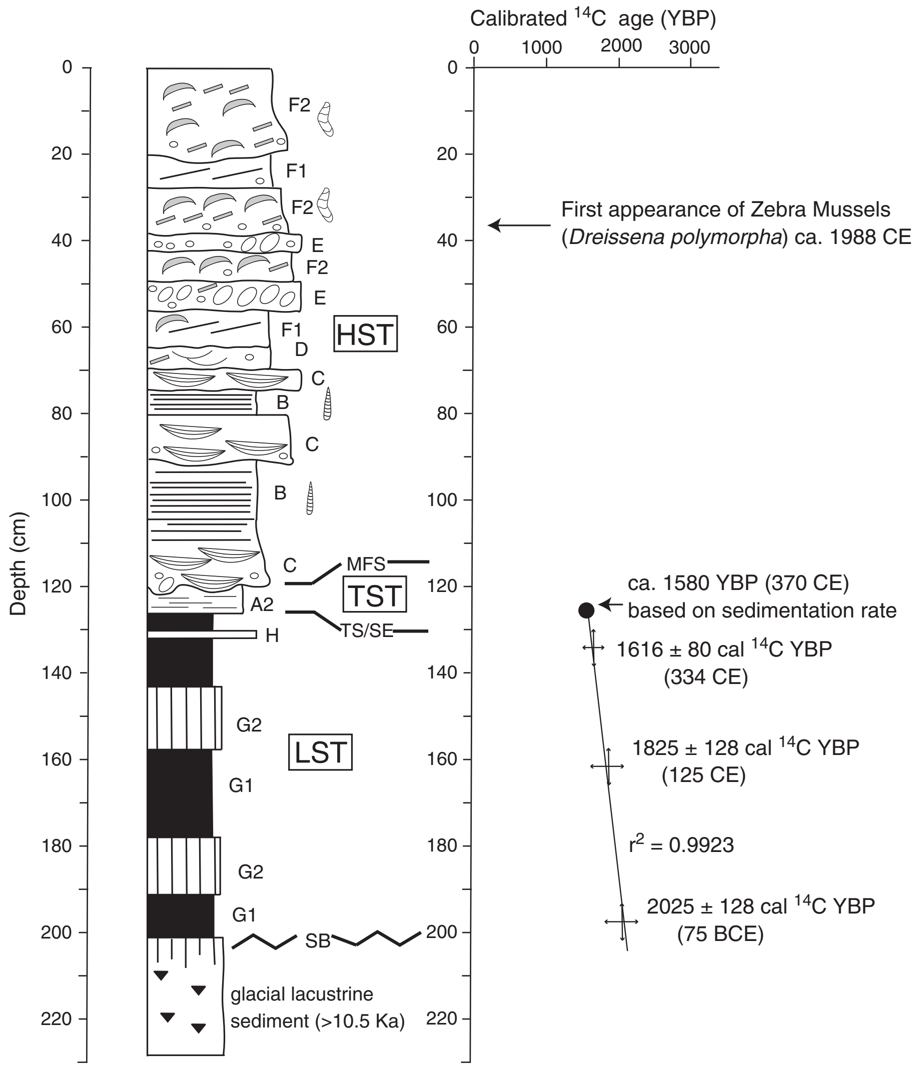

Fig. 9. Detail of the 2007 core number 10 from west (downdrift) of the Portage River delta. The erosional exposure surface on the glaciolacustrine sediments is a sequence boundary (SB). The overlying peats represent a lowstand systems tract (LST) where slowly rising lake levels created accommodation space for peat accumulation. The transition to offshore deposits (facies A2) represents flooding of the underlying coastal wetland, thus the surface is a transgressive surface/surface of erosion (TS/SE), and the overlying deposits are part of a transgressive systems tract (TST). The transition upward to tempestites represents the migration of wave base across the deposit, this would place the maximum flooding surface (MFS) at the basal contact as shown. The rest of the deposit is a shallowing-upward, prograding shoreline sequence forming at close to present lake levels as a highstand systems tract (HST). Radiocarbon dates show linear sediment accumulation rate of 1.6 mm yr^{-1} ($r^2 = 0.9923$) through the peats, suggesting the coastal wetlands were drown in this region at about 1580 YBP. See text for further discussion.

