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ORIGINAL PAPER

Geomorphic and sedimentologic evidence for the separation of Lake Superior from Lake Michigan and Huron

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Abstract A common break was recognized in four Lake Superior strandplain sequences using geomorphic and sedimentologic characteristics. Strandplains were divided into lakeward and landward sets of beach ridges using aerial photographs and topographic surveys to identify similar surficial features and core data to identify similar subsurface features. Cross-strandplain, elevation-trend changes from a lowering towards the lake in the landward set of beach ridges to a rise or reduction of slope towards the lake in the lakeward set of beach ridges indicates that the break is associated with an outlet change for Lake Superior. Correlation of this break between study sites and age model results for the strandplain sequences suggest that the outlet change occurred sometime after about 2,400 calendar years ago (after the Algoma phase). Age model results from one site (Grand Traverse Bay) suggest an alternate age closer to about 1,200 calendar years ago but age models need to be investigated further. The

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landward part of the strandplain was deposited when water levels were common in all three upper Great Lakes basins (Superior, Huron, and Michigan) and drained through the Port Huron/Sarnia outlet. The lakeward part was deposited after the Sault outlet started to help regulate water levels in the Lake Superior basin. The landward beach ridges are commonly better defined and continuous across the embayments, more numerous, larger in relief, wider, have greater vegetation density, and intervening swales contain more standing water and peat than the lakeward set. Changes in drainage patterns, foreshore sediment thickness and grain size help in identifying the break between sets in the strandplain sequences. Investigation of these breaks may help identify possible gaps in the record or missing ridges in strandplain sequences that may not be apparent when viewing age distributions and may justify the need for multiple age and glacial isostatic adjustment models.

Keywords Great Lakes · Lake Superior · Beach ridge · Lake level · Sault outlet · Holocene

Introduction

The youngest postglacial shorelines adjacent to Lake Superior have previously been attributed to one of three lake phases: Nipissing, Algoma, or Sault (Farrand 1960). Reconstructed water planes, based on the elevation of coastal geomorphic features, indicate that the three upper Great Lakes (Superior, Huron, and Michigan) were joined during the Nipissing and Algoma phases (Leverett and Taylor 1915; Hough 1958; Farrand and Drexler 1985). Current interpretation places the end of the Nipissing II phase at about 4,000 years ago (Hough 1958; Farrand 1969; Lewis 1969, 1970; Larsen 1985, 1994; Baedke and Thompson 2000; Johnston et al. 2004) when lake level fell 4 m. The cause of the end of the Nipissing II phase is unknown, but it corresponds to the closing of the Chicago outlet and may be related to erosion at the Port Huron/Sarnia outlet (Leverett and Taylor 1915; Hough 1958), large loss of water from the lake related to climate (Booth et al. 2005), or both (Baedke and Thompson 2000). The Sault phase was defined by Farrand (1960) as the period when the water body in the Lake Superior basin stood separate from that in the Lake Huron basin because of the emergence of a sill in the St. Marys River (near Sault Ste. Marie) that is topographically above the downstream lakes (Fig. 1). The mechanism for the separation is attributed to isostatic rebound (Farrand 1960), but may also

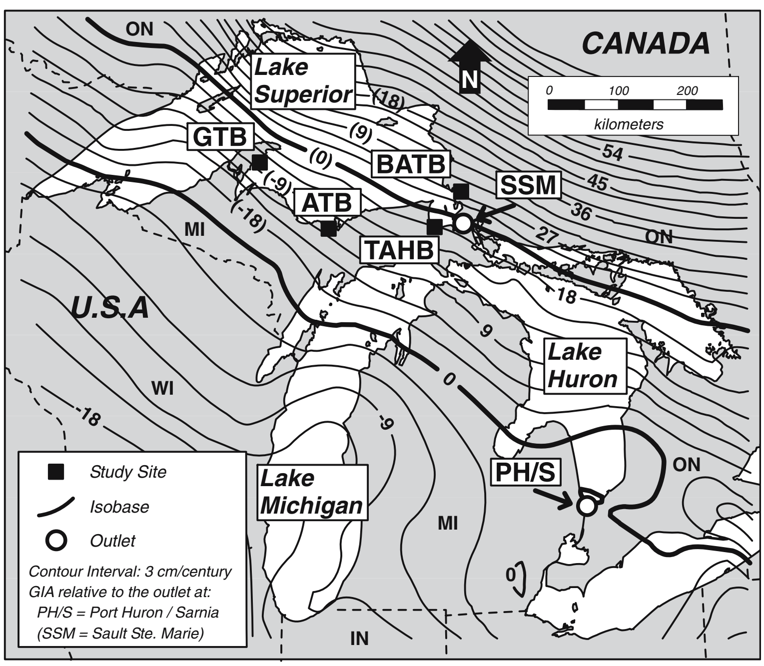

Fig. 1 Map of study sites in Lake Superior showing location of strandplains studied. They are in the Batchawana Bay (BATB) embayment in Ontario and the Tahquamenon Bay (TAHB), Grand Traverse Bay (GTB), and Au Train Bay (ATB) embayments in Michigan. Contours of glacial isostatic adjustment (GIA) relative to the outlet at Port Huron/Sarnia are overlain with rates relative to the outlet at Sault Ste. Marie (in brackets) (modified from Mainville and Craymer 2005)

be related to faulting at the sill (Johnston et al. 2004). There is consensus that the lakes separated sometime after about 2,400 years ago (Farrand 1962; Larsen 1994; Johnston et al. 2004), after the Algoma high water-level phase but Johnston et al. (2000) suggests it occurred closer to 1,200 calendar years ago.

Strandplains of beach ridges provide some of the most continuous sedimentary records during the late Holocene. Data from only three Lake Superior strandplains have been published previously to address the separation of the lakes (Larsen 1994; Johnston et al. 2000, 2004). The separation was identified in the strandplain sequences by a change in the trend of cross-strandplain topographic and foreshore contact elevations. Shorelines existing before the separation of the lakes decrease sequentially in elevation toward Lake Superior. This pattern occurs because the shorelines isostatically rebounded faster than the active outlet at Port Huron/Sarnia. Shorelines existing after the separation show no topographic change if the site is near the Sault outlet, or sequentially increase in elevation at sites west of the Sault outlet. For sites west of the outlet, the Sault outlet was rising more rapidly than the individual sites. Although these general trends were recognized within strandplains, two different approaches for determining long-term water-level elevations were formulated. The sedimentologic approach of Thompson (1992) employed by Johnston et al. (2000, 2004) used basal foreshore elevations, and the geomorphic approach (Larsen 1994) used beach-ridge topography. The geomorphic approach is used to provide a fast and reasonably accurate estimate of the elevation of past lake level and isostatic rebound (Larsen 1994). However, the sedimentologic approach provides more accurate results because lake level at the time of beach-ridge development can be determined more closely from basal foreshore elevations (Thompson 1992; Thompson and Baedke 1997). Changes in topography do not necessarily coincide with changes in basal foreshore elevations (Thompson 1992). Regardless of accuracy in determining past lake-level elevations, both methods provide data that are useful in establishing the time of separation of the lakes identified in the strandplain sequence, and information on changing patterns of shoreline behavior in response to new lake-levels.

