

Provided for non-commercial research and education use.  
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

<http://www.elsevier.com/copyright>



Contents lists available at ScienceDirect

## Aeolian Research

journal homepage: [www.elsevier.com/locate/aeolia](http://www.elsevier.com/locate/aeolia)

## Reconstructing the age of coastal sand dunes along the northwestern shore of Lake Huron in Lower Michigan: Paleoenvironmental implications and regional comparisons

Alan F. Arbogast<sup>a,\*</sup>, Michael E. Bigsby<sup>a</sup>, Mark H. DeVisser<sup>a</sup>, Shaun A. Langley<sup>a</sup>, Paul R. Hanson<sup>b</sup>, Trevor A. Daly<sup>a</sup>, Aaron R. Young<sup>b</sup>

<sup>a</sup> Department of Geography, 121 Geography, Michigan State University, East Lansing, MI 48824, USA

<sup>b</sup> University of Nebraska–Lincoln, School of Natural Resources, Lincoln, NE 68583-0996, USA

## ARTICLE INFO

## Article history:

Received 20 February 2010

Revised 12 July 2010

Accepted 12 July 2010

## Keywords:

Sand dunes

Michigan

Lake Huron

OSL dating

## ABSTRACT

Coastal sand dunes are very common in Lower Michigan, especially along Lake Michigan due to prevailing westerlies and high sand supply. These western dunes have been the focus of numerous geomorphic investigations that demonstrate a history for the past 5000 years. Coastal dunes on Lower Michigan's shore with Lake Huron are far less common and have yet to be examined. They have the potential to yield important information about regional wind patterns and their response to lake-level fluctuations. This study is the first to investigate such dunes and focuses on Manitou Beach in northeastern Lower Michigan. The chronology was reconstructed through optical dating of eolian sands.

Three dune groups were examined. The *Algonquin group* contains low-relief dunes on the Algonquin lake plain that apparently formed about 6 ka, perhaps due to a warmer/drier climate. The extensive *Manitou group* contains prominent ridges between the shore and a bluff eroded during the Nipissing high lake stand about 5.5 ka. Most ridges apparently formed shortly after the lake regressed and about 4 ka. A large, easterly oriented parabolic dune developed about 2.8 ka on the eastern side of the dune field. The *Hammond group* consists of a dunes perched on the Nipissing bluff on the west side of the study area. These dunes also formed between about 5 and 4 ka. This study demonstrates that (1) dunes here are generally older than those on the west coast of Lower Michigan, and (2) unusually strong easterly winds apparently occurred around 2.8 ka.

© 2010 Published by Elsevier B.V.

## 1. Introduction

Sand dunes are very common along the shores of Michigan (Fig. 1). These landforms are especially numerous along the eastern shore of Lake Michigan where they range from large parabolic dunes up to 60-m high (e.g., Arbogast et al., 2002a) to much smaller foredunes only a few meters tall (Olson, 1958; Van Dijk, 2004). In many places extensive dune fields line the shore for many kilometers. As a result, these landscapes collectively have a very high public profile in the state, with numerous national, state, and local parks located along the shore.

Since the middle 1990s, dunes along the west coast of Lower Michigan have been the focus of intensive geomorphic research that has centered on reconstructing the history of eolian sand deposition. The dynamics of west coast dunes (activation and stabilization) have been determined primarily by analyzing stratigraphic relationships in conjunction with radiocarbon dating and

optical stimulated luminescence dating (e.g., Arbogast and Loope, 1999; Van Oort et al., 2001; Arbogast et al., 2002a; Hansen et al., 2002; Cordoba-Lepczyk and Arbogast, 2005; Fisher and Loope, 2005). The general goal of this research has been to assess the temporal relationship of growth intervals and stability with lake-level fluctuations (e.g., Baedke and Thompson, 2000; Thompson et al., 2004).

These studies demonstrate that coastal dunes along the eastern shore of Lake Michigan have a very complex history. Dune fields along the southeastern shore of the lake line much of the coast, mantle pro-glacial lacustrine plains from ancestral Lake Michigan, and contain numerous large parabolic dunes. Research indicates that most of these dunes apparently began to grow about 5000 years ago (Arbogast et al., 2002a, 2004; Hansen et al., 2002) during the Nipissing high stand (Hansel et al., 1985; Monaghan et al., 1986; Larson and Schaetzl, 2001). They subsequently grew rapidly, but in an episodic fashion, until about 2000 years ago when they stabilized for about 1500 years, resulting in the formation of the prominent Holland Paleosol (Arbogast et al., 2004; Hansen et al., 2010). This soil was buried locally between about 900 and 500

\* Corresponding author. Tel.: +1 517 355 5262; fax: +1 517 432 1671.

E-mail address: [dunes@msu.edu](mailto:dunes@msu.edu) (A.F. Arbogast).

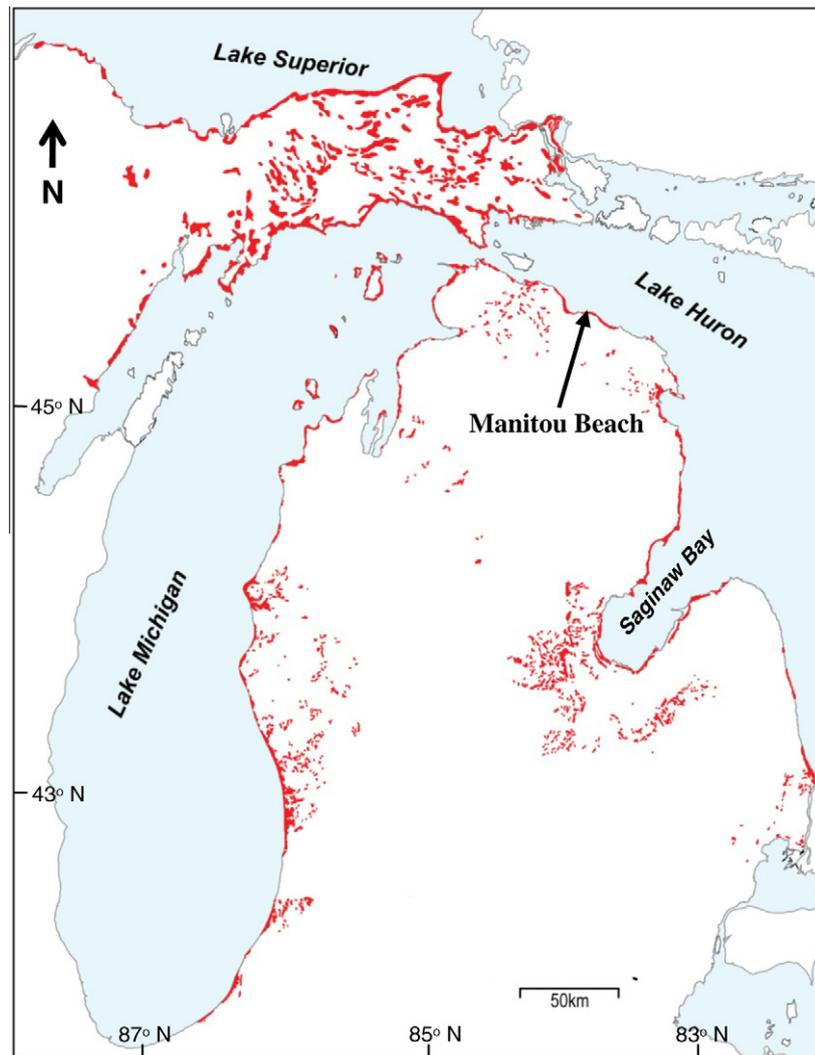


Fig. 1. Dune fields of Michigan's Lower and Upper Peninsulas (modified from Schaeztl et al., 2009).

years ago, with further episodic dune activation since that time (e.g., Arbogast et al., 2004; Fisher and Loope, 2005; Hansen et al., 2010). In general, periods of dune stability and soil formation along the southeastern shore tend to align temporally with low lake stages, whereas episodes of dune growth generally appear to have most often occurred during high lake phases when beach erosion was common and landscapes were geomorphically active.