Downdrift portion of the delta

Downdrift (west) of the Portage River delta is a widespread, single accreted beach ridge. This beach ridge either overlies glaciolacustrine deposits (Fig. 4) or wetland deposits that overlie glaciolacustrine deposits (Fig. 5). Close to the mouth of the Portage River, these same sequences are seen to be interstratified with estuarine or lagoonal deposits (Fig. 6). The beach ridge sequence is identical to those described from the updrift portion of the delta, but they are thinner (typically <1 m thick). Core transects (Fig. 4) show that the deposits can be correlated laterally, confirming this is a single beach ridge complex. In addition, an increase in the presence of zebra mussel shells on the lakeward side of this beach ridge suggests the upper parts of the sequences shown in Figs. 4 and 5 are progradational.

Wave-influenced delta model

The wave-influenced delta model (Bhattacharya and Giosan, 2003) accounts for delta asymmetry as the result of the interaction between fluvial discharge and the prevailing longshore transport. According to this model, if the jet of fluvial discharge through the delta distributary channel is sufficient to act as a "groyne effect" on the prevailing longshore current, then sand will preferentially accumulate on the updrift portion of the delta while the downdrift portion of the delta will be sand starved. For the Portage River delta, an aerial photograph (from July 26, 2006) dramatically illustrates this effect (Fig. 10). In the aerial image, Portage River flooding conditions (lower left portion of the image) result in a distinctive discharge jet (due to suspended sediment) in the center of the image. Nearshore sand transport is visible along the updrift portion of the delta, while the prevailing wave directions dissipate the plume of suspended sediment (silts and muds) to the west, lakeward of the discharge jet.

Sand accumulation updrift of the Portage River delta is evident in the accumulation of beach ridges in the strandplain (Fig. 2), but can also be observed in more recent aerial images showing beach accretion on the updrift sides of engineered structures between 1980 and 2006 (Fig. 11). The images shown in Fig. 11 have been evaluated to calculate the asymmetry index. The average monthly discharge of the Portage River was calculated from USGS stream gage data on the Portage River between 1980 and 2006 (USGS, 2010). For each of the three beaches shown in Fig. 11, the area was determined

