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Late Holocene Lake-level Variation in Southeastern Lake Superior: Tahquamenon Bay, Michigan

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ABSTRACT. *Internal architecture and ages of 71 beach ridges in the Tahquamenon Bay embayment along the southeastern shore of Lake Superior on the Upper Peninsula of Michigan were studied to generate a late Holocene relative lake-level curve. Establishing a long-term framework is important to examine the context of historic events and help predict potential future changes critical for effective water resource management. Ridges in the embayment formed between about 4,200 and 2,100 calendar years before 1950 (cal. yrs. B.P.) and were created and preserved every 28 ± 4.8 years on average. Groups of three to six beach ridges coupled with inflections in the lake-level curve indicate a history of lake levels fluctuations and outlet changes. A rapid lake-level drop (approximately 4 m) from about 4,100 to 3,800 cal. yrs. B.P. was associated with a fall from the Nipissing II high-water-level phase. A change from a gradual fall to a slight rise was associated with an outlet change from Port Huron, Michigan/Sarnia, Ontario to Sault Ste. Marie, Michigan/Ontario. A complete outlet change occurred after the Algoma high-water-level phase (ca. 2,400 cal. yrs. B.P.). Preliminary rates of vertical ground movement calculated from the strandplain are much greater than rates calculated from historical and geologic data. High rates of vertical ground movement could have caused tectonism in the Whitefish Bay area, modifying the strandplain during the past 2,400 years. A tectonic event at or near the Sault outlet also may have been a factor in the outlet change from Port Huron/Sarnia to Sault Ste. Marie.*

INDEX WORDS: *Lake Superior, lake level, beach ridge, late Holocene, Tahquamenon.*

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INTRODUCTION

Lake Superior is the largest by volume of the Great Lakes of North America; by area, it is the largest freshwater lake in the world and is a part of the largest fresh surface-water system in the world (Cohen 1998). It provides water for consumption, transportation, power, and recreation and borders two nations, Canada and the United States. Documenting the magnitude and frequency of past Great Lakes water-level fluctuations is critical to optimize water resource management, to help understand past climate change, and to predict potential future changes in lake levels. Although lake-level gauges provide short-term records of water-level fluctuations for the past 150 years, it is difficult to establish the importance of these fluctuations without a framework of long-term fluctuations. Records of lake-level fluctuations spanning the last several millennia can be extracted from the sedimentary deposits preserved in ancient shorelines.

Researchers have studied late Holocene shoreline features preserved along the coastline of Lake Superior for more than a century (Lawson 1893), but no one has developed a detailed continuous chronology of events that can be used to establish the physical limits and timing of paleo lake-level fluctuations. Most previous research focused on three different water-level phases of ancestral Lake Superior: Nipissing, Algoma, and Sault. These high-water phases are best preserved in shoreline features found along the northern part of the Lake Superior basin where relatively large isostatic rebound rates have elevated the features far above lake level and separated different lake-phase features. Stanley (1932) documented these phases on the eastern side of Lake Superior, Farrand (1960) on the northern and western side of Lake Superior, and Cowan (1978, 1985) near the outlet for Lake Superior in the Sault Ste. Marie area. These studies infer past lake levels from geomorphic evidence, but lack detail between major lake phases. Work by Larsen (1994) at Whitefish Point, Michigan, partially adopted the sedimentological approach of Thompson (1992) to interpret lake level from a chronosequence of beach ridges, but Larsen focused his studies on isostatic rebound and used an age model different from that used here. Further work by Larsen (1999a, b, c) and Larsen *et al.* (1999) filled in parts of the late Holocene water-level record by constraining the timing and elevation of past lake-level low-stands and attempting to determine the time when the outlet at Sault Ste. Marie began regulating water levels in the Lake Superior basin. Despite these recent efforts and studies by Johnston *et al.* (2000a, b; 2001a, b; 2002a, b) and Thompson *et al.* (2002), more sedimentological studies are needed to accurately define long-term patterns of lake- level variability (e.g., Baedke and Thompson 2000).

This paper summarizes a study of beach ridges in the Tahquamenon Bay embayment along the southeastern coast of Lake Superior in the Upper Peninsula of Michigan updating and expanding upon previous work by Johnston *et al.* (2001a). We chose this site because it contains many well-defined ridges separated by well-developed wetlands and is easily accessible. Tahquamenon Bay is important because it is located near the outlet of Lake Superior and may have experienced a similar rate of vertical ground movement (isostatic uplift) as the outlet. Data from this site will help define past vertical ground movement, lake-level fluctuations, and outlet constraints crucial to interpreting the lake's history.

Our purpose is to produce a relative lake-level curve for the embayment. We used methods that were consistent with those outlined by Thompson *et al.* (1991) and Thompson (1992), where researchers used foreshore elevations to approximate the elevation of the lake at the time each beach ridge formed; they also used radiocarbon dates to develop an age model to approximate the age of each beach ridge. Similar data sets from around the lake are useful in removing vertical ground movement from each site's relative curve to produce a combined high-resolution curve for the entire lake (cf. Baedke and Thompson 2000). The resulting record helps to determine the physical limits and timing of lake-level variation, long-term patterns of shoreline behavior, vertical ground movement, and paleoclimate change over the past several thousand years. We believe this study will provide a geologic framework for other research in the Lake Superior basin, including ongoing ecological (e.g., Keough *et al.* 1999, Kowalski and Wilcox 1999), geomorphological (e.g., Loope and Arbogast 2000, Arbogast *et al.* 2002), paleoecological (e.g., Booth *et al.* 2002, Jackson and Booth 2002), pedological (e.g., Barrett 2001), regulatory (e.g., International Joint Commission 2002), and sedimentological (e.g., Fuks and Wilkinson 1998, Nichols 2002) studies.

STUDY SITE

The study area is located in northwest Chippewa County, Michigan, between 46°27′30″ and

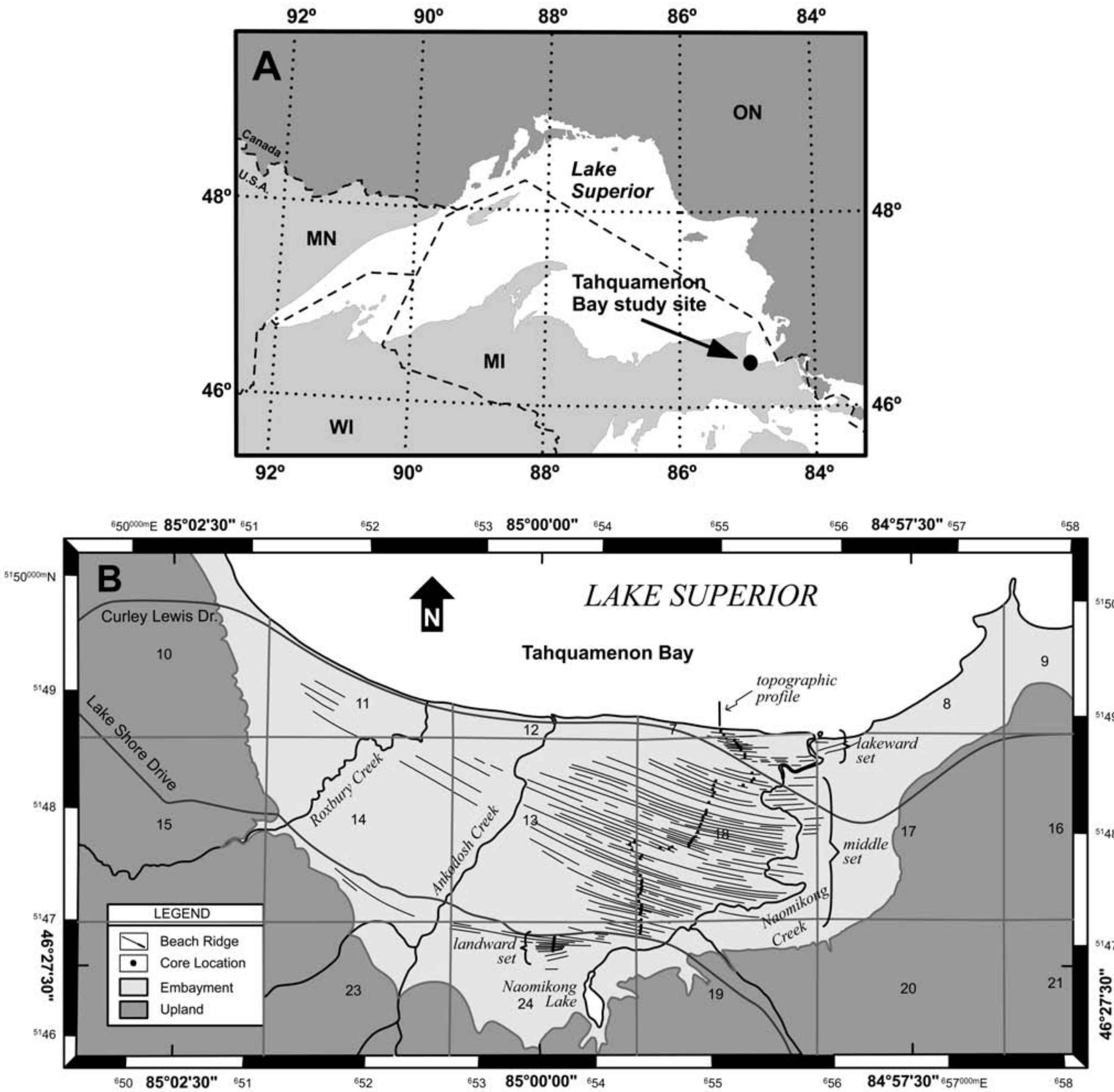

FIG. 1. Map showing the Tahquamenon Bay study area. (A) Map of Lake Superior showing the location of Tahquamenon Bay. (B) Map of the Tahquamenon Bay embayment. The lakeward side of 71 beach ridges were cored to determine the elevation of the lake when each beach ridge formed. Lines indicate beach-ridge crests and dots indicate core locations.