This paper presents geomorphic and sedimentologic evidence for a common break in the Lake Superior strandplain sequences associated with the separation of Lake Superior from Lake Michigan and Huron. Such evidence includes beach-ridge topography, relief, and spacing, as well as facies elevations, thickness, and grain-size properties. Although several characteristics help target the separation of the lakes, a subsurface sedimentary contact (i.e. basal foreshore) that has a direct correlation with the elevation of the past lake level is argued as being the most accurate for glacial isostatic adjustment and water-level calculations.

Study area and methods

Four embayments (Fig. 1) were studied along the Lake Superior shoreline: Au Train Bay (Fig. 2), Grand Traverse Bay (Fig. 3) and Tahquamenon Bay (Fig. 4) in Michigan and Batchawana Bay (Fig. 5) in Ontario. These study sites were chosen because they have a large number of preserved beach ridges (>70) and, therefore, potentially contain records of long duration. Geomorphic data were obtained from aerial photographs and topographic surveys across the strandplains, while sedimentologic data were obtained from cores into the beach ridges. Beach ridges were traced from aerial photographs of the embayments to determine the number, orientation, and spatial extent. A total of 294 beach ridges were vibracored at these four sites following the methods described by Thompson et al. (1991). Ground-surface elevations at each core site were surveyed using a transit and stadia rod and corrected to the International Great Lakes Datum of 1985 (IGLD85) by tying surveys to the closest water-level gauging stations. The elevations of beach-ridge crests and swales were also surveyed at two study sites (Au Train Bay and Batchawana Bay). Distance from the modern shoreline was calculated from maps created by tracing beach ridges from aerial photographs and global positioning system measurements recorded at core sites. Each

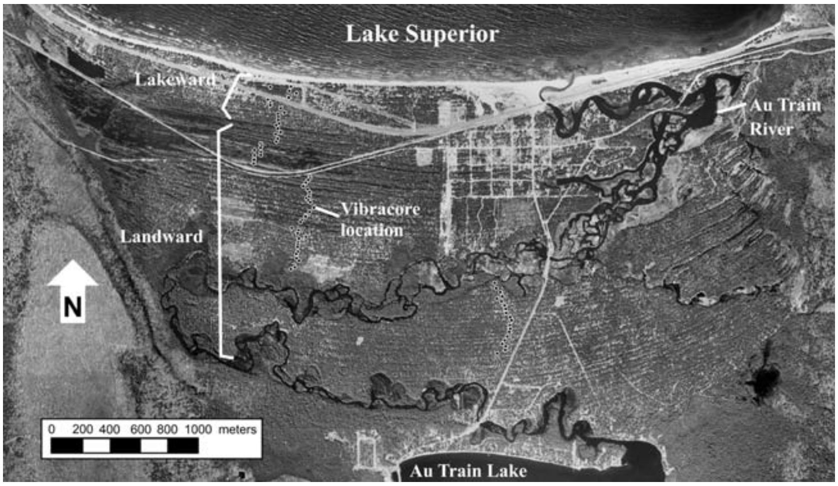

Fig. 2 Aerial photograph of the Au Train Bay strandplain illustrating the landward and lakeward sets of beach ridges and geomorphic features that occur at the strandplain break between sets. See Table 1 for a complete list of geomorphic characteristics between landward and lakeward sets. Vibracore locations are shown by circles. Aerial photograph from Terraserver, courtesy of U.S. Geological Survey

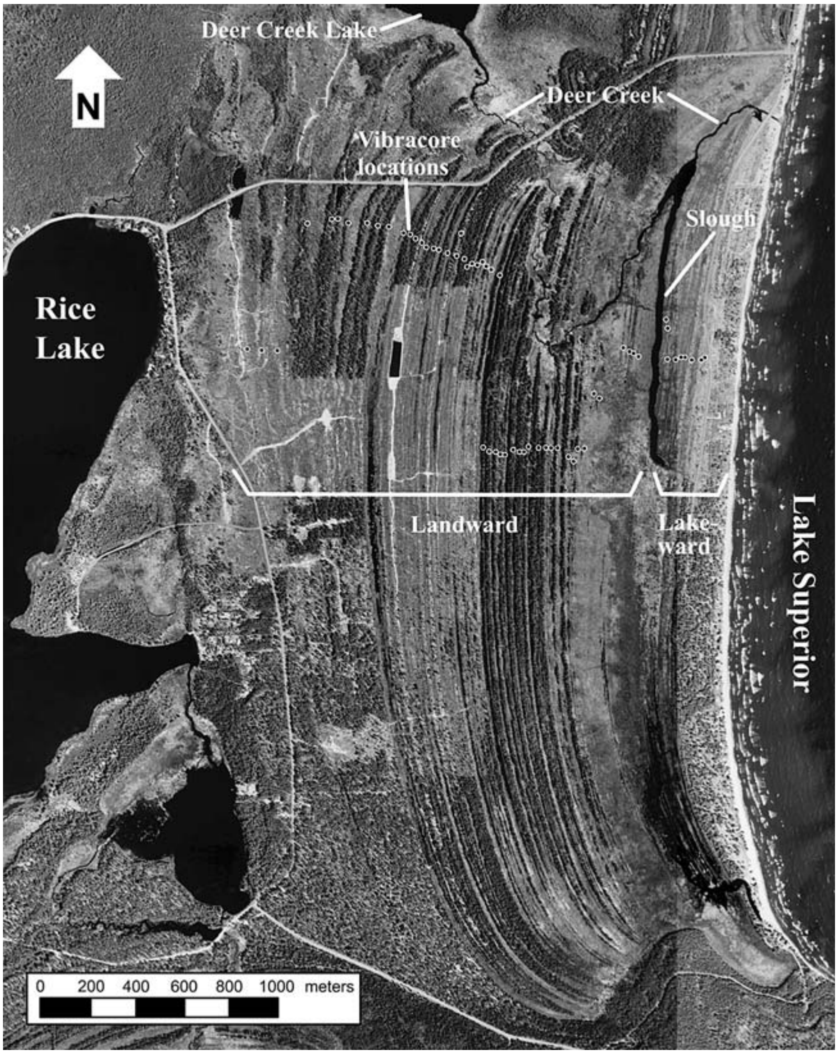

Fig. 3 Aerial photograph of the Grand Traverse Bay strandplain illustrating the landward and lakeward beach-ridge sets and geomorphic features that occur at the strandplain break between sets. See Table 1 for summary of geomorphic characteristics between sets. Vibracore locations are shown by circles. Aerial photograph from Terraserver, courtesy of U.S. Geological Survey

