2014

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Rawling, J. Elmo III and Hanson, Paul R., "Dune formation on late Holocene sandy bay barriers along Lake Michigan's Door Peninsula: The importance of increased sediment supply following the Nipissing and Algoma high lake-level phases" (2014). *Papers in the Earth and Atmospheric Sciences*. 417.

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Dune formation on late Holocene sandy bay barriers along Lake Michigan's Door Peninsula: The importance of increased sediment supply following the Nipissing and Algoma high lake-level phases

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Abstract

This study focuses on the geomorphology and geochronology of dunes formed on three sandy barrier systems at Clark, Europe and Kangaroo Lakes in Wisconsin's Door Peninsula. The Lake Michigan shoreline in the peninsula contains abundant evidence for fluctuations in lake level with paleo-shoreline features that lie up to ~7 m above the present shoreline. Dunes are not very common along the Lake Michigan shoreline in Wisconsin, but the three bay barriers studied contain beach ridges that were buried by varying depths of eolian sand in the form of low relief sandsheets as well as parabolic and transverse dunes that have relief of up to 21 m. The purpose of this study was to document when the barriers formed and when the subsequent eolian activity occurred. The chronology presented here for barrier emplacement and dune development is based on 65 optically stimulated luminescence (OSL) samples which were collected from littoral sediment in the barriers (n = 17) and the overlying eolian sand (n = 48). Sediment samples were collected using bucket augers or a vibracoring device at depths ranging from 0.5 to 4.1 m below the ground surface. The OSL ages show that barriers in each of the study sites were constructed between ~5.9 and 3.9 ka, corresponding closely to the Nipissing high lake phase. OSL ages falling between 3.3 and 2.5 ka at the Kangaroo Lake site suggest the portion of the barrier closest to Lake Michigan formed during the Algoma phase. The majority of the eolian ages fall into two primary groups that overlap with or are slightly younger than the ages acquired from the barriers. These results suggest eolian activity ended between 4.5 and 3.7 (n = 20 ages) and 2.5 and 1.8 (n = 11 ages) ka. Both geomorphic and geochronological evidence suggests that dune development occurred rapidly when sand supply increased as lake levels fell following these two transgressive events.

Introduction

Dunes are common along the southeastern shoreline of Lake Michigan and have been extensively studied there because of their geologic interest and socioeconomic value (e.g., Arbogast et al., 2002; Hansen et al., 2010). These dunes have fairly high relief (e.g., 50–55 m) and frequently contain buried soils suggesting multiple phases of eolian activity. In addition, dune systems there are generally complex. For example, near Holland, Michigan, there are inactive backdune ridges and both active and inactive parabolic dunes (Hansen et al., 2010). Dune formation along Lake Michigan's eastern shoreline has been attributed to several forcing mechanisms, most of which relate dune formation to changes in Lake Michigan water levels. Dunes are far less prevalent on the lake's western shore where they have fairly low relief and are often limited to foredunes along the modern shoreline, or local blowouts in abandoned shoreline features such as beach ridge strandplains (hereafter just strandplains) and barriers. As a result, the dune systems on Lake Michigan's western shoreline have received little attention from the earth science community. This study focuses on the formation of high relief dunes that formed in unique environments along Lake Michigan's western shoreline in Wisconsin's Door Peninsula.

Shoreline evolution is a function of water-level fluctuations, sediment supply, geologic inheritance, and human impacts (Carter and Woodroffe, 1994). While much of the research on shoreline evolution has been conducted in oceanic settings, the North American Laurentian Great Lakes (hereafter, the Great Lakes) offer unique opportunities to study shoreline processes under different conditions. Great Lakes shorelines differ from those in oceanic settings in several key ways, including their minimal tidal influence, frequent lake-level fluctuations in the past 10 ka (Lewis and King, 2012), and the importance of isostatic adjustments that may cause concomitant lake-level rise and fall in the same basin (Mainville and Craymer, 2005). These key differences, particularly the importance of fluctuating lake levels, play an important role in the formation of dunes along shorelines of the Great Lakes.

Many Great Lakes beaches are dissipative wave-dominated shorelines (see summary by Roy et al., 1994), and one subset of these, sandy bay barriers, are those that are laterally bounded in a bay. Bay barriers can have complex surficial morphologies and their formation is influenced by factors such as substrate gradient, water-level fluctuations, and sediment supply rates. These barriers include beach, dune and nearshore lithofacies that are typically sandy or coarser grained. In low gradient embayments, which dominate the Great Lakes, bay barrier morphology is highly influenced by sediment supply. Both barriers and strandplains are preserved along shorelines throughout the Great Lakes, and these features, especially strandplains, have proven crucial for reconstructing middle to late Holocene lake-level fluctuations in the Lake Michigan (e.g., Thompson and Baedke, 1995; Dott and Mickelson, 1995; Baedke and Thompson, 2000; Argyilan et al., 2010; Thompson et al., 2011) and Superior basins (Johnston et al., 2012). Because

they are commonly dominated by sand, barriers are frequently capped with varying amounts of eolian sand, as are the three barriers at our study sites in the Door Peninsula. The dunes on the bay barriers in the Door Peninsula offer a unique opportunity to study dune activation on Lake Michigan's western shoreline, and allow earth scientists to develop a better understanding about the environmental conditions that favored dune formation in the Great Lakes.

The surficial geology of Wisconsin's Door Peninsula is dominated by Quaternary glacial deposits that overlie erosion-resistant Silurian dolostone of the Niagara Escarpment (Carson et al., 2013; Luczaj, 2013). Relict shoreline features are abundant on the Door Peninsula (Goldthwait, 1907), including wave-cut terraces, strandplains, barriers, and dunes. This study focuses on three sandy barrier systems on the peninsula's eastern shore including the Clark, Europe and Kangaroo Lake barriers (Figure 1). Each of these sites contains captured lakes that were isolated from Lake Michigan by the emplacement of the sandy barriers. After formation, the sandy barriers were subsequently modified by deflation resulting in the deposition of varying thicknesses of eolian sand, including both sand sheets and dunes. At each of the three study sites, the currently inactive eolian sand is largely forested, with isolated blowouts present locally. Lake Michigan's water level has historically averaged 176.7 m elevation and has fluctuated within $\sim \pm 1.0$ m of this average value (Wilcox et al., 2007). The strandplains within each of the three barriers we studied lie ~ 1.5 –7 m above the present Lake Michigan shoreline. The lacustrine sediment in two of these lakes has been the focus of paleoenvironmental studies (Miller et al., 1998, 2000), but these studies did not address the geomorphology of the barriers or the formation of the dunes. Elsewhere in the Lake Michigan basin, several previous studies used the lacustrine sediment within similar captured lakes to provide information on past eolian activity (e.g., Fisher and Loope, 2005; Timmons et al., 2007; Fisher et al., 2012). The goal of this study was to determine when dunes formed on these barriers by directly dating the dune and underlying barrier sand.

Methods

Geomorphology and Stratigraphy

The geomorphology of the three study sites was described using ground-based observations in conjunction with digital elevation models (DEM) constructed from light detection and ranging (LiDAR) data. The LiDAR survey was flown in April 2002 and the resulting LiDAR data was acquired from the Door County Wisconsin Land Information Office. The horizontal and vertical resolution of the LiDAR survey was within ± 10 and ± 25 cm, respectively, and the DEM was generated directly from the original data. Topographic cross-sections were drawn directly from the DEM that was created from the LiDAR data. Latitude and longitude coordinates of our field sites were acquired using hand-held GPS units, and these values were plotted on the LiDAR data to determine the elevation of

Figure 1. Locations of the Clark, Europe, and Kangaroo Lake study sites within the northern portion of Wisconsin's Door Peninsula. Shaded relief images were generated from LiDAR data. The weather station used for modern wind direction and speed is from the town of Sturgeon Bay, Wisconsin. Inset of western Great Lakes shows location of Door Peninsula within Lake Michigan.

the field sites. Uncertainty associated with our estimates for the elevations of both the surfaces and the top of the littoral sediment within the barriers is in part from the accuracy of the LiDAR data and the plotting of the field sites using commercial hand-held GPS units. It should be noted that in other portions of the Lake Michigan basin the elevations of shoreline features need to be adjusted using calculated long-term isostatic rebound rates. However, our sites on the Door Peninsula are very close to the 0 cm/century isobar (Mainville and Craymer, 2005) suggesting that isostatic adjustment has not significantly changed shoreline features in our study sites from their original elevations above lake level, as others have concluded from the area (Argyilan et al., 2010).

