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Late Holocene dune development and shift in dune-building winds along southern Lake Michigan

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Abstract

The youngest dune belt along Lake Michigan's southern coast evolved through four stages. The first stage began during the Nipissing transgression, ~6.0 ka, and culminated at the Nipissing high, ~4.5 ka. Rising lake levels eroded the lake margins and generated sediment that was transported to southern Lake Michigan, creating the Tolleston barrier beach. The second stage, beginning ~4.5 ka with a rapid lake level fall and continuing to ~3.0 ka, represents a major episode of transgressive parabolic dune field development. Large, simple parabolic dunes, with easterly apices (85–105° azimuth) suggestive of westerly wind formation, developed in a sand belt ~1–2 km wide. The third stage, from ~3.0 to 1.0 ka, was characterized by strandplain progradation and transverse ridge development west of Miller, Indiana, and dune stabilization creating the Holland Paleosol east of Miller. Sporadic blowout activity from strong westerly winds redistributed the sand within the dune field, amalgamating simple dune forms into compound, rake-like, and nested parabolic dunes. The fourth and youngest stage, beginning ~1.0 ka, represents blowout development in a southeasterly direction (120–135° azimuth), indicating a wind direction shift to the northwest. Blowouts, whether developed in transverse ridges or in the northern arms of parabolic dunes, occur closest to the lake. The timing of this blowout initiation coincides with a rise in the level of Lake Michigan. However, a more likely development and maintenance mechanism for these dunes is increased storminess with strong northerly and northwesterly winds during the cooler months of the year.

Introduction

The Great Lakes' shorelines host some of the largest freshwater coastal dune systems in the world (Peterson and Dersch, 1981). Most of the southern Lake Michigan coast (Figure 1) was progradational throughout the Holocene (Chrzastowski and Thompson, 1992; 1994), receiving sediments transported predominantly by the westward littoral drift from the erosion of eastern shores. A high sediment supply, low regional topography, and a favorable location, with respect to strong westerly and northerly winds, led to the formation of a barrier beach in the western part of the Tolleston Beach and large parabolic dunes in the eastern part. The barrier beach, which consists of a strandplain of dune capped beach ridges, and the down drift strandplain are known as the Tolleston Beach. These features formed in association with the mid-Holocene Nipissing lake level high (Hansel et al., 1985; Thompson and Baedke, 1997; Thompson et al., 2011; Fisher et al., 2012; Thompson et al., this volume). The barrier beach totals ~80 km_2, measuring ~3 km wide on its western end in the Gary- Miller, Indiana area (Figure 1B), and narrowing in an east to northeasterly direction (azimuth 68°) to ~0.6 km wide at the Indiana-Michigan border.

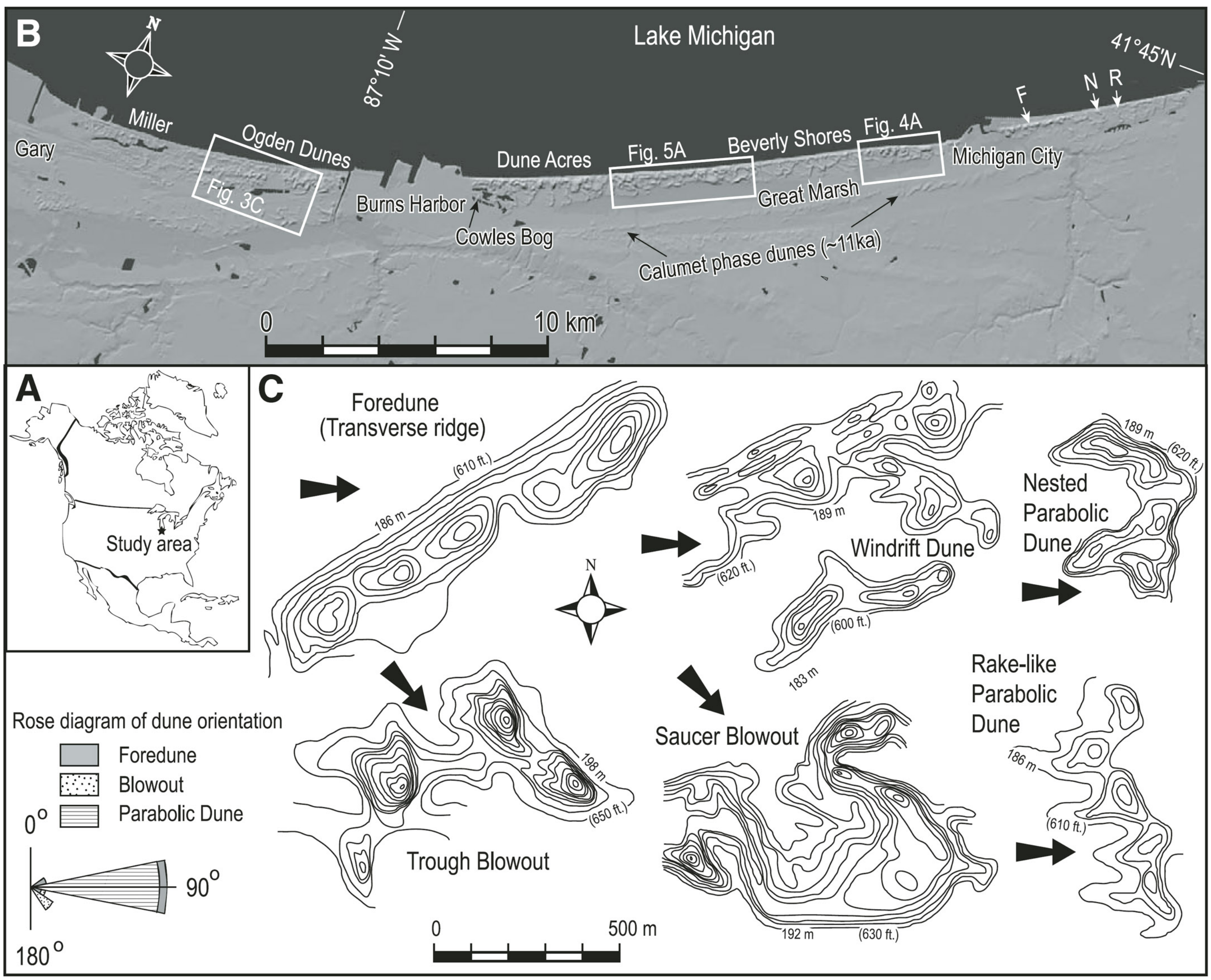

Figure 1. (A) Location of the study area in North America. (B) Shaded relief map of the study area (modified from http://eros.usgs.gov/ imagegallery/collection.php?type=ned_states). Letters with arrows east of Michigan City point to the dune locations shown in Figure 1C. F— foredune (transverse ridge); N—nested parabolic dune; R—rake-like parabolic dune. White rectangles show the locations of Figures 3C, 4A, and 5A. (C) Contour lines from topographic maps of coastal dunes in the study area. Contour interval is 3 m (10 ft). Black arrows show the dune forming wind directions.

Figure 2. (A) Foredunes in the eastern portion of the Indiana Dunes State Park. (B) Transverse ridge (~6 m high) and swale in the Miller Woods area of the Indiana Dunes National Lakeshore.

Cowles (1899) made the earliest coastal dune references, relating foredune types (Figure 2) to the plant species growing on them and noting that active dunes and blowouts were shaped by northwesterly winds. Cressey (1928) described foredunes in the central part of Indiana's coast, from Gary to western Beverly Shores (Figure 1B), and noted that some of the most striking features were tongue-like blowouts, called "slides" by early settlers. He also noted an ~2.5 km^2 zone in the present-day West Beach (Figure 3C) area of Indiana Dunes National Lakeshore (IDNL) from which dunes were removed for construction projects in Chicago (Cressey, 1928). Olson (1958a, 1958b, 1958c) completed the most comprehensive work on the dunes' evolution, describing the role of vegetation on eolian processes and foredune ridge development in this region of Lake Michigan. The timing of coastal dune development and dune reactivation was estimated from the study of paleosols (Winkler, 1962; Gutschick and Gonsiewski, 1976; Arbogast et al., 2004), and sedimentary structures (Thompson, 1989) at Mount Baldy dune in the IDNL. The evolution of the beach, spits, and beach ridges along the southern Lake Michigan coast was summarized by Chrzastowski and Thompson (1992; 1994), Thompson (1992), and Thompson et al. (2004). More recent studies in the area's coastal dunes have examined the sand transport rates in active blowouts (Olyphant and Bennett, 1994; Bennett and Olyphant, 1998; Fraser et al., 1998; Yurk et al., this volume). This paper describes the types of coastal dunes along southern Lake Michigan and reconstructs their geomorphic history since the mid-Holocene.

Methods

U.S. Geological Survey (USGS) 7.5 min topographic maps, aerial photographs, color orthoimagery, and digital elevation models (DEMs) were used during field work and in the lab to measure dune dimensions, recognize specific dune types, trace dune crests, and to determine the orientation of parabolic and blowout dune axes.

Optically stimulated luminescence (OSL) samples were collected by driving PVC pipe laterally into the walls of pits dug 0.3–2.1 m deep into the dunes. OSL analyses were conducted at the Department of Earth and Atmospheric Sciences, University of Nebraska–Lincoln. OSL sample preparation was performed under amber-light conditions. Samples were first wet sieved to extract the 150–250 µm fraction, and then treated with HCl to remove the carbonates and hydrogen peroxide to remove organics. Quartz and feldspar grains were extracted by flotation in a 2.7 g cm^{-3} sodium polytungstate solution, then soaked in a 48% HF treatment for 75 min, followed by 30 min in a 47% HCl solution. The samples were resieved and the <150 µm fraction discarded to remove the residual feldspar grains. The etched quartz grains were mounted on the innermost 2 mm or 5 mm of 1 cm aluminum disks using Silkospray.

Chemical analyses were performed using a high-resolution gamma spectrometer. Dose-rates were calculated using the methods of Aitken (1998) and Adamiec and Aitken (1998). The cosmic contribution to the dose-rate was determined following Prescott and Hutton (1994). OSL analyses were performed on a Riso Automated OSL Dating System Model TL/OSL-DA- 15B/C, equipped with blue and infrared diodes, using the single aliquot regenerative dose (SAR) technique (Murray and Wintle, 2000). Preheat and cutheat temperatures were based on preheat plateau tests between 180° and 280 °C. Dose-recovery and thermal transfer tests were also conducted (Murray and Wintle, 2003). Growth curves were examined to determine whether the samples were below saturation ($D/D_0 < 2$; Wintle and Murray, 2006). Optical ages are based on a minimum of 20 aliquots. However, more than 50 aliquots were used for the majority of samples. Individual aliquots were monitored for insufficient count-rate, poor quality fits (i.e., large error in the equivalent dose, D_e), poor recycling ratio, strong medium versus fast component (Durcan and Duller, 2011), and detectable feldspar. Aliquots deemed unacceptable using these criteria were discarded from the data set prior to averaging. Averaging was performed using the Central Age Model (CAM) (Galbraith et al., 1999), unless the D_e distribution (asymmetrical distribution; decision table of Bailey and Arnold, 2006), indicated that the Minimum Age Model (MAM) (Galbraith et al., 1999) was more appropriate.