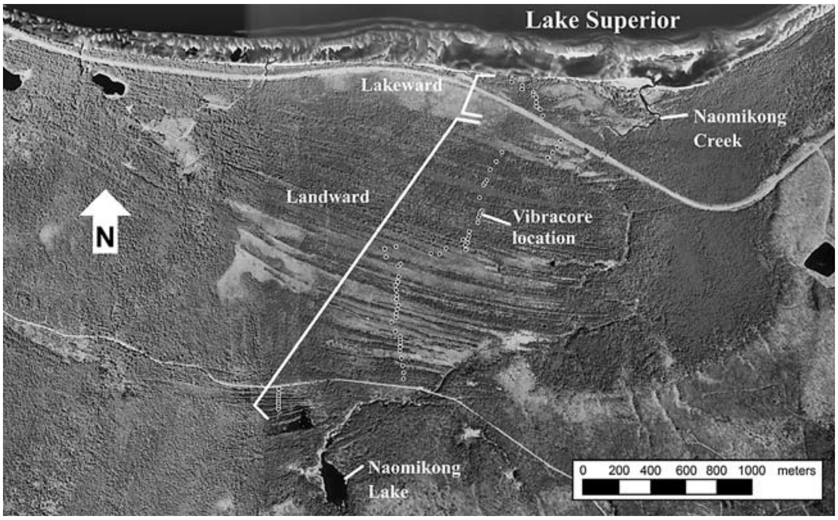

Fig. 4 Aerial photograph of the Tahquameonon Bay strandplain illustrating the landward and lakeward beach-ridge sets and geomorphic features that occur at the strandplain break between sets. See Table 1 for a complete list of geomorphic characteristics between sets. Vibracore locations are shown by circles. Aerial photograph from Terraserver, courtesy of U.S. Geological Survey

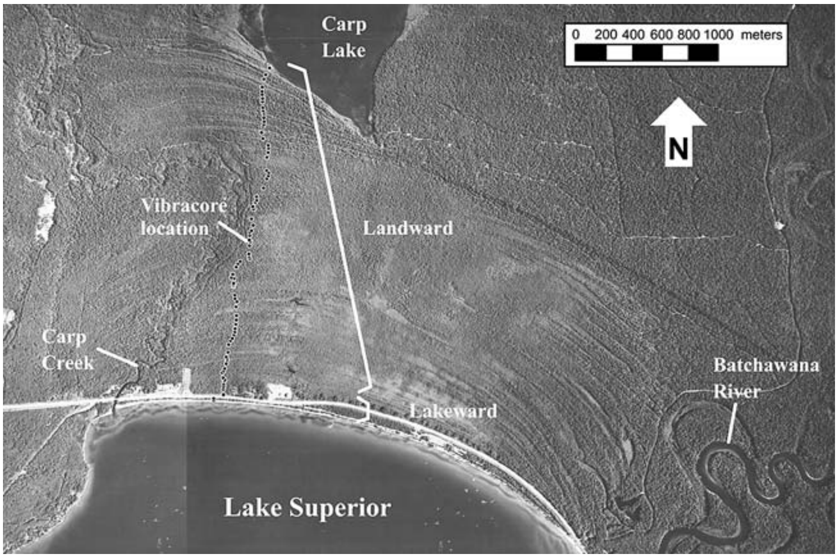

Fig. 5 Aerial photograph of the Batchawana Bay strandplain illustrating the landward and lakeward beach-ridge sets and geomorphic features that occur at the strandplain break between sets. See Table 1 for a complete list of geomorphic characteristics between sets. Vibracore locations shown as circles. Aerial photograph courtesy of Ontario Ministry of Natural Resources

7.6-cm diameter core was split open lengthwise and visually described for grain size, lithology, color, structures, bedding, and any other distinguishing characteristics. One half of each core was photographed, latex-peeled, and stored for future reference; the other half was sampled at selected contact boundaries for grain-size analyses. Approximately 5,000 grain-size samples (each weighing about 100 grams) averaging about 1,200 samples per study site, were dry sieved using a 1/2 phi interval from gravel to sand to determine their grain-size distribution. Grain-size statistical parameters (mean, standard deviation, coarsest one-percentile, skewness, and kurtosis) were calculated for each sample by the mathematical method of moments (Krumbein and Pettijohn 1938). Visual descriptions, photographs, and grain-size results were integrated to define three facies (dune, foreshore, and upper shoreface). Grain-size and sedimentary structure trends across the modern shoreline and their relationship to lake level at each study site were collected and used to help define facies relationships at each site (cf. Thompson and Baedke 1997; Johnston et al. 2004). The most consistently useful properties to determine facies were sedimentary structures and grain-size parameters.

Results

Each strandplain was divided by a break or discontinuity in its geomorphic and sedimentologic attributes that defined landward and lakeward sets of beach ridges (Figs. 6–9). Geomorphic characteristics that differ between landward and lakeward sets at a majority of sites include cross-strandplain topography, drainage patterns, vegetation density, ridge and swale lateral continuity, average relief and width, and presence of standing water and peat in the intervening swales (Table 1). The landward sets of beach ridges are commonly more laterally continuous across the embayments, more numerous, larger in relief, and wider, with a greater vegetation density. The associated swales contain more standing water and peat than those in the lakeward sets. The

