Reconstructing the geomorphic evolution of large coastal dunes along the southeastern shore of Lake Michigan

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Abstract

Coastal dunes are common along the eastern shore of Lake Michigan, with the most common being large (> 30 m high), parabolic dunes that mantle lake terraces south of Manistee, MI. Although these dunes are an important resource in Michigan, and thus intensely managed by various state agencies, their geomorphic history is poorly understood. This study examines four sites near Holland, MI, through stratigraphic and radiocarbon analyses and is the most detailed geomorphic reconstruction conducted of coastal parabolic dunes in the region. Results from this study could benefit the environmental agencies in their management of the coastal dune ecosystem. Deposition of Eolian sand apparently began ∼ 5500 cal. years BP (i.e., during the Nipissing high stand). Most (∼ 75%) dune building occurred between ∼ 4000 and 2500 cal. years BP but was punctuated by brief periods of stability that resulted in the development of Entisols (A/C horizonation). Entisol burial occurred because the sand supply apparently increased during both the receding and rising lake levels. Subsequently, each dune stabilized for ∼ 2000 years, allowing the formation of Inceptisols (i.e., A/E/Bs/C horizonation). This interval of dune stability correlates with sites south of Holland and occurred while Lake Michigan fluctuated slowly and the beach potentially prograded. These combined variables of slow fluctuation and potential beach progradation hypothetically protected the dunes from wave erosion. Dunes near Holland became active again ∼ 1000–500 cal. years BP and grew both vertically and laterally. This activity intensified in the past 500 cal. years BP and hypothetically occurred due to recession of the lake shore such that wave erosion at the modern bluff base resumed. Results from this study indicate that coastal dunes along Lake Michigan are similar to many coastal dunes around the world, including those along the intermediate beaches in SE Australia.

Keywords: Parabolic dunes; Lake Michigan; Radiocarbon; Buried soils

1. Introduction

Sand dunes commonly occur along the eastern shore of Lake Michigan (Farrand and Bell, 1982; Fig. 1). Collectively, these landforms may be the largest complex of freshwater dunes in the world (Peterson and Dersch, 1981) and are unique resources that occupy several important socioecological niches in Michigan (Michigan State Legislature, 1976, 1994). From an ecological perspective, they contain a sensitive flora, including the threatened Pitcher’s thistle (Cirisium pitcheri; McEachern et al., 1994). The dunes are also extensively used for recreation with a variety of national, state, and county parks located along the shore.
Lastly, some dunes are intensively mined for foundry sand (Santer, 1993). In short, the dunes have a very high public profile and are thus managed by the Michigan Departments of Natural Resources (MDNR) and Environmental Quality (MDEQ) in an effort to balance the various public and private demands placed upon the landscape. Most of this management occurs within the context of the Sand Dune Protection and Mining Act (Michigan State Legislature, 1976), which was designed for the study, protection, management, and reclamation of Great Lakes sand dunes. This statute was later amended (Michigan State Legislature, 1994) to increase the regulatory authority of MDEQ in the context of all proposed activities within designated sand dune areas, especially those identified within the new category of “critical dunes”.

Coastal dunes along the eastern shore of Lake Michigan can be broadly subdivided into two geomorphic categories. One category is functional and consists of foredunes, which are relatively small (~5 m high) sublinear dunes. These dunes are spatially confined to protected embayments and narrow zones along the shore in the northern part of the Lake Michigan basin (e.g., Lichter, 1995), whereas they extensively occur in the southern end of the lake (e.g., Thompson, 1992). Although foredunes are fundamentally a minor part of the active coastal Eolian landscape, their geomorphology has been extensively

![Map of coastal dunes in lower Michigan and NW Indiana including the location of significant sites noted in the text. Map modified from Santer (1993) and Farrand and Bell (1982).](image-url)
studied (e.g., Olson, 1958a,b,c; Lichter, 1995), with Olson’s (1958d) model being the accepted paradigm describing the foredune growth. In this model, foredunes grow during low lake stages when beaches enlarge and sand supply increases and subsequently stabilize when the lake level rises and the supply of Eolian sand decreases or the dunes are destroyed. According to Lichter (1995), time-series aerial photographs indicated that Olson’s (1958d) model accurately explained ongoing foredune development.

In addition to foredunes, the other coastal dune category is “large dunes”, which consists of dunes >20 m high that dominate the Eolian landscape along the eastern shore of Lake Michigan (e.g., Fig. 2). This category is not a formal designation nor is it meant to be parallel to the functional classification of foredunes. Instead, it is informally used here to group a suite of dunes that have historically been called many names. These terms include secondary dunes (Scott, 1942) where they contain blowouts, clifled dunes (Olson, 1958d) where they are undercut by waves, high dunes (Dorr and Eschman, 1970) because of their great relief, and barrier dunes (Buckler, 1979) because they form a physiographic boundary from the interior to the lakeshore. Regardless of the nomenclature, the large dunes generally share a parabolic form and collectively occur within a variety of well-developed dune fields (Fig. 1) that contain vast majority of areas mapped as “critical dunes” (Michigan State Legislature, 1994). North of Manistee, the dune fields are spatially distinct and mantle high headlands underlain by thick glacial deposits; they also cap beach-ridge sequences in some places. Research indicates that sand is supplied to these perched parabolic dunes during high lake stages because adjacent bluffs are destabilized by wave undercutting (Dow, 1937; Loope et al., 1995; Arbogast and Loope, 1999).