In contrast to dunes along the southeastern shore of Lake Michigan, dunes along the northwestern coast of Lower Michigan appear to have a somewhat different geomorphic history. At a fundamental level, the landscape position of most dune fields differs from the more southerly dune fields. Most of these dune fields occur in isolated embayments (e.g., Cordoba-Lepczyk and Arbogast, 2005; Arbogast et al., 2009a,b), rather than along an entire reach of coastline. In these settings, dunes mantle lacustrine surfaces that have been raised isostatically above the water line since the Nipissing stage (Scott, 1942). Most dunes consist of individual ridges that sometimes contain imbedded parabolic forms. Other isolated dune fields, such as at Sleeping Bear National Lakeshore (Snyder, 1985) and Arcadia (Blumer, 2008) are perched high on glacial headlands.

In addition to their different landscape position, it appears that most northerly dunes began forming somewhat later in time than the dunes farther south. According to Arbogast et al. (2009a), the earliest period of intensive dune growth in this part of Michigan

began about 3500–3300 years ago when dunes that are now the most inland developed. Instead of growing upward, as many dunes along the southeastern shore have through time (e.g., Arbogast et al., 2002a), dunes in northwestern Lower Michigan are progradational with progressively younger dunes found towards the modern lake. Most of the more lakeward dunes began to form about 1000 years ago, with some additional deposits accumulating in the past few hundred years (Cordoba-Lepczyk and Arbogast, 2005). In general, the oldest dune ridges are the largest (up to ~30 m high). Progressively younger dunes tend to also be systematically smaller (Arbogast et al., 2009a), suggesting a reduction in sand supply over time.

In addition to the extensive dune fields on the western coast of Lower Michigan, some dune landscapes are also found on the east coast of the peninsula (Fig. 1). These dune fields are far less extensive than those on the peninsula's west coast, are much more widely scattered, and contain a fraction of the eolian sand. Given their very low profile in Michigan, their depositional and geomorphic histories have yet to be reconstructed. These dune fields may be informative geomorphic features, however, because they might shed light on regional wind histories as they relate to the timing of eolian sand supply and dune formation. As a result, dunes on the eastern coast of Lower Michigan likely preserve a different record of eolian sand mobilization than their western counterparts and thus will contribute to our understanding of paleoenvironmental

history in the region. In this context, this study focuses on the geomorphic history of a dune field on the northeastern shore of Lower Michigan.

## 2. Study area

The study area for this investigation is located at Manitou Beach, which is a north-facing shoreline along Lake Huron about 12.5 km northwest of Rogers City in northeastern Lower Michigan (Figs. 1 and 2). According to Arbogast et al. (2009b), this dune field easily contains the largest volume ( $\sim 10^{-1}$  km<sup>3</sup>) of eolian sand along Lower Michigan's coast of Lake Huron. As a result, Manitou Beach was the focus of this initial investigation of coastal dunes along Lower Michigan's coast of Lake Huron.

Dunes in the study area are stabilized by dense forest and clustered in three specific areas (Fig. 2). The largest group (*Manitou group*) is in the northeastern part of the study area where it extends along the coast for about 4.8 km (3 mi). This dune group is bisected by US highway 23 and is approximately 1.2 km (0.75 mi) wide. The area south of the highway is a natural area owned by the Twin Lakes Association, whereas the US Forest Service owns the area north of the highway to a point within about 200 m of the shore where private land begins. The Manitou group is bordered immediately to the south by a prominent bluff that is about 5 m high. The base of this bluff is at about 190 m, which is approximately the elevation of Nipissing beach gravels that were identified at Hammond Bay (Fig. 2) by Leverett and Taylor (1915). As a result, this bluff is assumed to be a wave-cut bluff that developed during the Nipissing I high stand of Lakes Michigan and Huron at approximately 5.5 ka (e.g., Hansel et al., 1985; Monaghan et al., 1986; Larson and Schaetzl, 2001). Dunes within the Manitou group consist mostly of distinct ridges, mostly shore parallel, similar to those identified in embayments along the shore of northwestern Lower Michigan (Cordoba-Lepczyk and Arbogast, 2005; Arbogast et al., 2009a). The largest of these ridges borders the bluff and is about 7 m high. A prominent parabolic dune also occurs in the eastern part of the dune field that is about 15 m high and oriented to the east.

In addition to the primary dune field at the study site, a pair of secondary dune groups occurs nearby (Fig. 2). The most geograph-

ically extensive of these additional eolian deposits consists of widely scattered parabolic dunes that lie south of the Nipissing bluff on what appears to be the Algonquin lake plain, which formed between about 12 and 11 ka during the late-glacial Algonquin high stand (Krist and Schaetzl, 2001; Larson and Schaetzl, 2001). This concentration of dunes is called the *Algonquin group*. These dunes are generally oriented to the west/northwest and are only 2 or 3 m high. The third body of eolian sand deposits is a very isolated pair of connected parabolic dunes in the *Hammond group* that occur about 6 km (3.7 mi) west of the primary dune field at the eastern end of Hammond Bay. This pair of dunes lies immediately south of the Nipissing bluff, which is about 25-m high at this locality.

The climate in the study area is classified as mixed marine continental. Mean annual temperature is 6.2 °C, with January and July temperatures averaging  $-7.4$  and  $19.6$  °C, respectively. The average growing season is 141 days. Mean annual precipitation is 72.2 cm, with the highest monthly average occurring in August (9.3 cm) and the lowest monthly average occurring in February (3.1 cm). Mean annual snowfall is 183.6 cm (Midwest Regional Climate Center, 2008). Modern wind data (1961–1990; USDA, 2003) indicates that northwesterly winds occur most frequently, almost 20% of the time (Fig. 3). The strongest of these winds have speeds between 8.49 and 11.05 m/s. The next most frequent (15%) winds are southeasterly, with similar high speeds (Andresen, Personal Communication).

Vegetation in the study area consists of northern mixed hardwoods. The most common species found on the dunes includes red pine (*Pinus resinosa*), and jack pine (*Pinus banksiana*). Other species typically found in this area are eastern white pine (*Pinus strobes*), northern red oak (*Quercus rubra*), American beech (*Fagus grandifolia*), quaking aspen (*Populus tremuloides*), paper birch (*Betula papyrifera*) and black cherry (*Prunus serotina*) (Knapp, 1993).

## 3. Methods

Before we entered the field, a map reconnaissance was conducted with US Geological Survey 1:24,000 topographic quadrangle maps. Once the study area was initially assessed, field reconnaissance was conducted to learn more about the landscape