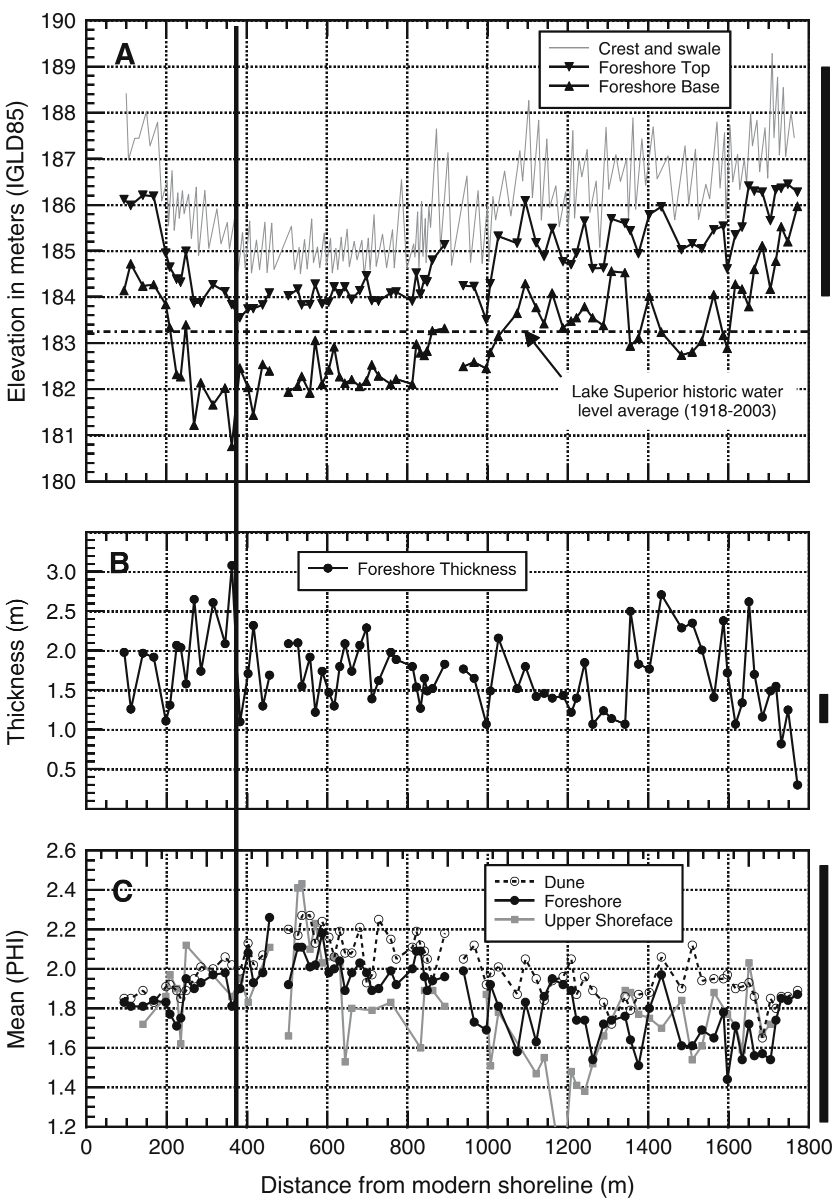

Fig. 6 Graphs of (**A**) crest, swale and facies contact elevations, (**B**) foreshore thickness, and (**C**) mean grain size per facies from the Au Train Bay strandplain in Michigan. Gaps in data sets are locations where beach ridges were not cored. Line represents break between lakeward and landward sets. Filled rectangles to the right of each graph are reference bars to easily compare *y*-axis magnitude between sites (Figs. 6–9): upper = 5 m, middle = 0.4 m, lower = 1.3 phi

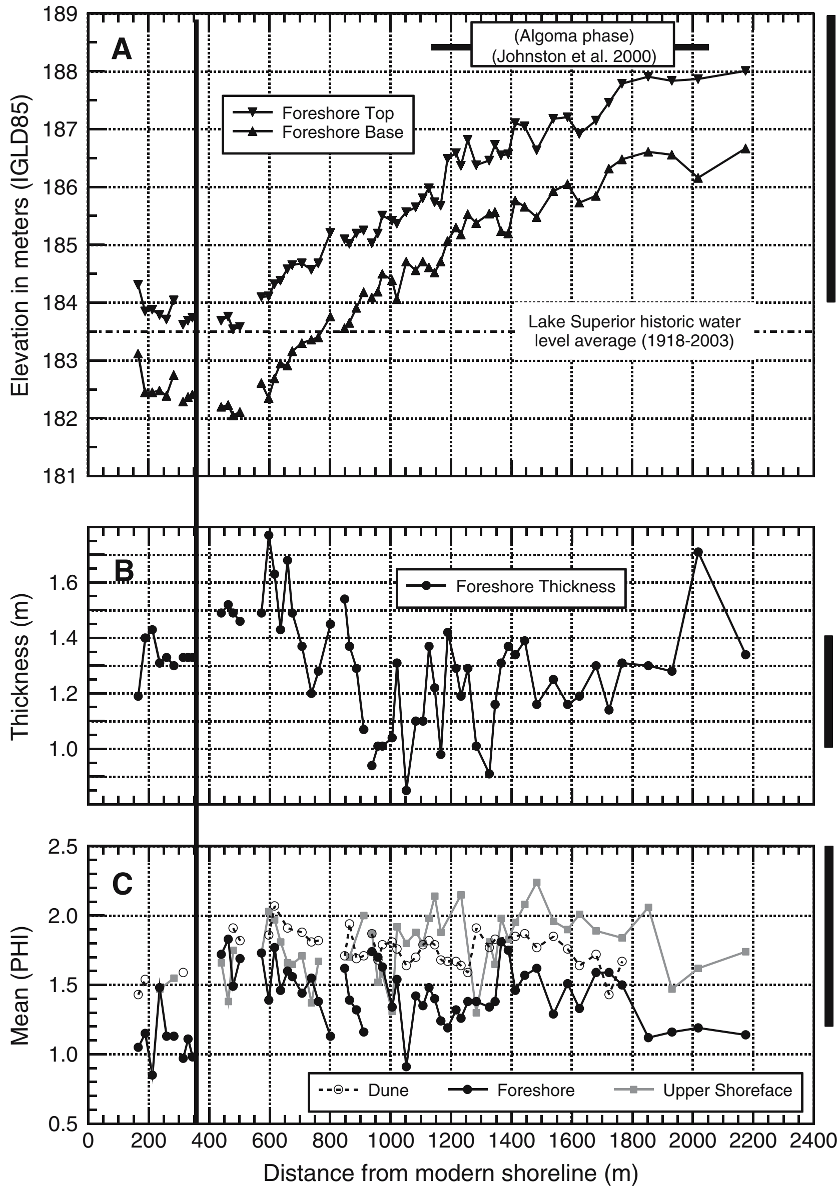

Fig. 7 Graphs of (**A**) facies contact elevations (**B**) foreshore thickness, and (**C**) mean grain size per facies from the Grand Traverse Bay strandplain in Michigan. Age model results from Johnston et al. (2000), indicating beach ridges created during the Algoma phase are shown by a line and labeled box. See Fig. 6 caption for further explanation

position between landward and lakeward sets is often associated with a bend in surface drainage patterns, a decrease in the number of channels, and a cross-strandplain change in topography. Cross-strandplain elevations of beach-ridge crest and swale surface elevations decrease towards the lake in the landward set (Figs. 6A–9A) but increase (Figs. 6A–8A) or reduce in slope (Fig. 9A) in the lakeward set.

Each study site is unique in its combination of characteristics that differ between landward and lakeward sets. In aerial photographs, drainage, vegetation, or crest and swale orientation changes are most noticeable between sets. At Au Train Bay, the sinuous Au Train River changes from many smaller channels flowing to the northeast in the landward set to a single larger channel flowing westward in the lakeward set (Fig. 2). At Grand Traverse Bay, there is a 1.4 km-long slough that parallels the modern Lake Superior shoreline (Fig. 3). At Tahquamenon Bay, ridge and swale orientations change from about 15 degrees from the modern shoreline (ESE-WNW) in the landward set to roughly parallel to the modern