46°29′30″. north latitude and 84°57′30″ and 85°02′30″ west longitude (Fig. 1A). It is approximately 35 km south of Whitefish Point, Michigan, 42 km northeast of Newberry, Michigan, and 50 km west of the outlet for Lake Superior at Sault Ste. Marie, Michigan. This northward-opening embayment extends approximately 6 km east-west and 2.5 km north-south (Fig. 1B). The limit of the embayment is marked by an elevated bedrock headland to the east and an elevated bedrock and/or till surface to the south and west. The approximate edge of the embayment follows a 198.1-m (650-ft) elevation contour on the U.S. Geological Survey McNearny Lake and Piatt Lake quadrangles and is about 14.6 m above the average elevation of Lake Superior (183.5 m, 602 ft). A bluff 10- to 15-m-high forms the southeastern and eastern margin of the embayment, and a 6-m bluff forms the western margin. The southwestern margin of the basin extends approximately 1 km further inland than the adjacent margins and forms an elevated platform that slopes to the northeast into the embayment.

Several nearshore bars, paralleling the modern coastline, are on a platform that extends 300 m offshore and lies under less than 2 m of water. Further offshore, the embayment is a part of a larger platform (< 9 m deep) that extends lakeward to a line near Paradise, Michigan, to Salt Point, Michigan. This platform opens up into Whitefish Bay (< 90 m deep). The Tahquamenon River flows into Lake Superior about 9 km north of the Tahquamenon Bay embayment, and a submerged spit at the mouth of the river extends southward to about 3 km north of the study site. The southward-projecting spit suggests that the Tahquamenon River is a source of sediment to the embayment and distributes it southward. The extension of a sand spit at the mouth of Naomikong Creek, which drains the embayment as observed in the 1975 USGS Emerson quadrangle and 1997 Michigan Department of Natural Resources (MDNR) air photographs (scale 1:15,840), indicates that littoral transport is currently toward the east along the coast in the study area.

The Tahquamenon Bay embayment contains approximately 80 beach ridges separated by wetland-filled swales. The most well-defined ridges are in the eastern part of the embayment (Fig. 1B). Dense vegetation in the most landward part of the strandplain limits access and makes it difficult to define ridges and swales from air photos. The 13 ridges adjacent to Lake Superior are oriented east-west, as is the modern shoreline (Fig. 1B). The relief between ridge crests and adjacent swales is less than 1 m, and most of the swales between ridges are dry or contain discontinuous wetlands. In the middle of the strandplain ridge-crest orientations are 15° from the modern shoreline and follow a ESE to WNW direction (Fig. 1B). These ridges generally have greater relief than the lakeward ridges, with an average of about 3 m. Most of the swales in this group are continuous across the central part of the embayment. Ridge-crest orientations of the ten most landward ridges vary from east-west to WSW-ENE (Fig. 1B). These ridges are on an elevated platform and have less than 1 m of relief. Swales in this last set commonly are ponded and contain little organic matter; standing water in some of these swales may be related to nearby beaver dams in Naomikong Creek.

Groups of three to six ridges separated by wider than average wetlands are evident in air photographs and in changes in relief. These groups are defined by a systematic rise and fall in elevation between wider-than-average wetlands, and they are less common in the most lakeward and landward ridges.

METHODS

During the summer of 1999, we collected 71 cores vibracored through 80 beach ridges along four transects roughly perpendicular to the modern shoreline (Fig. 1B) using a land-based vibracorer (Thompson *et al.* 1991). The lakeward sides of all accessible beach ridges were cored to minimize the amount of recovered dune sand and to ensure that penetration was deep enough to recover basal foreshore sediments. We cored several of the vibracore holes twice to penetrate clay beneath the nearshore sequence. The clay acted as a plug in the end of the aluminum tubes and prevented loss of the basal sediments. Most cores contained the entire vertical nearshore sequence. We recorded core orientations before cores were removed from the ground so the orientation of the sedimentary structures were maintained. Core elevations were surveyed and calibrated to the International Great Lakes Datum 1985 (IGLD85) (Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data 1995) using the National Oceanic and Atmospheric Administration (NOAA) Point Iroquois, Michigan, gauging station. Core sites were located using differentially corrected Global Positioning System (GPS) and 1997 MDNR air photographs (scale 1:15,840). Using a stereo zoom transfer scope, we then transferred beach-ridge crests and core locations to the USGS McNearney Lake and Piatt Lake 7½ minute quadrangles to determine distance landward from the modern shoreline to each beach ridge.

We surveyed an onshore/offshore-oriented profile 250 m in length across the modern shoreline, and retrieved sediment samples from each recorded elevation (Fig. 1B). The profile extended from the top of the first dune ridge landward from the modern shoreline, into the lake, and across two nearshore bars and two troughs. Theses data allowed us to observe modern sediment and bedform distributions that should be reflected vertically in beach-ridges cores as changes in grain size and sedimentary structures.

In the laboratory, vibracores were split in half, described, sampled, photographed, and glued to strips of masonite using Rub-R-Mold™ latex. The latex strips enhance the visibility of sedimentary structures and create a permanent physical record of the core. We sieved 1,300 grain-size samples using 1/2-phi intervals, and calculated statistical parameters (mean, standard deviation, and skewness) for each sample by the mathematical method of moments. The coarsest one-percentile (C1%) was determined from cumulative grain-size distributions. Statistical parameters were plotted per core to identify grain-size variations with depth. We compared visual descriptions, grain-size data, photographs, and latex strips to distinguish nearshore and onshore facies, specifically the upper and lower contacts of foreshore deposits.

To constrain the ages of the ridges, we used a combination of conventional and accelerator mass spectroscopy (AMS) to radiocarbon-date the basal wetland sediments (Table 1). Samples consisted of peat collected from the deepest point in the swales along the same transects as the beach-ridge cores. We collected samples for AMS radiocarbon dating using a wide-diameter (10.2 cm) piston corer (Wright *et al.* 1984) and for conventional dating by hand-augering 7.5-cm-diameter aluminum tubes through the peat profile. We sampled only wetlands that were laterally continuous, which contained at least 0.5 to 1.0 m of peat; about a third of the wetlands were cored. A single sample was collected from the lakeward set of swales and none from the landward set as those areas lacked a suitable thickness of peat. For conventional radiocarbon dating, we removed one basal peat sample, approximately 3 cm thick, from each core. For AMS radiocarbon dating, terrestrial plant macrofossils (needles, seeds) or macroscopic charcoal fragments spanning the lowest 1 cm of peat were used. Geochron Laboratories (Cambridge, Massachusetts) performed conventional radiocarbon dating of bulk sediment. AMS dating of macrofossils and macroscopic charcoal fragments was prepared at the Institute of Arctic and Alpine Research (INSTAAR) (Boulder, Colorado) and analyzed at the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) (Woods Hole, Massachusetts). All radiocarbon dates were adjusted for variations in atmospheric ^{14}C through time and we calibrated them to calendar years before 1950 using the University of Washington's Quaternary Isotope Lab Radiocarbon Calibration Program, CALIB version 4.3 (Stuiver and Reimer 1993, Stuiver *et al.* 1998) (Table 1).

RESULTS AND DISCUSSION

Facies Model

Horizontal trends in sediment facies across the modern shoreline compare well with vertical trends in beach-ridge cores and help to interpret the ancient record preserved in beach ridges. Grain size and sedimentary structures define three different facies (dune, foreshore, and upper shoreface) in both modern and ancient sediments. Dune, foreshore, and upper shoreface sediments all show certain characteristics that distinguish them from each other in both the modern and ancient sediments. The contact between the foreshore and upper shoreface is of great importance because it best approximates the average elevation of the lake (Thompson 1992). We describe modern and ancient characteristics in two separate sections to avoid confusion.

Modern Facies

The modern topographic shore profile comprises three different sedimentary and geomorphic parts: 1) the dune in the onshore zone and in the nearshore zone, 2) the foreshore, and 3) the upper shoreface. The foreshore extends from where waves break to the maximum run up on the beach face. The dune (also called the foredune) extends landward from the foreshore, and the upper shoreface extends lakeward from the foreshore. The plunge point occurs at the still water line and is at the contact between the foreshore and upper shoreface.

Elevations decrease lakeward, with the largest fall occurring in the landward part of the profile between the foredune and the water line (plunge point). The profile in this area decreases about 1.2 m over 10 m and contains several scarps. No bedforms were present, and the foreshore had no well-defined cusps. From the plunge point lakeward, the profile decreases another 0.6 m across a 35-m-wide sand bar and into a trough in the upper shoreface. From there lakeward, the profile is relatively flat and varies only about 0.2 m over a second nearshore bar and trough. The surface of the upper shoreface was rippled along the entire profile at the time of the survey.

Most samples along the profile are medium-

TABLE 1. Radiocarbon dates collected from the base of swales between beach ridges in the Tahquamenon Bay embayment.

Ridge number [a]	Distance landward (m)[b]	Material dated	Lab number c	Date reported	^{14}C yr B.P. d	Calibrate yr B.P. d
14	374.0	Peat	GX-25952	9/30/1999	2,470 ± 80	2,644
15	408.0	Peat	GX-25953	9/30/1999	2,000 ± 120	1,936
16	442.0	Peat	GX-25954	9/30/1999	2,450 ± 70	2,481
17	482.8	Peat	GX-25955	9/30/1999	2,640 ± 120	2,753
18	523.6	Peat	GX-25956	9/30/1999	2,810 ± 70	2,908
23	714.0	Peat	GX-25957	9/30/1999	2,890 ± 120	2,996
24	795.6	Peat	GX-25958	9/30/1999	3,110 ± 80	3,350
29	945.2	Peat	GX-25959	9/30/1999	2,950 ± 80	3,128
37	1,135.6	Peat	GX-25960	9/30/1999	2,770 ± 120	2,853
38	1,190.0	Peat	GX-25961	9/30/1999	3,160 ± 130	3,378
40	1,244.4	Peat	GX-25962	9/30/1999	2,990 ± 130	3,184
41	1,258.0	Peat	GX-25963	9/30/1999	3,170 ± 80	3,381
45	1,380.4	Peat	GX-25964	9/30/1999	3,090 ± 80	3,279
46	1,428.0	Peat	GX-25965	9/30/1999	2,880 ± 80	2,979
48	1,468.8	Peat	GX-25966	9/30/1999	3,730 ± 80	4,088
51	1,543.6	Peat	GX-25967	9/30/1999	2,840 ± 100	2,949
52	1,577.6	Peat	GX-25968	9/30/1999	3,160 ± 130	3,378
54	1,625.2	Peat	GX-25969	9/30/1999	3,230 ± 130	3,465
55	1,659.2	Peat	GX-25970	9/30/1999	3,090 ± 60	3,279
56	1,686.4	Peat	GX-25971	9/30/1999	3,320 ± 130	3,564
59	1,774.8	Peat	GX-25972	9/30/1999	2,890 ± 80	2,996
61	1,808.8	Peat	GX-25973	9/30/1999	3,530 ± 100	3,786
8	163.2	*Betula* sp. (seeds), *Larix laricina* (needles) and *Pinus strobus* (needles)	NSRL-11678	31/10/2000	1,580 ± 35	1,493
17	482.8	*Larix laricina* (needles) and *Pinus strobus* (needles)	NSRL-11556	16/10/2000	2,180 ± 35	2,273
23	714.0	*Larix laricina* (needles)	NSRL-11557	16/10/2000	3,110 ± 35	3,350
37	1,135.6	*Larix laricina* (needles) and *Pinus strobus* (needles)	NSRL-11558	16/10/2000	2,570 ± 50	2,740
42	1,292.0	*Larix laricina* (needles) and *Pinus strobus* (needles)	NSRL-11680	31/10/2000	2,990 ± 40	3,184
43	1,326.0	Macroscopic charcoal fragments	NSRL-11559	16/10/2000	3,570 ± 45	3,844
51	1,543.6	Macroscopic charcoal fragments	NSRL-11560	16/10/2000	3,750 ± 35	4,125
61	1,808.8	*Larix laricina* (needles) and *Pinus strobus* (needles)	NSRL-11561	16/10/2000	3,840 ± 35	4,240