In order to more closely correlate ^{14}C and OSL data, radiocarbon ages were calibrated to calendar years (with a 2σ range) using the software CALIB REV 6.1.0

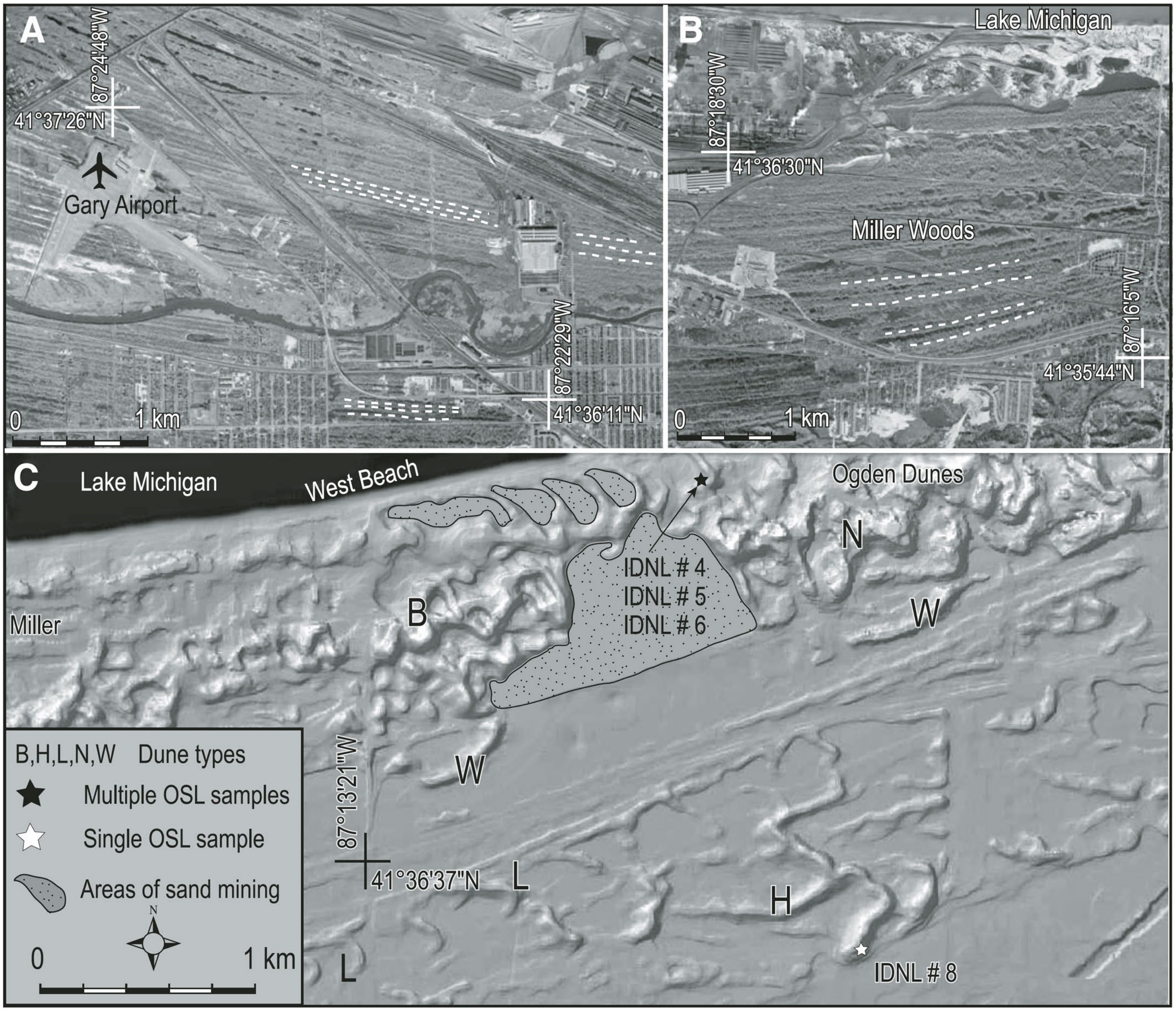

Figure 3. (A) Aerial photograph of the Gary, Indiana, airport area taken on 12 September 1951. (B) Aerial photograph of Miller Woods area taken on 12 September 1951. White dashed lines follow the trend of the transverse (beach) ridges. (C) Digital elevation model of the Miller–West Beach–Ogden Dunes area delineated in Figure 1B. Letters mark the different coastal dune types: B—blowout; H—hairpin parabolic; L—lobate parabolic; N—nested parabolic; W—windrift.

(Stuiver and Reimer, 1993) with the IntCal04 calibration curve (Reimer et al., 2004).

Results

Dune Geomorphology

There are three eolian dune belts along Lake Michigan's southern margin. Farthest inland are the oldest and least preserved dunes that transgressed on the Glenwood-level (195 m) shoreline of glacial Lake Chicago, dated between 11,380 cal yr B.P. (W-161) to 16,650 cal yr B.P. (ISGS-1570). North of these are younger dunes (Figure 1B) that transgressed on the Calumet-level (189 m) shoreline, 10,730 cal yr B.P. (ISGS-1097) to 13,200 cal yr B.P. (ISGS-1218) (Hansel and Mickelson, 1988). The most abundant, tallest, and youngest dune belt, which is the subject of this study, developed in association with the Tolleston Beach (184.5 m) shoreline, beginning with the Nipissing high (~4.5 ka) and continuing through to the present time (Hansel and Mickelson, 1988; Thompson, 1992). This youngest dune belt has a great variety of foredunes, blowouts and parabolic dunes, which will be described following the dune morphology classification scheme presented in Table 2 (modified after Pye, 1982, 1983; Hesp, 2002).

The geomorphic history of the youngest dune belt along the southern coast of Lake Michigan is revealed by the OSL sand ages collected from: (1) the Mount Baldy blowout (Table 1, OSL samples MB1-6); (2) a hairpin parabolic dune south of the Mount Baldy blowout (Table 1, OSL samples IDNL#1, 2); (3) a windrift dune east of the Kintzele Ditch (hereafter referred to as the Kintzele Ditch dune) (Table 1, OSL samples IDNL #3 and KD #1–3); (4) a windrift dune south of the IDNL parking lot at Kemil Road (hereafter referred to as the Kemil Road dune) (Table 1, OSL sample IDNL #7); (5) the Beach House blowout in the Indiana Dunes State Park (IDSP; Table 1, OSL samples IDSP # 1–6); (6) a blowout in West Beach of the IDNL (Table 1, OSL samples IDNL #4–6); and (7) a nested parabolic dune in the Inland Marsh at the IDNL (Table 1, OSL sample IDNL #8).

Foredunes

Foredunes are defined as shore-parallel dune ridges that form above the backshore by eolian sand deposition within vegetation (Hesp, 2002). There are four types of foredunes along the backshore of southern Lake Michigan: (*a*) incipient foredunes; (*b*) established foredunes; (*c*) transverse ridges; and (*d*) anthropogenic foredunes (Table 2).

Incipient foredunes, also known as primary, shadow, or embryo dunes (Pye, 1983), are new or developing foredunes that form within pioneer plant communities (Hesp, 2002). Incipient foredunes along southern Lake Michigan (Figure 2A) have a 1–3-m-high ramp-like lakeward profile. Their inland side has a terrace-like morphology, measuring ~30 m wide, and abuts an established foredune or dune. A patchy cover of marram grass (*Ammophila breviligulata*) traps the sand and promotes vertical and lateral foredune growth. Incipient foredunes along the backshore in the IDSP, western Dune Acres, West Beach, Miller, and Gary, Indiana, areas (Figure 1B) developed since the late 1980s, following the highest Lake Michigan levels in the last century. These foredunes are prone to extensive erosion by late fall and spring storms.

Established foredunes develop from incipient foredunes. They are distinguished by their greater morphological complexity, height, width, age, and geographical position (Hesp, 2002) and by the growth of intermediate successional, typically woody, plant species on them. In our study area, there are two or three established foredune ridges (Figure 2A) farther inland from and parallel to the incipient dunes. The transition from an incipient to an established foredune is marked by a 2–3-m-high ramp and a denser vegetative cover consisting of marram grass, sand reed grass (*Calamovilfa longifolia)*, little bluestem bunchgrass (*Schizachyrium scoparium*), sand cherry (*Prunus pumila*), and small cottonwoods (*Populus deltoides*) (Olson, 1958b). In the Gary and western Dune Acres backshore (Figure 1B), there are three sets of terrace-type (Hesp, 2002) established foredunes, 90–120 m wide. There is little difference in the vegetation cover on these foredunes, suggesting that they formed within the last half century. Olson (1958c) noted that late in the nineteenth century, after the high lake levels of 1861, 1876, and 1886, many areas of the southern Lake Michigan shore had no foredunes at all. There is a single established, 10–30-m-wide foredune with the terrace morphology in Miller, West Beach, the western Ogden Dunes, central Dune Acres, the western IDSP, and western Beverly Shores (Figs. 1B and 4A).

The most complete set of foredunes is in the eastern part of the IDSP. An incipient foredune, ~1 m tall and 20 m wide, lies next to an established terrace-type foredune, ~3 m tall and 30 m wide. Farthest inland is a 2-km-long, 60-m-wide, and 10-m-tall transverse ridge separated from the parabolic dunes by a 10–15-m-wide swale (Figs. 2B and 5B). Vegetation on this transverse ridge includes red dogwood (*Cornus sericea*), choke cherry (*Prunus virginiana*), white pine (*Pinus strobus*), jack pine (*Pinus banksiana*), black oak (*Quercus velutina*), red oak (*Quercus rubra*), and basswood (*Tilia americana*), similar to vegetation on the parabolic dunes (Olson, 1958b).

There are three active and four recently healed blowouts cross-cutting this transverse ridge (Figure 5A). Observations of the sediments in the blowout dunes developed through this transverse ridge suggest that the foredunes formed on the gravels and sandy gravels of the Nipissing shoreline.

Originally, there were numerous transverse ridges (Figure 3) separated by swales (Olson, 1958c; Thompson, 1992) in the rapidly prograded Tolleston Beach area west of Miller (Figure 1B). More than 150 transverse ridges, 1.5–2.5 m high (Thompson, 1992) and up to 10 km long, ran parallel to the modern shoreline west of Gary (Figure 3A). Most of these transverse ridges were obliterated by industrial and municipal development beginning in the early 1900s. A series of smaller transverse ridges is best preserved east of the Gary Airport, while taller transverse ridges (Figure 2B) are best preserved within the Miller Woods area of the IDNL.