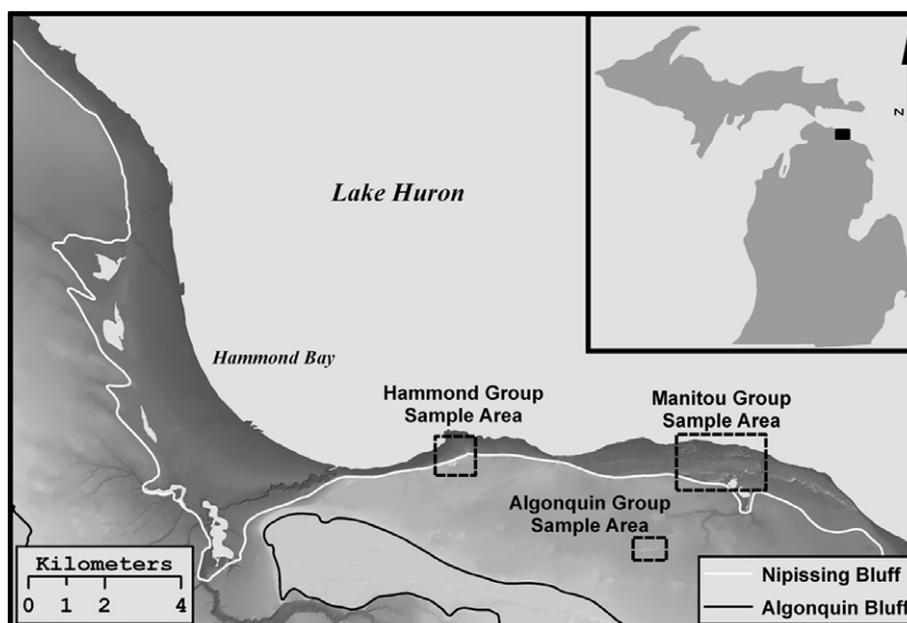
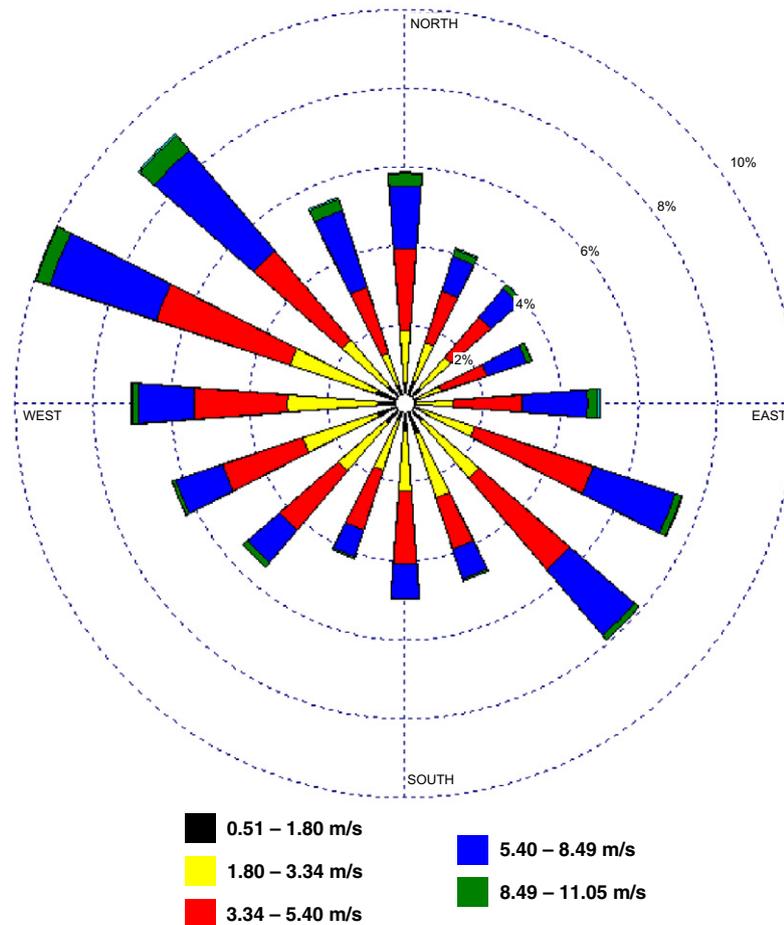


Fig. 2. Map of the study area showing the location of the three dune groups and shoreline configuration.



**Fig. 3.** March (1961–1990) wind rose from Alpena, which is about 50 km southeast of the study area. Percent occurrence is represented by the concentric circles, whereas wind strength is reflected by the color of bars. The proportion of time of each speed interval is indicated by the length of each color segment in rose spokes. The most common (10% occurrence) winds are from the west/northwest. Direct easterly winds occur <6% of the time, with brief gusts of between 8.49 and 11.05 m/s (USDA, 2003). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

and determine possible dunes for sampling. The Manitou group was the main source of interest because of the size and number of dunes at the site, series of distinct ridges, and the presence of a large parabolic dune on its eastern edge. After dunes in this group were assessed, we turned our attention to a reconnaissance of the Algonquin and Hammond groups. This assessment verified that the Manitou group is the best developed dune field in the study area.

In order to assess the age of each dune field, a series of sample sites were targeted in the study areas (Figs. 4 and 5). A total of 12 samples were collected from these sites for age estimation. Eight of these samples were collected with a hand auger on dune crests at a depth of 1.5–2 m to avoid erroneous ages by mixing due to bioturbation (e.g., Hanson et al., 2009, 2010). Of these crest samples, seven were obtained from the Manitou group (Fig. 4) and 1 was acquired from the Algonquin group (Figs. 2 and 5). An additional sample was collected from a lower depth with a hand auger in the eastern parabolic dune in the Manitou group (Fig. 4) to assess the age of hypothetically older eolian sands. Three additional samples were collected from the dunes in the Hammond group (Figs. 2 and 5). These samples were obtained from natural and quarry exposures that were first cleaned so the sands were properly presented.

The locations of all sample sites were recorded using a Leica GS20 GPS unit to measure latitude, longitude and elevation. Elevation data was extracted from the 10 m National Elevation Dataset (NED) Digital Elevation Model (DEM). Topographic representations of the sample areas (Figs. 4 and 5) were produced using a resam-

pled 1 m DEM, which was constructed using the natural spline interpolation method on the 10 m NED DEM. The resampled 1 m DEM was only used for visualization purposes, and based on our field observations does accurately represent the landscape's topography.

Optical dating samples were analyzed at the Luminescence Geochronology Laboratory at the University of Nebraska using pre-treatment and data reduction methods similar to those in Hanson et al. (2009, 2010). Samples were dated using the single aliquot regenerative (SAR) method (Murray and Wintle, 2000) on 90–150  $\mu\text{m}$  quartz grains. A preheat plateau test (Wintle and Murray, 2006) showed these samples responded best to luminescence procedures when using a preheat of 220 °C. Prior to each step in the SAR sequence aliquots were pre-heated for 10 s. A cut heat was used for the test dose which was also performed at 220 °C. Dose rate values were estimated using concentrations of K, U and Th as determined by ICP-MS and ICP-AES. All optical ages are presented in calendar years before 2009 (Table 1).

## 4. Results and discussion

### 4.1. Dune groups and optical ages

#### 4.1.1. Algonquin group

The Algonquin group lies on the Algonquin lake plain between the Algonquin bluff on the southern end of the study area

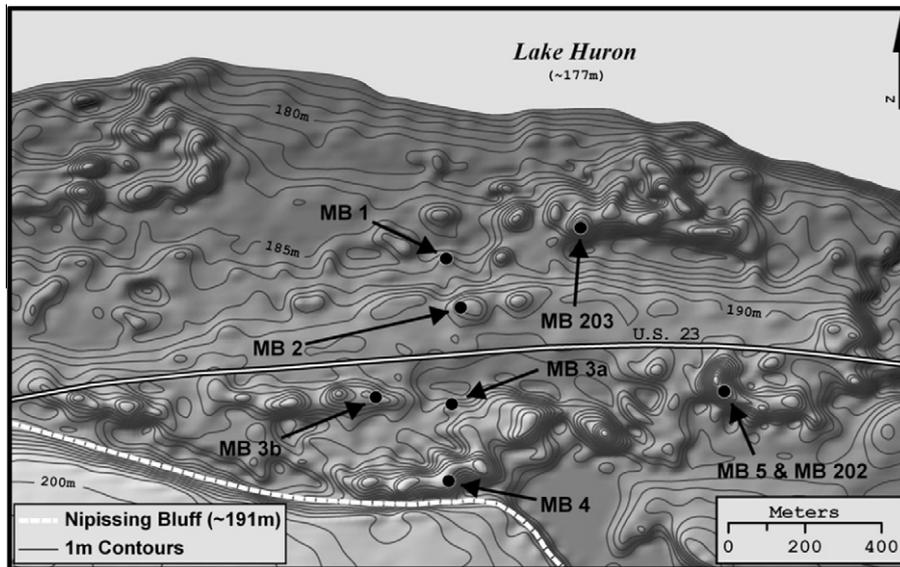


Fig. 4. Map of sample sites in the Manitou dune group. Note the dune ridges and large parabolic dune with easterly orientation (circle) on the eastern edge of the sample area.