[a]Ridge number assigned to each beach ridge identified in the embayment, starting from the modern shoreline increasing in number landward.

[b]Distance landward of the beach ridge crest from the modern shoreline.

[c]Lab numbers GX correspond to conventional analysis reported from Geochron Laboratories (Cambridge, Massachusetts) and NSRL correspond to accelerator mass spectroscopy (AMS) analysis reported from INSTAAR (Boulder, Colorado).

[d]Ages were calibrated to calendar years before 1950 using the University of Washington's Quaternary Isotope Lab Radiocarbon Calibration Program, CALIB version 4.3 (Stuiver and Reimer 1993, Stuiver *et al.* 1998).

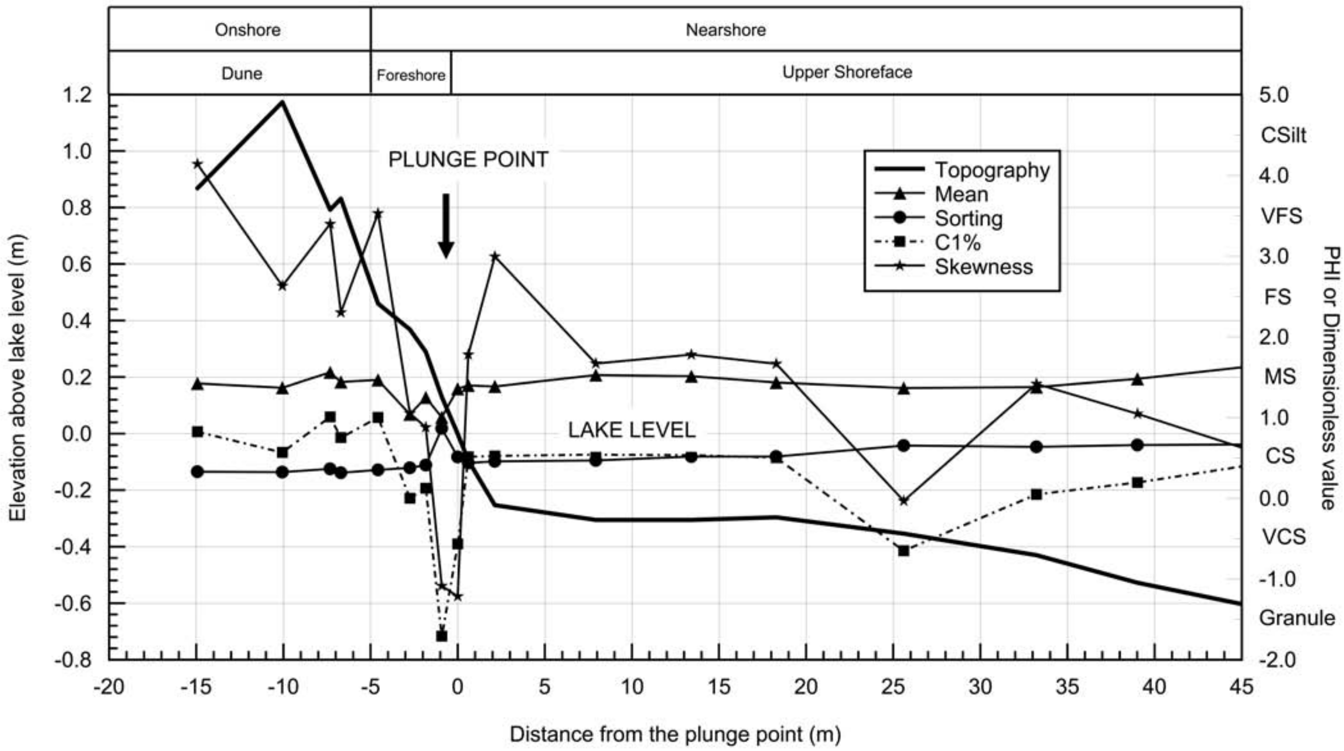

FIG. 2. Graph of onshore/nearshore topography and grain-size trends perpendicular to the modern shoreline at Tahquamenon Bay, Michigan. The profile extends across the modern beach and plunge point (land/water interface) and into the nearshore. The modern shoreline is eroding, producing a steep topographic profile on the landward part of the profile. Abbreviations along the second y-axis describe the grade of sediment (granular gravel to very coarse, coarse-, medium-, fine-, and very fine grained sands to coarse-grained silt).

grained sand, with a slight increase in mean grain size across the foreshore (swash zone) (Fig. 2). The coarsest part of the foreshore occurs at the plunge point. Lakeward from the plunge point, grain size decreases 0.5-phi across the bar. In all, the mean size of foreshore sediments are coarser than adjacent dune and upper shoreface sediments, with the coarsest mean grain size occurring at the plunge point.

Coarsest one-percentile trends change from coarse-grained sand in the dune, medium-grained sand to granules in the foreshore, and coarse- to very coarse grained sand in the upper shoreface (Fig. 2). The coarsest C1% values occur at the plunge point and on the lakeward slope of the bar. Although the foreshore has the widest range in C1%, most of the foreshore sand was coarser than adjacent dune and upper shoreface sediment.

Sorting trends change from very well sorted in the dune, well sorted in the foreshore (moderately sorted at the plunge point), and well sorted to moderately sorted in the upper shoreface (Fig. 2). Within the upper shoreface, C1% and mean grain size is finer and more poorly sorted with increasing distance offshore.

Skewness changes from more strongly fine skewed (more positively skewed) in the dune, to strongly fine skewed to strongly coarse skewed in the foreshore, to less strongly fine skewed (more negatively skewed) in the upper shoreface (Fig. 2). Dune and upper shoreface sediments contain more fine grains; foreshore sediments contain more coarse grains.

Ancient Facies

Data from the modern topographic profile indicate that the most discriminating statistical parameters of the three facies are mean grain size, sorting, and C1% (Fig. 2). Therefore, we use these statistical parameters in conjunction with sedimentary structures to identify three sedimentary facies in

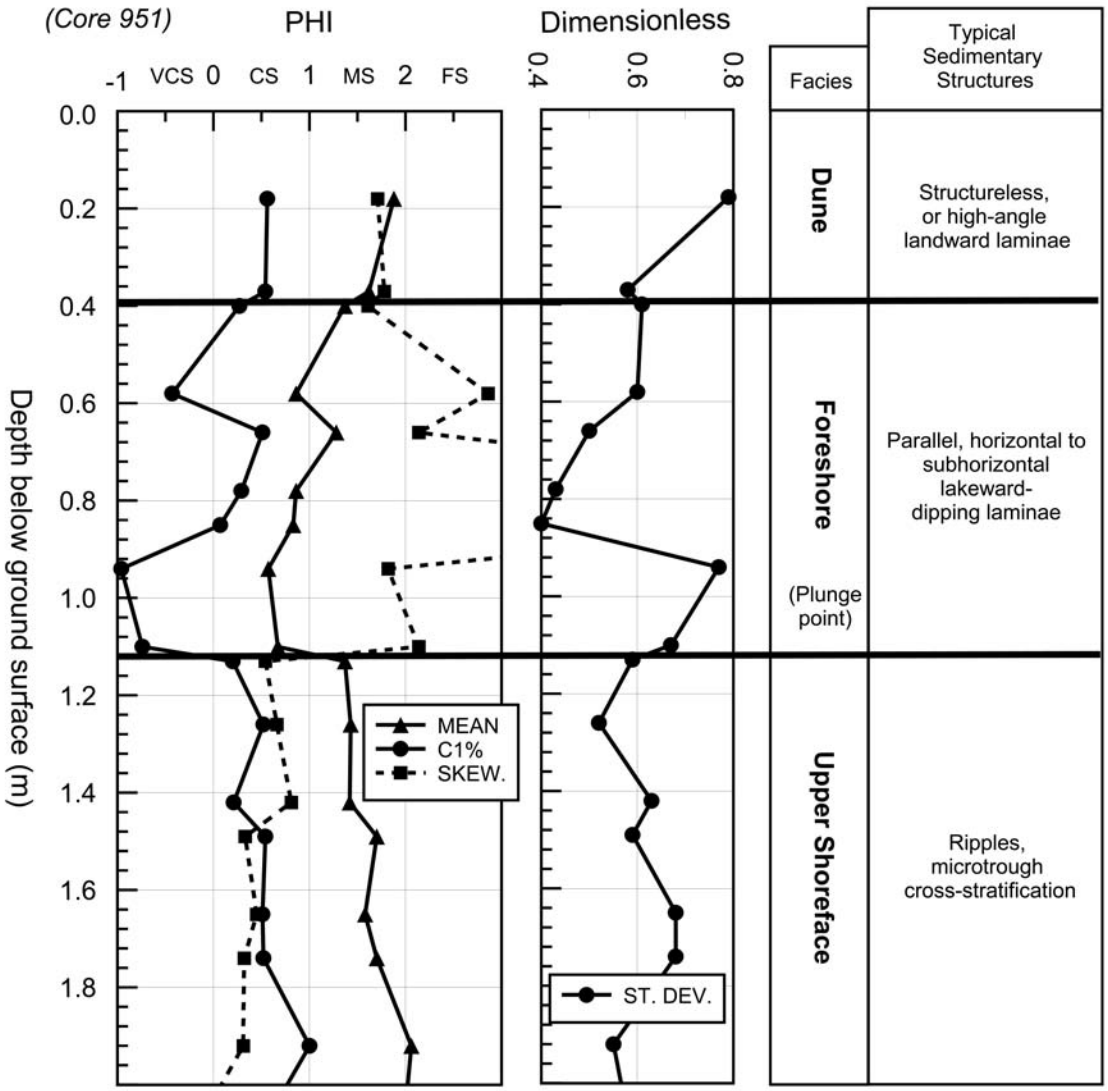

FIG. 3. Schematic diagram illustrating facies grain-size characteristics in core 951 with respect to depth and typical sedimentary structures in all cores. See Figure 2 for grain-size abbreviations.

cores (dune, foreshore, and upper shoreface) (Fig. 3).