In order to both characterize and distinguish between the eolian and littoral deposits, and to determine the elevation of the contact between them, subsurface sediment samples were collected from each of the three barriers. Samples were collected from below the solum of both the dune and littoral deposits from 171 sites shown in Figure 2 using either bucket augers ($n = 158$) or a vibracoring device ($n = 13$). The elevation of the littoraleolian sediment contact was estimated at 48 of the 171 sites where the contact was

above the present water table or the contact was present in sediment retrieved from a vibracore. Samples for particle-size analysis were collected from the 8 cm diameter bucket auger at 25 or 50 cm depth intervals from depths of up to 7.5 m. These samples were all collected above the water table, and to minimize the potential contamination from sediment that collapsed into the hole, all samples were collected from the auger bit. The vibracore barrels were 7.6 cm in diameter, and samples for particle-size analysis were collected from depths of up to 2.7 m at 10 cm depth intervals.

Analysis of the ~950 particle-size samples was conducted on a Malvern Mastersizer 2000E following methodologies from Rawling et al. (2008). Sediment samples were dispersed by chemical treatment (NaHMP) and sonicated for 60 seconds prior to analyses. The resulting particle-size data and sediment characteristics were used to distinguish between eolian and littoral sediments. Littoral sediment was distinguished from eolian sediment based on characteristic bedding, grain size, and sand lithology. In particular, we used the presence of pebbles and coarse to very coarse sand (see Figure 3), and the presence of angular dolostone fragments (which are notably reduced or absent from eolian sediment here) as indicators of littoral sediment.

Figure 2 (continued on facing page). Shaded relief image of the Clark (A), Europe (B), and Kangaroo (C) Lake barrier systems, showing locations of sediment and optically stimulated luminescence (OSL) samples collected from bucket augers and vibracores. The topographic profile was constructed from the LiDAR data. Elevations of the captured lakes, Lake Michigan, and higher shoreline features are provided in meters above mean sea level.

Figure 2 (continued).

Figure 3. Examples of sediment typical of eolian and littoral sand from vibracores. (A) Eolian sediment from a Clark Lake dune; (B) bedded littoral sediment from the Clark Lake barrier; (C) fine-grained littoral sediment with occasional pebbles from the Kangaroo Lake barrier; and (D) example of particle-size data collected from vibracore VC-1 on the Clark Lake barrier. The estimated contact between eolian and littoral sediment is shown, and was chosen based on the increase in coarse sand percentage that occurs at ~80 cm depth. Sample locations for the vibracores are in Tables 1 and 2.

Figure 4. Topographic profiles of the Clark, Europe, and Kangaroo Lake barriers. Cross-section locations are shown on Figures 2A–2C. Surface elevations are taken from LiDAR data. Dashed lines indicate the approximate elevations of the littoral-eolian boundary that was determined through bucket auger and vibracoring. The number of sample sites that the elevations are based on are given (n = 48 total). The inset in the lower right shows the topographic profiles drawn at the same scale.

The resultant depths of the contact between the eolian and littoral sediment were used to estimate the elevation of the original littoral surface and those boundaries are shown on the topographic profiles in Figure 4. The uncertainty in the elevation of the eolian-littoral contact is based on the assumptions related to plotting the sediment profile sites on the DEM, and our ability to distinguish between

eolian and littoral sediment from our subsurface investigations. This latter distinction is important to note, because bedding cannot be analyzed in the hand augered holes, and in some cases the littoral sediment is similar in grain size to the eolian sediment. To assess the validity of our ability to distinguish between eolian and littoral sediment we analyzed sediment from nine bucket auger borings that

Figure 5 (continued on following pages). Shaded relief images of the Clark (A), Kangaroo (B), and Europe (C) Lake barriers including OSL age estimates with 1 σ errors from littoral sediment (upper image) and the overlying eolian dunes and sandsheets (lower image). Circles indicate samples collected using a bucket auger and squares indicate samples collected using a vibracoring device. The inset rose diagrams show 52 measurements of slip face orientations from dune crests at Clark Lake and 5012 wind directions with speeds that exceed 6 m/s. These latter readings were taken from Sturgeon Bay (Figure 1), and included data from the years 1982–1996 (data from 1984 and 1985 were not used because of incomplete data collection in those years).

were collected adjacent to vibracore sites. In these comparisons estimated depths of the eolian-littoral contacts varied within $\sim \pm 0.5$ m, suggesting bucket augering was not adversely impacting our estimations. Finally, because the barriers are capped by eolian sand throughout our study areas, the original barrier surface may have been lowered by eolian deflation, and therefore the original littoral surface may have been appreciably higher prior to wind erosion. Considering each of these potential caveats and sources of uncertainty, our estimated eolian-littoral contacts are likely accurate to within ± 1 m.

Finally, at the Clark Lake barrier we measured the aspect of 52 dune slip faces with compasses, and the dune-forming wind directions were estimated at 180° from the field measurement. These estimates were compared to historical data taken from a weather station at the town of Sturgeon Bay (see Figures 1, 5A) using wind speed and direction data from the years 1982–1996 (data from the 1984 and 1985 years were eliminated because of incomplete data collection in those years). For this purpose only winds that

had a velocity of at least 6 m/sec, a common threshold for the movement of fine-medium sand (cf. Sridhar et al., 2006; Mason et al., 2008) was used from the historic data.

Optically Stimulated Luminescence Dating

The 65 optically stimulated luminescence (OSL) samples were collected from eolian ($n = 48$) and littoral ($n = 17$) sediment using the bucket auger and vibracoring devices described above. OSL samples were collected from depths of at least 0.8 m below the ground surface to avoid problems with the potential resetting of OSL signals by bioturbation as discussed by Rawling et al. (2008), with the exception of the one sample that was collected along the modern Lake Michigan shoreline. The majority of our samples were collected with bucket augers because the technique allowed us to collect sediment from >1.0 m below the ground surface where bioturbation had been identified as a problem by Rawling et al. (2008). In addition, the dry sediment present in the dune crests precluded us from using the vibracoring

Figure 5 (continued).

device in the higher relief dunes of this study. OSL samples were taken from the inner portions of the bucket auger and the vibracore tube to avoid potentially contaminated grains that are commonly found along the inside edges of these devices.

OSL samples were processed at the University of Nebraska–Lincoln and were wet sieved to isolate 90–150 μm sand grains, treated in hydrochloric acid to remove carbonates, floated in 2.7 g/cm³ sodium polytungstate to remove heavy minerals, and treated in 48% hydrofluoric acid for ~75 min to remove feldspars and etch quartz grains. Following this procedure, the remaining sample was treated in hydrochloric acid for ~30 min to remove any fluorides and then re-sieved to remove grains that were <90 μm . The purity of the quartz separate was checked by both visual inspection and with exposure to infrared diodes on the luminescence reader.

OSL measurements were conducted on two Risø model DA-20 luminescence readers. Preheat temperatures were

determined by using preheat plateau tests (Wintle and Murray, 2006), and based on these tests, the samples were run with 10 second preheats of either 200 or 220 °C. Similarly, Argyilan et al. (2010) used a preheat temperature of 220 °C to date young sediment (<1000 yr) in beach ridges with OSL at Bailey's Harbor (located ~8 km northeast of Kangaroo Lake; Figure 1). Dose recovery tests (see Wintle and Murray, 2006) were performed on one sample from each of the three study sites to ensure that the luminescence dating protocol was appropriate for these samples. The natural luminescence signals were zeroed using two room temperature shinedowns with the reader's blue diodes that were separated by a 10,000 second pause. This procedure was followed by the addition of a 9.6 Gy beta dose, which was recovered using the same SAR procedure used to generate the natural D_e values. The recovered dose fell within 1 σ errors of the administered laboratory dose for all samples, suggesting the chosen protocol was appropriate for dating sediment at the three sites.

Figure 5 (continued).