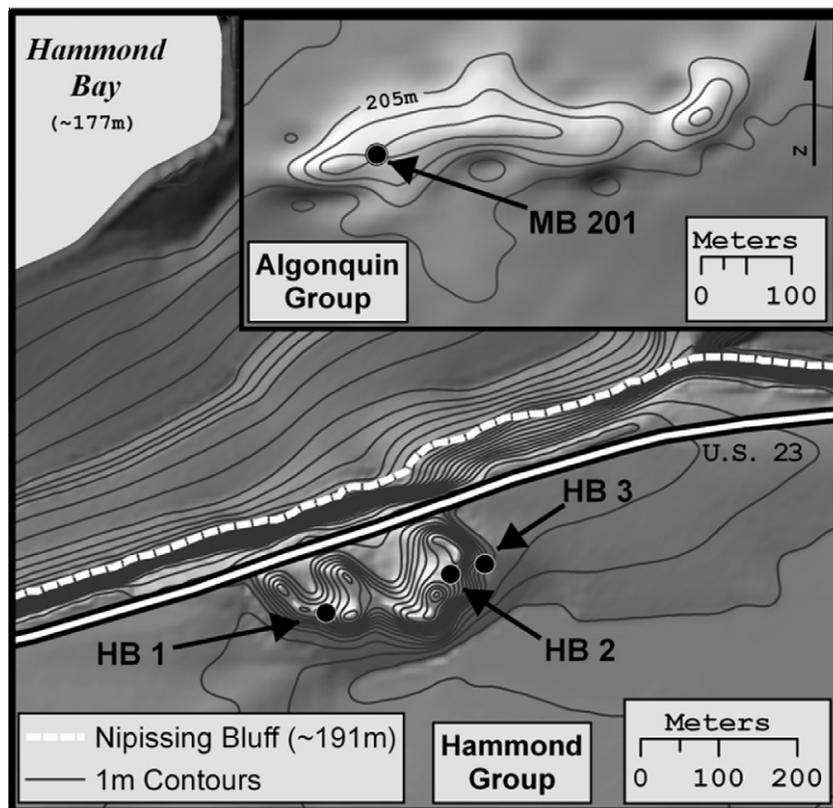


Fig. 5. Map of the sample sites in the Algonquin dune group and Hammond dune group.

and Highway M-23, which fundamentally follows the Nipissing Bluff (Fig. 2). This lake plain was created during the Algonquin stage of the ancestral Great Lakes between about 12 and 11 ka (Krist and Schaetzl, 2001; Larson and Schaetzl, 2001). Dunes within this cluster are widely scattered, have low relief (<3 m), and are generally oriented to the west. A dune in the central part of this cluster (Figs. 2 and 5) was sampled at a depth of 2 m (site MB201) and provided an age estimate of  $6.0 \pm 0.5$  ka (UNL-2294).

#### 4.1.2. Hammond group

The Hammond group consists of a pair of well-defined and connected parabolic dunes that lie on the lip of the Nipissing bluff in the western part of the study area (Figs. 2 and 5). The dunes are about 15-m high, facing the bluff front for about 275 m, and are oriented to the northwest. These dunes extend inland about 100 m from the top of the Nipissing bluff.

Three optical ages were acquired from this dune group (Fig. 5), with two of the samples derived from the dune crests. The

**Table 1**  
Equivalent dose, dose rate data, and optical age estimates for the Manitou Dunes.

Field #	UNL Lab #	Depth (m)	U (ppm)	Th (ppm)	K <sub>2</sub> O (wt%)	In situ H <sub>2</sub> O (%) <sup>a</sup>	Dose rate (Gy/ka)	D <sub>e</sub> (Gy) ±1 Std. Err.	Aliquots (n) <sup>b</sup>	Optical age ±1σ
HB1	UNL-2286	1.8	0.4	1.3	1.4	3.3	1.39 ± 0.09	6.2 ± 0.5	22/33	4.5 ± 0.5
HB2	UNL-2287	1.3	0.4	1.4	1.2	3.1	1.31 ± 0.08	5.5 ± 0.5	21/30	4.2 ± 0.5
HB3	UNL-2288	2.8	0.4	1.4	1.4	3.2	1.44 ± 0.10	5.6 ± 0.3	23/28	3.9 ± 0.4
MB1	UNL-2289	1.5	0.6	1.4	1.0	2.9	1.18 ± 0.07	5.9 ± 0.4	21/31	5.0 ± 0.5
MB2	UNL-2290	1.5	0.5	1.4	1.3	3.4	1.40 ± 0.09	5.7 ± 0.3	20/34	4.1 ± 0.4
MB3a	UNL-2291	1.5	0.4	1.6	1.4	3.4	1.47 ± 0.10	14.4 ± 0.8	22/24	9.8 ± 0.9
MB3b	UNL-2565	1.5	2.7	1.56	1.4	4.0	1.92 ± 0.11	5.3 ± 0.3	27/37	2.8 ± 0.3
MB4	UNL-2292	1.5	0.5	1.3	1.3	2.2	1.36 ± 0.09	5.5 ± 0.3	20/32	4.0 ± 0.4
MB5	UNL-2293	1.5	0.5	1.5	1.4	2.8	1.49 ± 0.10	3.9 ± 0.8 <sup>c</sup>	22/24	2.6 ± 0.6
MB201	UNL-2294	2.0	0.4	1.3	1.2	1.5	1.30 ± 0.08	7.7 ± 0.2	25/28	6.0 ± 0.5
MB202	UNL-2295	5.8	0.4	1.4	1.3	2.6	1.29 ± 0.09	7.5 ± 0.2	20/28	5.8 ± 0.5
MB203	UNL-2296	3.0	0.5	1.5	1.6	1.9	1.58 ± 0.10	8.6 ± 0.4	21/23	5.4 ± 0.5

<sup>a</sup> Assumes 100% error in measurement.

<sup>b</sup> Accepted disks/all disks.

<sup>c</sup> Median D<sub>e</sub>; mean D<sub>e</sub> is 5.3 ± 0.6 Gy.

westernmost of the samples (HB1) was collected at a depth of 1.8 m from a cleaned natural exposure and provided an age of 4.5 ± 0.5 ka (UNL-2286). The easternmost crest was sampled (HB2) at a depth of 1.3 m in a cleaned exposure and provided an age of 4.2 ± 0.5 ka (UNL-2287).

Immediately east of this second sample a large quarry pit was discovered that provided access into the core of the dune. In an effort to assess the age of the lowermost dune deposits, a south-facing exposure was cleaned on the easternmost edge of the dune to a point below the stratigraphic contact with the underlying lacustrine sediments. A sample (HB3) was collected at the base of the eolian deposits at a depth of 2.8 m and provided an age of 3.9 ± 0.4 ka (UNL-2288). The three optical age estimates fall within their 1σ errors and therefore, an average age of about 4 ka can be assessed to the Hammond dune field system.

#### 4.1.3. Manitou group

The Manitou group is the largest concentration of dunes in the study area. The best defined dunes in this group are a series of three dune ridges in the central part of the field that contain some embedded subparabolic forms that are subtly oriented to the northwest (Fig. 4). On the eastern edge of the group is a very prominent parabolic dune, which is about 50-m high, that is clearly oriented to the east. In addition to these large dunes, the rest of the group consists of smaller, poorly defined dune forms. A total of eight samples for optical dating were collected in this dune group.