In contrast to the isolated perched dune fields in NW lower Michigan, large parabolic dunes south of Manistee cover topographically lower Late-Pleistocene and Holocene lake plains and form a semi-continuous band between ~0.5 and 1 km in width (Farrand and Bell, 1982). Although this stretch of coastal dunes qualitatively contains the most Eolian sand and includes majority of the critical dunes, coastal state parks, and quarries, the geomorphic history of these landscapes is poorly understood due to limited study. From a historical perspective, the management (by MDNR and MDEQ) of these lakeplain dune fields has occurred in the context of two broadly applied and untested presumptions that are
related to time and process. Regarding time, the majority of dunes are widely assumed to have formed during the Nipissing high stand (~ 6000–4000 years BP; Hansel et al., 1985) of ancestral Lake Michigan, resulting in frequent use of the term Nipissing dunes (e.g., Dorr and Eschman, 1970). With respect to process, the prevailing belief is that the dunes evolved according to Olson’s (1958d) foredune model (Dorr and Eschman, 1970; Buckler, 1979). According to this model, applied to the parabolic dunes by default at MDNR and MDEQ, the dunes grow during low lake level when the sand supply increases through enlarged beaches and subsequently stabilize when the lake level rises and beaches narrow.

Given the dichotomy that exists between the high public profile of the lake-plain dunes and their generally obscure origins, they have recently been the focus of intensive geomorphic research. Arbogast and Loope (1999) tested the Nipissing (age) hypothesis by investigating the maximum-limiting ages of dunes at four sites between Grand Haven and Muskegon (Fig. 1). This study indicated that dune building did not begin concurrently at all of the sites and that the largest dune (Rosy Mound, near Grand Haven; Fig. 1) began to form well after (~2900 years BP) the Nipissing interval. Arbogast and Loope (1999) noted that some dunes contain buried soils, suggesting that dunes in the east-central part of the Lake Michigan basin also evolved episodically in time rather than solely during the Nipissing stage.

The most intensive study thus far of coastal dune evolution along Lake Michigan was conducted by Loope and Arbogast (2000), who radiocarbon dated 75 buried soils at 32 widely spaced sites. This study yielded very limited stratigraphic data because sections were measured and described in coarse fashion only. Instead, the study focused on testing the broad applicability of Olson’s (1958d) foredune model to large lake-plain dunes by comparing dates from often isolated soils with the most recent lake-level curve (Baedke and Thompson, 2000) derived from beachridge studies. Statistical correlations indicated that dune growth, which resulted in soil burial, occurred mostly during 150-year lake level peaks. According to Loope and Arbogast (2000), this correlation suggests that sand is supplied to parabolic dunes on lake plains in a manner consistent with parabolic dunes that are perched on headlands (Dow, 1937; Snyder, 1985; Loope et al., 1995; Loope and Arbogast, 2000). In this scenario, lake-plain dunes grow because the lake-ward face of the lake plain is eroded during high lake stages, resulting in the destabilization of the upper dune slope and transport of Eolian sand. Loope and Arbogast (2000) also proposed that most Eolian deposits along the NE shore of Lake Michigan are <1500 cal. years BP old.

2. Study rationale

Loope and Arbogast (2000) presented a new working hypothesis to explain sand supply to large coastal dunes (e.g., Fig. 2) that mantle lake plains along the eastern shore of Lake Michigan. This model has yet to be rigorously tested, however, in a full stratigraphic framework where sections are thoroughly described and compared along a reach of the shore. The primary goal of this study, therefore, is to chronostratigraphically test the Loope and Arbogast (2000) model in the context of newly proposed chronologies of lake-level fluctuation (e.g., Baedke and Thompson, 2000) for an entire reach of the shore. In an effort to “see” how the dunes grew, a secondary goal is to reconstruct their geometric evolution. This study attempts the first detailed assessment of the geomorphic history of a portion of the parabolic dune system on the SE shore of Lake Michigan. One potential benefit of this investigation is that a more accurate geomorphic model explaining the coastal dune evolution may assist the MDNR and MDEQ in their management of this sensitive resource. In addition, this research will also contribute to the ongoing discussion about the general evolution of coastal dunes around the world (Bauer and Sherman, 1999), especially in places not affected by strong tides (e.g., Short and Hesp, 1982). These dunes may respond to changes in water level, sediment supply, and the frequency and intensity of episodic storms in much the same way as the dunes along Lake Michigan.

3. Study area

The study area is a ~1-km-long section of the coastline ~10 km SW of Holland, MI (Fig. 1). Dunes here are very large (>40 m high; Fig. 2),
forming a continuous but narrow (~0.5 km wide) band of overlapping features that parallel the beach (Fig. 3), and are well exposed in a series of lake-facing (~ westerly) sections. The dunes are cliffed (Olson, 1958d), mantle lacustrine deposits (Farrand and Bell, 1982) of probable Nipissing age (Hansel et al., 1985) and are parabolic with limbs generally perpendicular to the shore (i.e., ~ 260°).