In cores, foreshore sediments are coarser grained, more poorly sorted, more fine skewed, and have coarser C1% than dune and upper shoreface sediments. Dune deposits are more poorly sorted, more fine skewed, and have a coarser C1% than upper shoreface deposits. Dune sands are also finer grained in mean and C1% and more coarse skewed than foreshore deposits. Upper shoreface sediment is finer grained, more poorly sorted, more coarse skewed, and has a finer C1% than foreshore and upper shoreface sediments.

In cores, dune sediments are commonly structureless or contain high-angle landward-dipping laminae, whereas foreshore sediments typically contain parallel, horizontal to lakeward-dipping, subhorizontal laminae; upper shoreface sediments are rippled and contain micro-trough cross-stratification.

Facies Synthesis

Facies relationships derived from grain size and sedimentary structures are similar in cores and across the modern beach. Dune sediments are commonly structureless, consist of more fine grains, and are better sorted than foreshore and upper shoreface sediments. This is mainly owing to wind transportation, because wind is efficient at transporting only a small range of fine grains and, therefore, structures are less apparent (Hunter 1977, Allen 1985, Komar 1998).

Foreshore sediments commonly contain parallel, horizontal to low-angle lakeward-dipping laminae, consist of abundant coarse grains, and are relatively well sorted to poorly sorted. These characteristics primarily result from oscillation and transportation by water in the nearshore zone; coarse grains are driven onshore and the few fine grains are winnowed out by offshore return flows (Fox *et al.* 1966, Fraser *et al.* 1991, Komar 1998). Wind also removes fine grains from the edge of the nearshore zone in the foreshore and transports them onshore into the dune (Komar 1998). The coarsest and most poorly sorted sand is deposited where the waves break at the plunge point in the foreshore, at the water line (Fraser *et al.* 1991). It is important to recognize this facies in core because it records the approximate elevation of the lake (Thompson 1992).

Upper shoreface sediments commonly contain ripples and micro-trough cross-stratification, organics, fine grains, and are relatively well sorted. This is mainly owing to nearshore processes where coarse and fine-grained sediments are driven onshore but only fine-grained sediment is returned offshore (Komar 1998). Ripples and micro-troughs are developed by onshore-offshore and alongshore currents in the nearshore zone (Greenwood and Davidson-Arnott 1979, Reineck and Singh 1980, Fraser *et al.* 1991).

Cross-strandplain Facies Relationships

A cross section of the entire strandplain shows that contact elevations for each pair of facies generally decrease lakeward (Fig. 4), except in the lakeward and landward sets of beach ridges (Fig. 1). A platform of foreshore elevations occurs in the most landward part of the strandplain above the rest. Constant to slightly rising foreshore elevations occur in the lakeward part of the strandplain closer than 250 m from shore. The top and bottom contacts of the foreshore do not parallel each other across the entire strandplain. Basal foreshore elevations decrease about 12 m from the landward to lakeward part of the strandplain, with the largest decrease occurring in the most landward part, dropping at least 4 m from 2.1 to 1.8 km from the shore (Fig. 4). Basal foreshore elevations indicate that relative lake levels ranged from a maximum elevation of 195.12 m to a minimum elevation of 182.86 m above sea level (IGLD85) in the Tahquamenon Bay area.

Foreshore elevations rise and fall in groups of three to six beach ridges (Fig. 4). This trend is similar to ground elevation changes described previously. As we will discuss later, such groupings are more readily apparent in the residual curve where vertical ground movement is removed. Although the trends are similar between contacts, basal foreshore elevations best approximate the elevation of the lake when the beach ridges formed.

The sand/clay contact forms the pre-depositional surface underneath the strandplain. The slope of the clay surface decreases lakeward but is almost five times steeper between 2,000 m and 1,800 m than its slope farther lakeward (Fig. 4). The clay surface also forms a slightly lakeward-dipping platform between 900 m and 1,300 m. The sharp sand/clay contact and coarse sand to gravel commonly found above this contact in core suggests that this surface is erosional. The age or thickness of the clay is unknown, but it was most likely deposited offshore during a previous lake stage and subsequently eroded before progradation and beach-ridge deposition. Between the basal foreshore contact and the clay surface are upper shoreface deposits that accumulated subaqueously. The lower limit of the shoreface corresponds to the depth of average fair weather wave base (Reineck and Singh 1980). Upper shoreface sediment thicknesses range from 0 along the steeply sloping clay surface to as much as 1.94 m. The upper clay surface trends are roughly parallel to basal foreshore trends, except in the most lakeward set where basal foreshore elevations rise slightly and clay upper surface elevations fall, and in the most landward part of the curve where they join.

Age Model

We collected 30 peat samples from the base of 25 swales along the Tahquamenon Bay vibracore transects (Table 1). All 30 samples (22 conventional and 8 AMS radiocarbon) were used to estimate the ages of beach ridges (Fig. 5). Calibrated conventional and AMS ages generally show a similar trend, decreasing in age toward the modern shoreline. This lakeward decline illustrates the progradational nature of the shoreline. Although the conventional samples were not AMS dated, two

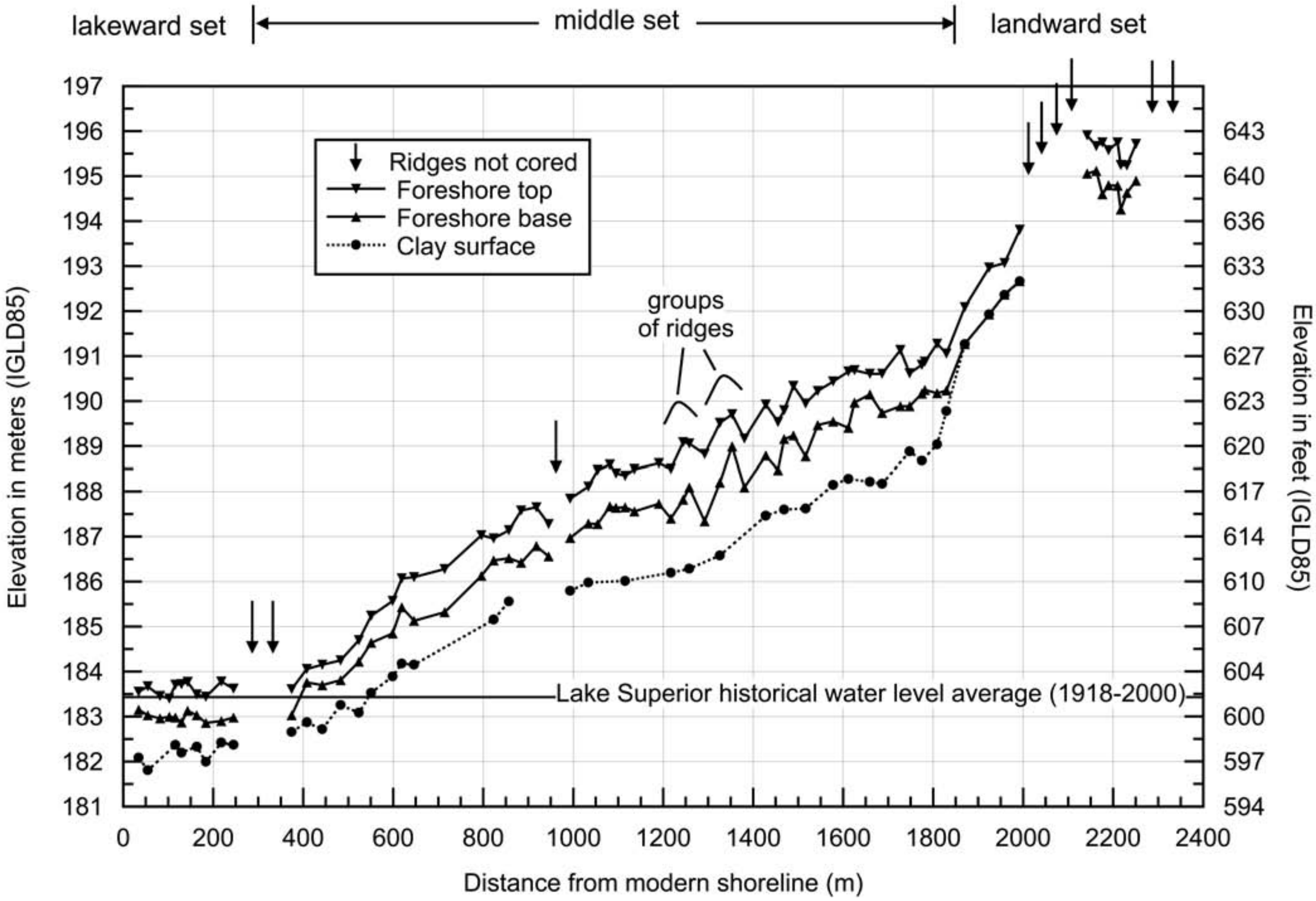

FIG. 4. Graph of the elevation of upper and lower limits of foreshore sediments versus distance landward from the modern shoreline. The middle line represents the boundary between foreshore and upper shoreface deposits and approximates the elevation of the lake during beach-ridge formation. The uppermost line represents the boundary between dune and foreshore deposits and is used in conjunction with the middle boundary to calculate foreshore thickness. The lowermost line corresponds to the contact between upper shoreface sediment and the predepositional surface composed of clay.

basal peat samples from five common wetlands were analyzed using the two dating methods. We used two different collection techniques to sample basal peat at various locations within the same wetland. All of the conventional ages except one varied from the AMS ages by 100 to 500 calendar years (older and younger). One AMS age was about 1,200 calendar years older than a conventional age in samples from the same wetland. However, this may be a result of dating a macroscopic charcoal fragment that was transported from older deposits. Conventional ages should be younger than AMS ages; they are an average age representing a larger amount of sample and may be contaminated by modern rootlets. Although it is expected that the AMS ages more accurately reflect the date of peat inception in the swales, there does not appear to be a consistent relationship between AMS and conventional ages across the strandplain.