Equivalent dose (D_e) values were calculated using the single aliquot regenerative (SAR) method (Murray and Wintle, 2000) on 90–150 μm quartz grains mounted to the inner 5 mm of 10 mm aluminum disks. Individual aliquots were rejected if their recycling ratios were $> \pm 10\%$, if they had measureable signals when exposed to infrared diodes, or if their D_e value was greater than 3σ from the mean D_e value. The Central Age Model (CAM) (Galbraith et al., 1999) was used to calculate the D_e values used in the age estimates. Dose rate estimates were based on elemental concentrations of bulk sediments taken from an ~ 30 cm radius surrounding the OSL sample. Bulk sediment samples were milled and analyzed for concentrations of K, U, and Th using a high-resolution gamma spectrometer. The cosmogenic component of the dose rate values were calculated using equations from Prescott and Hutton (1994), and the final dose rates calculated following equations from Aitken (1998). OSL dating results are shown in Tables 1, 2, and 3.

Study Area Geomorphology and Surficial Geology

The three study areas are within 50 km of each other and presumably experienced similar climatic, lake-level fluctuation, and Holocene histories, and as a consequence the three barriers show some key similarities. Barrier morphology and elevations are shown in Figures 2 and 4. All elevations were estimated using the LiDAR-based digital elevation models. These estimates are approximate and within errors of the methods discussed previously.

Clark Lake

At least two prominent paleo-shorelines are found along Clark Lake, including a cobble ridge with a crest at 183.5 m and a wave-cut platform at 193.5 m elevation (Figure 2A). Both of these ridges lie above the Clark Lake barrier, which lies between Clark Lake (179.9 m) and Lake Michigan (176.7 m) (Figure 2A). The barrier

ranges from 700 to 1000 m wide and the extreme eastern end of the Clark Lake barrier abuts Silurian dolostone bedrock (Figure 2A).

The Clark Lake barrier is covered by varying thickness of eolian sand sheets and dunes, causing its surface elevation to exceed 190 m elevation locally. The modern Lake Michigan beach contains low relief foredunes that transition into large parabolic dune forms on most of the barrier (Figure 4A), although there is a strandplain in the extreme southwestern edge of the barrier. The portion of the barrier adjacent to Lake Michigan is overlain by an ~250-m-wide stretch of high relief (~18–25 m) parabolic and transverse dunes (Figure 4A). Superimposed parabolic dunes occur in the northeastern half of the barrier and transverse dunes with few parabolic forms are found in the southwest. There is an ~150-m-wide area of lower relief (~6 m high) parabolic dunes landward, some of which are superimposed upon one another. Finally, the portion of the barrier platform between the low relief dunes and Clark Lake is 300–500 m wide and is low in relief with a few 1–2-m-high discontinuous beach ridges. These beach ridges are locally capped with eolian sand sheets.

Kangaroo Lake

Two relatively high shoreline features are found along the western edge of Kangaroo Lake, and include a wave-cut platform in Silurian dolostone (193.5 m) and a cobble shoreline (183.5 m at the crest) (Figure 2B). The barrier itself ranges from 700 to 1000 m in width separating Kangaroo Lake (183 m) from Lake Michigan (Figure 4B). The modern Lake Michigan beach transitions into a 70–120-m-wide area of relatively low-relief transverse dunes, most of which are ~3.5 m high but several exceed 12 m in height. The very northeastern portion of the barrier is a strandplain with beach ridges that have ~1.5 m of relief (Figure 2B). An ~400-m-wide barrier platform separates the low relief transverse dunes from a 100–175-m-wide zone of high relief parabolic and transverse dunes that lie adjacent to Kangaroo Lake (Figure 2B). The dunes along this ridge, some of which are superimposed on one another, increase in size from southwest to the northeast. The dunes are ~6 m high in the southwest, increasing to ~16 m high in the central portion, and are up to ~24 m high along the northeastern edge of the barrier (Figure 2B). Along the southwestern portion of this prominent dune ridge is an ~3-m-high beach ridge that may be covered with eolian sand to the northeast. There is a narrow barrier platform between the large dunes and Kangaroo Lake that ranges from ~50 to 450 m wide. The surface elevation of the broad barrier platform that lies between the low and high relief dunes ranges between 178 and 180 m and lies at an elevation of 182.5 m between the large dunes and Kangaroo Lake (183 m).

Europe Lake

Europe Lake is the northernmost study site and is located near the tip of the Door Peninsula (Figure 1).

Geomorphic evidence exists for at least two paleo-shoreline features along the west and north sides of Europe Lake that are found at elevations of ~199.6 and 190 m (Figure 4C). The latter of these features is shown in Figure 2C. The barrier that separates Europe Lake (184.3 m) from Lake Michigan is ~250–300 m wide and has a surface elevation of at least 180 m (Figure 2C). At Europe Lake, the modern Lake Michigan beach transitions into an ~200-m-wide strandplain with beach ridges that are ~1.5–2 m high. These beach ridges are covered by a varying thickness of eolian sand. The remainder of the barrier does not contain decipherable beach ridges but instead is predominantly a ridge of transverse dunes with relief ranging from ~3.5 to 7.5 m high. These dunes are highest along Europe Lake in the northeastern portion of the barrier.

Results

The elevation of the eolian/littoral contact within the three barriers ranges from 178 to 183.5 m. The upper limit of the littoral sediment within the Clark Lake barrier is fairly uniform and rests at 179–181 m (Figure 4). In the Kangaroo and Europe Lake barriers the littoral sediment has considerably more relief. At Kangaroo Lake, the top of the littoral sediment adjacent to Lake Michigan ranges from 178 to 180 m elevation and rises to 182 m elevation beneath the high relief parabolic and transverse dunes on the northern edge of the barrier. The top of the littoral fill in the Europe Lake barrier ranges from 178.5 m near Lake Michigan to 180–183.5 m on the inland side of the barrier. In each of the barriers, the top of the littoral sediment is close to the elevation of the isolated lake. Fifty-two measurements of dune slip face directions were recorded to estimate the paleowind direction that formed the dunes at the Clark Lake site. Most of these measurements were taken from the higher relief dunes present in the eastern portion of the barrier, and the inferred paleowind directions are plotted in a wind rose in Figure 5A. Estimated wind directions ranged from 124 to 254° with most measurements ranging from 150 to 210°. These findings suggest that most dunes formed from southerly winds. At the weather station in Sturgeon Bay, Wisconsin (Figure 1) winds oriented from 150 to 210° occurred frequently throughout the year (Figure 5A), and strong winds with these orientations were particularly frequent during both fall and spring. At the Kangaroo and Europe Lake sites the general lack of well-developed parabolic dune forms precluded us from directly measuring dune slip faces, however those present also appear to have formed from southerly winds (Figures 2B, 2C).

OSL Dating Results

Clark Lake Barrier

Twenty-seven OSL ages were collected from the Clark Lake eolian deposits ($n = 22$) and littoral sediment from the barrier ($n = 5$) to determine the timing of barrier sand deposition and provide a maximum age for eolian activity

Table 1. Equivalent dose, dose rate data, and OSL age estimates for Clark Lake barrier on the Door Peninsula, Wisconsin

