Growth and Migration of Parabolic Dunes Along the Southeastern Coast of Lake Michigan

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Our goal was to uncover the geomorphic history of large parabolic dunes along the southeastern coast of Lake Michigan. We mapped dune paleosols, obtained radiocarbon and OSL dates, and measured contemporary wind patterns, sand transport and sand deposition with arrays of anemometers, wind vanes, sand traps and pins. Dune paleosols were divided into 4 units. The Basal Soil was buried during the Nipissing Transgression. Older members of the Lower Entisol Series were buried by a pulse of dune growth corresponding with the rise to and fall from Nipissing II high lake levels. Younger members of the Lower Entisol Series were buried during the inland migration of parabolic dunes that ended with a period of stability marked by an Inceptisol (The Holland Geosol). The Inceptisol was buried during a period of remobilization beginning before the arrival of European settlers and continuing today. Measurements on a typical, large parabolic dune showed that sand was deposited on upper and mid lee slopes during the fall and winter. Over steepened slopes were maintained through the winter by ice between sand grains. Slopes collapsed during the spring thaw and sand arrived at the base of the dune through mass wasting. Roughly 50% of deposition on the lee slope was associated with the two highest energy wind events. Very little deposition occurred in late spring and summer. Deposition along the lee slope reaches a maximum along the axis and falls off rapidly towards the limbs reflecting the topographic steering of winds within the trough.

INTRODUCTION

The dunes along the eastern shore of Lake Michigan collectively form one of the largest coastal dune complexes in the world. Scientific studies in these dunes played an important role in the development of the theory of ecological succession (COWLES, 1898) and our understanding of the role of water level and vegetation in the development of coastal dunes (OLSON, 1958a, 1958b). Along the southeastern shore the dune complex is dominated by large parabolic dunes with up to 60 meters of relief. Prize for both their aesthetic value and unique ecological community, the dunes are protected by legislation (MICHIGAN STATE LEGISLATURE, 1976) and defended by nongovernmental citizens groups. Ironically, these efforts have occurred in the absence of a clear picture of the geomorphic history of the dunes. It is logical to assume that decision making would be enhanced if a better understanding of how the dunes evolved existed.

Large parabolic dunes occur along many ocean coasts (e.g. COOPER, 1958, RITCHIE, 1992, PYE, 1993). Coastal dune models, such as those by SHORT and HESP (1982) and PYE (1990), attempt to explain the growth and migration of these dunes in terms of water level, wave and wind energy, kind and extent of vegetation and sediment supply. The dunes along Lake Michigan have developed without tides or salt spray but in the presence of snow, ground freezing and coastal ice. A limited fetch means that wave energy tends to be lower and with a more limited range than on many oceanic coasts. Thus, Lake Michigan dunes represent one end member against which coastal dune models can be tested.

Early attempts to unravel the geomorphic history of Lake Michigan’s large parabolic dunes relied on such field criteria as the shape and size of dunes and their orientation and position with respect to other shoreline features (TAGE, 1946). In the model that emerged from these studies, the large parabolic dunes formed over a limited period during the drop of lake levels from their Nipissing high - 4500 years ago (DORR and ESCHEMAN, 1970). This model encouraged a regulatory atmosphere in which any change in these dunes was attributed to an anthropogenic disturbance in a stable, “fossil” landscape. In the late 1990’s Walter Loope and Alan Arbogast tested this model by obtaining radiocarbon ages from dune paleosols from throughout the eastern shore of the lake (ARBOGAST and LOOPE, 1999; LOOPE and ARBOGAST 2000). They discovered a history of active dune growth and migration in much of the post Nipissing period, and suggested that periods of eolian activity correlated with periods of high lake levels (LOOPE and ARBOGAST, 2000).