Thompson (1992) described these landforms as beach ridges. They consist of a core of foreshore deposits capped with eolian strata. The ridges formed in response to quasi-periodic 30-yr lake level fluctuations (Olson, 1958c; Thompson, 1992). Radiocarbon ages on organic material collected from nineteen transverse ridges varied from ~3000 cal yr B.P. (3 km away from the modern shoreline) to ~500 cal yr B.P. (700 m away from modern shoreline) (Thompson, 1992). Farther east, in the Miller Woods area (Figure 3B), the 150 transverse ridges coalesce into 50 transverse ridges, ranging from 3.7 to 6.1 m high (Thompson, 1992) and 2 to 5 km long (Figure 3C). These transverse ridges formed in response to meso-scale (0.8–0.9 m) lake level fluctuations with an approximate ~150 year periodicity (Thompson, 1992). These ridges also show a lakeward decrease in age (Thompson, 1992), from ~3500 cal yr B.P., 1.8 km away from the modern shoreline, to ~500 cal yr B.P. ~0.3 km away from the modern shoreline.

Anthropogenic foredunes exist in the backshore of the western Indiana coast, west of Gary (Figure 1B), where few, if any, of the natural coastal landforms exist today.

Table 1. The optically stimulated luminescence ages of sand samples from southern coast of Lake Michigan

UNL #	Field #	Latitude (N)	Longitude (W)	Burial depth (m)*	H_2O (%)†	K_2O (%)	U (ppm)	Th (ppm)	Cosmic (Gy)	Dose rate (Gy/ka)	D_e (Gy)§	No. of aliquots	Age (ka)	Model#
UNL2475	MB1	41°42′33.89″	86°55′49.28″	32	25	1.58	0.81	1.25	0.01	1.20 ± 0.07	5.55 ± 0230	31	4.63 ± 0.35	CAM
UNL2476	MB2	41°42′33.70″	86°55′49.23″	31	13.9	1.27	0.61	1.13	0.02	1.08 ± 0.05	4.95 ± 0.14	30	4.60 ± 0.29	CAM
UNL2477	MB3	41°42′33.79″	86°55′47.07″	24	6.3	1.36	0.53	1.73	0.02	1.27 ± 0.05	2.44 ± 0.18	42	1.92 ± 0.17	CAM
UNL2478	MB4	41°42′33.80″	86°55′46.75″	23.5	3.9	1.29	0.72	1.99	0.02	1.31 ± 0.05	1.22 ± 0.24	32	0.93 ± 0.19	CAM
											0.63 ± 0.10	32	0.49 ± 0.08	MAM
UNL2479	MB5	41°42′31.60″	86°55′49.41″	18	4.7	1.49	0.48	1.58	0.03	1.38 ± 0.05	5.51 ± 0.19	27	4.00 ± 0.25	CAM
UNL2480	MB6	41°42′31.45″	86°55′49.03″	16	4.1	1.16	0.67	1.43	0.04	1.17 ± 0.05	0.62 ± 0.87	39	0.53 ± 0.74	CAM
											0.07 ± 0.05	39	0.06 ± 0.04	MAM
UNL3036	IDNL#1	41°42′22.60″	86°55′44.00″	4	1.1	1.33	0.39	1.33	0.13	1.36 ± 0.06	3.67 ± 0.13	51	2.70 ± 0.15	CAM
UNL3037	IDNL#2	41°42′22.60″	86°55′44.00″	3.4	0.6	1.33	0.32	1.20	0.14	1.35 ± 0.06	0.54 ± 0.58	53	0.40 ± 0.43	CAM
											0.17 ± 0.03	53	0.12 ± 0.02	MAM
UNL3038	IDNL#3	41°42′25.52″	86°56′22.26″	25	14.7	1.20	0.44	1.57	0.02	0.92 ± 0.06	3.71 ± 0.16	60	4.02 ± 0.30	CAM
UNL3039	IDNL#4	41°37′23.70″	87°12′17.60″	7	4.4	1.26	0.50	1.79	0.09	1.28 ± 0.05	1.44 ± 1.26	55	1.12 ± 0.99	CAM
											0.39 ± 0.11	55	0.30 ± 0.09	MAM
UNL3040	IDNL#5	41°37′23.50″	87°12′17.80″	11	4.1	1.27	0.38	1.68	0.06	1.22 ± 0.05	1.72 ± 0.21	61	1.40 ± 0.18	CAM
											0.84 ± 0.07	61	0.68 ± 0.07	MAM
UNL3041	IDNL#6	41°37′23.30″	87°12′17.70″	9.8	6.4	1.19	0.32	1.58	0.07	1.12 ± 0.05	1.26 ± 0.17	58	1.12 ± 0.16	CAM
											0.42 ± 0.03	58	0.37 ± 0.03	MAM
UNL3042	IDNL#7	41°40′36.90″	87° 0′23.60″	15	2.1	1.48	0.46	1.88	0.04	1.43 ± 0.06	5.63 ± 0.20	55	3.92 ± 0.22	CAM
UNL3110	IDNL#8	41°36′24.54″	87°11′50.02″	8	5.7	1.73	0.45	1.64	0.08	1.58 ± 0.06	9.21 ± 0.28	63	5.81 ± 0.29	CAM
											5.72 ± 0.62	63	3.61 ± 0.42	MAM
UNL3459	KD#1	41°42′24.14″	86°56′25.65″	21	3.8	1.31	0.44	1.48	0.03	1.23 ± 0.05	5.87 ± 0.21	53	4.77 ± 0.25	CAM
UNL3460	KD#2	41°42′24.03″	86°56′25.59″	20	4.0	1.71	0.42	1.71	0.04	1.54 ± 0.06	6.82 ± 0.19	53	4.41 ± 0.21	CAM
UNL3461	KD#3	41°42′24.15″	86°56′24.21″	15	4.1	1.18	0.53	2.11	0.04	1.21 ± 0.05	4.67 ± 0.13	57	3.87 ± 0.19	CAM
UNL3043	IDSP#1	41°40′10.20″	87° 2′21.50″	28.5	25	1.17	0.44	1.42	0.02	0.89 ± 0.05	3.49 ± 0.15	50	3.90 ± 0.29	CAM
UNL3044	IDSP#2	41°40′10.20″	87° 2′21.50″	28	25	1.21	0.57	2.24	0.02	0.96 ± 0.06	4.26 ± 0.15	51	4.33 ± 0.30	CAM
UNL3045	IDSP#3	41°40′10.20″	87° 2′21.50″	27.8	25	0.96	0.33	1.70	0.02	0.76 ± 0.05	3.64 ± 0.84	84	4.79 ± 1.02	CAM
											3.20 ± 0.13	84	4.22 ± 0.31	MAM
UNL3046	IDSP#	4 41°40′6.20″	87° 2′22.80″	12	5.6	1.28	0.44	1.45	0.05	1.21 ± 0.05	1.65 ± 0.12	59	1.36 ± 0.11	CAM
											1.21 ± 0.05	59	1.00 ± 0.06	MAM
UNL3047	IDSP#5	41°40′6.20″	87° 2′22.80″	11.7	3.3	0.84	0.51	1.44	0.06	0.92 ± 0.04	0.75 ± 0.63	62	0.82 ± 0.68	CAM
											0.58 ± 0.19	62	0.64 ± 0.21	MAM
UNL3108	IDSP#6	41°40′6.30″	87° 2′23.00″	13	6.3	1.24	0.43	1.58	0.05	1.17 ± 0.05	4.13 ± 0.03	54	3.54 ± 0.15	CAM

* Historic burial depth.
† In situ moisture content; saturated moisture content (UNL2475, 3043, 3044, 3045).
§ Error on D_e is 1 standard error, Error on age includes random and systematic errors calculated in quadrature.
\# Central Age Model (CAM), Minimum Age Model (MAM).

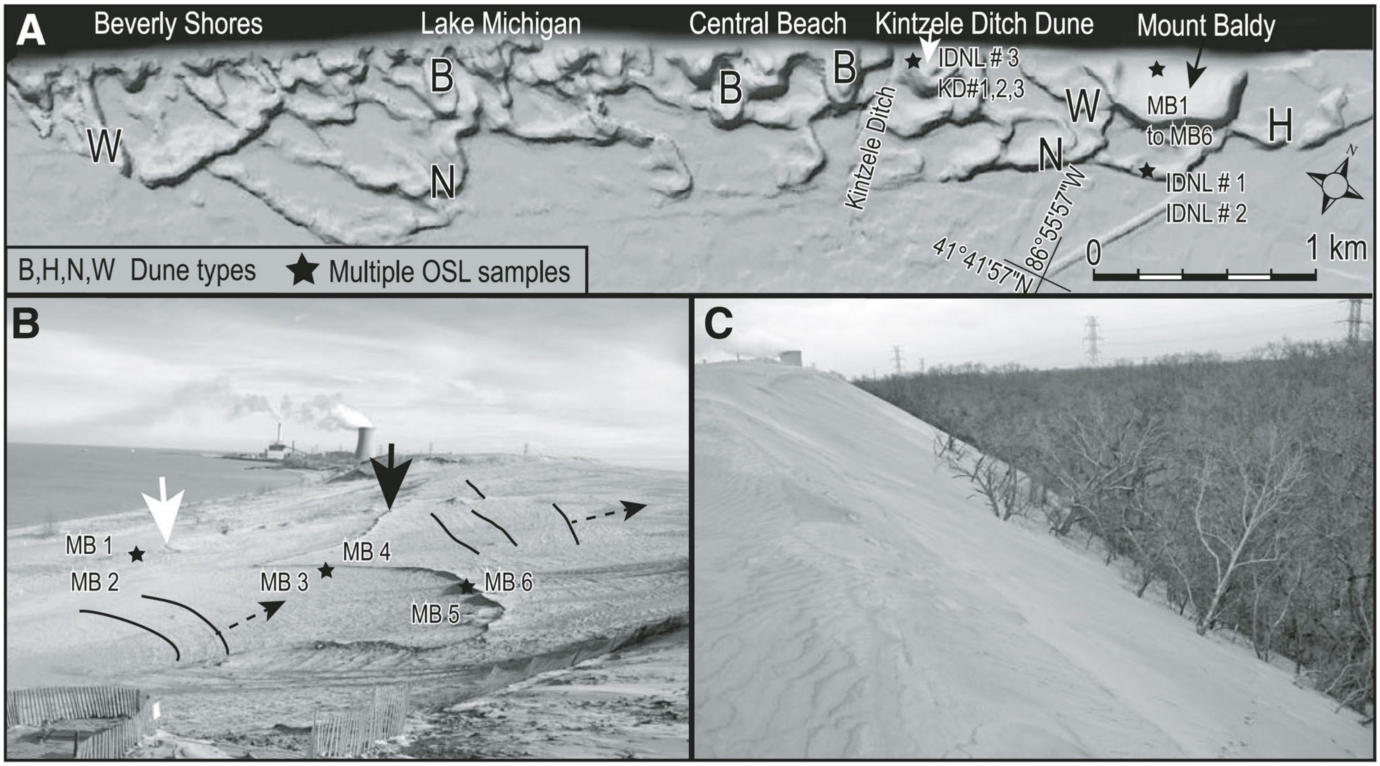

Figure 4. (A) Digital elevation model of the area delineated in Figure 1B. Letters mark the different coastal dune types: B—blowout; H—hairpin parabolic; N—nested parabolic; W—windrift. (B) Stoss side of the Mount Baldy blowout. The dark arrow points to the Holland Paleosol and the white arrow points to the Entisol/clay layer. Black lines mark the orientation of eolian strata above and below the Holland Paleosol. Dashed lines with arrows point in the dip direction of the eolian strata. Letters MB with numbers 1 through 6 show the locations of the optically stimulated luminescence samples listed in Table 1. (C) The lee side of Mount Baldy blowout is a long, wide precipitation ridge, advancing over the adjacent forest.