Climate data for the region was obtained from the station at Muskegon, which lies north ~50 km (Fig. 1). The local climate is classified as mixed marine, continental. Average annual temperature ranges from ~5 °C in January to ~21 °C in July. Annual precipitation is ~81 cm. Winds are multidirectional, with winter and summer winds being northwesterly and southwesterly, respectively (Eichenlaub et al., 1990).

4. Methods

The general goal of this study is to reconstruct and understand the behavior of the coastal dune system near Holland through inferential reasoning and analogy. Thus, this study has a holistic-constructivist approach as defined by Bauer and Sherman (1999) because it focuses on basic geomorphic tendencies.
Accordingly, the study methodology was designed to locate several complete exposures in close geographical proximity that contained buried soils for age determination. Although a variety of good vertical exposures exist in the study area, the best three (in terms of uncovered sections) were chosen for this study. In addition, a large parabolic blowout was investigated (Fig. 3), which permitted the reconstruction of lateral migration in the dune system. Dune stratigraphy was mapped with a plane table and alidade, and the strike and dip of sedimentary structures and buried soils were measured with a Brunton compass. All of the sites were described and sampled during investigations in fall 1998 and spring 1999.

Soils were described using standard terminology (Soil Survey Division Staff, 1993). For simplification, all weakly developed soils (i.e., A/C horizonation; A horizon < 5 cm thick) were classified as Entisols. The term Inceptisol defines better-developed soils, with some spodic-like characteristics (i.e., A/E/Bs/C horizonation; sola >60 cm thick), that probably formed by podzolization (Rourke et al., 1988). In this study, time is assumed to be the discriminating soil-forming variable (e.g., Franzmeier and Whiteside, 1963; Barrett and Schaetzl, 1992) because of the similarity in parent materials.

Radiocarbon ages were obtained to provide the chronological control and were derived from soil horizons that contained charcoal fragments and wood. Fifteen samples were collected for age determination (Table 1) and were analyzed at the Beta Analytic Laboratory in Miami, FL. In order to correct for long-term variations in the radiocarbon time scale, all dates were calibrated to the tree-ring curve established by Stuiver et al. (1998), allowing radiocarbon dates to be adjusted to calendar years before the present (i.e., cal. years BP). We assume that the radiocarbon dates reflect burial of the associated paleosol by Eolian sand (e.g., Loope and Arbogast, 2000).

5. Results and discussion

5.1. Site stratigraphy

In the following text, the stratigraphic relationships at each site are described. Site order is based upon the geographical location of the primary vertical exposures; i.e., the northernmost and southernmost sites are Dunes 1 and 3, respectively. The blowout site (Dune 4) lies inland of the primary exposures and between Dunes 2 and 3 (Figs. 3 and 4).

### Table 1

<table>
<thead>
<tr>
<th>Location</th>
<th>Horizon (depth)</th>
<th>Laboratory number</th>
<th>δ¹³C (‰)*</th>
<th>Radiocarbon age (1σ)</th>
<th>Calibrated age (2σ)*</th>
</tr>
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<tbody>
<tr>
<td>Dune 1</td>
<td>2Ab ( ~ 4.5 m)</td>
<td>NSRL-10488</td>
<td>-25.6</td>
<td>1050 ± 65</td>
<td>1190 – 730</td>
</tr>
<tr>
<td>Dune 1</td>
<td>4Ab ( ~ 21 m)</td>
<td>NSRL-10489</td>
<td>-25.1</td>
<td>2980 ± 55</td>
<td>3390 – 2860</td>
</tr>
<tr>
<td>Dune 1</td>
<td>5Ab ( ~ 29 m)</td>
<td>NSRL-10490</td>
<td>-21.4</td>
<td>3560 ± 55</td>
<td>4150 – 3620</td>
</tr>
<tr>
<td>Dune 1</td>
<td>6Ab ( ~ 37 m)</td>
<td>NSRL-10491</td>
<td>-26.0</td>
<td>3750 ± 55</td>
<td>4420 – 3830</td>
</tr>
<tr>
<td>Dune 2</td>
<td>2Ab ( ~ 18 m)</td>
<td>NSRL-10347</td>
<td>-26.1</td>
<td>430 ± 55</td>
<td>570 – 280</td>
</tr>
<tr>
<td>Dune 2</td>
<td>5Ab ( ~ 35 m)</td>
<td>NSRL-10346</td>
<td>-25.0</td>
<td>4090 ± 55</td>
<td>4850 – 4350</td>
</tr>
<tr>
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<td>6Ab ( ~ 36 m)</td>
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<td>-26.1</td>
<td>4840 ± 65</td>
<td>5890 – 5310</td>
</tr>
<tr>
<td>Dune 3</td>
<td>3Ab ( ~ 4 m)</td>
<td>NSRL-10492</td>
<td>-26.6</td>
<td>35 ± 45</td>
<td>modern</td>
</tr>
<tr>
<td>Dune 3</td>
<td>4Ab ( ~ 11 m)</td>
<td>NSRL-10493</td>
<td>-24.4</td>
<td>200 ± 45</td>
<td>310 – 0</td>
</tr>
<tr>
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<td>NSRL-10494</td>
<td>-24.9</td>
<td>310 ± 50</td>
<td>530 – 140</td>
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<tr>
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<td>NSRL-10495</td>
<td>-25.8</td>
<td>2390 ± 65</td>
<td>2710 – 2330</td>
</tr>
<tr>
<td>Dune 3</td>
<td>10Ab ( ~ 35 m)</td>
<td>NSRL-10496</td>
<td>-24.1</td>
<td>3730 ± 55</td>
<td>4240 – 3920</td>
</tr>
<tr>
<td>Dune 4</td>
<td>2Ab ( ~ 3 m)</td>
<td>Beta-132389</td>
<td>-25.0</td>
<td>130 ± 50</td>
<td>280 – 0</td>
</tr>
<tr>
<td>Dune 4</td>
<td>2Ab ( ~ 30 m)</td>
<td>Beta-132390</td>
<td>-25.0</td>
<td>320 ± 50</td>
<td>490 – 290</td>
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<tr>
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<td>Beta-132392</td>
<td>-26.0</td>
<td>930 ± 40</td>
<td>930 – 740</td>
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</table>