The studies of Walter Loope and Alan Arbogast (ARBOGAST and LOOPE, 1999; LOOPE and ARBOGAST 2000) were regional, reconnaissance studies involving the entire eastern lake shore. They were followed by detailed work in local dune complexes by Alan Arbogast in collaboration with a group from Hope College supervised by Ed Hansen (VAN OORT et al., 2001, ARBOGAST et al., 2002, HANSEN et al. 2003). These studies concentrated on sites along the southeastern shore of Lake Michigan where numerous paleosols were exposed. The team combined careful mapping of dune paleosols with radiocarbon and OSL dates to reconstruct dune evolution. At the same time the group at Hope College collaborated with Deanna van Dijk of Calvin College, to study contemporary patterns of sand transport and deposition in a parabolic dune near Holland, Michigan (SHERBON et al., 2002; YURK et al., 2002). Taken together, these studies give a picture of how the large parabolic dunes formed, grew and migrated over the last 5000 years.

Geomorphology of the Study Areas

This paper reports the results of studies of both geomorphic history and contemporary processes in large parabolic dunes along the southeastern coast of Lake Michigan (Figure 1). Most of the data comes from the most extensively studied of these complexes: a kilometer long stretch of coast southwest of Holland Michigan and roughly 125 kilometers north of the southern edge of the lake. This paper combines already published data (ARBOGAST et al., 2002; HANSEN et al., 2003) with new data on this locality. It is supplemented with data from the study of VAN OORT (2001) on the geomorphic history of the
dunes at Van Buren State Park roughly 45 km south of the Holland dunes. Also included is data from reconnaissance studies of the geomorphic history of Warren Dunes State Park, 97 km south-southeast of the Holland dunes, and Indiana Dunes National Lakeshore near the southern end of the lake. Climate in this region is mixed marine, continental with precipitation of approximately 80 cm per year, and average temperatures ranging from ~ -5 °C in January to ~ 20 °C in July (Arbo gast et al., 1999).

The typical coastal dune complex along the eastern shore of Lake Michigan consists of four elements (moving from the lake inland): foredunes, coastal dune ridges, massive parabolic dunes and back dunes. A coastal dune ridge is absent at the Holland dunes and is either absent or present in only isolated fragments in the portions of Van Buren State Park, Warren Dunes State Park and Indiana Dunes National Lakeshore studied. When the studies began in the late 1990's most of these areas had narrow beaches without foredunes. It is in these circumstances that waves can reach and undercut the base of the large dunes creating excellent exposures that typically show multiple paleosols. Backdunes are densely wooded parabolic dunes that lie in the lee of the larger parabolic dunes and are typically only ~10 m high.

METHODS

Plane table and alidade were used to map paleosols and topography along a total of 15 dune faces at the 4 localities. In most cases these were lake front exposures in large dunes created by a combination of wave erosion, slumping and wind scour. In two cases they were exposures created by wind scour in the interior of parabolic dunes. Strike and dips of paleosols were measured with a Brunton compass by excavating shallow pits and aligning a board in the pit parallel to the contact between the dark A horizon and the lighter colored C or B horizon. Soils were described using the terminology of the Soil Survey Division Staff (1993). Radiocarbon ages were obtained on charcoal, wood or peat collected from paleosols at 46 different places in the massive parabolic dunes. Analyses were done by either Beta Analytic Laboratory in Miami, Florida or by the Institute for Arctic and Alpine Research (INSTAAR) at Boulder Colorado. The majority of the samples were analyzed by AMS (accelerator mass spectrometry), although when larger samples could be collected they were assayed by conventional radiocarbon analyses. All dates were calibrated to the tree ring curve established by Stuiver et al. (1998). Paleosols were not exposed in the heavily wooded backdunes. To test the age of these dunes, sand samples were collected beneath the modern surface and dated via optical stimulated luminescence (Atken, 1998) by Susan Packman at the University of Wales (Hansen et al., 2003).

Studies of contemporary processes have focused on Green Mountain Beach Dune southeast of Holland: a large, actively migrating, parabolic dune with a simple U shaped geometry. This dune begins roughly 60 meters from the lake shore and extends 450 meters inland with a maximum height of 52 meters above average lake level. The windward side is free of vegetation all year round. There is relatively heavy foot traffic on this part of the dune as well as the occasional dune buggy. Off-road vehicles have not been observed on the lee slope and foot traffic appears to be largely confined to two relatively narrow trails. The lee slope along the “nose” of the parabola is not vegetated through the winter and early spring but is covered by grasses during the summer and early autumn. There is an oak-maple-beech forest at the base of the dune while the lee slopes on the limbs are covered by a mixture of shrubs and trees.