Table 2. Classification scheme for coastal dune forms along southern Lake Michigan

Coastal dune type	Brief description of dune geometry
Foredunes	Shore-parallel dune ridges formed on top of the backshore by aeolian sand deposition.
(a) Incipient foredunes	Low (1–3 m) ridges with widths ranging from 1s–10s of meters, forming within pioneer plant communities closest to the shore.
(b) Established foredunes	Taller (2–5 m) and broader (10s–100s m) ridges with denser vegetation, possibly including woody plants, separated from the shore by incipient foredunes or by shore-facing erosional scars.
(c) Transverse ridges (beach ridges)	Narrow (1s–10s m) and tall (1s–10s m) forested ridges with steep (15–30°) slopes, often separated by a swale from the parabolic dunes.
(d) Anthropogenic foredunes	Man-made sand ridges parallel to the shore, built for protection from the waves and often planted with nonnative vegetation.
Transgresive dunes	Aeolian sand deposits formed by the downwind movement of sand transgressing a preexisting terrain.
(A) Blowouts	Depressions formed by wind erosion on a preexisting sand deposit.
(a) Trough-shaped	Narrow (1s–10s m) and elongated (10s–100s m) depressions in aeolian dunes with a 3:1 or higher length to width ratio.
(b) Saucer-shaped	Depressions in aeolian dunes that often have a greater width (10s–100s) than length (10s m).
(c) Precipitation ridges	Transgressive dunes or saucer-shaped blowouts with laterally extensive slip faces which advance landward over forested areas.
(B) Parabolic dunes	Bow-shaped dunes with trailing arms pointing upwind and fixed on their outer sides by vegetation.
Simple	Aeolian dunes with a simple parabolic form.
(a) Lobate	Bow-shaped aeolian dunes with an arm length to width ratio of 1 to 3.
(b) Hairpin	Elongated, U-, or V-shaped dunes with a length to width ratio higher than 3.
(c) Windrift	Linear parallel or converging ridges with a breached nose (apex).
Compound	Aeolian dunes with multiple or complex parabolic forms.
(a) Rake-like	Aeolian dunes which consist of three or four arms emanating from a common parabolic apex.
(b) Nested	Two or more lobate or hairpin dunes coalesced together or within a larger parabolic dune.

Modified from Pye (1982; 1983); and Hesp (2002).

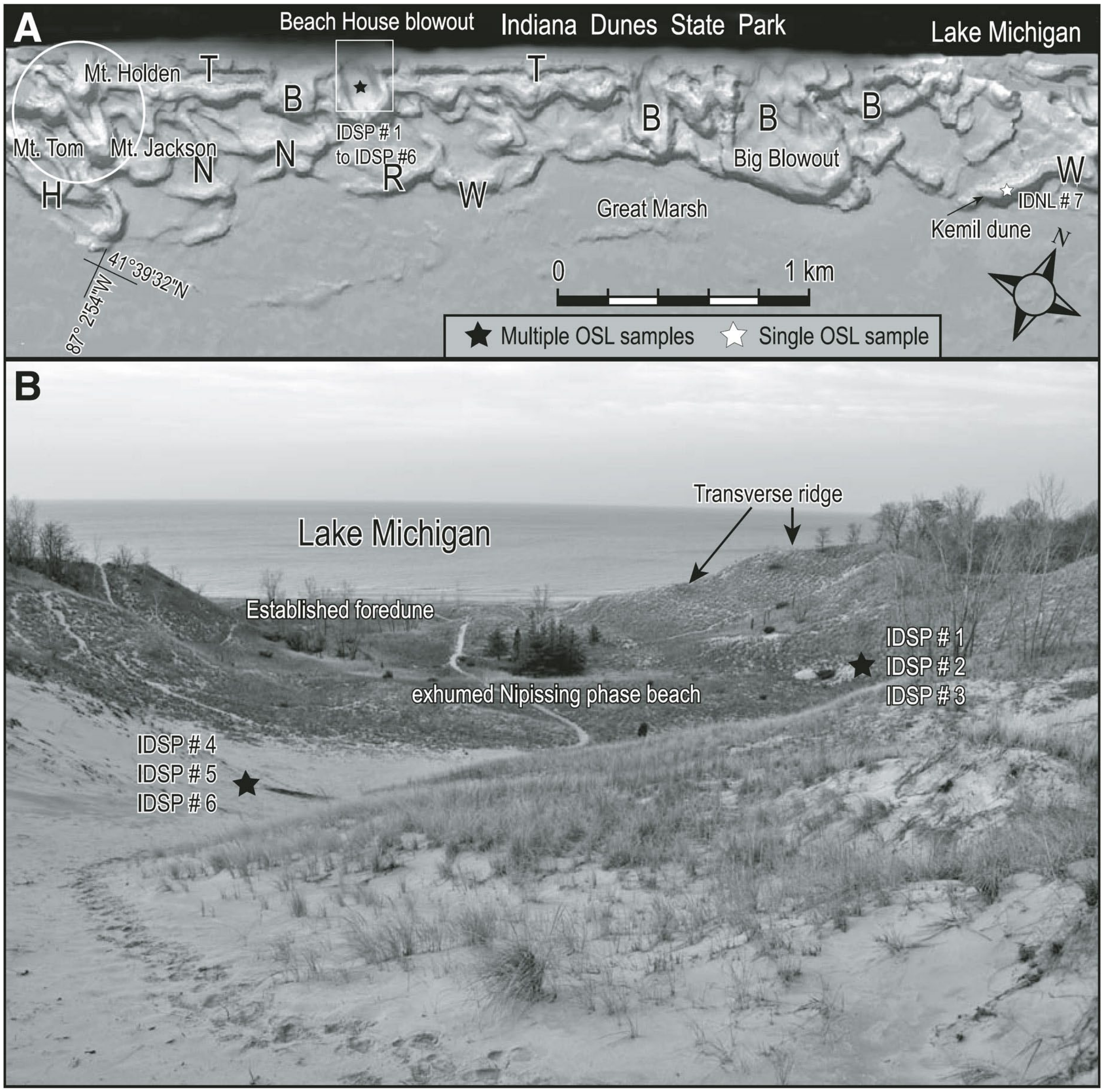

Figure 5. (A) Digital elevation model of the area delineated in Figure 1B. Letters mark the different coastal dune types: B—blowout; H—hairpin parabolic; N—nested parabolic; R—rake-like parabolic; T—transverse ridge; W—windrift. The white circle shows the area with the tallest dunes along the southern shore of Lake Michigan discussed in this paper. The white rectangle shows the location of the Beach House blowout shown in Figure 5B. (B) A view from the southern crest of the Beach House blowout. Letters IDSP with numbers 1 through 6 show the locations of the optically stimulated luminescence samples listed in Table 1.

There are also anthropogenic foredunes adjacent to the seawall in eastern Ogden Dunes, to the bulkheads in eastern Dune Acres, to the revetment in Beverly Shores, and along the entire length of the backshore from Michigan City to the Michigan border (Figure 1B). Similar to other densely populated coastal areas (Nordstrom, 1994), foredunes are often eliminated to facilitate shorefront construction and then are subsequently rebuilt to provide protection from the waves. However, the reconstructed foredunes are usually smaller than the original foredunes and built lakeward of their former equilibrium location.

Transgressive Dunes

Transgressive dunes are eolian sand deposits formed by the downwind movement of sand advancing or transgressing over an existing terrain (Hesp and Thom, 1990). In a humid coastal region, there is a strong contrast between moving sand and the types of surfaces being transgressed. Buried soils, peat, or stumps exposed on deflated windward slopes indicate dune transgression (Hesp and Thom, 1990). Transgressive dunes along the southern shore of Lake Michigan are typically low perched dunes (Arbogast, 2009) as they lie on former lake plains only a few meters above the present lake level. Other transgressive dune forms in the study area include two types of blowouts: trough and saucer shaped, three types of simple parabolic dunes: lobate, hairpin, and windrift, and two types of compound parabolic dunes: rake-like and nested (Table 2, Figure 1C; Pye, 1982, 1983; Hesp, 2002).

Blowouts

Blowout dunes are saucer-, cup-, or trough-shaped depressions formed by wind erosion on a preexisting sand deposit (Cooper, 1958; Hesp, 2002). Currently, there are two dozen active blowouts and another two dozen recently stabilized blowouts in the study area. Mount Baldy dune (Figure 3) in the IDNL, ~2 km west of Michigan City, Indiana, is the largest active blowout along the southern coast of Lake Michigan. Mount Baldy is a saucer-shaped, 600-m-wide dune with a 250 m axis trending 135° azimuth. This blowout developed by erosion of a compound, nested parabolic dune. Its history was revealed by the pattern of the exposed Holland Paleosol (Arbogast et al., 2004) and the easterly (80–90° azimuth) dip direction of the grainflows and pin stripe laminations below this paleosol (Figure 4B). A change in the orientation of the grainflows (125–135° azimuth) above the Holland Paleosol (Figure 4B) suggests a shift from the earlier westerly parabolic dune building wind direction to a dominant northwesterly wind.

The development of coastal structures (piers at the mouth of Trail Creek and a breakwater in front of the harbor) in Michigan City prompted severe beach erosion in this area. Consequently, the Mount Baldy blowout advanced rapidly inland in response to the decreased sediment supply on the lakeward side of the dune. Previous studies (Wood and Davis, 1986; Olyphant and Bennett, 1994; Bennett and Olyphant, 1998; Fraser et al., 1998) showed Mount Baldy advanced inland at an annual rate of 1–1.5 m. However, our current studies (from 2007 to 2012) indicate an annual advance up to 4–6 m. These rates are based on the position of the base of the lee slope as measured against the trunks of selected reference trees. This is the highest rate of dune movement in the Great Lakes region (Hansen et al., 2004, 2006, 2009; van Dijk, 2004). Therefore, due to its rapid landward advance (Figure 4C) and the subsequent burial of the heavily forested arm of another parabolic dune, Mount Baldy dune could also be classified as an advancing precipitation ridge (Cooper, 1958; Pye, 1983).

Big Blowout (Figure 5A) was the largest of all the blowout dunes along southern Lake Michigan when it was completely mobile. Its 700-m-long axis, trending in a southeasterly direction (125° azimuth), extends over the entire width of the Tolleston Beach dune belt in the eastern IDSP. This saucer-shaped blowout attains a 450 m width and a 30 m height near its landward boundary with the Great Marsh (Figure 5A). Most of Big Blowout is currently stabilized by marram grass, reed grass, and scattered cottonwood trees. However, a few patches of barren and active sand remain in the northern part of the blowout.