In an effort to assess the age of the ridges a series of samples were collected across the dune field (Fig. 4). The southernmost ridge is about 15 m tall at its highest point and borders the Nipissing bluff immediately to the south. An optical dating sample (MB4) was collected from a depth of 1.5 m and provided an age of 4.0 ± 0.4 ka (UNL-2292). Approximately 150 m north of this southernmost dune ridge is another ridge that is about 10 m high. Although this feature merges with the more southerly dune on its eastern and western ends, it was sampled in the center of the ridge where it stands alone.

An initial sample (MB3a) was collected from a depth of 1.5 m from the secondary ridge and provided an age of 9.8 ± 0.9 ka (UNL-2291). Given the relative antiquity of this assessment, coupled with the assumption that the underlying surface was subaqueous during the Nipissing high stand about 5 ka (e.g., Monaghan et al., 1986; Larson and Schaetzl, 2001), it was believed that the sample was incompletely bleached. As a result, the site was sampled again at a later date to test the validity of this age. This later sample (MB3b) was collected about 50 m to the west of the original sample site from a depth of 1.5 m and provided an age of 2.8 ± 0.3 ka (UNL-2565).

The last pair of ages from the dune ridges was collected in a shorter, less well-defined ridge north of Highway M-23 (Fig. 4). This ridge is about 5–7 m high at its tallest point. The southernmost of these samples (MB2) was collected from a depth of 1.5 m and provided an age of 4.1 ± 0.4 ka (UNL-2290). The last sample (MB1) in the transect was collected about 100 m to the north, also from a depth of 1.5 m, and provided an age of 5.0 ± 0.5 ka (UNL-2289).

Aside from determining the age of dune ridges, a secondary focus of this study was to reconstruct the history of the large parabolic dune on the eastern edge of the dune field (Fig. 4). In an effort to assess the age of the lower deposits in the dune, a sample (MB202) was collected from a depth of 5.8 m in the southern limb of the feature. This sample provided an age of 5.8 ± 0.5 ka (UNL-2295). A second sample (MB5) was collected from a depth of 1.5 m near the crest of the dune that provided an age of 2.6 ± 0.6 ka (UNL-2293). Although several samples had some fairly old aliquots for dune samples, this sample was the only one we collected that had an appreciably skewed D<sub>e</sub> distribution, and a high mean to median ratio for the D<sub>e</sub> values. Although this spread in D<sub>e</sub> values could be attributed to problems with the luminescence signal of the quartz, we attribute the spread to problems with bleaching prior to deposition. Therefore, rather than calculating the age based on its mean D<sub>e</sub> value, we instead used its median D<sub>e</sub> (Table 1).

The last sample acquired in this study was collected from the crest of a dune ridge north of Highway M-23 (Fig. 4). Although this feature is actually an extension of the dune sampled at the northern end of the ridge sequence, it was selected for additional dating because this ridge is better defined (about 10 m high) in this part of the dune field. A sample (MB203) was collected from a depth of 1.5 m that provided an age of 5.4 ± 0.5 ka (UNL-2296).

## 5. Discussion

Results from this study are the first to shed light on the history of eolian sand deposition and dune dynamics along the coast of Lake Huron in Lower Michigan. It focused on three dune groups at Manitou Beach in the northeastern part of the peninsula (Fig. 1). These dunes collectively form the largest body of coastal dunes along Lower Michigan's coast with Lake Huron (Arbogast et al., 2009b). As a result, this work provides a foundation for future studies of Lake Huron coastal dunes in Michigan.

Optical ages obtained in this study provide a clear record of eolian sand deposition in the Manitou dune field. Fig. 6 shows the relationship of these ages and their probability density, as well

their temporal comparison with reconstructed lake-level fluctuations. The early part (~7–4.8 ka) of this lake-level curve is derived from research conducted by Monaghan et al. (1986) in Saginaw Bay on the east coast of Lower Michigan (Fig. 1). The remainder of the curve represents reconstructed lake levels curves since about 4.8 ka in Lake Michigan by Thompson et al. (2004). Comparing lake levels in Huron and Michigan is valid because the two lakes share the same water plane (Larson and Schaetzl, 2001). The optical age of about 10 ka from MB3a (Fig. 4) was omitted from our discussion because it is assumed to be an erroneous age due to incomplete bleaching.

Our chronologies from the three study areas indicate that most of the eolian sand deposited in the groups associated with the Manitou dune field accumulated between about 6 and 4 ka. The oldest apparent age (~6 ka) was derived from the low-lying parabolic dune on the Algonquin lake plain in the southern part of the study area (Figs. 2 and 5). Given the position of this dune about 2 km south of the Nipissing bluff, this dune is not considered to be a coastal feature but rather similar to interior dunes studied by Arbogast et al. (2002b) and Arbogast and Packman (2004) in the central and western part of Michigan's Upper Peninsula, respectively. These dunes also provided mid-Holocene ages similar to the interior dune at Manitou Beach, which Arbogast et al. (2002b) and Arbogast and Packman (2004) attributed to increased aridity and landscape destabilization associated with the Altithermal climate interval (e.g., Baker et al., 1992; Davis et al., 2000). It is possible that the interior dune in this study initially formed for similar reasons. Alternatively, it may have initially developed following the regression of glacial Lake Algonquin about 11 ka and was subsequently reworked during the middle Holocene. Regardless, a middle Holocene age on dune sand in this forested environment is noteworthy because it reflects a previously unidentified episode of landscape instability in this part of Michigan. More ages are needed from this dune group to test these hypotheses further.

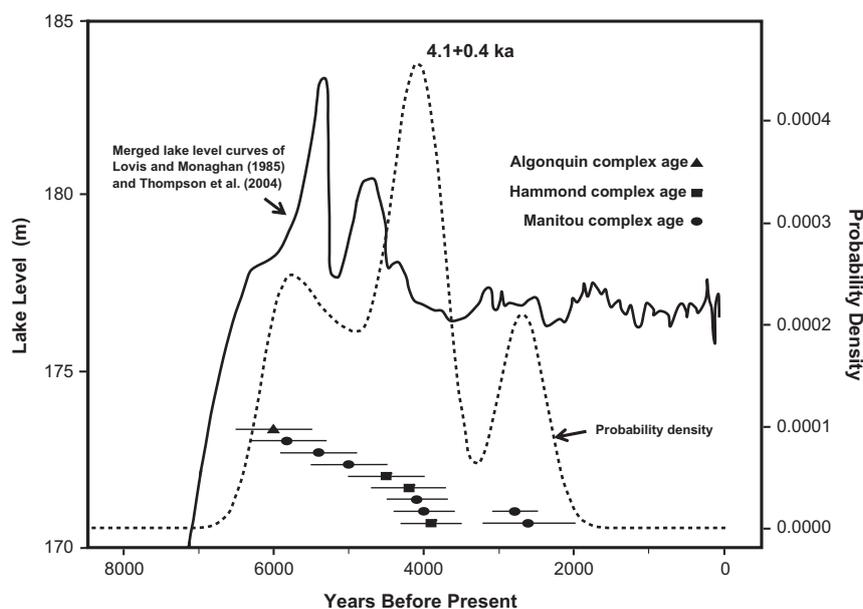
The remaining dunes at Manitou Beach are clearly coastal landforms similar to those along the eastern shore of Lake Michigan that have been recently studied (e.g., Loope and Arbogast, 2000; Arbogast et al., 2002a; Hansen et al., 2002, 2010; Cordoba-Lepczyk and Arbogast, 2005). The dunes in the Manitou group lie between the lake and the Nipissing bluff (Figs. 2 and 4) that apparently formed during the Nipissing I high stand about 5.5 ka (e.g., Hansel

et al., 1985; Monaghan et al., 1986; Larson and Schaetzl, 2001). In contrast, the dunes in the Hammond group are positioned on the lip of the Nipissing bluff (Figs. 2 and 5), which is higher (~25 m high) in this part of the study area than where it borders the Manitou group at a height of about 5 m. Given this landscape position, the Hammond group is a high-perched dune field (Arbogast, 2009) similar to the dune fields at Sleeping Bear National Lakeshore (Snyder, 1985) in northwestern Lower Michigan, as well as the Grand Sable dunes (Anderton and Loope, 1995) and Nodaway Point (Arbogast, 2000) along the southern shore of Lake Superior in Upper Michigan.