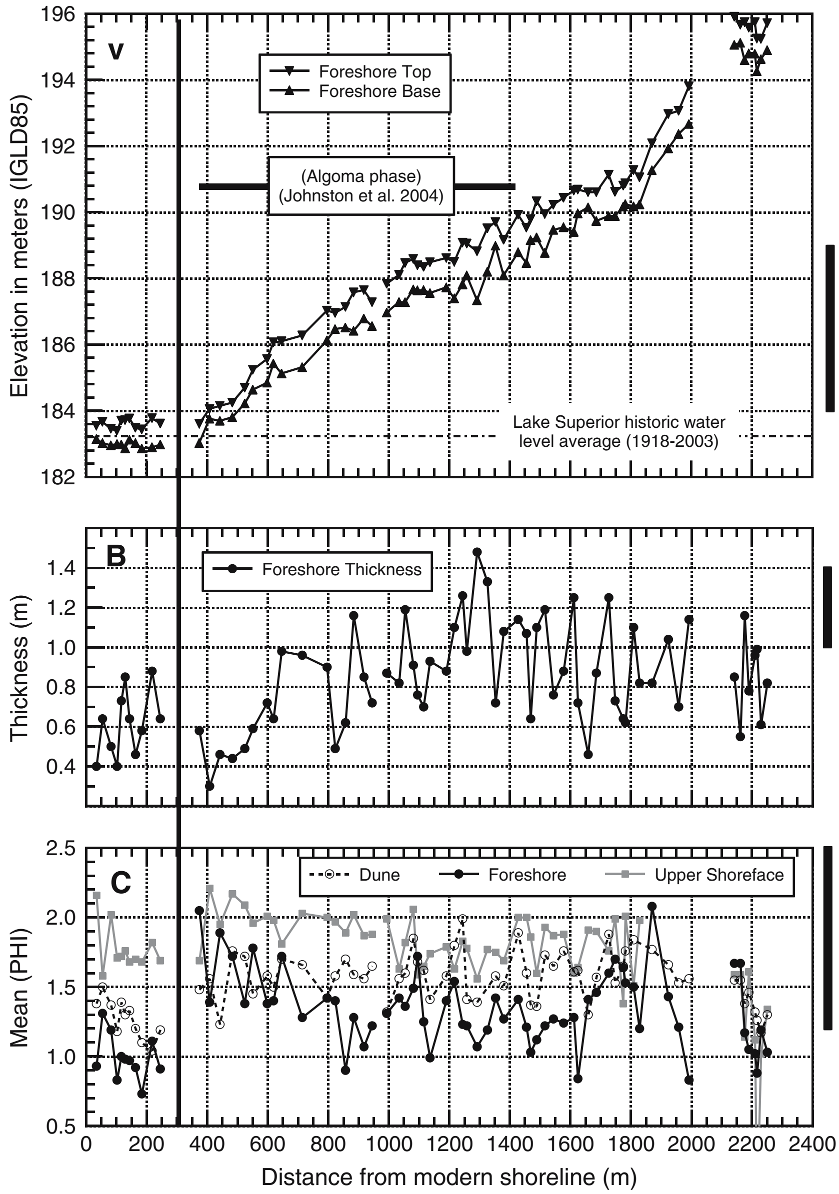

Fig. 8 Graphs of (**A**) facies contact elevations (**B**) foreshore thickness, and (**C**) mean grain size per facies from the Tahquamenon Bay strandplain in Michigan. Age model results from Johnston et al. (2004), indicating beach ridges created during the Algoma phase are shown by a line and labeled box. See Fig. 6 caption for further explanation

shoreline (E-W) in the lakeward set (Fig. 4). A vegetation change due to standing water occurs between sets at Batchawana Bay and is observed in aerial photographs (Fig. 5) and in the field. Drainage pattern variations are noted in topographic maps at all sites, but a change in topography between sets is commonly not observed because relatively large contour intervals (3–10 m) do not always intersect low relief beach ridges. A cross-strandplain elevation change between sets is observed at all sites in plots of topographic surveys of beach-ridge crest and swale elevations (i.e. reduction in slope at Batchawana Bay; Fig. 9A). Other topographic changes occur across the strandplains, but are not accompanied by subsurface changes (e.g. about 800 m at Au Train Bay; Fig. 6A).

Sedimentologic characteristics that differ between landward and lakeward sets at several sites include cross-strandplain variations in facies contact elevations, average foreshore sediment thicknesses, and facies mean grain sizes. Al-

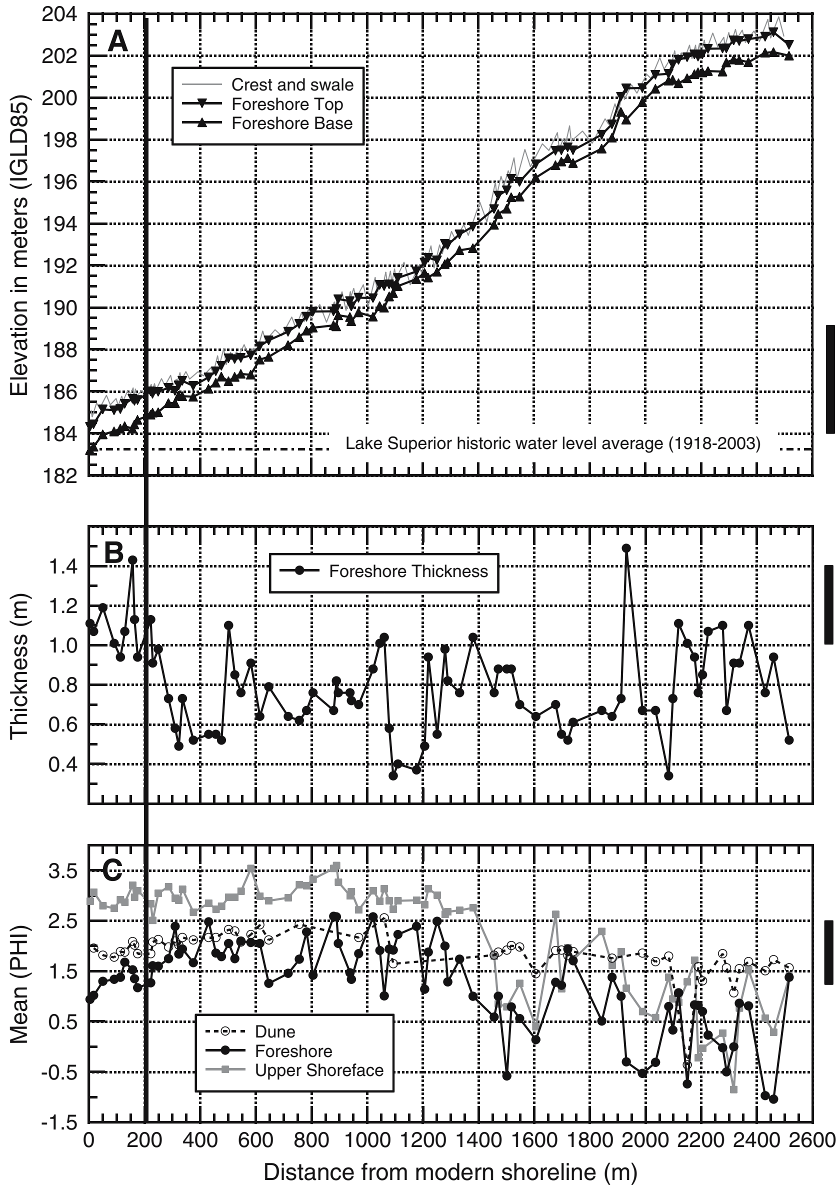

Fig. 9 Graphs of (**A**) crest, swale, and facies contact elevations, (**B**) foreshore thickness, and (**C**) mean grain size per facies from the Batchawana Bay strandplain in Ontario. See Fig. 6 caption for further explanation

though facies contact elevations do not strictly parallel each other or beach-ridge crest and swale elevations, they all follow a similar cross-strandplain trend of decreasing elevation towards the lake (Figs. 6A, 7A, 8A and 9A) in the landward set and increasing elevation towards the lake (Figs. 6–8) or decreasing elevation gradient (Fig. 9) in the lakeward set. Results from a two-sample *t*-test for comparing the average foreshore sediment thicknesses of the entire landward and lakeward sets indicate they are significantly different only at Tahquamenon Bay (Table 1). When data from an equal number of ridges on either side of the break are compared, the only statistically significant difference occurs at Grand Traverse Bay. A statistically significant grain-size coarsening from the landward-to-lakeward sets occurs for average dune, foreshore and upper shoreface facies at all sites when comparing equal number of ridges on either side of the break but only half of them are significantly different when considering the entire landward set (Table 1). A