To measure the amount and pattern of eolian sand deposition in the dune, steel rods 1.5 meters long were installed in 11 lines perpendicular to strike along the lee slope of the dune. The lines consisted of pins at the crest of the dune; 5 m, 15 m, and 30 m down-slope from the crest; 10 m up-slope from the toe; and at the toe of the dune. Initially the pins extended 1 meter above the surface. The height of the pins above the sand was measured with a meter stick roughly once a week from September, 2001 until June, 2003. Unfortunately, vandalism of pins on the crest was fairly common. For the first four months of the study we replaced pins on the crest whenever they were removed, after which we abandoned our attempt to measure erosion and deposition along the crest. Vandalism of pins on the lee side was rare although occasionally a pin would need to be replaced and one week's worth of data would be lost for that location.

In order to estimate the volumes of sand deposited at different places on the depositional lobe, we divided the lobe into rectangles with a pin at the center of each rectangle. The amount of deposition in each rectangle over a given time period was estimated by taking the depth of sand accumulated around the pin in that period and multiplying by the area of the rectangle. From August 27 until October 24, 2001 sand was collected at various points at the crest of the dune with Leatherman (1978) style sand traps. Wind velocity and direction are measured at least hourly at Tulip City Airport 7 km due east of the dune. Local wind patterns were measured on five different days between July, 2002 and June, 2003. Velocities and wind speeds were measured simultaneously at the beach and at six different places on the dune with anemometers and wind vanes set 1.2 meters above the surface. Within the dune the instruments were aligned in a cross with the long arm running down the axis of the parabola.

RESULTS

History of Dune Evolution

Numerous paleosols exist in dune localities along the southeastern shore of Lake Michigan, allowing both a chronological and geometric history to be reconstructed. Typical examples of the sequence of soils in the dunes are shown in Figure 2 which shows 2 of the 15 mapped exposures from the four areas. Relative positions and extents of development can be used to group the soils into four different units:

1. The basal soil is typically a horizontal soil developed on lake deposits. In the dunes near Holland, the soil is an Entisol (A/C horizonation), while at both Van Buren and Indiana dunes it consists of peat.
2. Lower Entisol Series. These are paleosols with an A/C horizonation that lie stratigraphically between the basal paleosol and a prominent paleo-Inceptisol (A/B/C horizonation). The lowest members of this series are horizontal to gently dipping and are generally separated from the basal soil by only a few meters of fine to medium grained well sorted sand identical to the undisputed eolian sand higher in the dunes. The higher members of this series usually have high relief in outcrop and

Figure 1. Map showing the positions and extent of coastal dunes around Michigan's lower peninsula (black), and the localities mentioned in this text. The map is taken from Arbo gast and Loope (1999).

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dips ranging up to 35°.

3. Inceptisol. This prominent soil is found in the upper portions of dunes at most localities along the southeastern shore of Lake Michigan (HUPY et al. 2003) and was found in 11 out of the 15 dunes mapped for this study. The soil profile is the best developed of all paleosols exposed in the Lake Michigan dunes ranging from A/Bw/Bc/C to A/E/Bs/Bw/Bc/C (Joe Hupy, personal communication, March, 2003). HUPY et al., (2003) suggest that this soil be formally recognized as a pedostratigraphic unit, specifically the Holland Geosol. The outcrop pattern of this soil generally appears to trace the outlines of earlier dune forms which are frequently subparallel to the modern dune surfaces.

4. Upper Entisol Series. These are paleosols with A/C horizonation that lie within dune sand above the Inceptisol.

In the Holland area the research extended into the forested backdunes. Paleosols were not found in these dunes but the surface soils are well developed with an A/E/Bs/C horizonation. Radiocarbon ages obtained on wood charcoal or peat collected in paleosols from the massive parabolic dunes are given in Figure 3. Also shown on this figure are OSL ages obtained from the wooded backdunes inland from the massive parabolic dunes near Holland (HANSEN et al., 2003) and the Lake Michigan water-level curve of BAEDKE and THOMPSON (2000). Our assumption in interpreting these dates is that they put a maximum limit on the time at which the paleosol was buried (e.g., LOOPE and ARBOGAST, 2000). As often as possible the material dated was collected in place, for example from peat or from tree trunks rooted in the soil. However in some cases the only datable material is charcoal and it is impossible to guarantee that none of this is older, reworked material. In every locality, the investigated radiocarbon ages were consistent with the stratigraphy; soils lower in the sequence always gave older ages than soils higher in the sequence.