Optical ages from the Manitou and Hammond dune groups indicate that most eolian sand was delivered to these systems between about 6 and 4 ka (Fig. 6). The most realistic way to view these ages is to contextually place them within the formation of the Nipissing bluff, which borders the Manitou dune group on the south and directly fronts the perched dunes in the Hammond group. This bluff apparently formed during the Nipissing I high stand and effectively provides a maximum-limiting age of about 5.5 ka (Monaghan et al., 1986) on dune formation in the Manitou group because the surface on which the dunes mantle must have been subaqueous at that time. Although Nipissing beach deposits were not identified in this study, they were recognized by Leverett and Taylor (1915) at an elevation of 190 m at Hammond Bay about 10 km to the west (Fig. 7). This elevation is the approximate level of Highway M-23, which bisects the Manitou dune group (Fig. 4).

In this context, the majority of optical ages derived from the Manitou dune group (Figs. 6 and 7) appear to reflect deposition of eolian sand following the instability associated with the Nipissing I and II phases. According to Chrzastowski and Thompson (1992) the Nipissing phase was a period of intensive bluff erosion in the Lake Michigan basin that resulted in high amounts of littoral sediment. Some of these sands were apparently reworked by beach and eolian processes to form dunes along the southeastern shore of Lake Michigan at that time (Arbogast et al., 2002a; Hansen et al., 2010).

This episode of erosion clearly extended to the shores of Lake Huron, as evidenced by the prominent Nipissing bluff in the study area. The coast probably remained unstable during the brief regression and subsequent transgression to the Nipissing II high stand shortly after about 5 ka. This interval of instability apparently lib-



**Fig. 6.** Probability density distribution of optical ages in this study and comparison with reconstructed Holocene lake levels in Lake Huron and Lake Michigan. Lake levels prior to about 4.8 ka are from Monaghan and others (1986), whereas those afterwards are from Thompson and others (2004).

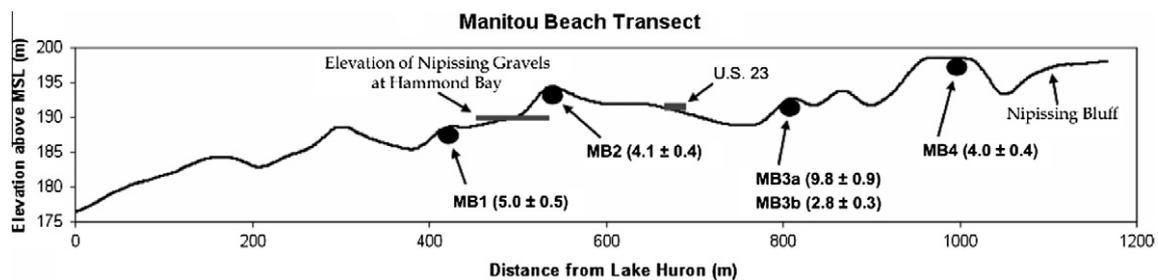


Fig. 7. Cross-section of study area illustrating the relationship of dune ridges, optical ages, and position relative to the elevation of Nipissing beach gravels at Hammond Bay (Leverett and Taylor, 1915) and the Nipissing bluff.

erated and deposited abundant sands that were subsequently reworked to form the majority of dunes in the Manitou group as lake-level adjusted and subsequently fell. Although the shoreline must have been prograding as lake-level fell from the Nipissing levels, the dunes do not show the same age patterns with respect to landscape position that was observed in similar settings in northwestern Lower Michigan (Cordoba-Lepczyk and Arbogast, 2005; Arbogast et al., 2009a). In those dune fields, the older dunes lay farther inland, with progressively younger dunes toward the lakeshore. At Manitou Beach, in contrast, the ages are decidedly mixed with respect to landscape position (Fig. 7).

The most inland dune ridge (MB4), for example, provided an age of 4.0, whereas a shallow sample relatively close to the shore at MB203 in the northeastern part of the field (Fig. 4) yielded an age of about 5.4 ka. This latter age is generally consistent with the age of about 5.8 ka from deep (5.8 m) within the large parabolic dune in the eastern part of the group. Consideration of these ages at even  $1\sigma$  allows time for these dunes to form on a subaerial surface shortly after lake-level fell. Overall, it appears that the majority of dunes in the Manitou group formed quickly and this initial period of dune activation lasted longer at some places than others. Given the northwesterly oriented subparabolic forms embedded in the dune ridges dating to that time, the prevailing winds must have been northwesterly.

In contrast to the dunes in the Manitou group, the high-perched dunes in the Hammond group apparently formed at about the same time but due to a slightly different set of circumstances. These landforms essentially formed during a single phase of dune construction that occurred from about 4.2 to 3.9 ka (Fig. 6). This period of dune formation closely follows the Nipissing II peak in Lake Huron, suggesting that the higher bluff was destabilized during the Nipissing interval and then became the source of eolian sand that was blown a short distance inland shortly after. This model for eolian sand transport is consistent with the perched dune model (Dow, 1937) that explains the formation of high-perched dunes elsewhere in Upper Michigan (Anderton and Loope, 1995; Arbogast, 2000) and Lower Michigan (Snyder, 1985; Loope and Arbogast, 2000). Deposition of eolian sand in high-perched dunes at this time along the northwestern shore of Lake Michigan has also been recognized by Snyder (1985) and Blumer (2008).

Consistent with the dunes in the Manitou group, the perched dunes in the Hammond group formed due to northwesterly winds. Interestingly, this group of dunes is the only one of its kind along the bluff south of Hammond Bay. One explanation for this isolation is that this portion of the bluff is the only place where a sufficient supply of sandy deposits is available to be reworked into dunes. Another explanation is that this location lies within the most eastern portion of Hammond Bay (Fig. 2) and could have been the only place with a sufficiently open exposure to northwest winds that sands could be moved. Still yet another explanation is that dunes formed along the entire bluff length, but that most were entirely

lost through bluff erosion and collapse. This latter hypothesis seems unlikely given that the bluff would have been last destabilized during the Nipissing interval. We believe the presence of the dune field is most likely explained by site location as it relates to wind exposure.

Following the period of dune growth associated with the Nipissing lake phase it appears that the next episode of eolian sand deposition in the study area occurred sometime around 2.8–2.5 ka. This period of dune mobility was identified in the Manitou group where two optical ages were obtained reflecting this interval of time. One of these estimates was acquired from sample MB3a, which represents a second age assessment of a dune ridge in the center of the group (Fig. 2). An additional age from this time was derived from a point near the crest of the very large parabolic dune in the eastern part of the group. This period of localized sand mobility occurred shortly after an apparent high stand about 3 ka, which has been referred to as the Algoma phase (Hansel et al., 1985; Larson and Schaetzl, 2001). This high stand was brief and had relatively little impact on bluffs in the area compared to the Nipissing phase. As a result, it is difficult to assess the role this lake phase had on dune mobility.

Although the relationship of localized dune mobility and lake-level at about 2.8 ka is tenuous, regional scale atmospheric patterns for that time can be indirectly reconstructed. In particular, the orientation of the large parabolic dune (Fig. 4) indicates that dune-forming winds at this time were easterly. Given the prevailing westerlies in the Great Lakes region, this implied easterly wind pattern most likely reflects an interval of time when a series of strong low pressure systems tracked through what is now the northern midwestern US, resulting in counter-clockwise atmospheric flow that produced easterly winds on the system's northern side. These winds, in turn, must have been sufficiently strong to remobilize eolian sands initially deposited after the Nipissing phase and create a 50-m high parabolic dune that is oriented easterly. Perhaps these same winds remobilized older sands at site MB3a, which is directly downwind, resulting in the younger optical age from this locality.