Table 1 Geomorphic and sedimentologic characteristics of landward and lakeward sets of beaches in four strandplains studied along the Lake Superior coastline

Study site	Grand Traverse Bay		Tahquamenon Bay		Au Train Bay		Batchawana Bay	
Beach Set	Lakeward	Landward	Lakeward	Landward	Lakeward	Landward	Lakeward	Landward
Geomorphology								
Cross-standplain trend in topography (towards Lake Superior)	Rises	Lowers	Slight rise (~horizontal)	Lowers	Rises	Lowers	Lowers (shallower)	Lowers (steeper)
(Approx. elevation diff.)	(~1 m)	(~5 m)	(~1 m)	(~13 m)	(~2.5 m)	(~3 m)	(~1 m)	(~20 m)
Number of ridges	14	56	13	67	14	69	9	72
Distance in meters	350	1,825	300	2,026	370	1,402	200	2,316
Drainage characteristics between landward and lakeward sets	Deer Lake creek bends & width increases; Slough		Naomikong creek bends & width increases		Au Train river bends & width increases		Carp creek bends & width increases	
Estimated vegetation density	Lower	Higher	Lower	Higher	Lower	Higher	Lower	Higher
Ridge and Swale:								
(a) Lateral continuity	Continuous to discontinuous	More continuous	Continuous to discontinuous	More continuous	Continuous to discontinuous	More continuous	Continuous to discontinuous	More continuous
(b) Orientation	~(N-S)	~(N-S)	~(E-W)	~(ESE-WNW)	~(E-W)	~(E-W)	~(E-W)	~(E-W)
(c) Average relief	Lower	Higher	Lower	Higher	Lower (0.81 m)	Higher (1.12 m)	Lower (0.37 m)	Higher (0.61 m)
(d) Average width	Narrower (26 m)	Wider (33 m)	Narrower (26 m)	Wider (30 m)	Similar (20 m)	Similar (20 m)	Narrower (24 m)	Wider (32 m)
Swale character:								
(a) Standing water	No	Yes	No	Yes	No	Yes	No	Yes
(b) Peat present	No	Yes	Yes (one swale)	Yes	No	Yes	No	Yes
Sedimentology								
Cross-standplain trends (towards Lake Superior):								
(a) Foreshore top	Rises	Lowers	Rises	Lowers	Rises	Lowers	Lowers	Lowers
(b) Foreshore base	Rises	Lowers	Rises	Lowers	Rises	Lowers	Lowers	Lowers
(c) Average foreshore thickness in meters (std dev)	1.33 (0.07)[b]	1.29 (0.21) 1.53 (0.12)[b]	0.61 (0.17)[a]	0.86 (0.25)[a] 0.63 (0.21)	1.96 (0.55)	1.64 (0.45) 1.65 (0.38)	1.1 (0.15)	0.76 (0.21) 0.73 (0.23)
(d) Average *dune* facies grain size (std dev)	1.52 phi[a,b] (0.08)	1.77 phi[a] (0.12) 1.91 phi[b] (0.09)	1.27 phi[a,b] (0.14)	1.57 phi[a] (0.18) 1.56 phi[b] (0.15)	1.92 phi[a,b] (0.07)	2.00 phi[a] (0.14) 2.14 phi[b] (0.09)	1.91 phi[b] (0.10)	1.86 phi (0.46) 2.07 phi[b] (0.10)
(e) Average *foreshore* facies grain size (std dev)	1.09 phi[a,b] (0.18)	1.45 phi[a] (0.21) 1.61 phi[b] (0.15)	0.99 phi[a,b] (0.16)	1.35 phi[a] (0.28) 1.52 phi[b] (0.30)	1.85 phi[b] (0.08)	1.85 phi (0.18) 2.04 phi[b] (0.11)	1.30 phi[b] (0.23)	1.24 phi (0.92) 1.84 phi[b] (0.39)
(f) Average *upper shoreface* facies grain size (std dev)	1.51 phi[a,b] (0.05)	1.80 phi[a] (0.23) 1.73 phi[b] (0.18)	1.77 phi[b] (0.17)	1.75 phi (0.36) 1.98 phi[b] (0.14)	1.86 phi[b] (0.16)	1.78 phi (0.27) 2.08 phi[b] (0.24)	2.95 phi (0.15)	2.33 phi (0.94) 2.9 phi (0.21)
(g) Overall average grain size trend	Coarser	Finer	Coarser	Finer	Similar	Similar	Similar	Similar

[a] Significantly different—two-sample *t*-test (probability = 0.05) of all ridges in the lakeward and landward sets

[b] Significantly different—two-sample *t*-test (probability = 0.05) of all ridges in the lakeward set and an equal number of ridges in the landward set

more rigorous comparison is needed after age models are completed. Additional study of the data, beyond the scope of this paper, may reveal variability relating lake level, sediment, and wind and wave regimes through time.

Discussion

Cross-strandplain elevation change

The most recognizable feature common to all sites is a cross-strandplain elevation change in either beach-ridge crest elevations or facies contact elevations (Figs. 6A, 7A, 8A and 9A). Such a change in elevation can only be explained by a change in the relative elevation of the outlet that controls the water levels in the Lake Superior basin. A lakeward decrease in elevation of strandplain features indicates that a study site is isostatically rebounding faster than the outlet. Where sediment supply is sufficient to support shoreline progradation, lakeward increases in elevations indicate that the outlet is rising more rapidly than the site. If there are no elevation changes across the strandplain, the site is rebounding at the same rate as the outlet. The slope of the cross-strandplain trend provides an estimate of the differential rate of elevation change between the site and the active outlet. Sites with smaller slopes experience rates of rebound more similar to the outlet and vice versa. A spatial context of the pattern of glacial isostatic adjustment is shown in the contoured rates of glacial isostatic adjustment in the Great Lakes taken from historical gauge data (Mainville and Craymer 2005) (Fig. 1). Overall, glacial isostatic adjustment rates increase to the northeast across the Great Lakes. Although these rates may have differed during the late Holocene, the contoured pattern is similar in studies of historical and geologic records (c.f. Gilbert 1898; Clark and Persoage 1970; Walcott 1972; Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data 1977, 2001; Larsen 1994; Mainville and Craymer 2005).

Comparing trends in slope in the landward set of beach ridges and patterns of contoured rebound in the upper Great Lakes suggests that the controlling outlet when landward strandplain features were decreasing in elevation was either the Port Huron/Sarnia or the Chicago outlet. Both outlets occur south of the study sites and underwent less rebound than the sites to the north. Age models created for Grand Traverse Bay (Johnston et al. 2000) and Tahquamenon Bay (Johnston et al. 2004) specify that part of the trend in decreasing elevations at each site (Figs. 7 and 8) was during the Algoma phase. Algoma phase shorelines were identified and correlated between the Superior, Huron, and Michigan basins as early as 1915 by Leverett and Taylor, suggesting that the Algoma level was common to all three basins and that the active outlet was at Port Huron/Sarnia. Our general trend in the landward sets supports the interpretation that the active outlet was at Port Huron/Sarnia when the landward beach ridges and swales were formed. Glacial isostatic adjustment rates need to be calculated for each site, after age models are established, to verify the active outlet during the Algoma phase.