* For the discussion of the δ¹³C-correction procedure, see Suiver and Polach (1977) and Taylor (1987).

* Calibrated from conventional δ¹³C-corrected radiocarbon age to calendar years using a tree-ring curve. All calibrations reported here were based upon the 20-year atmospheric curve (e.g., Linick et al., 1985; Suiver et al., 1986). Program used is discussed in Suiver et al. (1998).
5.1.1. Dune 1

The Dune 1 exposure is \(~ 45\) m high and contains seven depositional units (Fig. 4). The lowermost unit (Unit I) consists of lake sediments that are \(~ 4\) m thick in exposure and contain a horizontal Entisol (7Ab). This soil did not contain material suitable for accurate dating.

Overlying Unit I is \(~ 41\) m of Eolian sand. The Eolian stratigraphy indicates that Dune 1 initially grew rapidly and episodically, resulting in \(~ 40\) m of sand that contains six depositional units (II–VI). Formed in Units II–V are Entisols (6Ab–3Ab) that represent brief periods of stability. Radiocarbon dating of charcoal from the 6Ab, 5Ab, and 4Ab horizons indicates that periods of dune growth evidently occurred between 4420 and 3830, 4150 and 3620, and 3390 and 2860 cal. years BP, respectively. The 3Ab could not be dated. Dip measurements indicate that the dune was better defined as it grew during this interval, ranging from a near horizontal surface in 6Ab to an apparent slip face (30° easterly dip) in 3Ab.

Following the deposition of Unit VI (\(~ 6\) m thick), the dune apparently stabilized for a relatively long period of time. This extended interval of stability is indicated by the Inceptisol that caps Unit VI. Accurate measurements of dip could not be obtained given numerous contemporary tree roots but the soil appears to mirror the slope of the modern dune crest. Charcoal recovered from the uppermost part of the 2Ab horizon indicates that this paleosol was buried by the uppermost deposit of sand (Unit VII) between 1190 and 730 cal. years BP.

![Fig. 4. Cross-section of study area illustrating the relative location of exposures and their chronostratigraphy. Note that Dune 4 lies inland of Dunes 1, 2 and 3 and behind a shadow dune (e.g., Gares and Nordstrom, 1995). Thus, the Inceptisol at Dune 4 is illustrated by a dashed line. Elevation is in meters above the lake level (EALL).](image-url)
5.1.2. Dune 2

The Dune 2 exposure lies ~ 200 m south of the southern edge of Dune 1 (Figs. 3 and 4) and consists of up to 45-m-high exposure that contains six depositional units (Fig. 4). Unit I consists of finely cross-bedded lacustrine sediments ~ 3.5 m thick in exposure. An Entisol (6Ab) formed in Unit I is traceable to 7Ab at Dune 1. Although the age could not be obtained from 7Ab at Dune 1, the corresponding 6Ab at Dune 2 was apparently buried by Eolian sand between ~ 5890 and 5310 cal. years BP (Fig. 4).

As with Dune 1, the stratigraphy at Dune 2 (Fig. 4) indicates that growth initially occurred rapidly and episodically, resulting in ~ 27 m of sand that contains four depositional units (II–V) and associated Entisols. Only one date could be obtained from this stratigraphic sequence, indicating that 5Ab was buried sometime between 4850 and 4350 cal. years BP. Given the weak development of 4Ab and 3Ab, these soils probably formed and were respectively buried within a few hundred years after the burial of 5Ab.

The most prominent depositional unit at Dune 2 is Unit V. Consistent with Dune 1, this distinction results from the capping Inceptisol, which indicates a relatively long period of stability. In the outcrop, the soil forms a prominent U with the base and top lying ~ 16 and ~ 30 m above the shore, respectively (Fig. 4). The opposing limbs of the U both dip steeply (~ 25°) but in contrasting directions (i.e., northeast on the southern side; southeast on the north), suggesting that the soil developed in the saddle between two dune crests. The soil has the best overall development on the limbs of the paleosaddle, indicating that these areas were primarily stable during pedogenesis. In contrast, the soil in the paleodepression lacks a distinct Eb horizon and has a much thicker 2Ab horizon than on the limbs. This cumulic horizon indicates that sand slowly accumulated in the depression at a rate consistent with pedogenesis, while the remainder of the paleocatena was stable. Deposition in the paleosaddle subsequently accelerated such that soil formation ceased, first in the depression and slightly later, in the limbs. Large cross-beds in Unit VI indicate that filling occurred through dune migration or expansion from the north. This burial apparently occurred sometime between ~ 570 and 280 cal. years BP, as indicated by the age derived from 2Ab.