Nearby, the Beach House blowout (Figure 5) is still active and exhibits a bowl-like morphology. The landward rim of the Beach House blowout is ~30 m high, and its 300-m-long axis points in a southeasterly direction (135° azimuth). Until recently, the width of the blowout was ~250 m. However, the open portion of the blowout currently measures ~40 m wide and 150 m long as much of it is vegetated by marram, reed grass, and scattered cottonwood trees. A remnant of the Nipissing phase beach, containing beach shingle gravel, is exposed in the middle of the Beach House blowout.

Trough blowouts are more narrow and elongated than saucer, bowl or cup forms. In the early 1900s, many of these so-called "slides" (Cressey, 1928) were active. However, only a few trough blowouts are currently mobile along the southern coast of Lake Michigan as most are vegetated with marram grass and various shrubs. The three tallest dunes (48–52 m) along the southern shore of Lake Michigan, Mount Holden, Mount Jackson, and Mount Tom (Figure 5A), are recently stabilized trough blowouts with small patches of mobile sand.

Parabolic Dunes

Parabolic dunes have an open, bow-shaped form in plan view. The dune's "trailing arms" point upwind and are fixed by vegetation. Conditions favoring parabolic dune development include a generally stabilized surface over which the dunes migrate, a considerable thickness of sand, and unidirectional winds (Pye, 1983). Transgressive parabolic dunes are the most common dunes along southern Lake Michigan. These dunes have simple (lobate, hairpin, and windrift) parabolic dune morphologies. But compound parabolic dunes with either a rake-like or nested morphology are more common (Table 2, Pye, 1983; Kilibarda and Blockland, 2011).

Vegetation plays a key role in parabolic dune development. Conditions that stimulate vegetation growth over a migrating sand dune include an increase in precipitation or a reduction in wind strength. Plants first invade locations with low rates of sand erosion or deposition, such as the arms and/or the crest. This vegetation reduces the wind's strength and traps the sand. Sand accumulates mainly at the crest where the sand flux is highest. This deposition kills the vegetation, thus lowering the erosion or deposition rate at the crest again, and a new vegetation growth cycle on the crest may begin. As a result, the parabola's apex moves forward, and the arms are left behind, seemingly "stretching" the parabolic dune (Durán and Herrmann, 2006).

The fixation index, a dimensionless control parameter, defined as a ratio between the sand erosion rate and the vegetation growth rate (Durán and Herrmann, 2006), determines which type of parabolic dune will develop. Lobate parabolic dunes develop at a fixation index of 0.16, more elongated hairpin parabolic dunes at a fixation index of 0.22, and the most complex, nested parabolic dunes develop at a fixation index of 0.27 (Durán and Herrmann, 2006). In other words, higher rates of erosion and vegetation destruction create more complex parabolic dune morphologies. Transgressive parabolic dunes along the southern shore of Lake Michigan are now stabilized by lush mesic forests consisting of black oak (*Quercus velutina*), red oak (*Quercus rubra*), basswood (*Tilia americana*), white pine (*Pinus strobus*), jack pine (*Pinus banksiana*), and cottonwood (*Populus deltoides*) (Olson, 1958c).

The simplest parabolic dune form is the lobate dune (Table 2). The arm length in lobate dunes is ~250 m, while the arm width is ~50 m. The spacing between these arms is ~150 m. The relative height of the lobate dune increases from its windward arms (5– 10 m) toward its parabolic apex (15–20 m). Lobate dunes are found mostly in the western, upwind region of the dune belt and on the landward edge of the dune field (Figure 3C). Hairpin parabolic dunes (Figs. 3C, 4A) develop due to the extension of a lobate dune's arms by the downwind migration of dune's apex. The arms of several hairpin dunes in the western part of this dune field reach a length of 500 m. The lobate and hairpin parabolic dune apices point in an easterly direction (85–105° azimuth), indicating dominant westerly winds during their development (Figure 1B). OSL sample IDNL#1, collected 4 m below the top of a hairpin dune (Figure 4A), yielded an age of 2.70 ± 0.15 ka (Table 1). A group of smaller (less than 10 m in height), mostly lobate parabolic dunes, between Gary and Ogden Dunes, has a less ordered apex orientation that varies from east to southeast. This suggests both westerly and northwesterly wind directions during their formation. These dunes are north of an erosional disconformity, defined by Thompson et al. (2004) as the post-Nipissing fall discontinuity between the Algoma-phase and older Nipissing beach ridges.

Windrift dunes (Figs. 3C, 4A, 5A) are linear ridges that represent the remnant arms of hairpin parabolic dunes whose transverse sections have blown away (Pye, 1982). They are present on both the landward and lakeward margins of the dune belt between Central Beach and Mount Baldy (Figure 4A). Windrift dunes trend west-east and range in length from 500 to 800 m. Two windrift dunes west of Mount Baldy are the remaining arms of parabolic dunes whose other arm eroded during the early 1900s development of Michigan City. The Kintzele Ditch windrift dune is 3.9–4.2 ka old (Table 1, samples KD#2, 3). A similar OSL age of 3.92 ka (Table 1, sample IDNL#7) was obtained from the Kemil Road windrift dune on the inland edge of the dunefield (Figure 5A).

The most common dunes are compound parabolic nested dunes (Figs. 3C, 4A, 5A) that represent the amalgamation of lobate and hairpin dunes. Often three, four or five simple parabolic dunes will coalesce into compound, nested parabolic dunes, 0.8–1.2 km long, 0.6–0.8 km wide, and 20–30 m tall. Nested parabolic dunes are most abundant in the central part of the study area between the western Dune Acres and the Mount Baldy blowout (Figure 1B). The ages of the nested parabolic dunes vary from ~4.3 ka (OSL sample MB2 in Table 1) to ~1.9 ka (OSL sample MB3 in Table 1).

Rake-like compound parabolic dunes (Figure 1C) consist of three or four arms emanating from a common parabola apex. The height of these dunes is generally less than 15 m. Rake-like parabolic dunes are found north of Cowles Bog in the western Dune Acres (Figure 1B), southeast of the Beach House blowout in the IDSP (Figure 5A), and east of Michigan City (Figure 1B). In all these locations, the rake-like parabolic dunes have migrated obliquely of the landward side of the Tolleston Beach into the ~1-km-wide shore-parallel wetlands known as the Great Marsh (Figure 1B). Both the nested and rake-like parabolic dunes trend in an easterly direction (85–105° azimuth), indicating dominant westerly winds during their development (Figure 1B).

Sedimentary Structures

Nearshore and Eolian Strata in the Early Tolleston Beach

Foredunes and windrift dunes, when eroded by storms, and active blowouts provide the best views of the lacustrine and eolian sedimentary structures preserved in the Tolleston Beach sediments. October through April are the best months to study these structures here as the dune vegetation is dormant and strong winds are common. Northerly and northwesterly winds frequently exceed speeds of 15 m/s (54 km/h) (Yurk et al., this volume) during this time and these strong winds can deflate loose sand from the blowout surfaces, exposing older eolian sedimentary structures. In addition, these winds generate the highest waves, up to 6.3 m high (Hubertz et al., 1991), which severely erode the foredunes and dunes.

The Kintzele Ditch dune (Figure 4A) exhibits the most complete sequence of lacustrine and eolian strata (Figure 6). This sequence can remain exposed for several days after major storms. A dark-blue clay layer, ~1.5 m thick, and containing carbonized plants, freshwater algae, snails, clams, ostracods, and fish fossils (Gutschick and Gonsiewski, 1976), lies at the base of this exposure. The total length of the clay exposure in the last five years was ~100 m. During the high lake levels in the early 1970s (Gutschick and Gonsiewski, 1976) and the mid-1980s (Thompson, 1989), this clay layer could be traced along 3 km of the shoreline. A wood fragment from the top of the clay layer had a radiocarbon age of 4860–5890 cal yr B.P. (USGS-W3246) (Gutschick and Gonsiewski, 1976).

Above the clay lies a sequence of cross- and horizontally bedded strata ~6 m thick. Thompson (1989) distinguished four depositional facies, washover, eolian, longshore trough, and bar based on the overall geometry, sedimentary structures, and sediment textures within these strata. These facies represent the Nipissing transgression that peaked ~4.5 ka.

The eolian facies contains foresets of cross-bedded strata up to 2.5 m thick, dipping steeply (25–30°) toward the east-southeast (90–95° azimuth) (Thompson, 1989). Fresh exposures of these eolian foresets can be traced laterally for 30–35 m. OSL sample IDNL#3, collected 20 cm above the clay layer, had an age of 4.02 ± 0.30 ka (Table 1). A flat bounding surface, ~6 m above the clay layer, separates the thick sets of eolian strata from the nearshore sediments below them. The age of OSL sample KD#1 (Table 1), collected 76 cm below the bounding surface, was 4.77 ± 0.25 ka, while sample KD#2, collected 87 cm above the bounding surface (Figure 6), had an age of 4.41 ± 0.21 ka.

Several paleosols can be found within the eolian strata. There is a 5-cm-thick, organic-rich A horizon from an Entisol ~3 m above the base of the eolian strata