This disparity between ages poses a problem for manipulation and interpretation. Individual ages cannot be treated as "absolute" because of apparent age reversals that are inconsistent with strandplain development and a progradational system. Fitting complex functions to the data also creates apparent time reversals and apparent periods when no time has elapsed, which cannot be explained in this system. Further, these ages may reflect only the minimum ages of the deposits in the associated beach ridges. For this study, we used least-squares regression through all 30 calibrated ages versus distance from the modern shoreline to create an age model

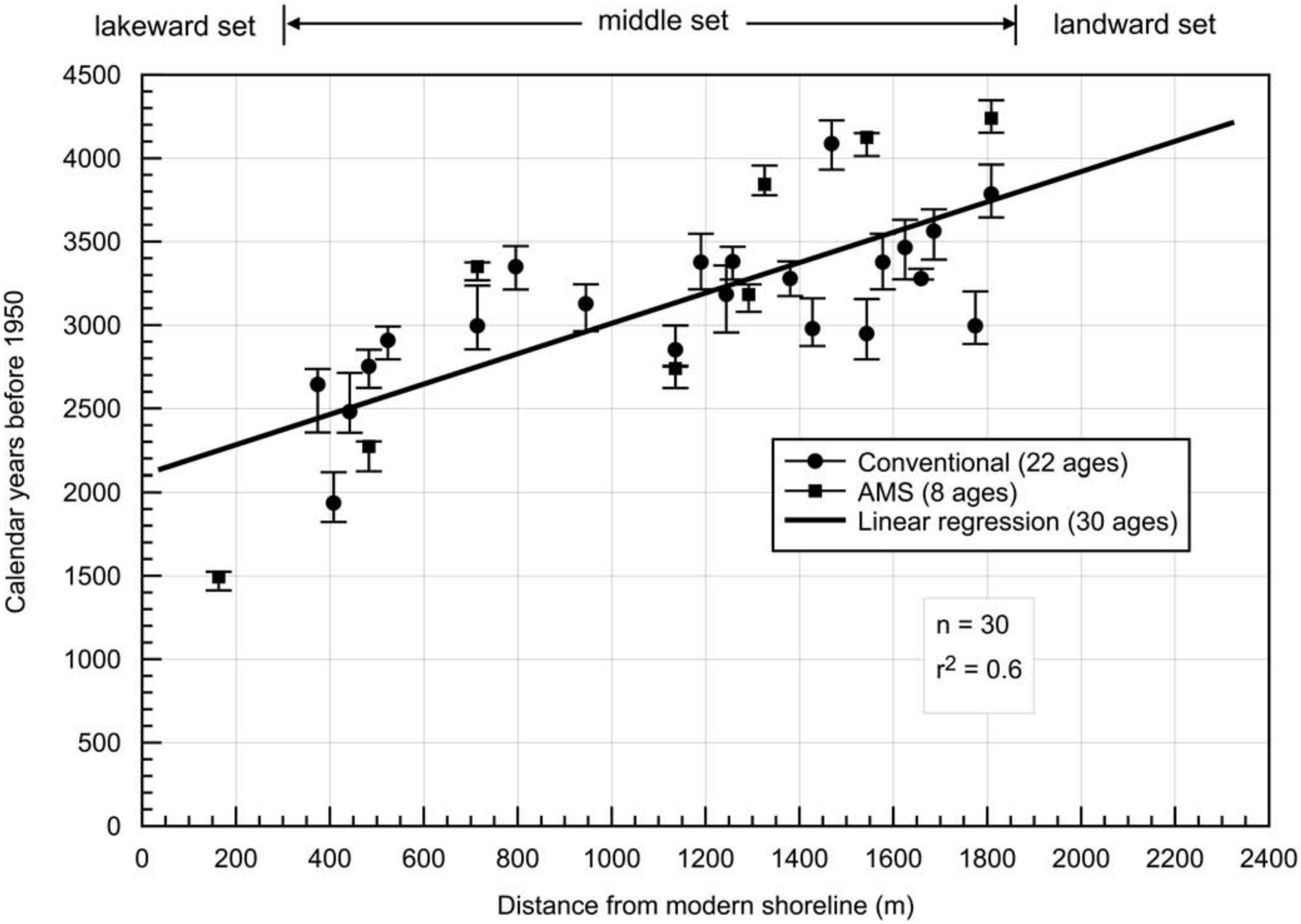

FIG. 5. Graph of calibrated ages versus distance from the modern shoreline. The regression line was used to calculate approximate ages for each beach ridge in the Tahquamenon Bay embayment.

that statistically approximates the age of each beach ridge (Thompson 1992, Thompson and Baedke 1997). This best-fit line was used because of the variability between dates ($r^2 = 0.60$) (Fig. 5) and it allows us to estimate ages for ridges that were not dated.

The ages of ridges in the landward set of beach ridges were extrapolated from the age model, as we did not collect data in this area. Age estimates correlated to a well-defined Nipissing II geomorphic feature (explained more fully in the next section). We also extrapolated the age of the lakeward set because it was within the range of variability for all ages collected; we have no other data to suggest otherwise. Janzen's (1968) archaeological work at the Naomikong Point site on a peninsula (about 1.5 km to the northeast of the Tahquamenon Bay embayment) uncovered material from a Middle Woodland culture (approximately 2,200 to 1,600 cal. yrs. B.P.). This age corresponds to our age model. We are currently investigating age dating with optically stimulated luminescence to help refine the age model.

In our model, the regression line intersects the modern shoreline (0 meters in Fig. 5) at about 2,100 cal. yrs. B.P. This suggests that beach ridges did not form or were not preserved during the last few millennia in the Tahquamenon Bay embayment, assuming continuous deposition between the middle and lakeward sets. Based on the regression and assuming continuous deposition, the oldest preserved shoreline is about 4,200 cal. yrs. B.P. The inverse of the slope of the regression line in the distance-versus-age plot indicates that the average long-term progradation rate was about 1.10 m/yr. To determine the average time it takes to create a beach ridge, we calculated a regression between the calibrated ages and numbers assigned sequentially to each beach ridge (cf. Thompson and Baedke 1997). The slope of the regression indicates that a beach ridge was created and preserved approximately every 28 ± 4.8 years, which leads us to believe that groups of beach ridges were created and preserved approximately every 140 years.

Relative Lake-level Variation

We combined upper and lower foreshore elevations with age estimates from the model to create a relative lake-level curve for Tahquamenon Bay (Fig. 6A). Beach ridges at Tahquamenon Bay provide information on relative lake-level fluctuations from about 4,200 to 2,100 cal. yrs. B.P., assuming continuous deposition between the lakeward, middle, and landward sets. Basal foreshore elevations indicate that relative lake-levels ranged from about 195.12 m to 182.86 m above sea level (IGLD85). The oldest part of the curve records a lake-level high about 4,100 cal. yrs. B.P. This high lake level corresponds to the Nipissing II high-water level phase when water in all three basins (Lake Superior, Lake Michigan, and Huron) were confluent and the lake drained through the Port Huron/Sarnia and Chicago outlets (Hough 1958; Farrand 1969; Lewis 1969, 1970; Larsen 1985, 1994). Hough (1958) reported the Nipissing II phase as ending about 3,700 cal. yrs. B.P., Lewis (1969) as occurring from about 5,400 to 4,000 cal. yrs. B.P. (4,700 to 3,700 ^{14}C yrs. B.P.), Larsen (1985, 1994) as ending about 4,200 cal. yrs. B.P. (3,800 ^{14}C yrs B.P.), and Baedke and Thompson (2000) as ending between 4,500 and 3,400 cal. yrs. B.P. And so the general consensus on the end of the Nipissing II phase is about 4,000 years ago, but its actual timing is still debated because of the variability associated with sample types, collection and laboratory methods, calibration, modeling and interpretation procedures, and the different interpretations of sediment types and vertical ground movement. Multiple sedimentological analyses of more complete records will help to better define this time period. The end of the Nipissing II phase currently is best constrained by the record of Thompson and Baedke (1997) from a strandplain in Manistique, Michigan, because it, to date, contains the most complete data in a continuous sequence. The record from Tahquamenon Bay also encompasses this time period and helps to correlate between basins.

A rapid relative lake-level drop of at least 4 m, recorded in the most landward part of the Tahquamenon Bay strandplain, is similar in magnitude to the drop recorded by Thompson and Baedke (1997) and suggests commonality between basins. The Nipissing II phase is placed about 200 to 300 calendar years later in the Tahquamenon Bay curve than in Thompson and Baedke's (1997) Manistique curve. The rapid drop in lake level is defined by more ridges at Manistique than at Tahquamenon Bay. Adding additional ridges at Tahquamenon Bay to account for those not formed or preserved or age model errors may account for differences between sites. At some time during this rapid relative lake-level drop, the Nipissing II phase ended and the Chicago outlet closed (Baedke and Thompson 2000). The end of the Nipissing high water-level phase and the closing of the Chicago outlet may be related to erosion at the Port Huron/Sarnia outlet and/or large loss of water from the lake (Baedke and Thompson 2000).