The lakeward sets at the four sites show two different long-term trends that can be used to identify the active outlet during their development. The lakeward increase in elevation at Au Train Bay (Fig. 6A), Grand Traverse Bay (Fig. 7A), and Tahquamenon Bay (Fig. 8A) indicates that the controlling outlet is rebounding faster than the study sites; the lakeward decrease at Batchawana Bay (Fig. 9A) indicates that the study site is rebounding faster than the controlling outlet. Therefore, the active outlet must be between the Batchawana and other sites (Figs. 6A, 7A and 8A, Mainville and Craymer 2005). Contoured patterns of historical isostatic rebound through the sites (Fig. 1) indicate that the Sault outlet was the active outlet when beach-ridges formed in the lakeward set at study sites.

Comparison of surface versus subsurface elevations

A change in beach-ridge crest and swale surface elevations can be used to locate the separation in the strandplain sequences and interpret the cause of changes in the cross-strandplain elevation trend (Larsen 1994). However, deposits directly above the basal foreshore contact accumulate near lake level, and the elevation of the contact directly identifies the elevation of the lake. This relationship was established on the modern shoreline of Lake Michigan (Fox et al. 1966; Fraser et al. 1991; Thompson 1992) and Lake Superior (Johnston et al. 2000, 2004). Because lake level is the only beach-ridge-forming factor that is common between strandplains in the same basin (Thompson and Baedke 1995, Johnston et al., in press), basal paleo-foreshore elevations for time-equivalent beach ridges at distant strandplains should be the same if glacial isostatic adjustment has not warped the basin (cf. Baedke and Thompson 2000). The approach of using beach-ridge crest elevation to reconstruct past lake level is not as reliable an indicator of lake-level change as foreshore elevation, because that approach measures the elevation of the dune cap on top of the beach-ridge core. Sediment within the dune cap is deposited after the core of the beach ridge formed. Because aeolian transport processes are not dependent on lake level, the thickness of dune sediment does not have a direct relationship to water-level elevation. It may be instead the result of an aeolian supply or process change (i.e. related to changes in the predominant wind direction). Increased variability in crest elevations and overestimation of lake-level elevations (by as much as 5.2 m at Au Train Bay (Fig. 6A) and 2.3 m at Batchawana Bay (Fig. 9A)) would alter water-level and rebound interpretations. Thus, basal foreshore contact elevations more accurately determine the location of a break within a strandplain sequence and provide a more accurate estimate of past lake-level elevations.

Interpretation of lakeward and landward sets

Interpretation and differentiation of the lakeward set is much more difficult than that of the landward set because the lakeward set has less than 15 ridges and the landward set commonly has more than 50 ridges. This is especially critical for Batchawana Bay that rebounded more rapidly than the outlet during the time of production of both sets. Here, a change in basal foreshore elevations is not always as apparent as with other sites where the slopes reverse. Basal foreshore elevation trends seem similar in both beach-ridge sets (Fig. 9A). However, the short preserved record in the lakeward set may not be representative of a long-term trend during continuous glacial isostatic adjustment. In fact it may reflect falling water-levels, as depicted in Fig. 4C of Baedke and Thompson (2000). Longer records (i.e. landward set) should provide a more accurate estimation of glacial isostatic adjustment and help decipher from lake-level fluctuations. Comparison of lakeward sets between sites should also help resolve this issue because each site should record the same lake-level pattern but different glacial isostatic adjustment. Other characteristics, such as foreshore thickness (Fig. 9B) and grain size (Fig. 9C), are needed to help recognize the strandplain break for sites north of the zero isobase through the active outlet where changes in strandplain slopes do not reverse and are subtle.

Age of lake separation

The first age estimation for the separation of Lake Superior from Lake Michigan and Huron was by Farrand (1962). He calculated an age by intersecting an exponential uplift curve for the Sault outlet with a linear curve representing downcutting at the Port Huron/Sarnia outlet on an age-versus-elevation plot. His age estimate was 2,200 calendar years ago, after the Algoma high water-level phase. Larsen (1994), working on a strandplain on the Whitefish Point promontory along the southern shore of Lake Superior in Michigan, reported a similar timing of separation at 2,100 calendar years ago. Larsen (1994) recognized this important time by a topographic change in beach-ridge crest heights from decreasing crest elevations followed by reaches with little elevation change toward Lake Superior. Larsen's (1994) age model consisted of a linear extrapolation between the mean of seven Nipissing ages to the present. This upper limit of scattered, calibrated radiocarbon ages is suggested to represent a minimum age for beach-ridge formation.

Radiocarbon (Johnston et al. 2004) and SAR-OSL (Argyilan et al. 2005) age model determinations for the Tahquamenon Bay strandplain appear to both suggest an age of separation similar to those reported by Farrand

(1962) and Larsen (1994). However, Johnston et al. (2004) reported that the separation of the lakes occurred later than 2,400 calendar years ago because a time gap may exist between lakeward and landward sets. An abrupt grain-size change in cores of the strandplain sequence at Tahquamenon Bay and beach-ridge crest reorientation and isolation in the northeastern part of the embayment supports this claim. The one swale that could be radiocarbon-dated in the lakeward set at Tahquamenon Bay was insufficient to create an age model. Although four SAR-OSL ages were collected in the lakeward set at Tahquamenon Bay, two anomalously high ages that diverged from the overall trend, close to the age of the lakes separation, creates uncertainty in age model formulation. This needs to be investigated further.

Data collected by Johnston et al. (2000) from a strandplain at Grand Traverse Bay, Michigan indicated that the separation of the lakes occurred closer to 1,200 calendar years ago, about 1,000 years later than proposed by Farrand (1962) and Larsen (1994). Johnston et al.'s (2000) age model was different from Larsen's (1994). He calculated a regression line through calibrated radiocarbon ages and did not fix the ends of the age model. Retaining the slope of the regression line and moving it to encompass the youngest ages, following Larsen's (1994) age model approach, would suggest an older age at Grand Traverse Bay closer to Farrand's (1962) and Larsen's (1994) for the separation of the lakes. However, the younger age of lake separation, closer to 1,200 years, is supported by regressing single-aliquot-regeneration, optically stimulated luminescence (SAR-OSL) ages of sand grains within beach ridges at Grand Traverse Bay (Argyilan et al. 2005). Calculated SAR-OSL ages in beach ridges are expected to better approximate the age of beach-ridge formation than radiocarbon dating organics in swales because they are from the feature studied and not an associated deposit. Several radiocarbon dates of similar age on either side of the break at Grand Traverse Bay indicate many swales began accumulating organics around a similar time in response to flooding of the swales with a relative lake-level rise after the separation of the lakes. However, it is uncertain why the radiocarbon ages are older than the SAR-OSL ages in the lakeward set. Differing results between age model methods and material types at Grand Traverse Bay need to be investigated further.