5.1.3. Dune 3

The Dune 3 exposure is the southernmost of the study sections (Figs. 3 and 4), located ~ 500 m from Dune 2 (Fig. 4). This exposure is ~ 42 m high and contains at least 12 depositional units, with four buried soils providing radiocarbon ages (Fig. 4). As with Dunes 1 and 2, the basal unit (Unit I) is lacustrine sands. Although no soil was recognized on top of Unit I at Dune 3, an Entisol occurs ~ 4 m above the lake in the lacustrine sediments ~ 50 m to the south. At Dune 2, this soil provided an age of 5890–5310 cal. years BP, suggesting a similar age hypothesis for burial of the lacustrine sands (Unit I) at Dune 3. During the initial stage of Eolian deposition, a pair of thin (~ 2 m thick) deposits (II and III) accumulated. A radiocarbon date indicates that 11Ab in Unit II was buried between 4240 and 3920 cal. years BP.

With the burial of Unit III, which must have occurred shortly after ~ 3900 cal. years BP, the dune grew rapidly and in a complex way. The next four units (Units IV–VII) dip to the north at angles between 23° and 26° and apparently represent stages in the northerly migration of a dune slope over the horizontal surface of Unit III. While the soils that cap Units IV–VI are Entisols (9Ab–7Ab) over their entire exposure, the soil in Unit VII varies from an Entisol (6Ab) in the more northerly and lower portion of its exposure to a transitional Inceptisol (A/Bs/C horizonation) along its upper portion. This variation suggests that sand encroached most rapidly on the topographically lowest part of Unit VII first and progressively moved up the paleoslope. Burial of the paleoslope apparently began between ~ 2710 and 2330 cal. years BP, as suggested by the radiocarbon age derived from where the Entisol caps Unit VII. Subsequently, the source of Eolian sand shifted from the south to a more northerly source, as indicated by the southerly dip (26° to 28°) in Units VIII–XII.

Unit VIII is the lowermost southerly dipping unit and contains an Inceptisol that merges with the transitional Inceptisol in the uppermost portion of Unit VII. Together, these soils form a prominent saddle between two paleocrests, consistent in form with that contained within Dune 2 (Fig. 4). The Inceptisols in Unit VIII (Fig. 5) were apparently buried between 530 and 140 cal. years BP. The remaining units (IX–...
XII) consist of poorly defined, southerly dipping strata that contain Entisols (4Ab–2Ab). The 4Ab provided an age of $310 - 0$ cal. years BP, suggesting that the youngest strata accumulated in the historic period between brief periods of stability.

5.1.4. Dune 4

Dune 4 is a large parabolic blowout that lies between the exposures of Dunes 2 and 3 (Figs. 3 and 4). The blowout is $300$ m long, generally oriented to the west, and grades eastward from a distinct floor into a 45-m-high dune crest. Dune 4 lies inland of the other dune exposures because it is separated from the beach by a $20$-m-high shadow dune, one that is laterally continuous with the other lakefront dunes. The primary stratigraphic feature in the blowout is an Inceptisol that is traceable across the entire depression (Fig. 4). This Inceptisol occurs high on the southern limb of the dune where it is buried by $3$ m of sand. From there, the soil curves downward ($30$ m) across the core of the blowout. This soil dips to the east at $33^\circ$, suggesting that this soil developed on a former slip face. Subsequently, the soil intersects another Inceptisol, one that extends downward from the northern dune limb and that apparently was part of an adjacent dune.

Radiocarbon dating of wood and charcoal from the 2Ab horizons of the Inceptisols indicates the timing of blowout initiation and progression. The oldest date was obtained from the NW edge of the blowout and suggests that the burial of the slip face began between $900$ and $740$ cal. years BP. Additional radiocarbon dates were obtained from two different places near the blowout core and provided very similar ages ($310 - 320$ and $490 - 290$ cal. years BP), which suggests that the blowout became fully active after the northern part of the dune complex.

The Inceptisol was not buried on the high part of the...
southern limb until sometime in the past ~ 300 cal. years BP.

5.2. Correlations between dunes, lake level, and other coastal dune fields

Our detailed geomorphic investigation reveals a complex history of Eolian sand deposition and stability in large coastal sand dunes near Holland, MI. Radiocarbon dating and stratigraphic correlations suggest that small amounts of Eolian sand began to accumulate at each study site (Figs. 3 and 4) sometime during the Nipissing stage ~ 5900–5300 cal. years BP (Fig. 5). Between ~ 5000 and 4000 cal. years BP, the landscape had very low relief (Fig. 4), initially consisting perhaps of coalesced dune hummocks (e.g., Carter et al., 1992) on the Nipissing lake terrace and later as a low foredune (Olson, 1958d; Hesp, 1984). Around ~ 4000 cal. years BP, the dunes began to grow rapidly with a large quantity of Eolian sand being deposited until ~ 2500 cal. years BP. This period of rapid growth culminated in dunes ~ 30 m high and was characterized by pulses of dune construction between periods of stability. These stable intervals must have been very brief (i.e., < ~ 200 years) because they are marked by Entisols. Nonetheless, δ¹³C values (Table 1; ~ 25 %o) from all dated soils indicate that sufficient time elapsed for an incipient forest (Cerling and Quade, 1993) to develop on these surfaces. Following this period of dune growth, the dunes stabilized for ~ 2000 years, as indicated by an Inceptisol with Spodosol-like characteristics at each site. The dunes reactivated sometime between ~ 900 and 500 cal. years BP, resulting in the burial of the Inceptisol. In the past ~ 500 years, the dunes have grown an additional ~ 10 m, with sand being supplied episodically in a manner consistent with the early dune history (~ 5500–2500 cal. years BP) until the present day.