A gradual relative lake-level lowering of approximately 7 m from about 3,800 to 2,400 cal. yrs. B.P. occurs in the middle part of the Tahquamenon Bay strandplain (Fig. 6A). This gradual lowering is similar to strandplain trends recorded by Thompson and Baedke (1997) in Lake Michigan. A comparison of the Tahquamenon Bay data to both the Lake Michigan record and the calculated record for the Port Huron/Sarnia outlet (Baedke and Thompson 2000) indicates that the Tahquamenon Bay embayment experienced more vertical ground movement than the outlet regulating water level in the Lake Superior basin. During this time, lake levels were common in all three basins (Lake Superior, Lake Michigan, and Huron basins), and the lake drained through the Port Huron/Sarnia outlet (Farrand and Drexler 1985). Long-term deviations of up to 1 m during the gradual lowering in relative lake level defines the Algoma high-water-level phase. Water-level fluctuations should become more apparent when multiple data sets from around Lake Superior are completed and compared with the Tahquamenon Bay record so that ground movement can be removed (e.g., Baedke and Thompson 2000).

Between about 2,300 and 2,100 cal. yrs. B.P., gradual relative lake-level rise of about 0.3 m occurs in the most lakeward part of the Tahquamenon Bay strandplain (Fig. 6A). This slight rise indicates that the Tahquamenon Bay embayment experienced similar or slightly less vertical ground movement than the outlet regulating lake levels in the Lake Superior basin at that time. The change in relative water levels from a fall to a rise suggests that the location of the outlet regulating water levels in the Lake Superior basin changed from Port Huron/Sar-

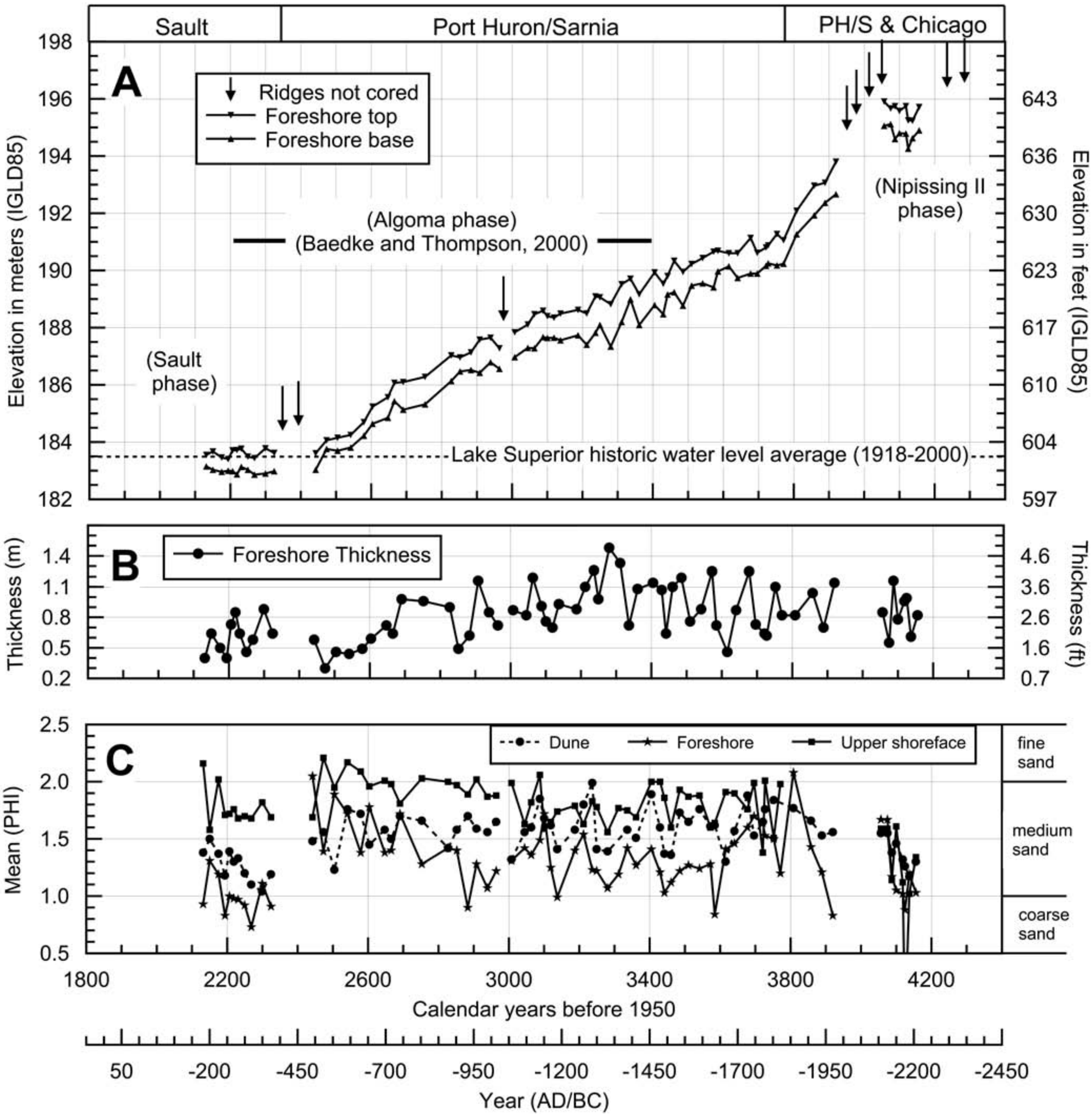

FIG. 6. Graph of (A) foreshore (top and base) elevation trends, (B) foreshore thickness, and (C) mean grain size of nearshore (foreshore and upper shoreface) and onshore (dune) facies per core versus calendar years before 1950 across the entire Tahquamenon Bay strandplain. Basal foreshore elevations in (A) indicate the **relative** *elevation of the lake through time. (Note: Basal foreshore elevations in (A) are relative lake-level elevations only with respect to Tahquamenon Bay because vertical ground movement is not removed.)*

nia to Sault Ste. Marie. The Tahquamenon Bay record suggests that the outlet change occurred after the Algoma high-water-level lake phase after about 2,400 cal. yrs. B.P. Farrand (1960) called the phase after the Algoma the Sault phase and corresponds to the time when Lake Superior stood at a separate level than Lakes Michigan and Huron.

Farrand (1962) intersected an exponential uplift curve for the Sault outlet and a linear curve representing downcutting at the Port Huron/Sarnia outlet on an age-versus-elevation plot. The intersection, he reasoned, was the time when the Sault outlet rebounded above Lakes Michigan and Huron. He calculated that the change in outlets occurred at about 2,200 radiocarbon yrs. B.P. Larsen (1994) worked on a strandplain on Whitefish Point, Michigan and reported that the change in outlets occurred at about 2,100 cal. yrs. B.P. Incomplete records, different types of data, varying methods, and errors associated with age models may account for the various age estimates for outlet change. The most likely locations for a time gap in the Tahquamenon Bay record are between sets (lakeward, middle, landward) of beach ridges, where beach ridges did not form or were created and subsequently eroded. Reorientation beach-ridge crests observed in air photographs, abrupt grain-size changes in cores, and reduced accumulation rates or a hiatus recognized in peat cores support the presence of a time gap. However, the lack of ages in lakeward and landward sets do not allow for the confirmation of time gaps in the Tahquamenon strandplain.

Larsen (1999a,b,c) and Larsen *et al.* (1999) researched submerged features below current lake level along the southern shore of Lake Superior and interpreted lake-level fluctuations after the outlets changed; this work may be useful in understanding the youngest part of the Tahquamenon Bay record after vertical ground movement is removed.

Our data record short-term relative lake-level fluctuations in the Tahquamenon Bay strandplain on the order of decades to centuries. The age model indicates that water levels rose and fell about every 28 years to form an individual beach ridge, and groups of beach ridges suggest that longer-term fluctuations occurred about every 140 years. Similar quasi-periodic fluctuations in Lake Michigan (Thompson and Baedke 1997) suggest that water levels fluctuated with a similar periodicity in both the Lake Superior and Lake Michigan basins. Similar water-level fluctuations in both basins are expected if they experienced similar rates of preservation, because the lakes were confluent during most of the period recorded in the Tahquamenon Bay strandplain.

Cross-strandplain Variations in Foreshore Thickness and Mean Grain Size

Cross-strandplain variations in foreshore thickness and mean grain-size provide insight into past changes in wave and wind climates, and sediment supply and transportation. Foreshore thicknesses range from 0.3 to 1.5 m, averaging 0.8 m at Tahquamenon Bay (Fig. 6B). A direct correlation between foreshore thickness and wave climate has not been formulated, but Howard and Reineck (1981) suggest that increased foreshore thickness is related to increased wave energy or average wave height. Because wind duration, speed, and fetch governs wave generation (Komar 1998), foreshore thickness may reveal past predominant wind characteristics. Foreshore thicknesses generally are greater during the Nipissing and Algoma phases than during the Sault phase in the Tahquamenon Bay record (Figs. 6A and 6B). We expect this relationship because the size of the water bodies was much greater during the Nipissing and Algoma phases (Hough 1958). This increased size would have increased the available fetch and the nearshore water depth, increasing wave height; however, a predominant wind direction, velocity, duration change or a combination of these may also have played an important role in affecting foreshore thickness. A slight rise in foreshore thickness about 3,800 to 3,300 cal. yrs. B.P., an abrupt rise around 3,300 cal. yrs. B.P., and a decrease about 3,300 to 2,400 cal. yrs. B.P. indicate variations in paleowave and wind climates or both during the Algoma phase. As water levels rose or stabilized, foreshore thickness generally increased. Short-term variations in foreshore thickness are similar in duration to short-term variations in relative lake level. This suggests that wave and wind climates may have fluctuated every 140 years. The range in magnitude of short-term variations in foreshore thickness and relative lake level decreased after the Sault outlet began to regulate water levels in the Lake Superior basin. This dampening may be related to a decreased size of the lake and changes in the predominant wind direction.

