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# Geomorphic History of Dunes at Petoskey State Park, Petoskey, Michigan

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**ABSTRACT**

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Coastal dune fields commonly occur along the shoreline of Lake Michigan. This study focuses on the geomorphic history of dunes at Petoskey State Park in northern lower Michigan. Results from this study revealed that 5 distinctive geomorphic units occur in the park: a lake terrace, parabolic dunes, linear and incipient parabolic dunes, and active dunes. Samples for optically stimulated luminescence (OSL) and radiocarbon dating were collected throughout the park and suggested that eolian activity began around 4800 cal. yr B.P. and has continued until the present time. In general, the dunes are progressively younger and smaller towards the shoreline. Intensive shoreline progradation and significant vertical aggradation of sand dunes has occurred at Petoskey State Park throughout the Middle and Late Holocene in association with fluctuations of the level of Lake Michigan.

**ADDITIONAL INDEX WORDS:** *Lake Michigan, coastal sand dunes, Holocene.*

## INTRODUCTION AND RESEARCH BACKGROUND

Coastal dune fields are common along the eastern shoreline of Lake Michigan (Figure 1) and are highly sensitive to natural and anthropogenic disturbances. Research conducted on these dune fields can be broadly grouped into three categories: (1) dune ecology studies—concentrated on the vegetation succession of dune progradational sequences (COWLES, 1899; CALVER, 1946; OLSON, 1958a, 1958b; LICHTER, 1997, 1998); (2) studies on foredune plains—focused on reconstructing late Holocene lake level curves through the dating of underlying beach ridges (COWLES, 1899; OLSON, 1958a, b; THOMPSON, 1992; LICHTER, 1995, 1997; THOMPSON and BAEDKE, 1995, 1997; PETTY *et al.,* 1996), and (3) regional studies—concentrated on establishing relationships between parabolic dune formation and lake level fluctuations (SCOTT, 1942; DORR and ESCHMAN, 1970; BUCKLER, 1979; ARBOGAST and LOOPE, 1999; LOOPE and ARBOGAST, 2000; ARBOGAST *et al.,* 2002).

Until very recently, the focus of geomorphic research on Lake Michigan coastal dunes has been the evolution of foredunes (COWLES, 1899; OLSON, 1958a, 1958b; THOMPSON, 1992; LICHTER, 1995, 1997; THOMPSON and BAEDKE, 1995, 1997; PETTY *et al.,* 1996). The most influential of the early studies was conducted by OLSON (1958b), who proposed that foredunes initiate as offshore bars that migrate inland as lake level falls. When lake levels are low, a wide beach is exposed to eolian processes and the bars are colonized by pioneer vegetation, resulting in the formation of a dune cap.

During the 1990s, research concentrated on reconstructing late Holocene lake level curves along Lake Michigan through the study of the beach ridges that underlie foredunes (THOMPSON, 1992; LARSEN, 1994; LICHTER, 1995, 1997; THOMPSON and BAEDKE, 1995, 1997; PETTY *et al.,* 1996). These studies, which focused on embayments where extensive strandplains are preserved, demonstrated that beach ridges form during high stands when waves cut a small notch in the beach. When lake level subsequently falls, deposition occurs because sediments eroded from headlands during the previous high stand are deposited in the embayments. Based on these studies, BAEDKE and THOMPSON (2000) suggest that lake-level fluctuations occur in Lake Michigan at approximately 600-, 150-, and 30-year intervals.

In addition to providing information about the middle and late Holocene fluctuations in Lake Michigan, the beach-ridge studies have yielded information about the evolution of the capping foredunes. THOMPSON and BAEDKE (1995), for example, demonstrated that foredunes can develop when a newly exposed beach ridge is colonized by vegetation that subsequently traps eolian sand. According to LICHTER (1995), currently active foredunes that cap beach ridges in Wilderness State Park formed during a period of regional drought and low lake level in the 1960s, confirming OLSON's (1958b) hypothesis that foredune aggradation occurs during lowstands.

Although significant research has been conducted on foredune development, few studies have addressed the evolution of the many parabolic dune fields along the shoreline of Lake Michigan. These dunes are easily the largest (>40-m high)