Given this basic geomorphic chronology for the Holland dunes, the following question remains. How do these results compare with pre-existing models that are used to explain coastal dune evolution along Lake Michigan (e.g., Olson, 1958d; Dorr and Eschman, 1970; Loope and Arbogast, 2000) and other coastal dunes around the world (e.g., Carter et al., 1992)? With respect to the basic age of dunes, the traditional model is that they are Nipissing landforms (Dorr and Eschman, 1970; Buckler, 1979), which formed quickly during this major Holocene lake transgression/high stage (Fig. 5). Although results from this study indicate that the Holland dunes began to form during the Nipissing high stand, they also clearly illustrate that most dune growth occurred well after this high lake stage, specifically between ~ 4000 and 2500 cal. years BP. On a regional level, this study corroborates the Arbogast and Loope (1999) investigation, which demonstrated that dunes between Muskegon and Grand Haven (Fig. 1) formed largely after ~ 4000 cal. years BP.

This research also raises the possibility that the chronology of dune building along Lake Michigan may differ between the northeastern and southeastern parts of the basin. According to Loope and Arbogast (2000), it appears that most coastal Eolian deposits along the northeastern part of the shore are < 1500 cal. years BP old. In the vicinity of Holland, in contrast, stratigraphic evidence indicates that the bulk of coastal Eolian sand accumulated before ~ 2500 cal. years BP. At this time, it is unclear why such a discrepancy exists between the opposing ends of the lake basin. It may be related to variations in littoral sediment supply or wave erosion that existed between the southern and northern parts of the shore.

What about process? As indicated previously, Olson’s (1958d) foredune paradigm (i.e., low lake = high sand supply) is the traditional model used to explain the growth of large coastal dunes along Lake Michigan (Dorr and Eschman, 1970; Buckler, 1979), even though it has been systematically linked only to the development of small lake-edge dunes in the region (Thompson, 1992; Larsen, 1994; Dott and Mickelson, 1995; Lichter, 1995; Thompson and Baedke, 1997; Van Kley and Van Dijk, 2001). Recently, however, Loope and Arbogast (2000) reported that the perched dune model, which resulted in increased sand supply during high lake level due to wave undercutting and bluff destabilization (Snyder, 1985; Anderton and Loope, 1995; Loope et al., 1995), statistically explains the growth of large dunes the best. Although the Loope and Arbogast (2000) study contained a large number (75) of radiocarbon dates, the study may be biased because buried soils were sampled in isolation from one another and not considered in any kind of chronostratigraphic framework.
Given that the Holland study yielded abundant chronostratigraphic information, it provides an opportunity to test the applicability of the foredune (Olson, 1958d) and perched dune (e.g., Loope and Arbogast, 2000) models to the evolution of large coastal dunes along the Great Lakes.

Although this test focuses on coastal dunes in the American Midwest, it can be seen as being contextually related to the debate regarding the formation of coastal dunes along marine shorelines in northwest Europe. Van Straaten (1965) argued, for example, that the development of coastal barrier deposits in the Netherlands occurs during marine transgressions. An opposing view was held by Jelgersma et al. (1970), who reported that coastal dune instability in the Netherlands transpires during regressive marine stages. Similarly, Tooley (1982) believed that dunes in northern England reactivated during falling sea levels.

According to Bauer and Sherman (1999), a primary weakness of holistic-constructivist coastal dune studies such as this is that it is difficult to impose the perspective of a short-term observer on the landscape. Although this problem is acknowledged here, especially in the context of 2σ radiocarbon correlations, the evidence nevertheless suggests that both the rising and falling lake levels contributed to dune growth at Holland, MI (Fig. 5). Initial construction of the dunes at ~5500 and ~4800 cal. years BP appears to correlate best with the rising lake levels during the Nipissing interval, although the details of this high lake stage are vague. In addition to the Van Straaten (1965) study, this pattern of dune construction during a major transgression has been reported in both the Pacific Northwest (Cooper, 1958) and the SE coast of Australia (Pye and Bowman, 1984). If this association is valid at Holland, then Eolian sand was probably supplied because the lake edge bluff was destabilized by waves in a manner consistent with the perched dune model (e.g., Loope and Arbogast, 2000).

The most dramatic growth of dunes at Holland correlates well with the general regression (from ~183 to 176.5 m) from the Nipissing interval between ~5500 and 2500 cal. years BP. In particular, the dunes grew up to ~25 m in the ~2000-year period following the Nipissing II stage ~4500 cal. years BP, with the best falling lake/dune growth correlation occurring between ~4500 and 3500 cal. years BP. This growth probably occurred because the dunes were a partial reservoir for the large volume of sand that hypothetically eroded from coastal bluffs during the Nipissing transgression/high stands (Chrzastowski and Thompson, 1992). In this scenario, the littoral zone was laden with sediment, which was subsequently transferred to a progradational beach as the lake level declined. Subsequently, the sand was apparently blown from the beach onto the low-relief dune platform (e.g., Carter et al., 1992) in a manner consistent with the foredune model (Olson, 1958d; Hesp, 1984) and other observations around the world (e.g., Wright, 1963; Jelgersma et al., 1970; Roy and Thom, 1981; Tooley, 1982).