The oldest age is 6530-6390 cal YBP for the basal soil at the Indiana dunes (Figure 1). The youngest age for a basal soil is 5570-5050 cal YBP obtained from the top of the peat layer at Van Buren State Park. All ages from the basal soils are older than the Nipissing II peak in lake levels. There is a cluster of ages from the Lower Entisol Series that correspond to the rise to and fall from Nipissing II peak lake levels (5000-3500 YBP). The sand below the surface soils in the backdunes southwest of Holland give OSL ages that fall into the same period. Younger ages, corresponding to a period of oscillating lake levels, were obtained from the higher members of the Lower Entisol Series. The youngest age obtained from a member of the Lower Entisol Series is 1720 to 1540 cal YBP obtained from a soil within a large parabolic dune (Figure 4b). The oldest age obtained on material from the Inceptisol is 1190-730 cal YBP. However, 14 out of the 16 ages obtained from the Inceptisol and all 7 ages obtained from members of the Upper Entisol Series are within the last 600 years.
However, maximum thickness of deposition tended to be along the dune axis even when the predicted direction of maximum sand transport deviated significantly from this direction. The sand trap data collected during September and October, 2001 shows a similar pattern. No mater what the regional wind direction, the maximum amount of sand transport at the crest of the dune tended to occur around the parabolic axis. Figure 4a shows that most deposition between September 27 (the date the pins were installed) and November 27 occurred on the upper and mid lee slope. During this period very little deposition occurred at the foot of the dune. Sand continued to accumulate along the upper and mid slopes throughout the winter with relatively little sand reaching the lower slopes. The result was an over steepening of the upper slopes: angles measured in January and February ranged up to 39° compared to 30°-33° in spring and summer. During the winter the sand grains on the dune were cemented by the presence of ice in the pore spaces. Large amounts of sand reached the bottom of the slope during a two week period in March coinciding with the spring thaw. During this period the upper slopes lost sand. A number of pins on the upper and mid slopes were bent downhill and needed to be replaced. At the end of the period the sand deposited during the previous fall and winter formed a sheet extending from the top to the bottom of the dune. The thickness of the sheet decreased systematically away from the dune axis (Figure 2a). A bulge in the isopachs of deposited sand at the top and mid slopes (Figure 2a) indicates that there was still a tendency for the thickness of this layer to increase up slope. Sand continued to be added throughout the slope through April and early May. During this time the bulge in the isopachs became less prominent and nearly disappeared indicating a net down slope movement of sand. By the end of May measurements made at pins originally set at the base of the dune indicated a net forward migration along the dune axis of 1.6 meters. Very little sand was deposited on the lee slope between May and September, 2002. Preliminary analysis of the data collected between September 2002 and June 2003 shows essentially the same pattern as the previous year.

During the observational period from September 2001 to September 2002 two particularly strong storms passed through the area. The first of these on October 25 was responsible for sustained wind speeds of 37 knots with gusts of up to 47 knots at Tulip City Airport. Measurements of sand accumulation around pins indicates that the storm was responsible for as much as 40 to 60% of the total fall-early winter deposition along the upper and mid sections of the lee slope. A late winter storm (March 9, 2002) had sustained wind speeds of up to 37 knots with gusts of up to 48 knots. Measurements on pins taken just before and just after this storm indicate that it was responsible for over 50% of the late winter and spring transport of sand to the lee slope of the dune. Over the entire year 49% of these two storms.

Figure 5 shows the results of a typical wind pattern experiment. Topographic steering and acceleration of wind was evident in this as well as our other experiments. The average wind direction on the beach was 197°, but within the dune wind directions were roughly parallel to the axis of the parabola (245°). Average wind velocities increased steadily up the windward slope and at the crest of the dune were 60% greater than they were on the beach. The orientation of ripples on the lee slope suggest that there is some transport of sand, perpendicular to the strike of the slope, by winds blowing along the slope. We have also observed down slope transport of sand by turbulent eddies that form on the upper slope and dissipate on the mid to lower slope.