Field ID	UNL Lab ID	Depth (m)	U (ppm)	Th (ppm)	K ₂ O (wt%)	In situ H ₂ O (%)	Dose rate (Gy/ka)	CAM [†] D _e (Gy) ± 1 Std. Err.	Aliquots (n) [§]	O.D. [#] %	OSL age ka ± 1 σ	Depositional environment	Latitude	Longitude
WFD 1-1	UNL-2755	1.3	0.4	1.5	1.2	4.1	1.27 ± 0.09	4.9 ± 0.4	22/27	31.8 ± 5.6	3.9 ± 0.4	Eolian	44.92673	-87.18994
WFD 2-1	UNL-2760	1.3	0.6	2.1	1.8	4.1	1.84 ± 0.13	3.5 ± 0.2	20/27	18.5 ± 4.3	1.9 ± 0.2	Eolian	44.92647	-87.18804
WFD 2-2	UNL-2873	2.7	0.8	2.0	1.7	4.2	1.75 ± 0.12	4.1 ± 0.2	23/37	23.1 ± 3.8	2.3 ± 0.2	Eolian	44.92647	-87.18804
WFD 3-1	UNL-2758	1.4	0.4	1.8	1.6	5.4	1.59 ± 0.12	3.8 ± 0.4	23/34	40.8 ± 6.9	2.4 ± 0.3	Eolian	44.92620	-87.19093
WFD 3-2	UNL-2863	2.5	0.6	2.6	1.8	4.1	1.80 ± 0.12	4.4 ± 0.4	20/24	38.3 ± 6.5	2.5 ± 0.3	Eolian	44.92620	-87.19093
WFD 4-1	UNL-2763	1.9	0.5	1.5	1.0	4.3	1.27 ± 0.17	5.6 ± 0.2	22/42	12.4 ± 3.5	4.9 ± 0.4	Eolian	44.92686	-87.19094
WFD 5-1	UNL-2759	1.4	0.5	1.9	1.4	3.3	1.50 ± 0.10	6.2 ± 0.4	27/40	28.3 ± 4.5	4.1 ± 0.4	Eolian	44.92566	-87.19213
WFD 6-1	UNL-2761	1.3	0.3	1.1	0.7	7.0	0.83 ± 0.06	6.1 ± 0.4	21/39	30.7 ± 5.5	7.4 ± 0.8	Eolian	44.92711	-87.19214
WFD 7-1	UNL-2756	1.2	0.6	1.6	1.3	7.7	1.35 ± 0.11	6.8 ± 0.3	35/53	23.6 ± 3.5	5.0 ± 0.5	Eolian	44.92476	-87.19680
WFD 8-1	UNL-2757	3.1	0.5	2.3	1.3	4.6	1.42 ± 0.10	6.2 ± 0.3	20/24	20.4 ± 3.8	4.4 ± 0.4	Littoral	44.92374	-87.19793
WFD 9-1	UNL-2762	1.2	0.6	1.5	1.2	19.9	1.09 ± 0.17	5.0 ± 0.4	24/29	32.6 ± 5.8	4.5 ± 0.8	Littoral	44.93176	-87.18654
WFD 11-1	UNL-2864	1.5	0.5	1.8	1.2	3.5	1.33 ± 0.12	5.2 ± 0.3	26/34	26.6 ± 4.1	3.9 ± 0.4	Eolian	44.92871	-87.18353
WFD 12-1	UNL-2865	1.1	0.7	2.0	1.5	4.9	1.60 ± 0.11	7.0 ± 0.4	21/26	23.5 ± 4.0	4.4 ± 0.4	Eolian	44.92876	-87.18463
WFD 13-1	UNL-2866	1.1	0.4	2.0	1.2	4.2	1.28 ± 0.08	4.7 ± 0.3	28/32	33.4 ± 5.0	3.7 ± 0.4	Eolian	44.92860	-87.18571
WFD 20-1	UNL-2867	1.7	0.6	2.1	1.1	3.8	1.30 ± 0.08	5.5 ± 0.4	20/26	28.9 ± 5.1	4.2 ± 0.4	Eolian	44.92255	-87.20030
WFD 21-1	UNL-2868	1.6	0.6	2.2	1.2	4.0	1.33 ± 0.08	5.6 ± 0.4	22/31	31.4 ± 5.2	4.2 ± 0.4	Eolian	44.92290	-87.19843
WFD 22-1	UNL-2869	1.5	0.6	1.9	1.5	3.9	1.57 ± 0.10	5.4 ± 0.3	21/29	24.1 ± 4.2	3.4 ± 0.3	Eolian	44.92357	-87.19604
WFD 23-1	UNL-2870	1.4	0.6	2.0	1.4	4.7	1.50 ± 0.10	6.1 ± 0.3	20/26	23.3 ± 4.1	4.1 ± 0.4	Eolian	44.92482	-87.19829
WFD 24-1	UNL-2871	1.7	0.5	1.9	1.7	3.7	1.68 ± 0.11	1.6 ± 0.2	30/54	43.9 ± 7.8	1.0 ± 0.1	Eolian	44.92552	-87.19058
WFD 25-1	UNL-2872	1.5	0.6	2.1	1.3	3.5	1.42 ± 0.09	3.2 ± 0.4	20/34	60.8 ± 9.9	2.3 ± 0.4	Eolian	44.92770	-87.18750
WFD VC1-1	UNL-3534	2.6	0.6	1.8	1.5	6.1	1.53 ± 0.12	6.2 ± 0.2	33/39	21.1 ± 3.0	4.5 ± 0.6	Eolian	44.92552	-87.19625
WFD VC3-1	UNL-3537	0.8	0.6	2.3	1.2	19.5	1.18 ± 0.17	5.0 ± 0.2	31/40	18.5 ± 2.9	4.4 ± 0.7	Eolian	44.92191	-87.20918
WFD VC3-2	UNL-3538	1.9	0.4	2.0	0.9	19.5	0.91 ± 0.13	4.9 ± 0.2	29/40	23.2 ± 3.8	5.4 ± 0.9	Littoral	44.92191	-87.20918
WFD VC4-1	UNL-3539	1.7	0.4	1.6	1.3	7.2	1.29 ± 0.10	5.1 ± 0.2	29/40	23.5 ± 3.7	4.1 ± 0.5	Littoral	44.92693	-87.18517
WFD 26-1	UNL-3549	2.9	0.7	2.3	1.8	21.7	1.53 ± 0.27	6.9 ± 0.3	34/41	22.6 ± 3.3	4.5 ± 0.9	Littoral	44.92551	-87.19625
WFD 27-1	UNL-3550	1.5	0.6	2.1	1.4	4.5	1.48 ± 0.10	5.9 ± 0.3	35/51	29.9 ± 4.2	4.0 ± 0.4	Eolian	44.91813	-87.20934
WFD 28-1	UNL-3551	1.8	0.6	1.9	1.7	4.1	1.69 ± 0.12	5.2 ± 0.2	33/40	21.1 ± 3.1	3.1 ± 0.3	Eolian	44.91628	-87.20907

OSL – optically stimulated luminescence. UNL – University of Nebraska-Lincoln.

*Assumes 100% error in estimated moisture content.

[†]Central Age Model (Galbraith et al., 1999).[§]Accepted disks/all disks.[#]Overdispersion.

on these landforms (Table 1). The five littoral samples were collected from depths ranging from 3.1 to 1.2 m below the ground surface and were collected from the eastern, central, and western portion of the barrier (Figure 5A). Three of these littoral samples were collected from below the dune and sandsheet deposits that cover the barrier, while two samples were taken from the barrier platform to the north of the high relief dunes. One of these samples from the barrier platform was collected from below a beach ridge in the northeastern portion of the study area (Figure 5A). This sample yielded an age of 4.5 ± 0.8 ka. The other sample collected from the littoral sediment below the barrier's surface was collected from 1.9 m depth from the western portion of the study area (Figure 5A), and this sample was dated at 5.4 ± 0.9 ka. An OSL age taken from 0.8 m depth from the eolian sandsheet directly overlying this sample was dated at 4.4 ± 0.7 ka. The remaining three littoral sediment samples were collected from within the portion of the barrier that underlies thicker eolian sediment and included two samples collected from below eolian sand sheets and one from littoral sediment underlying eolian sand below a dune crest. These three samples were collected from the eastern and central portion of the barrier (Figure 5A) and were dated between 4.5 and 4.1 ka. One of these samples, UNL-3539, was dated to 4.1 ± 0.5 ka and was collected from within ~150 m of the present-day shore of Lake Michigan. These five OSL ages collected from littoral sediment within the Clark Lake barrier fall between 5.4 and 4.1 ka and all overlap within their 1 σ errors.

The 22 OSL ages collected from eolian sediment at the Clark Lake barrier were taken from below either dune crests ($n = 20$) or sandsheets ($n = 2$) at depths of 2.7–0.8 m below the present ground surface. The two sandsheet samples were from vibracores from the barrier platform in the western portion of the study area and below a sandsheet from the central portion of the barrier (Figure 5A). These two samples were dated at 4.4 ± 0.7 and 4.5 ± 0.6 ka, respectively. The twenty remaining eolian samples were collected from throughout the high relief dunes, but most were taken in the central and eastern portion of the barrier (Figure 5A). The OSL samples collected from below dune crests were dated between 7.4 and 1.0 ka, with the majority of these ages (13/22) ranging between 5.0 and 3.7 ka (Table 1). The oldest eolian age from Clark Lake (7.4 ± 0.8 ka) was taken from a dune crest on the northwestern portion of the barrier. This sample falls well outside of the 1 σ errors from the other eolian samples collected from this site, and the older age for this sample is attributed to problems in estimating its environmental dose rate that varies considerably from the others (Table 1). The six youngest eolian ages from the Clark Lake dunes range in age from 2.5 to 1.0 ka. These samples were all collected from a region of relatively high relief dunes close to the modern Lake Michigan shoreline on the eastern side of the study area (Figure 5A). Two other notable younger dune ages are from below dune crests in the central and western portion of the study area; these two ages are dated at 3.1 ± 0.3 and 3.4 ± 0.3 ka (Figure 5A).