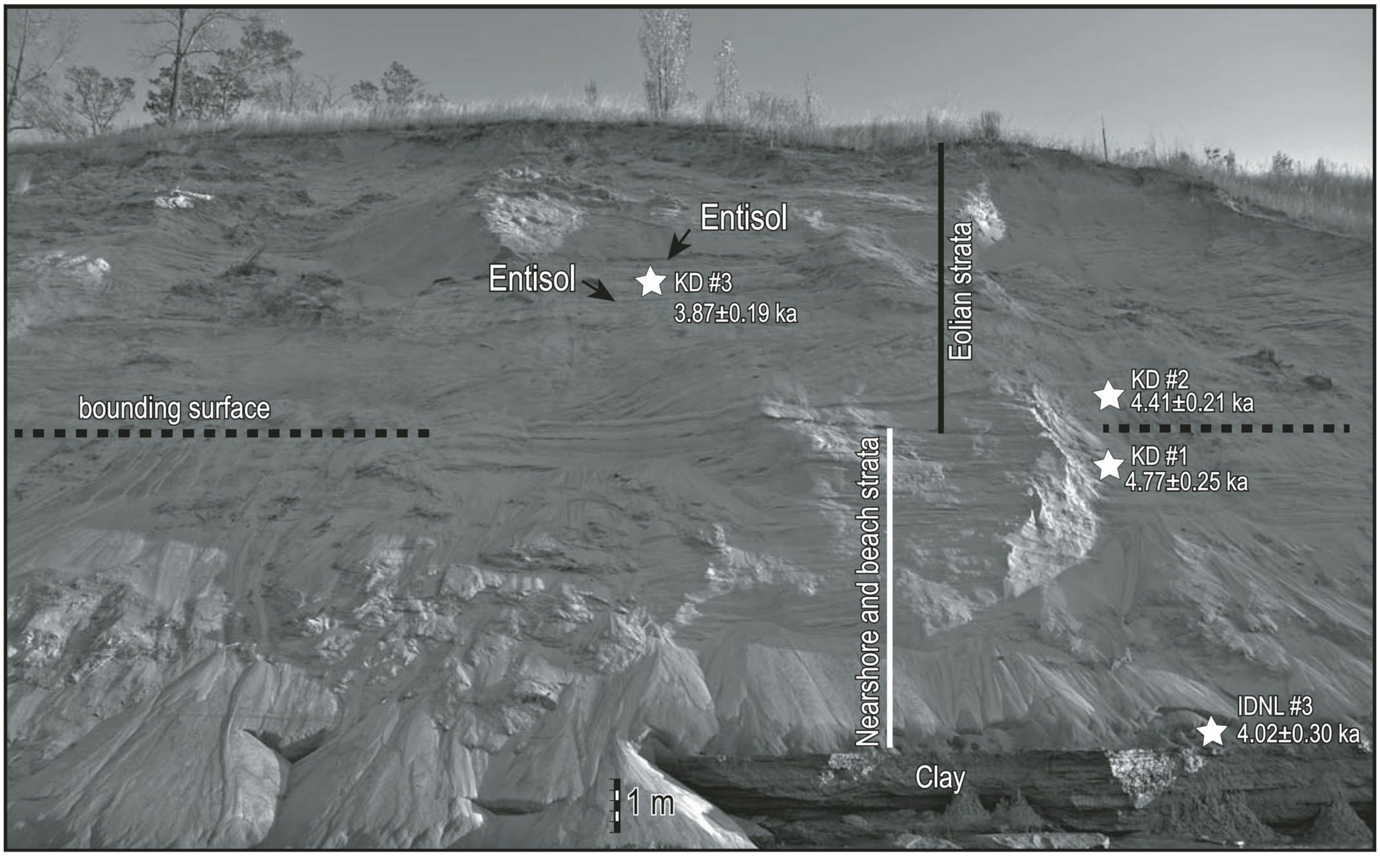

Figure 6. Exposure of the eroded windrift dune east of Kintzele Ditch (Figure 4A). The white stars with letters and numbers show the stratigraphic positions of the optically stimulated luminescence samples collected at this site. The most complete exposure of the Tolleston Beach stratigraphy in the study area is at this location.

(Figure 6). Another Entisol, with a thicker (10 cm) A horizon, lies approximately midway through the eolian sequence and above the previous Entisol at this exposure (Figure 6). The age of OSL sample KD#3, collected between these two Entisols, was 3.87 ± 0.19 ka.

Paleosols

There is one prominent Spodosol, the Holland Paleosol (Arbogast et al., 2004), and multiple Entisols buried in the coastal dunes along southern Lake Michigan. The best exposure of the Holland Paleosol is on the stoss side of the Mount Baldy blowout (Figure 4B). The Holland Paleosol profile is 135 cm thick here, and consists of a 7–15-cm-thick A and AE horizon (Figure 7A), below which are a 10-cm-thick BE, and a 30-cm-thick Bs horizon (Arbogast et al., 2004). The upper portion of the A horizon is feathery, suggesting slow soil burial. Arbogast et al. (2004) obtained radiocarbon ages on charcoal collected from one of the underlying Entisols (calibrated age of 2140–1930 years) and on three charcoal samples from the Holland Paleosol (calibrated ages ranged from 420 years to modern). Three radiocarbon ages were also obtained on charcoal collected from Mount Baldy's stoss side (Gutschick and Gonsiewski, 1976). The oldest sample, collected near the dune's base, ~50 cm above a pedogenically altered clay layer (Figure 4B, white arrow), had an age of 3480–4780 cal yr B.P. (USGS-W3243). A charcoal sample from the Entisol 50 cm below the Holland Paleosol yielded an age of 3000–4080 cal yr B.P. (USGS-W3242). The youngest age, 0– 640 cal yr B.P. (USGS-W3241), was on a wood sample collected from the Holland Paleosol.

We collected four sand samples for OSL age analyses above and below the Holland Paleosol at this site. OSL sample MB 5, collected 1 m below the Holland Paleosol (Figure 4B), yielded an age of 4.00 ± 0.25 ka. The age of OSL sample MB 6, collected 12 cm above the Holland Paleosol, was 0.06 ± 0.04 ka (Table 1). Farther east, where the paleosol bends downward toward its lowest elevation on the stoss side (Figure 4B), OSL sample MB 3, collected 90 cm below the Holland Paleosol, yielded an age of 1.92 ± 0.17 ka. The age of OSL sample MB 4, collected 40 cm above the Holland Paleosol, was 0.93 ± 0.19 ka (Table 1).

The Holland Paleosol is also exposed in the upper part of the Beach House blowout (Figure 7C), ~8–10 m below the crest. At this site, the A and AE horizons are 6–14 cm thick, the BE horizon is 5 cm thick, and the Bs horizon is ~25 cm thick. Eolian strata below this paleosol (Figure 7C) dip gently (~10°) in an easterly direction (95° azimuth). OSL sample IDSP#6, collected 1.4 m below the paleosol, had an age of 3.54 ± 0.15 ka. OSL

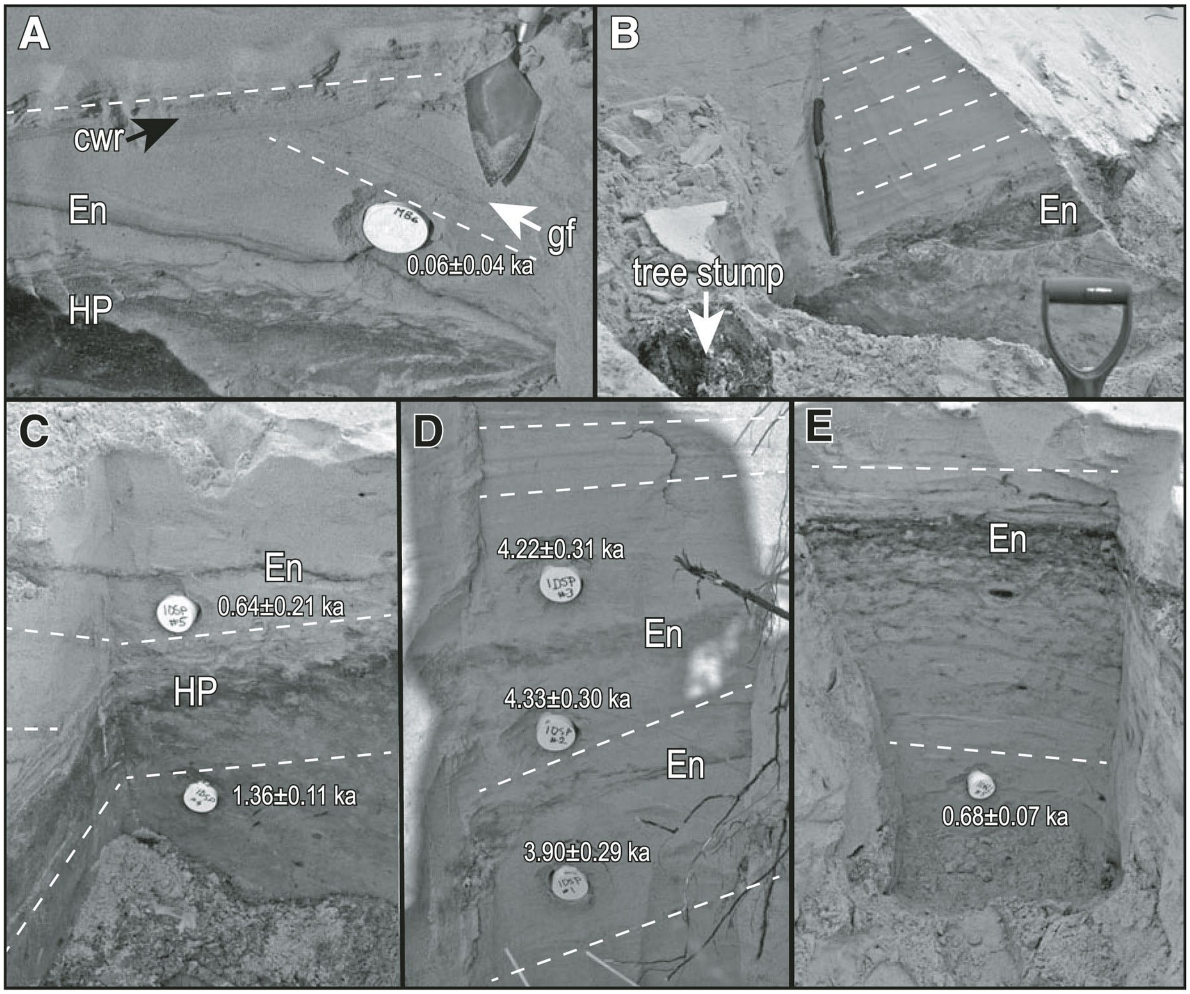

Figure 7. Paleosols in coastal dunes along southern Lake Michigan. (A) Holland Paleosol (HP) and a thin Entisol (En) at the Mount Baldy blowout near the MB 6 optically stimulated luminescence (OSL) sample location shown in Figure 4B. Climbing wind ripples (cwr) are seasonal features found on the dune's stoss side from May through October. These ripples are eroded by strong winds during the stormier months of the year (October–April). Below the climbing wind ripples are steeply dipping (~20°) eolian strata, including grainflows (gf). These grainflows have the coarsest sand of all the eolian strata. (B) Upper Entisol in the West Beach area (Figure 3C) where OSL sample IDNL #4 was collected. Note the large stump in its growth position on the left. The machete handle is 15 cm long. (C) HP—Holland Paleosol and a thin Entisol (En) in the upper part of the Beach House blowout. (D) Two weak Entisols (En) in the lower part of the Beach House blowout. (E) Lower Entisol in the West Beach area where OSL sample IDNL #5 was collected. The dashed white lines are drawn parallel to the lamination within the eolian strata. The white PVC caps of the OSL tubes are 6.5 cm in diameter.

sample IDSP#4 (Figure 7C), collected 25 cm below the paleosol, had an age of 1.36 ± 0.11 ka. A thin (1–2 cm) Entisol, ~20– 25 cm above the Holland Paleosol (Figure 7C), developed on a surface sloping 15° toward the southeast (145°). OSL sample IDSP#5, collected between the Holland Paleosol and this thin Entisol (Figure 7C), had an age of 0.64 ± 0.21 ka.

Two Entisols are found in the lower part of the Beach House blowout along its eastern wall. The upper Entisol (Figure 7D) is ~5 cm thick with relatively sharp boundaries, suggesting a short existence and rapid burial. OSL sample IDSP#3, collected 6 cm above this upper Entisol (Figure 7D), has an age of 4.22 ± 0.31 ka. The second Entisol lies ~25 cm below the upper Entisol. This Entisol is older, thinner (2–3 cm thick), and also has sharp boundaries, indicating, again, a brief episode of soil development and dune stability. The age of OSL sample IDSP#2, collected between these two Entisols, was 4.33 ± 0.30 ka. The age of OSL sample IDSP#1, collected 20 cm below the older Entisol (Figure 7D), was 3.90 ± 0.29 ka.