Following the initial phase of rapid dune growth, the correlation between lake levels and dune building is less clear. This uncertainty is largely magnified because the lake level fluctuations that occurred after ~3500 cal. years BP were not as dramatic as the variations associated with the Nipissing interval. The empirical evidence suggests, however, that dune building in the past ~3500 cal. years BP may be more closely linked with rising rather than falling lake levels. The additional growth that occurred at Dune 1 ~3200 cal. years BP, for example, clearly aligns best with a ~1-m increase in the lake level (Fig. 5). Subsequently, the 2σ radiocarbon centroids at ~2500 (Dune 3), ~900 (Dunes 1 and 4), and after ~500 cal. years BP (Dunes 2–4) appear to correlate best with subtle high stands. If this association is valid, then the dunes grew vertically in a manner consistent with the perched dune model (e.g., Loope and Arbogast, 2000). At Dune 4, the initiation of the blowout began because the protective (lakefront) vegetation was sufficiently thinned by wave erosion (e.g., Van Straaten, 1965; Carter et al., 1992). This blowout may be in the early stages of healing, as indicated by the small shadow dune in the throat of the feature. According to Gares and Nordstrom (1995), formation of shadow dunes in blowout threats along the New Jersey shore initiates healing by inducing new air flow regimes that favor stabilization. Overall, the dune landscape that has formed in the past ~1000 cal. years BP near Holland appears to be very consistent with large-scale parabolic dune systems in SE Australia that form in the lee of intermediate beaches with moderate wave energy (Short and Hesp, 1982).
Although the post ~ 3500 lake level/dune growth correlations are admittedly vague, various lines of geomorphic evidence support the hypothesis that sand was supplied to the Holland dunes at high lake stages. On a global scale, for example, dune building during high water phases has been recognized in Madagascar (Battistini, 1964), the Netherlands (Van Straaten, 1965), Bermuda (Land et al., 1967), and in SE Australia (Thom et al., 1981). Within the Great Lakes region, Lichter (1995) reported that low foredunes along the Great Lakes are reworked into parabolic dunes because they are eroded during the high lake level. In a similar fashion, Carter et al. (1992) demonstrated that blowout channels developed in foredunes in Ireland and California during high water events.

Moreover, empirical observations in the Holland region over the last two decades (1980–2000) indicate that large parabolic dunes change most during high lake levels when they are undermined by wave erosion, causing the vegetated dune face to collapse and exposing bare sand. Once the dune face is exposed, onshore wind moves Eolian sand inland, frequently through blowouts such as at Dune 4 (Fig. 3). When this funneling occurs, the height of the blowout crests increases as they move inland (Fraser et al., 1998). In contrast, low lake levels result in the formation of foredunes (Olson, 1958d; Thompson, 1992; Larsen, 1994; Dott and Mickelson, 1995; Lichter, 1995; Thompson and Baedke, 1997). These foredunes not only protect the larger parabolic dunes from wave erosion (e.g., Bauer and Sherman, 1999) but they also impede the flow of Eolian sand inland. This model is supported by recent research from Van Kley and Van Dijk (2001) who demonstrated that sand is not being supplied to a large coastal dune along Lake Michigan during the current low water phase but is accumulating instead on the lakeward foredune. Overall, the data from this study suggest that the Holland dunes have essentially been behaving like perched dunes north of Manistee (Fig. 1; Loope and Arbogast) for the past ~ 3500 cal. years BP. Although the term perched dunes has been largely associated with dunes that mantle high headlands along Lake Michigan (e.g., Dow, 1937), it may be an appropriate designation for the topographically lower dunes near Holland as well.

While coastal dune evolution near Holland is probably most associated with lake level fluctuations, stratigraphic evidence indicates that other, more ambiguous variables must also be involved that may not be directly related to lake level but are related instead to littoral sand transport and the position of the active shorezone. This ambiguity is suggested by the presence of the Inceptisols at each site, which represent dune stabilization for ~ 2000 cal. years BP. This lengthy interval is reconstructed by the minimum-limiting ages of Unit IV in Dune 1 (~ 3000 cal. years BP) and Unit VII in Dune 3 (~ 2500 cal. years BP; Fig. 4) and the subsequent burial of the Inceptisols ~ 900 and ~ 500 cal. years BP at each of these sites, respectively. Of particular interest is that the dunes were thoroughly stable for this relatively long interval even though the lake level frequently fluctuated within a ~ 1.75-m range (Fig. 5).

A similar period of extended stability was recognized at Mt. Baldy along the Indiana Dunes National Lakeshore (Fig. 1). According to Gutschick and Gonsiewski (1976), a major period of soil formation occurred in the dunes between ~ 3300 and 300 years BP (uncalibrated ages), which resulted in the development of a “prominent soil and bold conspicuous black former forest layer” (p. 59) in the upper part of the dune. Although Gutschick and Gonsiewski (1976) did not classify the paleosol as an Inceptisol, their basic description (e.g., oxidation, Fe mottling) and our examination of the soil indicate that it is consistent with the Inceptisols observed near Holland. A very similar paleosol was also reported by Van Oort et al. (2000) from coastal dunes at Van Buren State Park, 40 km to the south of the Holland exposures (Fig. 1). Radiocarbon dates indicate that this soil began developing ~ 2000 cal. years BP and was buried within the last 500 years.