Kangaroo Lake Barrier

Twenty-seven OSL samples were analyzed from the Kangaroo Lake site (Table 2), including 16 samples from eolian sand and 11 samples from littoral sediment (Figure 5B). Ten of the littoral sediment samples were collected from depths of 2.8–0.9 m below the present ground surface in the barrier, and one additional sample was taken from along the modern Lake Michigan beach at 0.5 m depth. Nine of these littoral sediment samples were collected from vibracores and the remaining two were taken from bucket augers. Seven littoral sediment samples were collected from either side of the high relief dunes found at the western edge of the Kangaroo Lake barrier. The two OSL samples collected from the littoral sediment on the Kangaroo Lake side of the barrier yielded ages of 5.9 ± 1.1 and 5.2 ± 1.0 ka (Figure 5B). Five OSL samples were collected from the southern portion of this prominent dune ridge in a region of relatively low relief dunes and beach ridges (Figure 5B). These five ages ranged from 5.3 to 4.4 ka, with one age dating to 3.4 ka (Figure 5B). This latter age is younger than most other ages from this portion of the barrier, but it does overlap with sample UNL-3181 which was dated to 3.9 ± 0.5 at the 1 σ confidence interval. These seven samples were collected from littoral sediment that has a maximum elevation of 181–182 m (Figure 4). The three samples from littoral sediment below the lower relief dunes adjacent to Lake Michigan were dated between 2.5 and 3.3 ka (Figure 5B). These samples were collected from littoral sediment that has a maximum elevation of 178–180 m (Figure 4). The sample taken from 50 cm below the modern beach in close proximity to these samples yielded an age of 0.9 ± 0.2 ka. The relatively old age for this sample is addressed in the discussion section.

Sixteen OSL samples were analyzed from eolian sediment collected from between 1.9 and 0.9 m below the present ground surface. Eolian samples were collected from the dune ridge near Lake Michigan, the higher relief dunes adjacent to Kangaroo Lake, and the intervening sand sheet and lower relief dunes between these two areas (Figure 5B). Five OSL samples were collected from dune crests on the prominent dune ridge adjacent to Lake Michigan. These ages ranged from 2.4 to 2.1 ka. One OSL sample collected from a sandsheet between the two prominent dune ridges was dated at 3.3 ± 0.6 ka (Figure 5B). Ten OSL ages were analyzed from samples taken below dune crests on the large dune ridge adjacent to Kangaroo Lake (Figure 5B). These ages ranged from 6.9 to 2.8 ka, with seven of the ten ages falling between 4.7 and 3.5 ka.

Europe Lake Barrier

Eleven OSL samples were analyzed from the Europe Lake site (Table 3), including ten samples from eolian sand and one from littoral sediment. Each of these samples was collected using hand augers. One sample was taken from littoral sediment below a beach ridge that was capped by a thin deposit of eolian sand. This littoral sample was taken from 3.3 m depth and yielded an age of 4.4 ± 0.7 ka (Figure 5C). A sample taken from 2 m depth in the overlying eolian sand on this same beach ridge was dated at 3.5 ± 0.3 ka.

Table 2. Equivalent dose, dose rate data, and OSL age estimates for Kangaroo Lake barrier on the Door Peninsula, Wisconsin

Field ID	UNL Lab ID	Depth (m)	U (ppm)	Th (ppm)	K ₂ O (wt %)	In situ H ₂ O (%) [*]	Dose rate (Gy/ka)	CAM [†] D _e (Gy) ± 1 Std. Err.	Aliquots (n) [§]	O.D. [#] %	OSL age ka ± 1σ	Depositional environment	Latitude	Longitude
KL 17-1	UNL-3553	1.8	0.6	1.5	1.9	5.5	1.80 ± 0.14	4.4 ± 0.2	29/34	16.0 ± 2.8	2.4 ± 0.2	Eolian	45.00617	-87.16293
KL 18-1	UNL-3554	1.8	0.5	1.7	1.8	5.7	1.76 ± 0.13	4.3 ± 0.2	28/34	14.6 ± 3.2	2.4 ± 0.2	Eolian	45.00850	-87.15779
KL 19-1	UNL-3555	1.9	0.5	1.8	1.7	4.8	1.71 ± 0.12	3.7 ± 0.2	29/34	17.9 ± 3.4	2.1 ± 0.2	Eolian	45.00859	-87.15770
KL 20-1	UNL-3556	1.8	0.5	1.5	1.7	3.6	1.70 ± 0.12	4.1 ± 0.3	27/34	28.2 ± 5.6	2.4 ± 0.3	Eolian	45.00877	-87.15739
KL 21-1	UNL-3557	1.9	0.6	2.1	1.8	4.5	1.77 ± 0.12	4.2 ± 0.1	27/32	7.1 ± 2.1	2.4 ± 0.2	Eolian	45.00992	-87.15455
KL VC1-1	UNL-3541	1.6	0.4	1.5	1.4	19.7	1.20 ± 0.19	6.2 ± 0.2	32/39	18.2 ± 2.6	5.1 ± 0.9	Littoral	45.00953	-87.16467
KL VC2-2	UNL-3559	2.8	0.5	1.9	1.8	19.0	1.52 ± 0.25	5.2 ± 0.3	37/39	30.2 ± 4.2	3.4 ± 0.6	Littoral	45.00992	-87.16452
KL VC3-1	UNL-3543	0.9	0.6	1.7	0.9	25.0	0.92 ± 0.16	5.4 ± 0.2	27/33	14.9 ± 2.7	5.9 ± 1.1	Littoral	45.01118	-87.16562
KL VC4-1	UNL-3545	0.9	0.7	1.8	1.6	22.8	1.18 ± 0.21	6.1 ± 0.2	37/41	17.5 ± 2.4	5.2 ± 1.0	Littoral	45.01166	-87.16536
KL VC5-1	UNL-3547	1.8	0.5	1.6	1.9	20.5	1.52 ± 0.26	6.5 ± 0.3	29/39	21.5 ± 3.3	4.4 ± 0.8	Littoral	45.00912	-87.16419
KL VC5-2	UNL-3548	1.2	0.6	1.9	1.5	20.4	1.32 ± 0.21	4.4 ± 0.2	35/40	26.4 ± 3.6	3.3 ± 0.6	Eolian	45.00912	-87.16419
KL-2	UNL-3174	1.8	0.5	1.7	1.1	3.9	1.27 ± 0.08	6.8 ± 0.5	34/50	40.8 ± 5.2	5.3 ± 0.6	Eolian	45.01439	-87.15989
KL-3	UNL-3175	1.8	0.6	2.0	1.2	4.1	1.37 ± 0.09	6.0 ± 0.5	23/28	42.1 ± 6.5	4.4 ± 0.5	Eolian	45.01361	-87.16167
KL-4	UNL-3176	1.7	0.5	1.8	1.0	3.8	1.18 ± 0.07	8.1 ± 0.7	36/40	47.4 ± 5.8	6.9 ± 0.8	Eolian	45.01271	-87.16305
KL-6	UNL-3178	1.8	0.6	2.4	1.1	4.0	1.32 ± 0.08	4.6 ± 0.4	31/54	43.4 ± 6.1	3.5 ± 0.4	Eolian	45.01182	-87.16365
KL-7	UNL-3179	1.8	0.8	2.3	1.1	3.6	1.36 ± 0.08	6.4 ± 0.6	36/47	55.5 ± 6.7	4.7 ± 0.6	Eolian	45.01226	-87.16280
KL-8	UNL-3180	1.8	0.5	2.0	1.4	4.0	1.47 ± 0.10	7.8 ± 0.5	37/45	33.5 ± 4.3	5.3 ± 0.5	Littoral	45.01015	-87.16410
KL-9	UNL-3181	1.8	0.6	2.4	1.5	4.9	1.61 ± 0.11	6.3 ± 0.5	24/27	36.6 ± 5.9	3.9 ± 0.5	Littoral	45.00959	-87.16467
KL-10	UNL-3182	1.8	0.6	1.7	1.3	1.5	1.47 ± 0.09	6.1 ± 0.4	33/46	39.0 ± 5.4	4.1 ± 0.4	Eolian	45.01609	-87.15240
KL-12	UNL-3384	1.8	0.7	1.9	1.1	3.4	1.31 ± 0.08	4.8 ± 0.5	20/24	41.9 ± 7.0	3.7 ± 0.5	Eolian	45.01136	-87.16516
KL-13	UNL-3385	1.8	0.6	2.0	1.4	4.2	1.49 ± 0.10	5.6 ± 0.4	25/27	35.0 ± 5.6	3.7 ± 0.4	Eolian	45.01316	-87.16032
KL-14	UNL-3386	1.7	0.5	2.2	1.3	3.9	1.44 ± 0.09	4.0 ± 0.4	20/27	44.9 ± 7.4	2.8 ± 0.4	Eolian	45.01302	-87.16138
KL-16	UNL-3387	1.8	0.5	2.1	1.3	3.1	1.43 ± 0.09	5.4 ± 0.4	21/27	27.8 ± 5.0	3.8 ± 0.4	Eolian	45.01562	-87.15354
KL-VC6-1	UNL-3643	1.0	1.0	1.2	1.1	2.1	1.35 ± 0.08	4.5 ± 0.2	30/33	25.3 ± 3.8	3.3 ± 0.3	Littoral	45.01029	-87.15445
KL-VC7-1	UNL-3644	1.4	0.9	1.4	1.6	2.8	1.69 ± 0.10	5.6 ± 0.3	27/34	23.7 ± 3.6	3.3 ± 0.3	Littoral	45.00615	-87.16337
KL-VC8-1	UNL-3645	0.5	1.2	1.3	1.0	5.6	1.31 ± 0.08	1.2 ± 0.3**	24/30	33.5 ± 9.6	0.9 ± 0.2	Littoral	45.00565	-87.16219
KL-VC9-1	UNL-3646	1.2	1.0	1.5	1.7	3.5	1.78 ± 0.11	4.4 ± 0.3	27/35	29.7 ± 4.6	2.5 ± 0.3	Littoral	45.01029	-87.15445