Regardless, this study is the first evidence for strong easterly flow in the Holocene paleorecord in the region. Although prior research (Krist and Schaetzl, 2001) documented strong easterly winds in the region, they were associated with the formation of spits in Glacial Lake Algonquin due to glacial anticyclonic flow at the end of the Pleistocene. Modern wind data (Fig. 3) indicates that direct easterly winds, which appear to have formed the large parabolic dune, are most common in March. Nevertheless they occur less than 6% of the time with the strongest winds between 8.49 and 11.05 m/s. Somewhat more frequent southeasterly flow occurs about 15% of the time with similar high speeds. This overall modern flow pattern is insufficient to have formed the large parabolic dune at about 2.8 ka. Clearly a different wind regime existed at this period of time than the one currently in place.

An interesting finding of this study is that no evidence was discovered for mobilization of eolian sand after about 2.5 ka. Studies of Lake Michigan coastal dunes (e.g., Arbogast et al., 2002a, 2004, 2009a; Blumer, 2008; Hansen et al., 2010) have consistently shown that the period between about 2.5 and 1 ka was a period of reduced dune activity, so the lack of ages from this time frame is not particularly surprising. On the other hand, abundant evidence from Lake Michigan dunes indicates significant mobilization of eolian sand occurred at about 1 ka, with episodic dune growth occurring since that time (Arbogast et al., 2002a, 2009a; Cordoba-Lepczyk and Arbogast, 2005; Blumer, 2008; Hansen et al., 2010). This period of dune growth was not recognized in this study.

The lack of dune mobilization in the past millennia at Manitou Beach can be explained in two ways. It is possible that eolian sands dating to this period were simply missed during sampling. One area that may contain younger dunes is the narrow zone of private land north of MB1 and MB202 (Fig. 4), or the area in the Manitou group northwest of the study transect. The other explanation is that no dunes younger than 1 ka exist in the study area or are indeed rare. Even if such younger deposits exist on a local level, however, it is clear that the dunes at Manitou Beach are generally older compared to the western side of the peninsula where few (if any) dunes dating to the Nipissing phase have been identified in any given dune field. Some eolian sands of this age have been reported on the west coast of Lower Michigan at the base of high-perched systems (e.g., Snyder, 1985; Blumer, 2008), at Petoskey State Park in northwestern Lower Michigan (Cordoba-Lepczyk and Arbogast, 2005) as well as along the southeastern shore of Lake Michigan (Arbogast et al., 2002a; Hansen et al., 2010) but these deposits are unusual. Instead, the record on the east coast of Lake Michigan is dominated by noticeably younger deposits of eolian sand than those observed at Manitou Beach.

Until more is learned, the age discrepancy between coastal dunes on the northeastern and western sides of the peninsula is best explained on the basis of prevailing wind patterns. The west coast of Lower Michigan faces the oncoming westerly winds that have a long fetch (~200 km) across Lake Michigan, whereas the northeastern shore is largely protected from this air flow (Fig. 1). This geography means that conditions on the western side of the peninsula are more conducive to the formation of dunes. In this environment, sand is more easily and consistently moved from the shorezone to dunes, and existing dunes are also more easily reworked by blowout formation. These conditions have resulted in relatively young dunes on the west coast of Lower Michigan.

In contrast, it appears that coastal dunes at Manitou Beach essentially reflect one major episode of dune building in the intermediate aftermath of the Nipissing high stand. This chronology implies that the most important factor in the formation of this dune field was the coastal instability caused by significantly higher water during the middle Holocene. Extensive coastal erosion obviously occurred, which apparently liberated a high supply of sand that could ultimately be reworked to form dunes even in the relatively protected environment of northeastern Lower Michigan. It is also possible that this dune-forming interval was also generally stormier, with stronger northwesterly winds more common to move eolian sand. The subsequent combination of lake-level changes, fluctuating sand supply, and winds were insufficient to cause extensive dune formation at Manitou Beach in the late Holocene. The notable exception is the observed reworking of eolian deposits at about 2.8 ka brought on by strong easterly winds. After this time, no chronologically younger dunes were observed.

## 6. Conclusion

This study was the first to reconstruct the age of coastal sand dunes along the coast of Lake Huron in Lower Michigan. It focused

on dunes at Manitou Beach, which collectively contain the highest volume of eolian sand on this side of the peninsula. Optical ages derived from dunes in three groups provide a chronology for eolian sand mobilization in the area. The *Algonquin group* consists of widely scattered, low-relief dunes on the Algonquin lake plain that apparently formed about 6 ka, perhaps due to a warmer/drier climate. The most extensive dunes lie within the *Manitou group*, which lies between the present-day shore and a prominent erosional bluff which formed during the Nipissing high lake stand. Most dune ridges apparently formed in the short interval after the bluff formed about 5.5 and 4 ka. A large (~50-m high), easterly oriented parabolic dune blew out about 2.8 ka on the eastern side of the dune field. The *Hammond group* consists of a merged pair of dunes perched high on the Nipissing bluff on the west side of the study area. These dunes apparently formed shortly after the Nipissing high stand between about 5 and 4 ka when the bluff face remained unstable and could supply eolian sand.

This study demonstrates that dunes at Manitou Beach are generally older than those on the west coast of Lower Michigan. This age dichotomy probably reflects the importance of Nipissing instability to form extensive dunes along the east coast of Lower Michigan. In contrast, active dune formation along the west coast of Lower Michigan has continued to the present time, suggesting that this coast of Michigan is fundamentally more unstable due to prevailing winds and associated waves. A particularly interesting finding is that strong easterly winds must have occurred for an undetermined interval of time about 2.8 ka, resulting in the formation of a large parabolic dune. This air flow contrasts with modern winds and needs to be explored further.

## Acknowledgements

We would like to thank the Twin Lakes Association for allowing us to work in their fine nature preserve. Special thanks go to the Krist family (Frank Sr., Theresa, Frank Jr.) for their valuable assistance in this project. Frank Sr. and Theresa represented us to gain permission from the Association to work in the preserve and assisted during the field reconnaissance. Theresa also helped with sample acquisition in the field. Frank Jr. has long been interested in the area and provided us with maps and valuable insights. We would also like to thank Dr. Jeff Andresen in the Department of Geography at Michigan State University for the wind rose data and interpretation.

## References

- Andresen, J.A., Personal Communication. Department of Geography, Michigan State University, East Lansing, MI.
- Anderton, J.B., Loope, W.L., 1995. Buried soils in a perched dunefield as indicators of Late Holocene lake-level change in the Lake Superior basin. *Quaternary Research* 44, 190–199.
- Arbogast, A.F., Loope, W.L., 1999. Maximum-limiting ages of Lake-Michigan coastal dunes: their correlation with Holocene lake level history. *Journal of Great Lakes Research* 29, 372–382.
- Arbogast, A.F., 2000. Estimating the time since final stabilization of a perched dunefield along Lake Superior. *The Professional Geographer* 52, 594–606.
- Arbogast, A.F., 2009. Sand dunes. In: Schaetzl, R.S., Darden, J.T., Brandt, D. (Eds.), *Michigan Geography and Geology*. Pearson Custom Publishing, Boston, MA, pp. 274–287.
- Arbogast, A.F., Hansen, E.C., Van Oort, M.D., 2002a. Reconstructing the geomorphic evolution of large coastal dunes along the southeastern shore of Lake Michigan. *Geomorphology* 46, 241–255.
- Arbogast, A.F., Wintle, A.G., Packman, S.C., 2002b. Widespread middle Holocene dune formation in the eastern upper peninsula of Michigan and the relationship to climate outlet-controlled lake level. *Geology* 30, 55–58.
- Arbogast, A.F., Packman, S.C., 2004. Middle-Holocene mobilization of Aeolian sand in western Upper Michigan and the potential relationship between climate and fire. *The Holocene* 14, 464–471.
- Arbogast, A.F., Schaetzl, R.J., Hupy, J.P., Hansen, E.C., 2004. The Holland Paleosol: an informal pedostratigraphic unit in the coastal dunes of southeastern Lake Michigan. *The Canadian Journal of Earth Sciences* 14, 1385–1400.