**DISCUSSIONS**

**Geomorphic History**

The geomorphic history of the dunes along the southeastern shore of Lake Michigan can be broken up into 5 distinct periods.

1. **Burial of the basal soil**: Ages on the basal soils (Figure 3) indicate that they were buried during the later part of a rise in water levels by more than 80 meters from the Chippewa low to the Nipissing 1 high lake levels. The basal soils are buried by well-sorted, medium to fine grained sand apparently identical to the eolian sand higher in the dunes. However, the lowermost paleosols of the Lower Entisol Series are typically horizontal to gently dipping and only a few meters above the basal soil. Although these soils do not trace out obvious dune forms, eolian structures with similar surfaces do make up the dune platforms and terraces found along the lakeshore today (BUCKLER, 1979). THOMPSON(1984) interprets...
the sedimentary record from the Indiana Dunes National Lakeshore as indicating the landward migration of a barrier beach and back barrier lake. It is possible that the sediments above the basal soil formed in a similar transgressive environment throughout the southeastern shore.

2. Early dune growth and migration: There is a distinct cluster of radiocarbon ages from the lower Entisol Series correlating with the rise to and fall from Nipissing II lake levels (Figure 3). The OSL ages from the Holland backdunes fall in the same period, suggesting that this early phase of eolian activity extended well inland. According to the coastal dune model of SHORT and HESP (1982), broad transgressive sand sheets can form in dissipative coasts that are the result of a fall in average water level. These coasts have broad beaches, high potential sand transport, and large foreridges that can be destabilized by exceptionally large storms. This leads to blowouts through which large amounts of sand can be moved inland.

3. Inland migration of parabolic dunes: In the Holland area the backdunes stabilized by roughly 3500 years ago and dune activity was apparently confined to a narrower zone closer to shore. The geometry of the upper members of the Lower Entisol Series suggests that this activity involved eastward (inland) migration of parabolic dunes. This is especially true for exposures within the interiors of modern parabolic dunes. Here paleosols appear to trace out portions of the lee slopes of older parabolic dunes with “noses” closer to the lake than the depositional lobes of the modern dunes (Figure 2b). However, even the exposures along the lakeshore are best interpreted in terms of the migration of parabolic dunes. This is illustrated by Figure 2c. In this dune a set of east-west trending buried Entisols with northward dips appears to mark the northward migration of the slip face of a dune. These soils are buried by an east-west trending southward dipping Inceptisol that appears to indicate the migration of the slip face of a second dune from north to south. However, the same pattern could be produced by the lateral expansion of the depositional lobes of two parabolic dunes migrating eastward at right angles to the modern exposure (HANSEN et al, 2004). Thus, the simplest explanation of the outcrop pattern appears to be the migration of older parabolic dunes in roughly the same direction as the dunes migrate today. For soils formed in the depositional lobes of these dunes to be exposed along the lakeshore, there must have been net shoreline recession in the area. The inland migration of large parabolic dunes, during periods of shoreline recession, is predicted by the coastal dune models of both SHORT and HESP (1982) and PYE (1990).

4. A period of extended stability: The greater extent of soil development in the Inceptisol (Holland Geosol) compared to the Entisols below it, probably indicates that the Inceptisol formed over a longer period of time. The fact that this soil is found in most of the large dunes we studied suggests that there was an extended period of dune stability throughout the southeastern shore. The youngest paleosol directly under the Holland Geosol gives an age of 1720-1540 cal YBP, and this may be taken as the maximum age for the onset of the period of stability in this dune. However, it is possible that the surface on which the Inceptisol formed stabilized earlier in other dunes. There is no obvious change in lake-level history (Figure 3) or climate (ZUMBERGE and POTZER, 1956) that can account for this period of stability. It may be that an increase in littoral sediment from the north (CHIRZATOWSKI and THOMPSON, 1992) created broad beaches with stable foreridges and dune ridges protecting the large parabolic dunes from wave erosion, allowing the interior trough to stabilize.