OSL – optically stimulated luminescence. UNL – University of Nebraska–Lincoln.

^{*}Assumes 100% error in estimated moisture content.[†]Central Age Model (Galbraith et al., 1999).[§]Accepted disks/all disks.[#]Overdispersion.^{**}Reported value is the mean D_e the D_e calculated using the Central Age Model was 2.4 ± 0.3.

Table 3. Equivalent dose, dose rate data, and OSL age estimates for Europe Lake barrier on the Door Peninsula, Wisconsin

Field ID	UNL Lab ID	Depth (m)	U (ppm)	Th (ppm)	K ₂ O (wt %)	In situ H ₂ O (%) [*]	Dose rate (Gy/ka)	CAM [†] D _e (Gy) ± 1 Std. Err.	Aliquots (n) [‡]	O.D. [§] %	OSL age ka ± 1σ	Depositional environment	Latitude	Longitude
NP-2	UNL-3184	1.7	0.8	2.3	1.5	4.6	1.60 ± 0.11	6.4 ± 0.5	33/40	44.1 ± 5.7	4.0 ± 0.5	Eolian	45.26655	-86.98644
NP-3	UNL-3185	4.1	0.5	2.5	1.5	2.6	1.61 ± 0.10	7.3 ± 0.4	30/40	31.0 ± 4.2	4.5 ± 0.4	Eolian	45.26715	-86.98542
NP-4	UNL-3186	1.9	0.5	2.2	1.5	4.1	1.56 ± 0.10	5.8 ± 0.5	32/40	47.4 ± 6.1	3.7 ± 0.4	Eolian	45.26873	-86.98370
NP-5	UNL-3187	1.8	0.7	2.2	1.7	4.5	1.72 ± 0.12	7.6 ± 0.6	34/38	41.2 ± 5.3	4.4 ± 0.5	Eolian	45.27051	-86.98190
NP-6	UNL-3188	1.7	0.5	1.8	1.0	3.9	1.16 ± 0.07	2.0 ± 0.2	20/37	40.1 ± 8.9	1.7 ± 0.2	Eolian	45.26336	-86.98499
NP-8	UNL-3190	1.8	0.6	1.8	1.5	3.9	1.54 ± 0.10	8.4 ± 0.5	37/50	31.0 ± 3.9	5.5 ± 0.5	Eolian	45.26407	-86.98656
NP-12 S	UNL-3389	2.0	0.6	2.2	1.7	3.3	1.71 ± 0.11	6.0 ± 0.3	22/27	22.7 ± 4.0	3.5 ± 0.3	Eolian	45.26826	-86.98283
NP-12 D	UNL-3390	3.3	0.7	2.5	1.3	16.9	1.24 ± 0.17	5.4 ± 0.4	25/37	34.3 ± 5.2	4.4 ± 0.7	Littoral	45.26826	-86.98283
NP-13	UNL-3391	1.3	0.6	2.1	1.4	4.3	1.47 ± 0.10	2.7 ± 0.2	28/34	22.0 ± 4.7	1.8 ± 0.2	Eolian	45.26773	-86.98206
NP-15	UNL-3392	1.6	0.5	1.9	1.8	4.3	1.80 ± 0.13	9.0 ± 0.8	26/36	46.0 ± 6.7	5.0 ± 0.6	Eolian	45.27054	-86.97985
NP-16	UNL-3388	1.8	0.7	2.5	1.9	4.1	1.99 ± 0.12	6.6 ± 0.3	24/33	21.3 ± 3.5	3.3 ± 0.3	Eolian	45.27015	-86.97961

OSL—optically stimulated luminescence. UNL—University of Nebraska-Lincoln.

^{*}Assumes 100% error in estimated moisture content.[†]Central Age Model (Galbraith et al., 1999).[‡]Accepted disks/all disks.[§]Overdispersion.

The remaining OSL ages were collected from both eolian sandsheets and low relief hummocky dunes that overlie beach ridges. Four OSL ages collected from depths of 4.1–1.7 m below relatively high relief dunes adjacent to Europe Lake ranged from 4.5 to 3.7 ka (Figure 5C). Six OSL ages taken from depths ranging from 2.0 to 1.3 m below thin sand sheets overlying beach ridges ranged from 5.5 to 1.7 ka (Table 1). In general, the youngest eolian sand is found adjacent to Lake Michigan at the Europe Lake site (Figure 5C).

In summary, the 16 OSL samples collected from the littoral sediment in the three barriers studied yielded ages that ranged from 5.9 to 2.5 ka (see Figure 6). The littoral sample collected along the modern Lake Michigan beach profile yielded an age of 0.9 ± 0.2 ka. The 48 OSL ages collected from eolian deposits from the three barriers ranged from 7.4 to 1.0 ka, with 45 of these ages falling between 5.5–1.7 ka.

Discussion

Previous works interpreted the Door County barriers as either baymouth (Schneider, 1993) or longshore (Carson et al., 2013) bars that formed during transgressive stages. Similarly, we interpret them as bay barriers that formed as a direct consequence of longshore movement of sand that was trapped in these bays during transgressive events. We further suggest that rates of longshore sand movement were elevated during transgressive events, and that during these events increased sand supply was fostered by wave erosion along the peninsula. This interpretation is based in part on the large volume of quartz-rich sand in these barriers and other strandplains in the eastern Door Peninsula, including Bailey's Harbor. In addition, although the clay-rich tills and related glacial sediment in the uplands contain quartz sand, the dolostone bedrock which is present at or very near the surface along each of the three study basins (Carson et al., 2013), is not a significant source for the sand in the barriers. In fact, dolostone headlands, cobble beach ridges and wave-cut platforms (Figures 2A, 2B, 2C) are found along each of the captured lakes we studied, and bedrock is commonly within 2 m of the ground surface through much of the Peninsula (Carson et al., 2013). We suggest much of the quartz-rich sand had to be eroded from sediment lying between the modern shoreline at 176.7 m and the transgressive peak, which was ~182 m for the Nipissing phase. Based on these observations we suggest the barriers were constructed as a consequence of wave erosion that liberated sand from the region's shorelines and subsequent longshore movement of the sand into the bays during and shortly after transgression events.