The correlation among this study, the Indiana Dunes (Gutschick and Gonsiewski, 1976) and Van Buren State Park (Van Oort et al., 2000), suggests that dunes in the SE part of the Lake Michigan basin responded to some regional environmental factor in the Late Holocene. One possibility is that there was a decrease in the frequency and intensity of strong storms, although such a decrease seems unlikely to have lasted ~ 1500 cal. years BP. Another variable may be that a climatic shift to more effective moisture occurred, which contributed to dune stabilization...
through increased vegetation. According to Zumberge and Potzer (1956), however, a local pollen record indicates that no significant climate shift has occurred in the region during the past \(\sim 3000\) cal. years BP.

Another potential hypothesis for this lengthy interval of apparent regional dune stability is that the dunes were somehow protected from wave undercutting. This protection may have occurred because the active shorezone was farther to the west between \(\sim 3000\) and \(1000\) cal. years BP. According to Chrzastowski and Thompson (1992), large volumes of littoral sediment were provided to the southern part of the Lake Michigan basin during this interval of time. These littoral sediments were eroded from sites such as the steep bluffs north of Manistee (Fig. 1) and caused rapid progradation of the Tolesten Beach in Indiana and Illinois. Beach progradation may also have occurred in front of the Holland dunes during this period, which hypothetically provided a strand plain buffer (e.g., Thompson et al., 2001) for the dunes that allowed them to stabilize. In this scenario, beach progradation hypothetically dominated as the lake level fell between \(\sim 3000\) and \(2000\) cal. years BP (Fig. 5). As the lake level rose incrementally between \(\sim 2000\) and \(1400\) cal. years BP, the strand plain may have been progressively eroded such that the active shorezone returned to the base of the dunes and cliffling of the dunes resumed. This hypothesis is supported by dip measurements on most of the exposed Entisols, which are at or near the angle of repose. These steep dips strongly imply that the paleocrests of the dunes were more lakeward at some point in time.

Overall, these results indicate that many factors may be involved in the construction of large parabolic dunes that mantle raised lake plains along the SE shore of Lake Michigan. The data suggest that rapid lake-level fluctuations and the position of prehistoric shorelines may be critical variables in dune behavior. Another potentially significant factor, but which is impossible to reconstruct, is the episcodicy of strong storms as they relate to blowout formation. Whatever the specific cause, this study clearly demonstrates that the models used by MDNR and MDEQ to explain the age and evolution of parabolic dunes in areas designated as critical dunes along the lakeshore are too simplistic. Instead, these agencies should view the coastal dunes as a complex system that responds to many variables in different ways across time and space. This study also demonstrates that large dunes along Lake Michigan evolve in many ways that are consistent with coastal dunes elsewhere around the world (e.g., Van Straaten, 1965; Jelgersma et al., 1970; Tooley, 1982; Pye, 1983; Pye and Bowman, 1984; Baaker et al., 1990; Carter et al., 1992; Gares and Nordstrom, 1995), especially southeastern Australia (Short and Hesp, 1982).

6. Conclusions

This study establishes detailed geomorphic reconstructions and correlations of a series of large dunes along the eastern shore of Lake Michigan. Deposition of Eolian sand probably began in four parabolic dunes near Holland, MI, during the Nipissing high stand (\(\sim 5500\) cal. years BP). The dunes grew rapidly between \(\sim 4000\) and \(2500\) cal. years BP, reaching an elevation of \(\sim 30\) m. Dune enlargement was punctuated by brief periods of stability, resulting in a variety of Entisols. During the early part of this growth interval, sand was apparently supplied to the dunes because the lake level fell. If this relationship is valid, then it may correlate with Olson’s (1958d) foredune model. Later periods of dune growth (e.g., \(\sim 3200\), \(\sim 2400\), \(\sim 900\) cal. years BP) are more likely associated with high lake stages, which is consistent with the perched dune model proposed by Loope and Arbogast (2000). Each dune contains one relatively well-developed soil (an Inceptisol), reflecting a major period (\(\sim 2000\) cal. years BP) of stability. This interval of dune stability correlates reasonably well with events farther south at the Indiana Dunes National Lakeshore and Van Buren State Park and occurred during a time when Lake Michigan fluctuated slowly and littoral sediment supply may have been high. Dunes near Holland reactivated in the past \(500\) cal. years BP, both by vertical accretion and lateral (blowout) migrations. This reactivation may have occurred due to rapid fluctuations of the lake level and/or recession of the shore to the dune base and undercutting of dune faces. Finding the specific cause for dune building is elusive but probably consists of several interacting variables that may be difficult to isolate, including lake level fluctuations, strong storms, and perhaps littoral sediment supply. This investigation indicates that large coastal dunes...
along the Great Lakes may develop in ways consistent with the marine coastal dunes. Given these results, MDNR and MDEQ should review their strategies for management of coastal dunes along Lake Michigan.

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