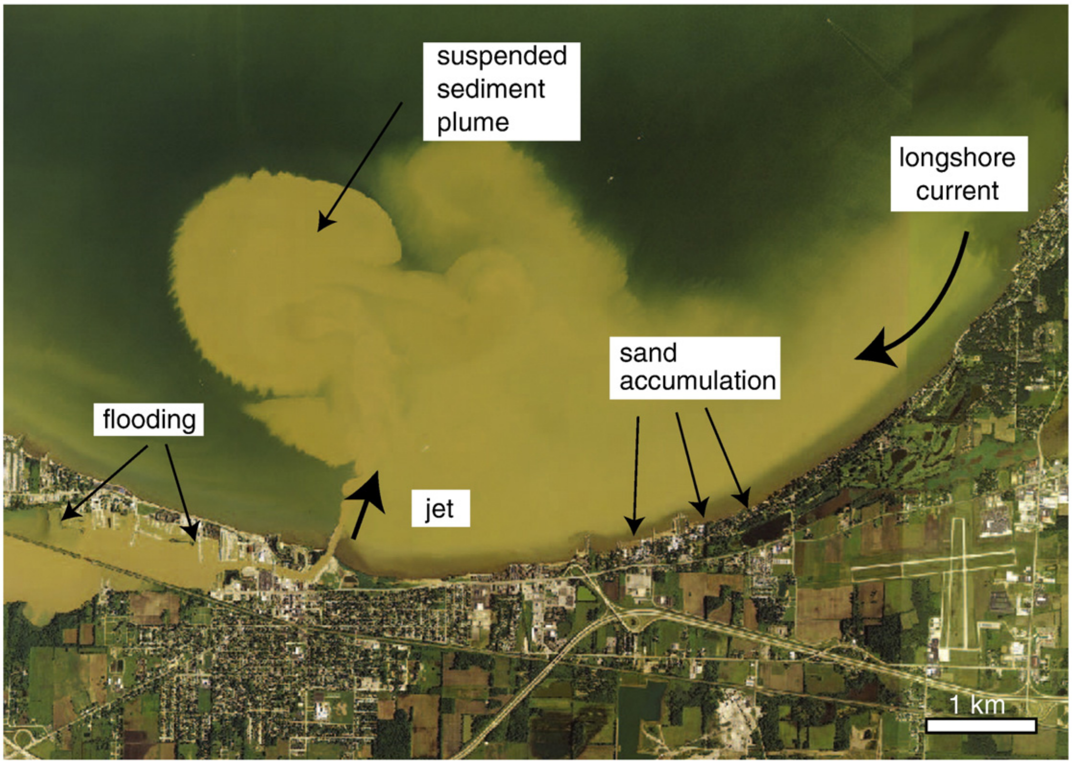

Fig. 10. Aerial photograph image from July 26, 2006 showing Portage River flood conditions producing a jet that blocks longshore sand transport leading to sand accumulation on the east (updrift) side of the delta. The suspended sediment plume dissipates offshore. Scale shown in lower right corner. See text for discussion.

by digital analysis of the image and converted to a volume of sand using sediment core data (Clark, 2008). The results indicate that the Portage River delta has an asymmetry index:

$$A = \frac{net\ longshore\ sediment\ transport\left(m^3\,yr^{-1}\right)}{average\ river\ water\ discharge\left(10^6\,m^3\,month^{-1}\right)} = 296$$

which exceeds the threshold value $A>200$ used by Bhattacharya and Giosan (2003) for global classification of deltas as asymmetric. As discussed previously, there is a continuum between fluvial-dominated deltas and wave-dominated deltas, and many of the world's deltas are similar to the Portage River delta, being asymmetric and showing strong effects of longshore drift. Similar deltas include the Mahanadi Delta of India (Mohanti, 1993) and the Damietta Lobe of the Nile Delta (Fanos et al., 1993).

The evolution of the Portage River delta can be reconstructed (Fig. 12) and appears very similar to the evolution of numerous wave-influenced deltas elsewhere in the world. The exposed bedrock high of Catawba Island has acted as a barrier to prevailing southwesterly winds in the western basin of Lake Erie, and caused the establishment of a southwesterly longshore current cell (Herdendorf, 1973). The Portage River has acted as a sufficient barrier to longshore drift, over time, to promote accretion of beach ridge complexes on the updrift portion of the delta. This series of accreted beach ridges resulted in the formation of a strandplain. On the downdrift side of the Portage River

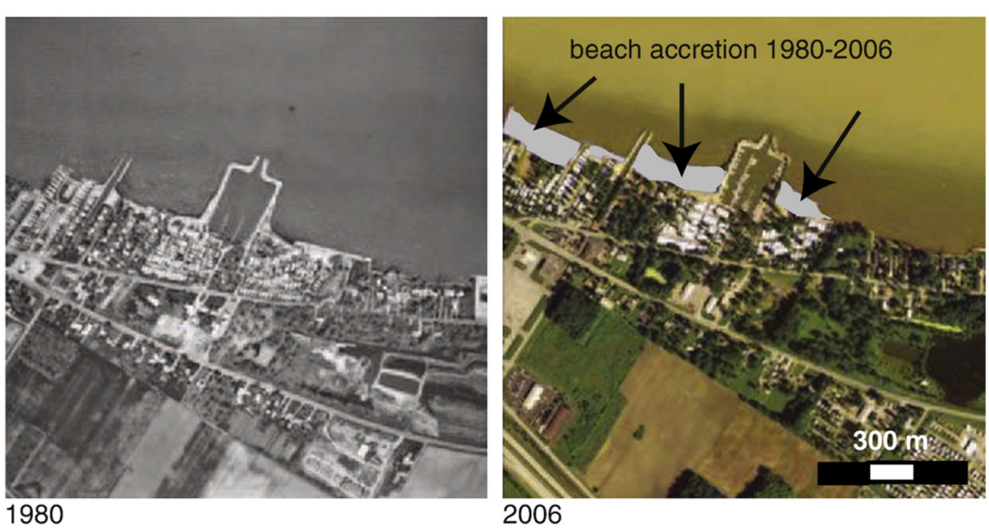

Fig. 11. Comparison of aerial photographs from May 6, 1980 and July 26, 2006, showing sand accumulation updrift of the Portage River delta. Incorporation of the digitized images into a GIS database permits calculating the areal extent of the beaches, and core data was used to calculate sand volumes. Scale shown in lower right corner. See text for discussion.