OSL Chronology

Although not supported by independent age control, our findings indicate the OSL results provide a reliable chronology for the dunes in these barrier systems. However, results from several of the samples indicate some problems that can be attributed to partial bleaching ($n = 3$)

Figure 6. Summary of OSL ages from eolian and littoral sediment from the Clark, Europe, and Kangaroo Lake barriers. Black circles represent eolian ages and gray squares show littoral ages. OSL ages are shown with their 1σ errors. Lake Michigan hydrograph is from Baedke and Thompson (2000). The vertical gray bars indicate the Nipissing and Algoma phases after Baedke and Thompson (2000) and Thompson et al. (2011).

and in estimating the environmental dose rate ($n = 1$). For instance, the OSL sample collected from along the modern Lake Michigan shoreline at the Kangaroo Lake site (UNL-3645) yielded an age of 0.9 ± 0.2 ka (Table 2). This sample was collected from 50 cm depth on the present beach, and while it is not a true modern sample, based on its proximity to Lake Michigan and its shallow burial depth we fully expect that the sediment was deposited within the nineteenth or twentieth centuries and not at ~ 0.9 ka.

Overestimated OSL ages can result from a number of problems, including both thermal transfer (the release of electrons from unwanted luminescence traps) and partial bleaching (incomplete exposure to sunlight prior to sediment burial). A thermal transfer test was run on sample UNL-3645 and the findings indicate charge transfers are minor and account for only ~ 0.2 Gy of the total luminescence signal, suggesting that thermal transfer of signal did not significantly impact the age. However, the D_e distribution does show a large number of aliquots with relatively high D_e values, a common indication of partial bleaching problems. Indeed, the mean D_e value for this sample was 1.2 ± 0.3 Gy, but 13 of the 24 aliquots accepted from this sample had D_e values that were lower than 0.5 Gy. Unfortunately, many of the aliquots with lower D_e values suffered from high uncertainty due to the low signal counts and high relative errors that are common in aliquots with very low D_e values. This is evident from examining the central age model result for UNL-3645 ($D_e = 2.4 \pm 0.3$ Gy) where many of the younger aliquots are clearly not having an impact on the results of the model (Table 2).

Although this age is clearly problematic, the other samples in the data set are not impacted to the same degree. For instance, while some littoral samples showed some spread toward higher D_e values, which could be a consequence of partial bleaching, the degree to which the ages have been impacted is significantly lower than the impact on sample UNL-3645. One method to assess the impact of partial bleaching on the age for a sample is to monitor the Mean to Median ratio (M/m) of the D_e values (Rowland et al., 2005). For 62 of the 65 OSL ages the age calculated using the median D_e value fell within 1σ errors of the age calculated using the CAM. In two cases the median age fell within 2σ errors of the CAM age, including sample UNL-2871 (a relatively young dune sample) and UNL-3176 (an older dune sample). For sample UNL-3645 the median D_e value fell outside of the 2σ errors of the CAM age; we interpret this to indicate that the partial bleaching effect on the samples was negligible but was significant on sample UNL-3645. The ages of very young samples may be particularly vulnerable to being adversely impacted by partial bleaching, and this may be the case for this sample. However, the modern bleaching environment may be significantly different than the mid- to late-Holocene bleaching environment. As suggested above, rates of longshore sand movement may have been higher during Holocene transgressive events relative to those of the modern shoreline. While the sand in the modern sample may have been eroded directly from older sediment buried in the beach or immediately offshore, the potentially strengthened

longshore drift activity in the previous highstands may have favored longer transport distances of sand grains, and hence, more effective bleaching of individual sand grains. As a result, we speculate that the modern bleaching environment is potentially very different than the bleaching environment of the ancient lake environments.

One OSL age collected from eolian sediment (UNL-2761) was significantly older than the others we analyzed, and in fact was older than the ages from the underlying littoral sediment we dated in the barriers (Table 1). Unlike those discussed above, this sample does not exhibit any indication of partial bleaching, and we expect the old age results solely from problems with estimating the dose rate for the sample. This interpretation is based on the fact that it has a D_e value similar to other samples from the Clark Lake site but a dose rate value that is much lower than the other samples (Table 1). In fact, the K, U, and Th contents are approximately half of the other samples taken from the Clark Lake dunes.

We further assessed the reliability of the OSL ages based on geomorphic and stratigraphic relationships in the barriers and the internal consistency of the ages. In five cases we took OSL samples from both shallow and deep in the same vibracore or in a hand-augured hole, including at least one from each of the study sites (Tables 1, 2, 3). In three of these cases the upper sample was eolian sand while the lower sample was littoral sand; in the remaining two the upper and lower samples were both eolian sand. In each of these cases, the upper OSL sample was younger than the lower OSL sample (Tables 1, 2, 3). Taken together, the favorable dose recovery results and these other factors all indicate the OSL chronology is reliable.

Barrier and Dune Formation

Barrier Formation

The OSL ages from both the eolian and littoral sediment collected from each of the three barriers are shown in Figure 6. The 16 OSL ages from the littoral sediment underlying the three barriers ranged from 5.9 to 2.5 ka. Twelve of these ages, including all of the littoral samples from the Clark ($n = 5$) and Europe ($n = 1$) Lake sites, fall between 5.9–3.9 ka. The five samples collected from near the top of the littoral sediment in the Clark Lake barrier indicate the sediment within the barrier formed between 5.4–4.1 ka. The relatively close agreement of the ages and the consistent elevation of the top of the littoral sediment (179–181 m) within the barrier both suggest the sediment within the entire barrier formed during one transgressive event. The elevation of the Nipissing highstand varies locally in the Great Lakes due to the region's isostatic adjustment, but Nipissing shoreline elevations typically range from 177 to 181 m (Baedke and Thompson, 2000). The age range for the Nipissing phase also varies, but recent studies have suggested the Nipissing phase ranges from ~ 6 to 4.5 ka (Figure 6; Baedke and Thompson, 2000; Thompson et al., 2011), where the peak water elevation likely occurred around 4.5 ka (Thompson et al., 2011; Fisher et al., 2012). Both the OSL ages and the elevation of the littoral sediment from Clark

Lake are consistent with the ages and elevations of the Nipissing lake-level high (Figure 6). In fact, all five of the OSL ages collected from littoral sediment within the Clark Lake barrier overlap with the Nipissing phase at the 1 σ confidence level. These lines of evidence suggest the sediment in the Clark Lake barrier formed during this phase and during lakelevel fall immediately following it.

The top of the littoral sediment within the Kangaroo Lake barrier shows relief of ~4 m, ranging from 182 m near Kangaroo Lake to 178–180 m near Lake Michigan (Figure 4). The seven littoral OSL samples that were collected close to Kangaroo Lake in littoral sediment at 182 m ranged in age from 5.9 to 3.4 ka (Figure 5B). The elevation of the littoral sediment and five of our seven OSL ages agree closely with ages and elevations from the Nipissing high lake-level phase (Figure 6). The three littoral ages collected from around the lower relief dunes on the Kangaroo Lake barrier were dated from 3.3 to 2.5 ka. These samples were collected from littoral sediment that presently lies up to 178–180 m elevation. These ages are consistent with the Algoma lake-level high which has been dated to ~3.4–2.3 ka (Baedke and Thompson; 2000). Both the elevation and the ages collected from this barrier indicate it was either reworked or increased in size during the Algoma transgression. The extent to which this re-working occurred is unknown, but the age control suggests that the Algoma transgression impacted the barrier at least 150 m inland from the present Lake Michigan shoreline.

At Europe Lake, the 4.4 ± 0.7 ka age and the 180–183.5 m elevation of the littoral fill both suggest the barrier was emplaced during the Nipissing phase (Figure 6). We cannot confidently interpret the age of the lower elevation littoral sediment (178.5 m; Figure 4) at this site due to the lack of age control on these deposits. However, given the elevations of the contact between the eolian and littoral sediment, we suggest there was likely reworking of the Europe Lake barrier after the Nipissing phase.

Based on the age control and geomorphic evidence, the majority of the sediment in the large barriers at Clark, Europe, and Kangaroo Lakes formed during the Nipissing phase (Figure 6). In addition, age control and geomorphic evidence from Kangaroo Lake suggests the portion of the barrier immediately adjacent to Lake Michigan formed between 3.3 and 2.5 ka during the Algoma phase (Figure 6). Based solely on the elevation data, the barrier at Europe Lake may also have been reworked during the Algoma phase. Collectively, these ages provide a maximum age for eolian activity on these barriers.