Mean grain size ranges from 0.7 phi (coarse sand) to 2.2 phi (fine sand) in the Tahquamenon Bay strandplain (Fig. 6C). This relatively small range in grain size may reflect a single source or numerous homogeneous sources of sediment. The most likely source of sand is the medium to fine-grained friable sandstone of the Munising Formation, which outcrops up-drift along the coastline and along the Tahquamenon River (Hamblin 1958). The only long-term mean grain-size change in all three facies across the strandplain is between the middle and lakeward set. Results from one of the very few grain-size studies across the nearshore in a nearly tideless setting were reported by Fox *et al.* (1966) in Lake Michigan, and suggest that mean grain size closely reflects the energy level of the wave processes. The coarse grain-size shift after 2,400 cal. yrs. B.P. at Tahquamenon Bay, therefore, may be related to an increase in the energy level of the wave processes; however, foreshore thickness, an indicator of wave climate, contradicts this and remains fairly constant and relatively low during this period. Alternatively, the abrupt change corresponds to the relative water-level change from a fall to a slight rise the middle to lakeward set and may be related to changes in the source of sediment and the distance/direction of transport after the change in outlets regulating water levels in the Lake Superior basin. The only major long-term change in mean grain size within facies occurs between 2,900 and 2,400 cal. yrs. B.P., where the foreshore sediment gradually fines while the dune and upper shoreface sediment remains relatively constant. This change corresponds to a decreasing foreshore thickness and a relative lake-level lowering near the end of the Algoma phase and may suggest an association between long-term mean grain size, foreshore thickness, and water level. Short-term changes in mean grain size are similar in magnitude to short-term changes in foreshore thickness and water-level elevations.

Vertical Ground Movement

A linear best-fit line was run through the middle set of the age-versus-basal-foreshore-elevation plot (Fig. 6) to determine a preliminary rate of vertical ground movement for the Tahquamenon Bay embayment. The regression was run only through the middle set because it is the longest part of the record where only one outlet regulated water levels in the Lake Superior basin. The best-fit line slope suggests that the Tahquamenon Bay strandplain rebounded at a rate of 51 ± 1.3 cm/century between 3,800 and 2,400 cal. yrs. B.P. This is almost double the rates calculated from historical and geologic data. The rate of linear isostatic rebound calculated from historic water-level-gauge data is between about 18 and 30 cm/century relative to the Port Huron/Sarnia outlet (Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data [CCBHD] 1977, 2001). Linear rates calculated from late Holocene geologic data reported by Baedke and Thompson (2000) at several sites in the Lake Michigan basin, by Larsen (1994) at a site in the Lake Superior basin, and by Lewis (1970) at a site in the Huron basin compare well with the range in rebound reported from historical gauge data. All of these studies used a linear age model because a best-fit line of each of their data sets suggests a linear relationship of rebound through time, not an exponential relationship.

The over-steepening at Tahquamenon Bay may be the result of age-model errors or incorrect elevation data. Elevation data were checked on topographic maps and in the field and we found no errors. There is the possibility of age-model error because of the variability observed in the radiocarbon dates. Although we collected a large number of dates, it was difficult to fully ascertain age-model errors because of the numerous variables and uncertainties involved. We are investigating using optically stimulated luminescence for age dating to resolve these problems. We are also studying other strandplains of beach ridges along Lake Superior to compare to the Tahquamenon Bay data set.

Tectonics near the Sault Ste. Marie area may be an alternative explanation for the over-steepening. There are many faults in this area extending from the province of Ontario into Lake Superior (Giblin *et al.* 1976; Ontario Geological Survey 1991; Manson and Halls 1994, 1997; Manson 1996), but they are not mapped in eastern upper Michigan near the Tahquamenon Bay embayment. Several factors support fairly recent tectonism in the Sault Ste. Marie area: isostatic rebound, earth adjustments after loss of large volumes of water in the Lake Superior basin after the Nipissing and/or Algoma high water-level phases, Michigan structural basin subsidence, Superior province (Canadian Shield) adjustment, and midcontinent rift-related adjustments. More research is needed to resolve these issues.

Future of the Tahquamenon Bay Embayment

The large supply of sand from the north (Tahquamenon River and coastal reworking) and the shallow-water platform defining Tahquamenon Bay are ideal for beach-ridge development and preservation. Because the Tahquamenon Bay embayment (as defined in this study) lacks sediment accommodation space, it is likely that future beach ridges will form along the shore of Tahquamenon Bay, which encompasses the Tahquamenon Bay embayment. The presence of scarps on the modern beach, the possibility that Whitefish Point and beach structures (jetties and groins) may capture littoral sediment, and a long-term rising lake level because of vertical ground movement at the lake outlet, however, all are conditions unfavorable to beach-ridge development and preservation. As long-term relative water levels rise in the future, the Tahquamenon Bay embayment will again be inundated and the youngest part of the strandplain record may eventually erode. Human activities as well as tectonic events could modify this long-term trend.

CONCLUSION

We have created a relative lake-level curve for Tahquamenon Bay, Michigan, by systematically vibracoring the lakeward margin of beach ridges; using data from the cores, we obtained paleo lake-level elevations and radiocarbon dates of basal wetland sediments between beach ridges to determine ages. The resulting curve indicates that beach ridges in the Tahquamenon Bay embayment recorded lake levels from about 4,200 to 2,100 cal. yrs. B.P., assuming continuous deposition across the entire strandplain. During this time, relative lake levels dropped rapidly (approximately 4 m) from 4,100 to 3,800 cal. yrs. B.P., lowered gradually (approximately 7 m) from 3,800 to 2,400 cal. yrs. B.P., and remained fairly constant from 2,300 to 2,100 cal. yrs. B.P. The rapid drop from 4,100 to 3,800 cal. yrs. B.P. is associated with a drop in water level at the end of the Nipissing II high-water-level phase; the change from a gradual fall in the middle set to a fairly constant slope in the lakeward set is associated with an outlet change from Port Huron/Sarnia to Sault Ste. Marie. Data from the Tahquamenon Bay embayment strandplain suggest that this outlet change occurred after about 2,400 cal. yrs. B.P. Mean grain-size coarsening after the outlet change suggests that the source of sediment or distance/direction of transport changed as relative water levels started rising.

A line of best fit through the Tahquamenon relative lake-level curve shows that the strandplain is over-steepened with respect to estimated rates of vertical ground movement from historical gauge and geologic data. This over-steepening may indicate an error in the age model or elevation data. More strandplains around Lake Superior are being studied and age-dating sand within beach ridges is being investigated to check for errors. One mechanism for over-steepening of the curve involves tectonism. Tectonism may have modified the Tahquamenon Bay strandplain after about 2,400 cal. yrs. B.P. Tectonism in the Sault area could be related to isostatic rebound, adjustments after the Nipissing and/or Algoma high-water-level phases, Michigan structural basin subsidence, Superior Province (Canadian Shield) adjustment, and/or mid-continent rift-related adjustments. A tectonic event in the Sault area may have also been a factor in the outlet change from Port Huron/Sarnia to Sault Ste. Marie, important because the outlet regulating water levels in Lake Superior. This possibility in the past few millennia raises concern about future events in the area.

In the past, sand eroded from the Munising Formation and transported by the Tahquamenon River and littoral currents around Whitefish Point provided a positive rate of sediment supply to Tahquamenon Bay and it continues today. However, a long-term rising lake level, caused by vertical ground movement at the lake's outlet at Sault Ste. Marie, has not favored beach-ridge development and preservation from about 2,400 cal. yrs. B.P. to the present.

A short-term quasi-periodic lake-level fluctuation with a period of about 28 years was instrumental in the formation of beach ridges in the Tahquamenon Bay embayment. Foreshore elevations rise and fall in groups of three to six beach ridges in each set of ridges observed; we interpret these to represent quasi-periodic fluctuations of longer duration (ca. 140 yrs.). Changes in mean grain size and foreshore thickness follow these longer duration fluctuations and are related to paleo wave and wind climates. Superimposed on these shorter-duration fluctuations are differential vertical ground movements, outflow location changes or restrictions, and Lake Superior hydrodynamics.

Long-term records of Great Lakes water-level variability are critical to understanding the potential future magnitude and frequency of water-level fluctuations. Long-term records of water-level variability and vertical ground movement also provide a geologic and climatic framework for paleoecological studies, so that past wetland and terrestrial responses to these changes can be investigated (e.g., Booth *et al.* 2002, Jackson and Booth 2002). The compilation of multiple sedimentological records of past lake-level variability (Thompson and Baedke 1997, Baedke and Thompson 2000), and the direct comparison of these records to independent paleoclimate records from the region (e.g., Booth and Jackson 2003) should provide insight into the relative importance of the mechanisms driving lake-level variability (e.g., differential ground movement, outlet switching and erosion, climate variability) at centennial to a millennial timescales. Understanding these mechanisms is critical to future management of the Great Lakes water resource.

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REFERENCES

Allen, J.R.L. 1985. *Principles of Physical Sedimentology.* London: G. Allen and Unwin.

Arbogast, A.F., Hansen, E.C., and Van Oort, M.D. 2002. Reconstructing the geomorphic evolution of large coastal dunes along the southeastern shore of Lake Michigan. *Geomorphology* 46(3-4):241–255.

Baedke, S.J., and Thompson, T.A. 2000. A 4,700-year record of lake level and isostasy for Lake Michigan. *J. Great Lakes Res.* 26:416–426.

Barrett, L.R. 2001. A strand plain soil development sequence in Northern Michigan, U.S.A. *Catena* 44(3):163–186.

Booth, R.K., and Jackson, S.T. 2003. A high-resolution record of late Holocene moisture variability from a Michigan raised bog. *The Holocene* 13(6):865–878.

_____, Jackson, S.T., and Thompson, T.A. 2002. Paleoecology of a northern Michigan lake and the relationship among climate, vegetation, and Great Lakes water-levels. *Quaternary Research* 57:120–130.

Cohen, S.B. 1998. *The Columbia Gazetteer of the World.* New York: Columbia University Press.

Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data. 1977. *Apparent Vertical Movement over the Great Lakes.* Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, Chicago, IL, and Cornwall, ON.

_____. 1995. *Establishment of International Great Lakes Datum* (1985). Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, Chicago, IL, and Cornwall, ON.

_____. 2001. *Apparent Vertical Movement over the Great Lakes—Revisited.* Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, Chicago, IL, and Ottawa, ON.

Cowan, W.R. 1978. Radiocarbon dating of Nipissing Great Lakes events near Sault Ste. Marie, Ontario. *Can. J. Earth Sci.* 15:2026–2030.

_____. 1985. Deglacial Great Lakes shorelines at Sault Ste. Marie, Ontario. In *Quaternary Evolution of the Great Lakes,* eds. P.F. Karrow and P.E. Calkin, pp. 33-37. Geological Association of Canada Special Paper 30.

Farrand, W.R. 1960. Former shorelines in western and northern Lake Superior basin, Ph.D. dissertation, Univ. Michigan, Ann Arbor, MI.