There are also two Entisols exposed on the east wall of the blowout in the West Beach area (Figure 3C). The younger Entisol (Figure 7B) lies ~6 m below the blowout crest and contains a 15–21-cm-thick A horizon, and an ~30-cm-thick AC horizon with scattered pieces of charcoal and dark organic matter. The age of OSL sample IDNL#4, collected 10 cm above this Entisol, was 0.30 ± 0.09 ka. The older Entisol lies ~4 m below the upper Entisol and consists of an ~15–20-cm-thick A horizon and an ~35-cm-thick AC horizon (Figure 7E). The age of OSL sample IDNL#6, collected 12 cm above the lower Entisol, was 0.37 ± 0.03 ka, while the age of OSL sample

IDNL#5, collected 65 cm below the lower Entisol (Figure 7E), was 0.68 ± 0.07 ka.

Combining the OSL sand ages with the ^{14}C ages on organic material from the paleosols (Gutschick and Gonsiewski, 1976; Arbogast et al., 2004) and the transverse ridges (Thompson, 1992) indicates that the formation of the Tolleston Beach (~6– 4.5 ka) was followed by three episodes of dune development. Data from the Mount Baldy blowout, the Kintzele Ditch and Kemil Road dunes, the Beach House blowout, and the Inland Marsh dune suggest that most of the parabolic dunes east of Ogden Dunes and south of the erosional disconformity (Thompson et al., 2004) developed in the first episode of dune building between 4.5 and 3.0 ka. The second episode of dune building (~3–1.0 ka) was marked by localized dune remobilization at the Mount Baldy and Beach House blowouts and the development of the Holland Paleosol in other locations. OSL and ^{14}C ages at Mount Baldy, and the Beach House and West Beach blowouts indicate the youngest episode of dune building began ~1.0 ka. At this time, a shift in the storm wind direction induced dune reactivation, forming southeast facing blowouts.

Internal Sedimentary Structures within Coastal Dunes

The most diverse display of the dunes' internal sedimentary structures occurs after wind storms accompanied with rain or snow. Low angle erosion of the wet dune surface at the relatively flat crest of Mount Baldy sometimes reveals the wood grain lamination (Loope and Abegg, 2001) of inversely graded climbing wind ripples (Figure 8A). Hunter's work in the coastal dunes of Oregon and the Gulf of Mexico (1977) defined these subcritically climbing translatent strata as the most important criterion in distinguishing eolian from waterlaid strata. Climbing wind ripples at Mount Baldy contain very fine, sand-sized, dark-colored, heavy mineral grains at their base and coarser, fine to medium, sand-sized quartz grains at their top.

Good exposures of pin stripe laminations (Fryberger and Schenk, 1988) can also be seen at Mount Baldy (Figure 8B) in the late fall and winter, a day or two after strong rainstorms. Pin stripe laminations represent concentrations of finer, silt- to very fine sand-sized particles within coarser sand in eolian grainflows, grainfalls, and climbing ripples strata (Fryberger and Schenk, 1988). Pin stripe laminations within the Mount Baldy dune, as well as within coastal dunes along the southeastern shore of Lake Michigan (Hansen et al., 2011), are concentrations of very finegrained sand and silt in the troughs of migrating ripples or at the bases of grainflows. These finer grained fractions in Lake Michigan dune sediments are enriched in denser, darker minerals giving the pinstripes a dark color. Detailed measurements along five traverses on Green Mountain Beach dune by Hansen et al. (2011) indicated that the average spacing between pin stripes varied from 11 to 26 cm, with a maximum spacing of 100 cm. A total of 38 pin stripes across a 1.5 m length of the Mount Baldy dune (Figure 8B) suggests an average spacing of ~4 cm, and a maximum spacing of ~18 cm. Pin stripes that are more closely spaced and even in thickness are associated with climbing wind ripple strata, while pin stripes that are more widely spaced and variable in thickness (thinning or pinching out laterally) delineate grainflow strata. In very cold weather when some moisture is retained within the dune, pin stripe laminations freeze and stand out in relief (Figure 8C), while coarser-grained areas crumble and remain flat or concave. Most pin stripe laminations form parallel to the lee slope. Therefore, their orientation can be used to reconstruct the dune's former geometry, migration pattern, and dominant wind direction during its development (Hansen et al., 2011).

Moreover, concave up deformations in the pin stripe laminations often represent vertebrate tracks (Figure 8D). These can be an important tool for the paleoecological interpretation of ancient sedimentary environments (Loope, 1986). Moist dune sand or clay-rich sand in interdunal areas provides the best medium for preserving vertebrate tracks (Loope, 1986), although unbroken downwarped pin stripe laminations made in dry sand can also be preserved (Loope, 2006). The size and pattern of the tracks shown in Figure 8D suggest that they were made by a deer walking over a dry (upper track) and a wet (lower track) dune surface.

Discussion

Based on the type and age of the landforms and sedimentary structures examined in this study, four major episodes of beach and coastal dune development (Figure 9) have occurred along southern Lake Michigan since the mid-Holocene. The oldest episode formed the early Tolleston Beach, beginning ~6.0 ka, with the Nipissing transgression in Lake Michigan and culminating at the Nipissing high, ~4.5 ka (Thompson et al., 2011; Fisher et al., 2012; Thompson et al., this volume). The early Tolleston Beach formed as a mainland-attached barrier bar with a lagoon behind it. The lagoon's waters were quiet, allowing sedimentation of dark-blue clay. Landward migration of the barrier beach is revealed by an onlapping sequence of intercalated washover, eolian, and nearshore sediments which cover the dark-blue clay (Thompson, 1989). The top of this transgressive lacustrine sequence at the Kintzele dune exposure (Figure 6) is ~6.5 m above the present lake level and this level represents the peak of the Nipissing (184.5 m) in Lake Michigan (Hansel and Mickelson, 1988).

The second major episode of development created the youngest belt of coastal dunes along southern Lake Michigan. This episode began ~4.5 ka (Figure 9) during the post-Nipissing 4 m fall in lake level (Baedke and Thompson, 2000; Thompson et al., 2011). Much of the sand in the modern Tolleston Dunes east of Ogden Dunes was likely emplaced during this early dune development between 4.5 and 3.0 ka. The timing of dune growth and development here is correlative to the dune development along the eastern and southeastern shores of Lake Michigan (Arbogast and Loope, 1999; Hansen et al., 2004; Lepczyk and Arbogast, 2005; Hansen et al., 2006; Hansen et al., 2010) and elsewhere across the

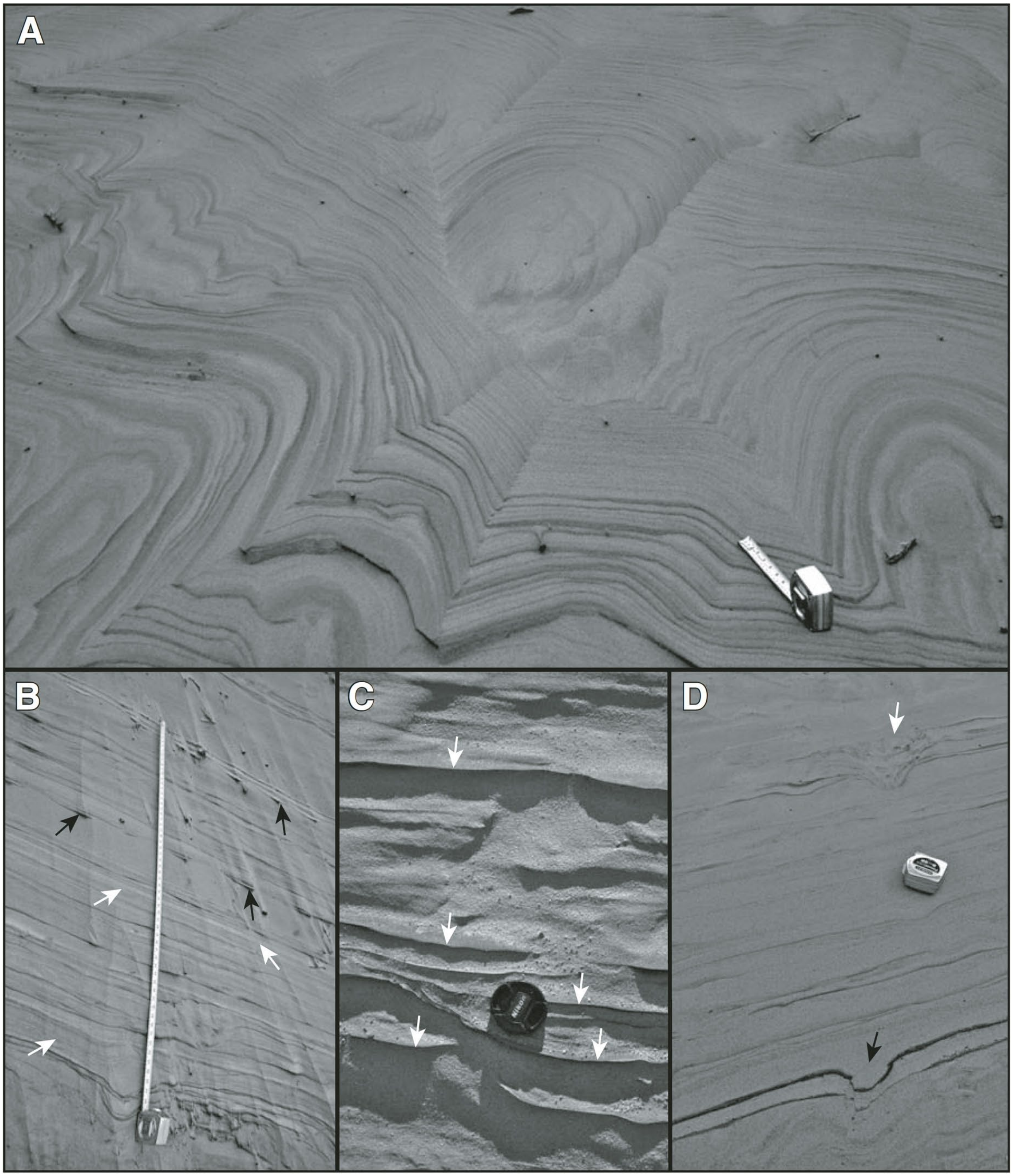

Figure 8. Internal sedimentary structures in dunes along southern Lake Michigan. (A) A wet dune surface eroded at a very low angle reveals the wood grain lamination of climbing wind ripples. The measuring tape is extended 20 cm. (B) Pin stripe laminations exposed at the midpoint of Mount Baldy's stoss slope. Concave up and pinching out pin stripes (black arrows) are associated with eolian grainflows. Laterally extensive and even pin stripes (white arrows) are associated with eolian climbing translatent strata. The measuring tape is extended 150 cm. (C) Because pin stripes retain moisture, they freeze in cold weather and protrude at the dune's surface (arrows), while the coarser quartz-rich laminae lose moisture and weather more easily. The camera lens cap is 5 cm in diameter. (D) These distorted pin stripe laminations are interpreted as deer tracks in wet sand (black arrow) and dry sand (white arrow). The measuring tape case is 10 cm long.