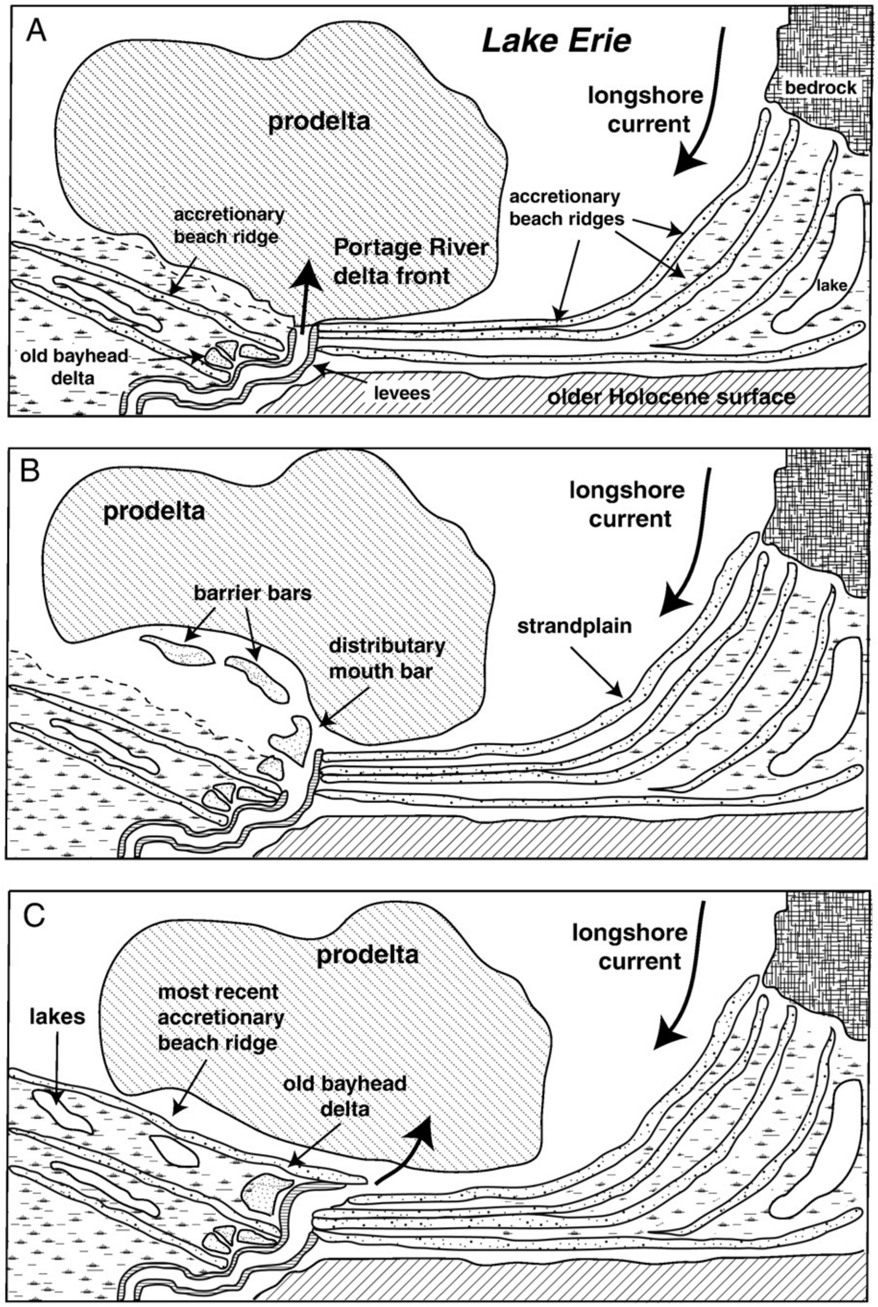

Fig. 12. Simplified representation of the asymmetric Portage River delta as a wave-influenced delta. In this model, the discharge jet of the Portage River blocks the westward longshore current, leading to beach ridge accretion and strandplain development on the east (updrift) side of the delta. In contrast, large river floods deposit offshore bars which migrate landward to accrete beach ridges on the west (downdrift) side of the delta.

delta, coastal wetlands formed peats beginning by at least 2025 cal YBP. A transgression after approximately 1580 YBP resulted in drowning the coastal wetland in place. This interpretation is in accord with evidence of wave-cut features 4–7 m below present lake-level dating from 3.4 to 2.0 ka in an adjacent part of Lake Erie (Holcombe et al., 2003). This evidence shows that Lake Erie levels rose 4–7 m in the past approximately 2000 YBP, generating this transgression. Accordingly, the deposits studied in these cores can be interpreted as a single stratigraphic sequence of lowstand system tract to transgressive system tract to highstand system tract (Fig. 9).