Refining the timing of the separation of the lakes has been partially limited because of scattered ages and a lack of continuous data sets (missing ridges in strandplain sequences) that cross this important time period. Strandplains of beach ridges in the Great Lakes are often interpreted as continuous, prograding sequences, but breaks need to be identified and investigated in both the age and glacial isostatic adjustment models to produce the best results. Creating models that cross breaks in the sequence ignores the possibility of a missing record and may alter interpretations. Larsen (1994) and Johnston et al. (2000, 2004) created age models that cross this important break associated with the lake's separation but accounted for it only in their glacial isostatic adjustment models. Although few ages exist in the lakeward set, age models need to be formulated. It appears from Larsen's (1994) ages collected in the Whitefish Point strandplain sequence that there may be missing beach ridges between about 2,000 and 1,000 years ago, around the time of the lake's separation. The possibility of missing beach ridges in this area and in other parts of the strandplain sequence (i.e. youngest part) needs to be investigated. One would expect missing beach ridges in the lakeward set because ample sediment is needed to create and preserve beach ridges during a long-term relative lake-level rise after the separation of the lakes. Larsen (1994) assumed continuous progradation up to the present in the Whitefish Point strandplain sequence whereas Johnston et al. (2000, 2004) estimated about 900 years and 2,000 years of missing record at Grand Traverse Bay and Tahquamenon Bay, respectively. Johnston et al. (2004) identified an erosional scarp on the modern beach at Tahquamenon Bay that may be related to missing ridges in the youngest part of the strandplain.

The time of lake separation warrants further investigation on the basis of similar irregularities to those at Tahquamenon Bay in other strandplains in other lake basins. Thompson and

Baedke (1997) and Argyilan et al. (2005) addressed missing ridges within the Manistique strandplain on the northern shore of Lake Michigan in their age models. They recognized missing ridges in the strandplain sequence for both times presented in this paper for the separation of the lakes. An inflection was identified in cross-strandplain topographic (Larsen 1994) and basal foreshore (Thompson 1992; Thompson and Baedke 1997) elevations in the Toleston Beach strandplain in southern Lake Michigan. In the youngest part of the strandplain, the calculated rates of glacial isostatic adjustment in the rising trend in basal foreshore elevations towards the lake compare to historical patterns and rates of glacial isostatic adjustment relative to the Port Huron/Sarnia outlet (Baedke and Thompson 2000). Prior to this time period, decreasing elevations towards the lake have been explained by erosion at the Port Huron/Sarnia outlet (Larsen 1994) or related to a peripheral bulge near southern Lake Michigan (Tushingham 1992). Thompson's (1992) and Thompson and Baedke's (1997) age models suggest the inflection occurred between 1,000 years and 1,500 years ago, after an unnamed phase (Baedke and Thompson 2000) of Lake Michigan. This seems to correspond to results from Grand Traverse Bay, implying a younger age for the separation of the lakes. However, Larsen's (1994) interpretation of the ages from the Toleston Beach strandplain suggest an age around 2,100 years ago, corresponding to Farrand's (1962) prediction where the lakes separated after the Algoma high water-level phase. Additional data sets from Lake Michigan and Lake Huron strandplains need to be investigated to evaluate the impact of the separation of Lake Superior from Lake Michigan and Huron on downstream strandplains. Also, existing strandplain data records need to be revisited to re-evaluate the timing of the separation of the lakes and the possibility of a younger age. Geomorphic and sedimentologic properties also need to be examined around this time period, especially at sites north of the zero isobase through the Lake Superior outlet where changes in basal foreshore elevation trends may not be apparent. This shortfall may inappropriately alter outlet, glacial isostatic adjustment, or water-level results and interpretations.

Summary and conclusions

Late Holocene beach deposits show distinctive changes in geomorphic and sedimentologic trends across strandplains in the Superior basin. Significant changes in elevation are detected in the cross-strandplain profiles of foreshore deposits, and with lesser accuracy and more variability in topographic profiles of the dune cap on beach ridges. Basal foreshore elevations in postglacial shorelines provide best estimates of the elevation of past lake levels.

Cross-strandplain elevations clearly group beaches into lakeward and landward sets. At all sites, landward sets slope downward toward the lake, as do lakeward sets north of the isobase of glacial isostatic adjustment through the lake outlet, but with lesser slope. South of the isobase, lakeward sets slope upward toward the lake with greater slopes at sites farther from the outlet isobase.

Analysis of lake-gauge crustal tilting data shows that the landward beach-ridge sets formed in a large water body confluent throughout the Superior, Michigan and Huron basins which was regulated by overflow mainly at the Port Huron-Sarnia outlet. The lakeward beach-ridge sets and their cross-strandplain attributes all relate to the advent of Lake Superior and its water-level regulated by an emergent bedrock sill at Sault Ste. Marie. This change in outlet for Lake Superior transformed strandplain formation by changing the relationship between the outlet raising the water plane and the rising ground surface at individual study sites.

Lake Superior separated from lakes Michigan/Huron sometime after about 2,400 years ago, after the Algoma high water-level phase. However, data from one strandplain in Lake Superior (Grand Traverse Bay) and one in Lake Michigan (Toleston Beach) may suggest an age about 1,000 years later, after an unnamed high water-level phase (Baedke and Thompson 2000) of Lake Michigan. Age models need to be formulated at Au Train Bay and Batchawana Bay.

Differing age models such as a line through the data (Thompson 1992; Thompson and Baedke's 1997) or the maximum edge of data points (Larsen 1994); different types of age dating methods (radiocarbon, SAR-OSL); and the effects of possible missing ridges in strandplain sequences need to be examined further.

More accurate identification of breaks in strandplain sequences, comparison of common breaks at many sites, and use of elevations that are directly related to lake level lead to better estimations of active outlets, past long-term lake level, and glacial isostatic adjustment. Multiple characteristics, using the geomorphic and sedimentologic approach, can be used to identify or refine the location of surface and subsurface breaks within strandplain sequences. Comparison of data from many sites helps identify common breaks in the strandplain sequences.

Few studies have been conducted south of the zero isobase relative to the active outlet because shorelines normally coalesce, erode, or are submerged during long-term relative rises in water levels. Embayments are advantageous locations for study south of the zero isobase because of ample sediment supply and accommodation space that help preserve relict shorelines. Continuous records in the range of many decades to millennia can be created and preserved in these embayments. It is sometimes easier to recognize past outlet changes at these sites because an obvious inflection in cross-strandplain beach-ridge crest and basal foreshore elevations is created. Other characteristics associated with the elevation inflections, such as grain-size changes and foreshore deposit thicknesses are used to help interpret data from sites north of the zero isobase where elevation changes are less apparent. Detailed shoreline research should focus not only on sites north of the zero isobase where glacial isostatic adjustment rates are advantageous for preservation but also in embayments south of the zero isobase where sediment accumulation and accommodation space support beach preservation.

Present outlet conditions and glacial isostatic adjustment patterns across the Lake Superior basin suggest that the Sault outlet will likely continue to rebound faster than three of the study sites (Tahquamenon Bay, Grand Traverse Bay and Au Train Bay) in the future. This will cause long-term relative lake-level to rise at each of these sites and cause erosion problems if ample sediment is restricted or not supplied to the shoreline for continued beach-ridge formation and strandplain progradation (or buffering). The presence of an erosional scarp on the modern beach at Tahquamenon Bay seems to correspond to a relative long-term lake-level rise south of the isobase through the current Lake Superior outlet. It is a reminder of the hazard of shore erosion if beach sediment-supply declines or is interrupted in the future.

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