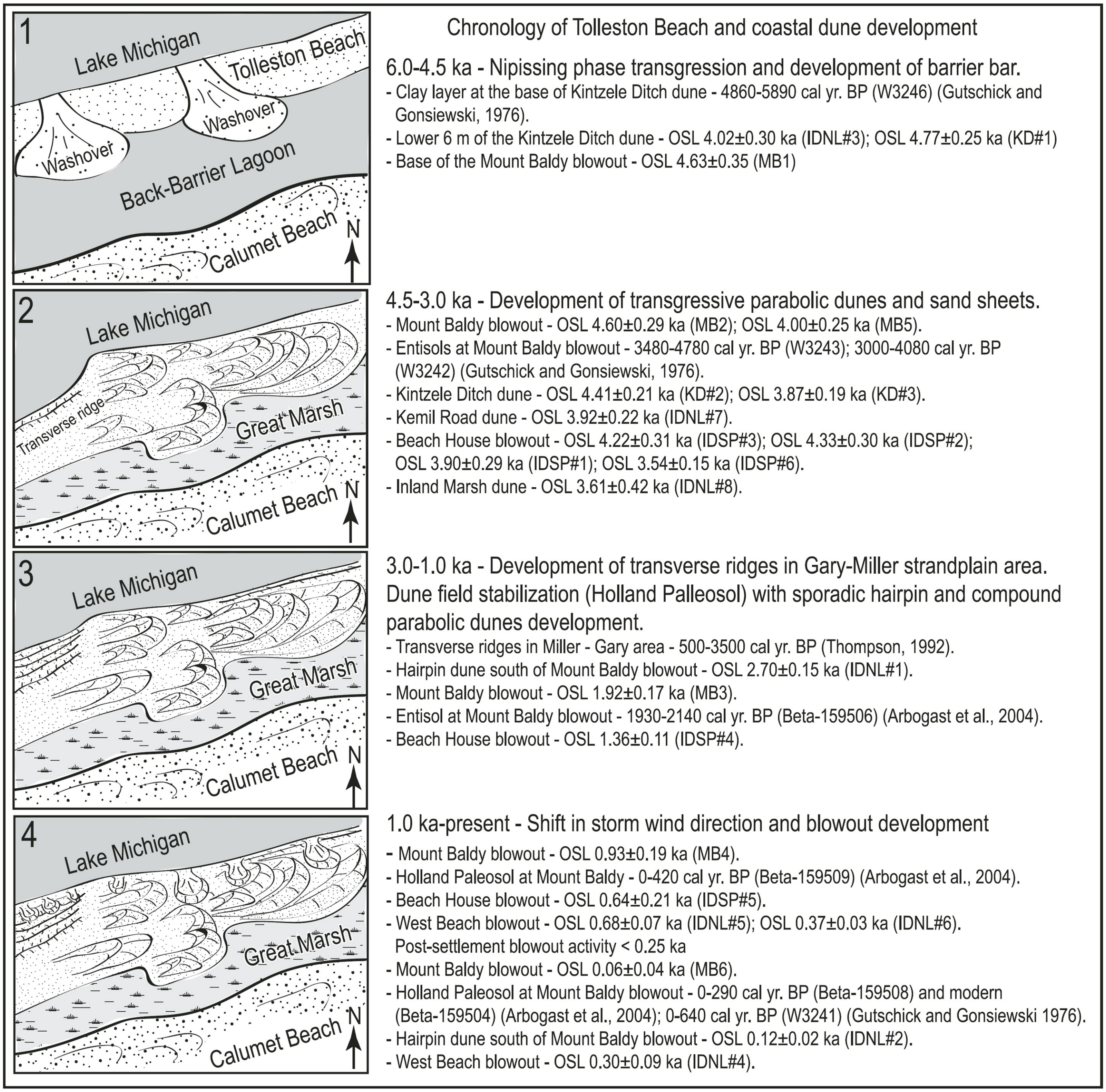

Figure 9. A model for dune development along southern Lake Michigan. Diagram 1 is modified from Thompson (1989). The ^{14}C ages were calibrated to calendar years (with a 2σ range) using the software CALIB REV 6.1.0 (Stuiver and Reimer, 1993) with the IntCal04 calibration curve (Reimer et al., 2004).

Tolleston Beach (Argyilan et al., this volume). The apices of the large simple and compound parabolic dunes suggest predominant westerly winds in their formation. Parabolic dunes along the eastern and southeastern coast of Lake Michigan (Hansen et al., 2010) formed by blowout initiation from linear, shore parallel dunes and their eastward transgression inland. Soon after the initial development began, there were two brief episodes of dune stabilization around 4.0 ka. These stabilization periods are indicated by two Entisols present in the lower part of the Beach House blowout. Two more brief episodes of dune stability occurred ~4 ka and ~3.5 ka based on the ages of two Entisols in the lower part of the Mount Baldy blowout.

Parabolic dunes in the western part of the study area, from Gary to Ogden Dunes, and north of the erosional disconformity (Thompson et al., 2004) might be the result of somewhat different processes, however. Less ordered parabolic dune orientations in this area suggest their possible initiation as random blowouts within the extensive sand sheet of a rapidly prograding shoreline.

The third stage of dune evolution along Lake Michigan's southern coast (Figure 9) occurred between 3.0 and 1.0 ka. following the Algoma lake level high (Baedke and Thompson, 2000). This stage was marked by the creation of transverse ridges in the Miller-Gary area and the development of the Holland Paleosol (Arbogast et al., 2004) and its equivalent paleosols east of the Miller area. The sediment supply to southern Lake Michigan diminished due to the lake level decline. Therefore, most of the sediment brought to the southern tip of Lake Michigan was stored in prograding strandplains rather than added to transgressive parabolic dunes. Transverse ridges developed along the prograding shoreline near Gary following the short-term (~31 year) highs in lake level. Concurrently in Miller, groups of four to six ridges combined to form a single ridge following longer term (~151 year) highs in lake level (Thompson, 1992).

Beach progradation in the Gary-Miller area limited the sediment supply to transgressive parabolic dunes east of Miller where the Holland Paleosol began to form. These dunes were episodically active during the Holland Paleosol interlude. This is supported by a broad range of OSL ages of sand below the Holland Paleosol and ^{14}C ages on organic material from the Holland Paleosol (Gutschick and Gonsiewski, 1976; Arbogast et al., 2004). The OSL sand and ^{14}C paleosol ages from the parabolic dunes along southeastern Lake Michigan also suggest sporadic dune activity during the Holland Paleosol development (Arbogast et al., 2004; Hansen et al., 2010). Additionally, a decrease in the number of sand peaks in sediment cores from several lakes adjacent to the coastal dunes (Fisher and Loope, 2005; Timmons et al., 2007) also supports this sporadic dune mobility. Most modern parabolic dunes along the southern and southeastern shore of Lake Michigan are stable, with thick soils and vegetation on their surfaces (Hansen et al., 2010). However, next to them are active dunes growing in length and/or height and migrating downwind at rates of a few meters per year. Post-Algoma lake level fluctuations were generally less than 1 m in amplitude (Baedke and Thompson, 2000) and were likely not as important in causing foredune erosion and blowout development as strong storms. During the last several years of below normal lake levels, we have witnessed strong storms temporarily (a few hours to a few days) inducing lake level rises that erode a tremendous amount of the beach and dunes. As most of the large parabolic dunes stabilized during the third stage, some continued evolving from lobate parabolic dunes into more elongated hairpin forms. An example of this is a dune south of Mount Baldy (Figure 4A). The reactivation and downwind migration of some parabolic dunes likely caused the amalgamation of simple, lobate, and hairpin parabolic dunes into more complex, compound, nested parabolic dunes. Many of these dunes achieved a height of 25–35 m during this stage.

A rise in the lake level at ~1 ka (Baedke and Thompson, 2000) marks the beginning of the fourth and latest stage (Figure 9) in coastal dune development along Lake Michigan's southern coast. Higher lake levels caused beach and foredune erosion and, subsequently, provided a steady sand supply for coastal dune growth (Loope and Arbogast, 2000). The higher lake levels also induced a higher drift potential for winds. That is, winds could blow from the water's surface directly into the dunes rather than blowing over an extensive backshore before reaching the dunes. For example, based on our recent (from 2007 to 2012) monitoring of sand accretion rates in this area, the wind drift potential and rates of sand transport are an order of magnitude higher at Mount Baldy dune, which has ~20-m-wide backshore north of it, than at the blowout dune in the western IDSP, which has an 80 m wide backshore.

This final episode of coastal dune evolution along southern Lake Michigan is characterized by the development of blowouts with axis orientations clearly discordant to that of the older parabolic dunes. This change suggests a shift in the dominant wind direction from the northwest. In most instances, blowouts developed through linear or parabolic dunes closest to the lake, except in the case of the Big Blowout which extended over the entire dune belt. Several narrow trough blowouts climbed on the crests of the older parabolic dunes, producing the three highest dunes, Mount Holden, Mount Tom, and Mount Jackson, along southern Lake Michigan. Several buried Entisols in the upper parts of the dunes suggest that most of the blowout activity occurred prior to anthropogenic disturbances associated with European settlement. In addition, this activity correlates well with dune activity along the eastern and southeastern coast of Lake Michigan (Arbogast et al., 2004; Hansen et al., 2010). Our ongoing studies of sand transport rates in active blowouts (Yurk et al., this volume) indicate that the strongest winds in this region occur from late fall through early spring. Northwesterly and northerly winds frequently blow in excess of 15 m/s with a 350–400 km fetch during this time. A single storm with winds of this strength is capable of eroding more than 1 m of sand from a dune's stoss side and depositing up to 1.3 m of sand on its slip face. An increase in the number of strong winter cyclones during the twentieth century (Angel and Isard, 1998) could be responsible for the maintenance of modern active blowouts. The initiation of a similar storm pattern ~1.0 ka may have triggered the latest episode in dune development along southern Lake Michigan. The coarsest sand within the studied dunes along southern Lake Michigan was found in grainflows that buried the Holland Paleosol at Mount Baldy dune. This further suggests winter storm initiation and maintenance of the modern blowouts.

Conclusions

The youngest belt of coastal dunes along southern Lake Michigan evolved through four stages. The first major episode of dune development began at the end of the Nipissing transgression, ~6.0 ka, and peaked at ~4.5 ka. Large amounts of sand eroded from the lake margins were transported to southern Lake Michigan where a barrier bar, the early Tolleston Beach, developed. During and following the rapid post-Nipissing lake level fall (~4.5–3.0 ka), the second major episode of dune development occurred. Large quantities of exposed sand were blown into transgressive parabolic dunes that advanced eastward along the barrier beach. The orientation of these dune axes suggests dominant westerly winds in their formation. The third stage in coastal dune evolution, ~3.0–1.0 ka, was characterized by strandplain progradation west of Miller and parabolic dune stabilization east of Miller. Transverse ridges developed west of Miller following short-term (~31 yr) and longer term (~151 yr) highs in the lake level. East of Miller, the diminished sand supply caused stabilization of the parabolic dunes and the Holland Paleosol developed. Localized blowout activity, under strong westerly winds, redistributed the sand within the dune field by changing lobate dunes into hairpin dunes and amalgamating simple dunes into compound parabolic dunes. The final episode in dune evolution began ~1.0 ka and is marked by a shift to northwesterly dune building winds. Most of the modern blowout activity occurs in the late fall and winter season when storm winds are the strongest.

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