Summary and conclusions

Coastal features in the nearshore region both updrift and downdrift of the Portage River delta have been affected by deltaic processes and evolution. Because the Portage River has a relatively small sandy bedload contribution, its primary influence on the Lake Erie coastal environment is the effect of the river discharge on the prevailing longshore current and the plume of muddy suspended sediment dispersed into deeper water in the lake. Discharge from the Portage River is evidently sufficient to exert a block the prevailing westward longshore current in this portion of Lake Erie. The result has been the accretion of at least 15 beach ridges to form a strandplain on the updrift (east) side of the delta. Sediment cores from this region each show a consistent vertical succession from glaciolacustrine sediment unconformably overlain by offshore deposits (prodelta turbidites), lower shoreface deposits (tempestites), upper shoreface deposits (cross-bedded sands), and beachface gravels, sands, or (most recently) coquinas composed of zebra mussel shell hash. Thus, these are prograding shoreline successions. However, the cores cannot be correlated laterally, showing that each successive beach ridge accreted independently. The prograding shoreline sequence is capped by an overlap sequence of backbeach deposits consisting of storm overwash sands, eolian dunes, and small interdune wetlands.

On the downdrift (west) side of the delta, the nearshore coastal deposits are sand starved due to the "groyne effect" of the Portage River. A thick succession of peats directly overlie and are rooted into older glaciolacustrine sediments, with the peats having a basal ^{14}C age of 2025 ± 128 cal YBP. The peats and related deposits are interpreted as a lowstand system tract overlying a sequence boundary (lake-level fall after the Nipissing I and II lake stages, and resultant exposure of the glaciolacustrine sediments). A series of ^{14}C ages through the peats demonstrate constant sediment accumulation rates of 1.6 mm yr^{-1} ($r^2 = 0.9923$), and is interpreted as peat accumulation during an episode of rising lake levels and rising groundwater levels. Such conditions are favorable to the growth and preservation of peats. After approximately 1580 YBP, these coastal wetlands were drown and overlain by offshore deposits (prodelta turbidites) signaling onset of the modern Portage River in this region. The contact between the offshore deposits and underlying peats is a transgressive surface/ surface of erosion. Above the offshore deposits are tempestites, indicating passage of wave base across this region, accordingly the maximum flooding surface is identified, and a thin transgressive systems tract recognized. The overlying sandy deposits have a similar vertical succession to the beach ridges discussed from updrift of the delta, however these cores can be correlated laterally because it is a single beach ridge complex. Models from similar deltas suggest that the origin of this downdrift beach ridge is related to river flooding, formation of distributary mouth bars and barrier bars, and landward bar migration at some time post-1580 cal YBP.

The facies, facies successions, and sequence stratigraphy observed from the Portage River delta are consistent with models for wave-influenced deltas observed in marine environments. The implications are significant. First, deltaic processes are key in the evolution of Great Lakes coastal environments, rather than minor players. Second, wave-influenced deltas are asymmetric in response to the relationship between fluvial and wave processes. It is the comparison of these processes that matters, rather than absolute values of river discharge, wave conditions, etc. Third, beach ridges form updrift or downdrift of the delta mouth due to different processes, thus the accretion of these features is unlikely to be synchronous. This final point has important implications for efforts to use beach ridges to reconstruct climate change and lake-level histories.

Acknowledgements

We wish to thank the Ohio Geological Survey for use of the vibracorer, especially Donald E. Guy, Jr. for his assistance and advice. We thank the staff of the Ottawa National Wildlife Refuge, especially Sara Mason, for access to beaches within the refuge. We greatly appreciate the assistance of Nathan Harris, Mary Faw, Zach Mueller, and Matt Bradford during 2007 coring operations. A research grant from BGSU provided for radiocarbon analysis. Evans wishes to thank two former students, Drue E. Roberts and Donna Emsley, for helping to evaluate the 1995 set of sediment cores. This paper was significantly improved thanks to the suggestions of three anonymous reviewers.

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