- Arbogast, A.F., Monaghan, G.W., Lovis, W.A., Forman, S.L., 2009a. Geomorphic Evolution of Coastal Dunes in the Northern Part of Lake Michigan: Environmental Controls, Regional Comparisons, and Geoarchaeological Implications. Geological Society of America Annual Meeting, Portland, Oregon. Programs and Abstracts.
- Arbogast, A.F., Shortridge, A.M., Bigsby, M.E., 2009b. Using volumetric estimates of eolian sand to explain the geography of coastal sand dunes in Lower Michigan. *Physical Geography* 30, 479–500.
- Baedke, S.J., Thompson, T.A., 2000. A 4700 year record of lake level and isostasy for Lake Michigan. *Journal of Great Lakes Research* 26, 416–426.
- Baker, R.G., Maher, L.J., Chumbley, C.A., Van Zant, K.L., 1992. Patterns of Holocene environmental changes in the midwestern United States. *Quaternary Research* 37, 379–389.
- Blumer, B.E., 2008. An Application of OSL Dating to Test the Perched-Dune Model on Coastal Dunes at Arcadia, Michigan. Unpublished, MS Thesis, Department of Geography, Michigan State University, East Lansing, MI, 132p.
- Chrzastowski, M.J., Thompson, T.A., 1992. Late Wisconsinan and Holocene coastal evolution of the southern shore of Lake Michigan. *Quaternary coasts of the United States: marine and lacustrine systems*. SEPM Special Publication 48, 397–413.
- Cordoba-Lepczyk, X.D., Arbogast, A.F., 2005. Geomorphic history of dunes at Petoskey State Park, Petoskey, Michigan: significance to coastal dune formation models. *Journal of Coastal Research* 14, 231–241.
- Davis, M., Douglas, C., Calcote, R., Cole, K.L., Winkler, M.G., Flakne, R., 2000. Holocene climate in the western Great Lakes national parks and lakeshores: implications for future climate change. *Conservation Biology* 14, 968–983.
- Dow, K.W., 1937. The origin of perched dunes on the Manistee moraine, Michigan. *Michigan Academy of Sciences, Arts, and Letters* 23, 427–440.
- Fisher, T.G., Loope, W.L., 2005. Aeolian sand preserved in Silver Lake: a new signal of Holocene high stands of Lake Michigan. *Holocene* 15, 1072–1078.
- Hansel, A.K., Mickelson, D.M., Schneider, A.F., Larsen, C.E., 1985. Late Wisconsinan and Holocene history of the Lake Michigan basin. In: Karrow, P.F., Calkin, P.E. (Eds.), *Quaternary Evolution of the Great Lakes*, Special Paper 30. Geological Society of Canada, St. John's, Newfoundland, pp. 39–53.
- Hansen, E.C., Arbogast, A.F., Packman, S.C., Hansen, B., 2002. Post-Nipissing origin of a backdune group along the southeastern shore of Lake Michigan. *Physical Geography* 23, 233–244.
- Hansen, E.C., Fisher, T.G., Arbogast, A.F., Bateman, M., 2010. Geomorphic history of low perched, transgressive dune groups along the southeastern shore of Lake Michigan. *Journal of Aeolian Research* 1, 111–127.
- Hanson, P.R., Joeckel, R.M., Young, A.R., Horn, J., 2009. Late Holocene dune activity in the eastern Platte River Valley, Nebraska. *Geomorphology* 103, 555–561.
- Hanson, P.R., Arbogast, A.F., Johnson, W.C., Joeckel, R.M., Young, A.R., 2010. Megadroughts and Late Holocene dune activation at the eastern margin of the great plains, North-Central Kansas, USA. *Aeolian Research* 1, 101–110.
- Knapp, B.D., 1993. Soil Survey of Presque Isle County, Michigan: US Department of Agriculture, Soil Conservation Service. US Govt. Printing Office, Washington DC.
- Krist, F., Schaetzl, R.J., 2001. Paleowind (11,000 BP) directions derived from Lake Spits in Northern Michigan. *Geomorphology* 38, 1–18.
- Larson, G.J., Schaetzl, R.J., 2001. Origin and evolution of the great lakes. *Journal of Great Lakes Research* 27, 518–546.
- Leverett, F., Taylor, F.B., 1915. The Pleistocene of Indiana and Michigan and the History of the Great Lakes. US Geol. Surv. Man. 53. US Govt Printing Office, Washington.
- Loope, W.L., Arbogast, A.F., 2000. Dominance of a 150-Year cycle of sand-supply change in late Holocene dune building along the eastern shore of Lake Michigan. *Quaternary Research* 54, 414–422.
- Midwest Regional Climate Center, 2008. Midwest Regional Climate Center Online Data and Climate Services. <[http://mrcc.sws.uiuc.edu/climate\\_midwest/historical/snow/mi/207094\\_ssum.html](http://mrcc.sws.uiuc.edu/climate_midwest/historical/snow/mi/207094_ssum.html)> (Last checked January 26, 2010).
- Monaghan, G.W., Lovis, W.A., Fay, L., 1986. Nipissing transgression in the Saginaw Bay region, Michigan. *Canadian Journal of Earth Sciences* 23, 1851–1854.
- Murray, A.S., Wintle, A.G., 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. *Radiation Measurements* 32, 57–73.
- Olson, J.S., 1958. Lake Michigan dune development 1: wind velocity profiles. *Journal of Geology* 66, 254–263.
- Schaetzl, R.J., Darden, J.T., Brandt, D. (Eds.), 2009. *Michigan Geography and Geology*. Pearson Custom Publishing, Boston, MA.
- Scott, I.D., 1942. The dunes of Lake Michigan and correlated problems. *Michigan Academy of Science Arts and Letters* 44, 53–61.
- Snyder, F.S., 1985. A Spatial and Temporal Analysis of the Sleeping Bear Dunes Group, Michigan: A Contribution to the Geomorphology of Perched Dunes in Humid Continental regions. Ph.D. Dissertation, University of Pittsburgh, Pittsburgh, PA.
- Thompson, T.A., Baedke, S.J., Johnston, J.W., 2004. Geomorphic expression of late Holocene lake levels and paleowinds in the upper Great Lakes. In: Hansen, E.C. (Ed.), *The Geology and Geomorphology of Lake Michigan's Coast*, vol. 35. Michigan Academician, pp. 355–371.
- USDA, 2003. Wind Rose Data. Natural Resources and Conservation Service, National Water and Climate Center, Portland, OR. Available from: <<http://www.wcc.nrcs.usda.gov/climate/windrose.html>>.
- Van Dijk, D., 2004. Contemporary geomorphic processes and change on Lake Michigan coastal dunes: an example from Hoffmaster State Park, Michigan. *Michigan Academician* 35, 425–453.
- Van Oort, M.D., Arbogast, A.F., Hansen, E.C., Hansen, B., 2001. Geomorphological history of massive parabolic dunes, Van Buren State Park, Van Buren County, Michigan. *Michigan Academician* 33, 175–188.
- Wintle, A.G., Murray, A.S., 2006. A review of quartz optically stimulated luminescence characteristics and their relevance in single-aliquot regeneration dating protocols. *Radiation Measurements* 41, 369–391.