5. Remobilization: This period of renewed dune mobility in the massive parabolic dunes is indicated by the burial of the Inceptisol. Brief periods of stability after this remobilization are marked by the soils of the Upper Entisol Series. Radiocarbon ages from the Inceptisol suggest that it may have been buried as early as 1100 YBP in some areas and as late as the last century in others. Most of the ages are older than 200 YBP, suggesting that the bulk of the mobilization predates the widespread settlement of the area by Europeans. This dune mobility continues today. Aerial photographs, anecdotal evidence, and scientific observations (e.g., TAGUE, 1946; GUTSCHICK and GONSIEWSKI, 1976) indicate that large parabolic dunes have been migrating inland during the last century.

Contemporary Migration

Transportation and deposition of sand in the massive parabolic dunes along Lake Michigan is strongly influenced by seasonal changes in wind energy and temperature. In late spring and summer of our study period very little sand was deposited on the lee slope of Green Mountain Beach Dune. The windward slope was devoid of vegetation during this period, and therefore sand was available for transport. Analysis of the data from Tulip City airport shows that winds were generally weaker in the late spring and summer months and this probably accounts for the relatively small amounts of deposition. During this break in depositional grasses became established on the lee slope. Wind energy increased in the fall and sand was deposited on the upper and mid lee slope burying this vegetation. Sand continued to be deposited on the upper and mid slope throughout the winter leading to slopes significantly steeper than the angle of repose for dry dune sand. It is possible that the buried grass helped maintain stable slopes in the fall. During winter these slopes were maintained by the cementing action of ice in pore spaces between sand grains. Relatively large amounts of sand moved to the lower lee slope in a relatively short period of time during the March thaw. Most of the forward migration of the base of the dune occurred during this time. The loss of sand from the upper slopes and down slope bunding of pits suggests that much of this movement was due to mass wasting. Sand continued to be deposited throughout the slope in April, but by late May deposition had largely ceased and grasses were becoming reestablished on the dune. A significant proportion of the total transport of sand to the lee slope occurred during a few high-energy wind events.

The geometry of the dune also has a strong influence on the transportation and deposition of sand. Topographic steering of winds insures that most sand is moved parallel to the dune axis. Relatively high steep slopes along the limbs of the dune impede the transportation of sand directly onto much of the limb. Thus most of the sand reaches the lee slope in a relatively narrow zone around the axis. Once it is delivered to the lee slope there is some redistribution of sand by turbulent eddies and winds blowing parallel to the slope. However, as Figure 4 shows, most of the sand was deposited near the axis of the dune. The amount of deposition fell off along the limbs where the height of the walls of the interior trough increases. The geometry of the dune therefore tends to direct the forward migration of the dune along the dune axis.

CONCLUSIONS

The history of the large coastal dunes along the southeastern shore of Lake Michigan begins with the burial of the basal soil between ~6500 and ~5000 YBP, towards the end of a rise in lake levels to the Nipissing I peak. The main phase of early dune building occurred between ~5000 and ~3500 YBP and corresponded to the rise to and then fall from Nipissing II high lake levels. This episode of dune building appears to have occurred over a relatively broad area that extended well inland. At the end of this period dune activity was confined to a narrower zone closer to shore and appears to have involved the inland migration of parabolic dunes. This was followed by an extended period of dune stability that was fully established by about 1600 YBP, but probably began earlier in many areas. This period of stability was followed by remobilization as the large parabolic dunes resumed their inland migration. This period of migration began before widespread colonization by European settlers and continues today.

Sand transport and deposition in the large parabolic dunes is influenced by both seasonal wind patterns and dune geometry. Very little sand is deposited on the lee slopes during the late spring and summer. Sand transport increases in the fall and continues throughout the winter and early spring with a relatively large proportion of the sand being moved by the
highest energy wind events. During the fall and winter sand is deposited on the upper and mid slopes causing them to become steeper than the normal angle of repose (~33°) in dune sand. In the late fall the steep slopes may be partially supported by vegetation that grew that previous summer. In the winter the sand grains are cemented together by ice. During the spring vegetation that grew that previous summer. In the winter the steep slopes may be partially supported by Martin Van Oort, Ben Hansen, Brad Johnson, Katie Sherron, Will Weiss, and Kevin Woloszyn.

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LITERATURE CITED