Dune Formation

The eolian record from the barriers shows dunes were predominantly active in the past ~6 ka, with 45 of the 48 age estimates suggesting eolian activity occurred between 5.5–1.7 ka. Because the majority of the ages were taken from directly beneath dune crests or in the upper portion of sand sheets, these OSL ages represent the last phase of dune construction or the termination of eolian activity, and therefore, they cannot be used to interpret when eolian activity began or how long eolian activity lasted. However,

in the three study barriers the littoral ages below the dunes provide an estimate for the maximum ages for eolian activity. In short, the preserved dunes on the barrier surfaces could not have been active when lake levels were rising to the peaks in lake level at ~4.5 ka for the Nipissing and ~3.0 ka for the Algoma phases. During both periods the surface the dunes formed on would have been submerged, and therefore, the dunes presently preserved on the landscape could only have formed following the lake-level peaks of the Nipissing and Algoma stages. We suggest that most of the major dune building corresponded to these two regression events.

At the Kangaroo Lake site the portion of the barrier dating to the Algoma phase has five dune ages that range from 2.4 to 2.1 ka (Figures 5B, 6). All five of these ages fall within 1 σ errors of the Algoma phase or immediately thereafter (Figure 6), suggesting dune activation occurred during recession from the Algoma high and soon thereafter. The two young eolian ages (1.7 and 1.8 ka) that are adjacent to Lake Michigan at the Europe Lake barrier (Figure 5C) may have formed following the Algoma phase or perhaps even the younger unnamed lake-level phase dating to ~1.6 ka (Figure 6; Baedke and Thompson, 2000). Resolving this would require future research that specifically targeted these younger deposits.

The majority of the remaining 41 dune ages from the three barriers were collected from eolian sand overlying littoral sediment that we interpret as Nipissing in age. In total, 26 of the 41 eolian OSL ages fall within 1 σ errors of the peak Nipissing lake level and recession (Figure 6; ~5.0–4.0 ka). These ages suggest dune activity occurred soon after the Nipissing recession began when sand would have been vulnerable to deflation prior to being stabilized by vegetation. Two of the ages (one from Clark Lake and one from Kangaroo Lake) are older than the Nipissing (Figure 6) and at least one of these ages (UNL-2761) may be too old because of problems with estimating its environmental dose rate as discussed above. The other older age (UNL-3176) may be too old for similar reasons, but we cannot adequately assess these problems without additional research.

The remaining 13 eolian samples overlie Nipissing littoral sediment, but are younger than 4 ka (Figure 6), with 11 ages falling within their 1 σ errors of the Algoma phase. These relatively young ages are not associated with buried soils, which were not encountered in any of the dunes we studied, but instead in most of these cases the ages indicate that relatively young dune crests lie adjacent to significantly older dune crests. This is particularly evident at the Clark Lake site where several dune crests in the northeastern portion of the barrier yielded ages that range from ~2.5 to 1.0 ka, and an eolian age of 3.1 ± 0.3 is also found in the western portion of the barrier (Figure 5A). At Kangaroo Lake, one relatively young age of 2.8 ± 0.4 ka is found in the central portion of the high relief dunes (Figure 5B).

Although not entirely consistent, the young ages are generally found in dune crests proximal to Lake Michigan and are less frequent in landward dunes. Assuming that these younger ages are valid and not the result of some

problem with the OSL dating, they may be attributed to one of several scenarios. First, they may have been formed due to the deflation of sand from the modern beach that was transported directly into the ancient dunes. Assessing the validity of this hypothesis would require constraining the location of the Algoma and later beaches, and at present we do not have this data. Alternatively, dune reactivation may have been fostered by the creation of local blowouts caused by large storms that leveled portions of the forest cover. In this scenario, dunes closer to Lake Michigan would have been more vulnerable to deflation and blowout growth as upwind vegetation densities would have been lower. Lastly, the dunes may have been more vulnerable to blowouts and reactivation during subsequent transgressive events. This scenario may have significantly reduced vegetation cover adjacent to Lake Michigan, favoring dune reactivation. For instance, dunes that stabilized after the Nipissing high may have been vulnerable to eolian deflation during the Algoma high lake level. This latter scenario may explain the five ages from the Clark Lake barrier that range from 2.5 to 1.9 ka, that are very similar to the ages from the Kangaroo Lake site. At the present we cannot definitively eliminate any of these scenarios, but aim to address these issues in future studies.

The presence of dunes and captured lakes in the three basins is rare along Lake Michigan's western shoreline in Wisconsin. These dunes have higher relief and cover a larger area than other dunes along the Lake Michigan shoreline in Wisconsin, most of which are either blowouts on strandplains (e.g., those found south of Sheboygan, Wisconsin), or small foredunes along the modern shoreline. Our proposed model for dune formation on the bay barriers, which suggests dunes form primarily during regressive phases, differs from those models that are commonly invoked to explain dune activation on Lake Michigan's eastern shoreline. For instance, for high-perched dunes Anderton and Loope (1995) attributed dune formation to an increase in sediment availability that occurs during transgressive phases because of increased erosion of lake-terrace bluffs. Hansen et al. (2010) suggested dunes along Lake Michigan's southeastern shore were active during transgressive events, but also suggested dunes were active during regression events, particularly during recession from the Nipissing high lake level. In the case of the dunes from our study, none of the preserved dunes could have been active during the Nipissing transgressive phase because the sediment within the underlying barriers was deposited during the maximum transgression. The dunes in our three study sites would only have been active during regression from the Nipissing high. The majority of our younger dune ages date to the termination of the Algoma phase (Figure 6), suggesting dunes formed during the regression after 2.3 ka. However, several dune ages in the three basins do closely overlap the onset of the Algoma phase, suggesting that we cannot rule out that dunes were active during the rise to the Algoma high water level. Overall, we conclude that most dune activity on the barriers occurred during the recessive phases of the Nipissing and Algoma highstands.

Conclusions

Dunes in each of these barriers are predominantly parabolic or transverse and were formed from southerly winds that were oriented approximately perpendicular to the shoreline. The OSL ages collected from littoral sediment in the barriers ranged from 5.9 to 2.5 ka, 12 of which, including all of the littoral samples from the Clark ($n = 5$) and Europe ($n = 1$) Lake barriers, fall between 5.9 and 3.9 ka. Littoral ages collected from the Kangaroo Lake site suggest at least a portion of the sand in this barrier was deposited between 3.3 and 2.5 ka. These two periods of barrier construction correspond to Lake Michigan's Nipissing and Algoma lake phases. During these two transgressive events the three bays acted as sediment traps that accumulated sand that was mobilized through wave erosion and subsequent movement through longshore drift.

Most OSL ages collected from eolian sand deposits on the barriers fall between 5.0–4.0 ka and 2.5–1.8 ka, suggesting dunes were most active around the Nipissing and Algoma high lake levels. We suggest that most of the eolian activity occurred immediately after peak transgressions during lake-level lowering when elevated sand supply was vulnerable to deflation prior to its being fixed by vegetation cover. This model differs from conclusions of studies conducted on the eastern shore of Lake Michigan, which showed that dune activation primarily occurred during transgressive phases, rather than regressive phases.

Acknowledgments – This project was carried out in large part through the efforts of undergraduate researchers and was funded through the National Science Foundation's Research Experience for Undergraduates (REU) program (EAR-0850024) and (EAR 0850525). The participating REU students both collected and analyzed much of the data for this project, and included Christiane Alepuz, Carolyn Branecky, Irina Beal, Brooke Burich, Natalia Chavez, Amy Delbecq, Nicholas Flinner, Leonardo Gamboa, Nicole Grabos, Eric Grazia, Matthew Hanson, Christina Hefron, Daniel Hobbs, Michaela Kim, Bethany Meskel, Ray Nechvatal, Christian Neumann, Maura O'Brian, Rachel Oien, Jacob Ruiz, Courtney Targos, and Jody Wycech. Aaron Young and Rebecca Puta assisted in both the field and laboratory. We also thank Carolyn Rock (Whitefish Dunes and Newport State Parks Naturalist), the Door County Parks System and several private landowners (Antholine, Ehler, Nelson, Olson, Pfeifer and Water) for access to field sites. Thanks also to Eric Carson, John Attig and Dave Hart (Wisconsin Geologic and Natural History Survey), and Erin Argyilan (Indiana Northwest University) for many helpful comments as this project progressed. Tammy Rittenour, Timothy Fisher and an anonymous reviewer provided many insightful comments that improved this manuscript. LiDAR data was provided by Door County. Finally, a special thanks to our families, who tolerated many weeks of absence to complete this field-based research.

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