_____. 1962. Postglacial uplift in North America. *Am. J. Sci.* 260:181–199.

_____. 1969. The Quaternary history of Lake Superior. In *Proc. 12th Conf. Great Lakes Res.*, pp. 181–197. Internat. Assoc. Great Lakes Res.

_____, and Drexler, C.W. 1985. Late Wisconsinan and Holocene history of the Lake Superior basin. In *Quaternary Evolution of the Great Lakes,* eds. P.F. Karrow and P.E. Calkin, pp. 17–32. Geological Association of Canada Special Paper 30.

Fox, W.T., Ladd, J.W., and Martin, M.K. 1966. A profile of the four moments measures perpendicular to a shore line, South Haven, Michigan. *J. Sed. Pet.* 36(4):1126–1130.

Fraser, G.S., Thompson, T.A., Kvale, E.P., Carlson, C.P., Fishbaugh, D.A., Gruver, B.L., Holbrook, J., Kairo, S., Kohler, C.S., Malone, A.E., Moore, C.H., Rachmanto, B., and Rhoades, L. 1991. Sediments and sedimentary structures of a barred, nontidal coastline, southern shore of Lake Michigan. *J. Coastal Res.* 7(4):1113–1124.

Fuks, K.H., and Wilkinson, B.H. 1998. Holocene sedimentation in two western Michigan estuaries. *J. Great Lakes Res.* 24:822–837.

Giblin, P.E., Leahy, E.J., and Robertson, D.W. 1976. *Sault Ste. Marie-Elliot Lake.* Ontario Geological Survey, Geological Compilation Series, Map 2419, scale 1:25,000.

Greenwood, B., and Davidson-Arnott, R.G.D. 1979. Sedimentation and equilibrium in wave-formed bars: a review and case study. *Can. J. Earth Sci.* 16:312–332.

Hamblin, W.K. 1958. *The Cambrian Sandstones of*

Northern Michigan. Michigan Geological Survey Publication 51.

Hough, J.L. 1958. *Geology of the Great Lakes.* Urbana, Illinois: University of Illinois Press.

Howard, J.D., and Reineck, H.-E. 1981. Depositional facies of high-energy beach-to-offshore sequence, Comparison with low-energy sequence. *Am. Assoc. Petro. Geol. Bull.* 65:807–830.

Hunter, R.E. 1977. Basic types of stratification in small eolian dunes. *Sedimentology* 24:361–387.

International Joint Commission. 2002. *Upper Great Lakes plan of study for review of the regulation of outflows from Lake Superior.* International Joint Commission, Cornwall, ON, and Detroit, MI.

Jackson, S.T., and Booth, R.K. 2002. The role of late Holocene climate variability in the expansion of yellow birch in the western Great Lakes region. *Diversity and Distributions* 8:275–284.

Janzen, D.E. 1968. *The Naomikong Point Site and the dimensions of Laurel in the Lake Superior Region.* Anthropological Papers No. 36, Museum of Anthropology, Univ. of Michigan, Ann Arbor, MI.

Johnston, J.W., Thompson, T.A., and Baedke, S.J. 2000a. *Preliminary report of late Holocene lake-level variation in southern Lake Superior: Part 1.* Indiana Geological Survey Open-File Study 99-18.

_____, Thompson, T.A., and Baedke, S J. 2000b. Strandplain evidence for late Holocene lake level in Tahquamenon Bay, southeastern Lake Superior. In *Abstracts with Programs Conf. Geological Society of America,* pp. A-19. Geological Society of America v.32, no. 4.

_____, Thompson, T.A., and Baedke, S.J. 2001a. *Preliminary report of late Holocene lake-level variation in southeastern Lake Superior Part II: Tahquamenon Bay, Michigan.* Indiana Geological Survey Open-File Study 01-04.

_____, Thompson, T.A., and Baedke, S.J. 2001b. Relative late Holocene lake levels and isostatic rebound in the Lake Superior basin. In *Abstracts with Programs Conf. Geological Society of America,* pp. A-11. Geological Society of America v. 33, no. 4.

_____, Thompson, T.A., and Baedke, S.J. 2002a. Preliminary report of late Holocene lake-level variation in southeastern Lake Superior: Tahquamenon Bay, Michigan. In *Proc. 5th Conf. State-of-the-Lake: Superior,* pp. 24. Aquatic Ecosystem Health and Management Society.

_____, Baedke, S.J., and Thompson, T.A.. 2002b. Beach-ridge architecture, lake-level change, and shoreline behavior in the Au Train Bay embayment, Au Train, Michigan. In *Deglaciation and Holocene landscape evolution in eastern upper Michigan,* eds. W.L. Loope, and J.B. Anderton, pp. 49–55. Field guide for the 48th Midwest Friends of the Pleistocene field conference.

Keough, J.R., Thompson, T.A., Guntenspergen, G.R., and Wilcox, D.A. 1999. Hydrogeomorphic factors and ecosystem responses in coastal wetlands of the Great Lakes. *Wetlands* 19:821–834.

Komar, P.D. 1998. *Beach Processes and Sedimentation.* New Jersey: Prentice-Hall, Inc.

Kowalski, K.P., and Wilcox, D.A. 1999. Use of historical and geospatial data to guide the restoration of a Lake Erie coastal marsh. *Wetlands* 19 (4):858-868.

Larsen, C.E. 1985. Lake level, uplift, and outlet incision, the Nipissing and Algoma Great Lakes. In *Quaternary Evolution of the Great Lakes,* eds. P.F. Karrow and P.E. Calkin, pp. 63–77. Geological Association of Canada Special Paper 30.

_____. 1994. Beach ridges as monitors of isostatic uplift in the upper Great Lakes. *J. Great Lakes Res.* 20:108–134.

_____. 1999a. Reconstructing Holocene lake-level fluctuations in the Lake Superior basin. In *Proceedings of the Great Lakes Paleo-Levels Workshop: The Last 4000 Years,* eds. C.E. Sellinger and F.H. Quinn, pp. 20-23. NOAA Technical Memorandum ERL GLERL-113.

_____. 1999b. Submergence along the south and western shore of Lake Superior since 2,100 B.P. In *Proc. 42nd Conf. Great Lakes Res.,* pp. A-66. Internat. Assoc. Great Lakes Res.

_____. 1999c. Evidence for anomalous climate-related low lake level stands of Lake Superior at Bay Mills, Michigan. In *Proc. 42nd Conf. Great Lakes Res.*, pp. A-66. Internat. Assoc. Great Lakes Res.

_____, Cameron, C.C., and Robbins, E.I. 1999. The reconstructed Late Holocene lake-level history of the Apostles Island National Lakeshore, Lake Superior. In *Proc. 42nd Conf. Great Lakes Res.,* pp. A-66. Internat. Assoc. Great Lakes Res.

Lawson, A.C. 1893. Sketch of the coastal topography of the north side of Lake Superior with special reference to the abandoned strands of Lake Warren (The greatest of the late Quaternary lakes in North America) In *The geological and natural history survey of Minnesota: 20th Annual Report of the Year 1892,* ed. N.W. Winchell, pp. 181–289. Minnesota State Geologist.

Lewis, C.F.M. 1969. Late Quaternary History of lake levels in the Huron and Erie basins. In *Proc. 12th Conf. Great Lakes Res.,* pp. 250–270. Internat. Assoc. Great Lakes Res.

_____. 1970. Recent uplift of Manitoulin Island. *Can. J. Earth Sci.* 7:665–675.

Loope, W.L., and Arbogast, A.F. 2000. Dominance of an ~150-year cycle of sand-supply change in late Holocene dune-building along the eastern shore of Lake Michigan. *Quaternary Research* 54(3):414–422.

Manson, M.L. 1996. Post-Keweenawan compressive tectonism in the Midcontinent Rift of eastern Lake Superior, Ph.D. dissertation, Univ. of Toronto, Toronto, ON.

_____, and Halls, H.C. 1994. Post-Keweenawan compressional faults in the eastern Lake Superior region and their tectonic significance. *Can. J. Earth Sci.* 31:640–651.

_____, and Halls, H.C. 1997. Proterozoic reactivation of the southern Superior Province and its role in the evolution of the Midcontinental rift. *Can. J. Earth Sci.* 34:562–575.

Nichols, S.L. 2002. Morphology, stratigraphy, and origin of last interglacial beach ridges at Bream Bay, New Zealand. *J. Coastal Res.* 18(1):149–159.

Reineck, H.-E., and Singh, I.B. 1980. *Depositional Sedimentary Environments.* Berlin, Springer-Verlag.

Ontario Geological Survey 1991. *Bedrock geology of Ontario, east-central sheet.* Ontario Geological Survey, Map 2543, scale 1:1,000,000.

Stanley, G.M. 1932. Abandoned strands of Isle Royale and northeastern Lake Superior. Ph.D. dissertation, Univ. of Michigan, Ann Arbor, MI.

Stuiver, M., and Reimer, P.J. 1993. Extended 14C data base and revised CALIB 3.0 14 C age calibration program. *Radiocarbon* 35:215–230.

_____, Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, KA., Kromer, B., McCormac, F.G., Plicht, J., and Spurk, M. 1998. INTCAL98 Radiocarbon age calibration 24,000–0 cal. BP. *Radiocarbon* 40:1041–1083.

Thompson, T.A. 1992. Beach-ridge development and lake-level variation in southern Lake Michigan. *Sediment. Geol.* 80:305–318.

_____, and Baedke, S.J. 1997. Strand-plain evidence for late Holocene lake-level variations in Lake Michigan. *Geol. Soc. Am. Bull.* 109(6):666–682.

_____, Miller, C.S., Doss, P.K., Thompson, L.D.P., and Baedke, S.J. 1991. *Land-based vibracoring and vibracore analysis: tips, tricks, and traps.* Indiana Geological Survey Occasional Paper 58.

_____, Johnston, J.W., and Baedke, S.J. 2002. Reconstructing past lake-level change in Lake Superior from relict shorelines. In *Proc. 5th Conf. State-of-the-Lake: Superior,* pp. 35. Aquatic Ecosystem Health and Management Society.

Wright, H.E., Jr., Mann, D.H., and Glaser, P.H. 1984. Piston corers for peat and lake sediments. *Ecology* 65:657–659.

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