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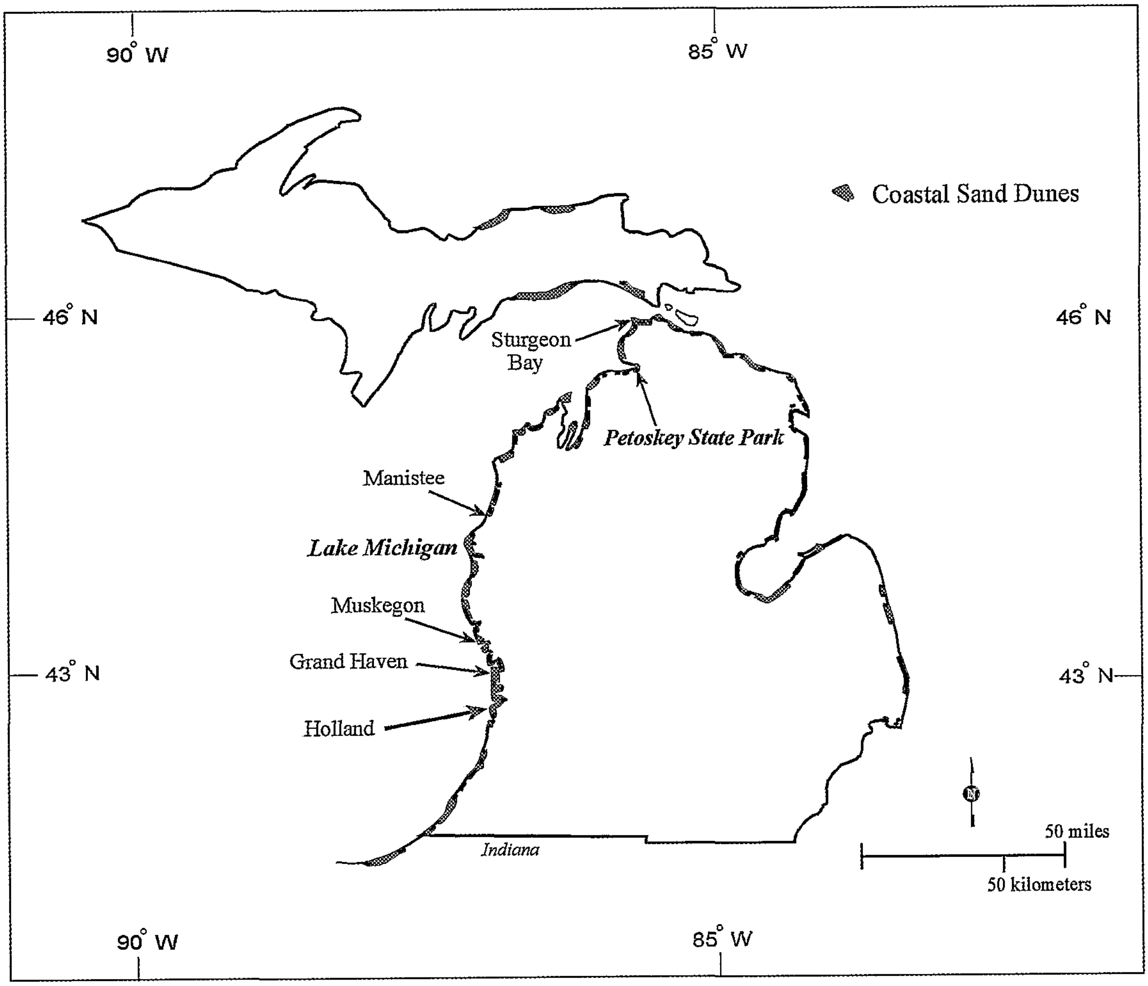


Figure 1. Coastal sand dunes in Michigan and the location of Petoskey State Park (PSP) modified from ARBOGAST *et al.* (2002).

and most common eolian features along the coast. Foredunes, in contrast are typically <10-m high and occur in large numbers only in embayments that are protected from the full erosive power of waves. North of Manistee (Figure 1), complexes of parabolic dunes are generally isolated on high headlands. Research indicates that sand is supplied to these *perched* parabolic dunes during high lake stages because adjacent bluffs are destabilized by wave undercutting, which allows sand from the upper bluff face to be blown to the lee plateau (DOW, 1937; SNYDER, 1985; LOOPE *et al.,* 1995). South of Manistee, parabolic dunes mantle topographically low lacustrine surfaces (FARRAND and BELL, 1982) and are more numerous, collectively forming extensive transgressive dune fields (*e.g.,* HESP and THOM, 1990) that may extend for several kilometers along the shore and up to ½ km inland.

Prior to the late 1990s, no detailed chronostratigraphic investigations had been done. In this context, SCOTT (1942) theorized that parabolic dunes are indicative of lake high stands and that their formation is associated with blowout development. DORR and ESCHMAN (1970) argued that most parabolic dune fields along Lake Michigan formed during the Nipissing high stand about 5000 yrs B.P. BUCKLER (1979) also suggested that parabolic dunes formed during the Nipissing stage, and in an extrapolation of OLSON's (1958b) foredune model, hypothesized that most dune growth occurred during relatively low lake stages within the high stand when wide beaches were exposed.

Recent studies by ARBOGAST and LOOPE (1999), LOOPE and ARBOGAST (2000), and ARBOGAST *et al.* (2002) have focused on testing the pre-existing hypotheses (*e.g.,* DORR and ESCHMAN, 1970; BUCKLER, 1979) about parabolic dune formation through rigorous stratigraphic correlations and radiocarbon dating. ARBOGAST and LOOPE (1999) dated basal paleosols and concluded that dunes between Grand Haven and Muskegon (Figure 1) formed at various times after the Nipissing high stand, with the onset of dune growth occurring at one site around 2900 cal. yrs B.P.

A later study by LOOPE and ARBOGAST (2000) further tested the periodicity of dune aggradation on proglacial lake terraces along the northwest coast of lower Michigan through the systematic dating of buried soils contained within the dunes. The most important contribution of this study was the conclusion that parabolic dune growth occurs in response to the 150-yr lake level high stands identified by THOMPSON and BAEDKE (1997; LOOPE and ARBOGAST, 2000). Additionally, this study suggested that approximately 75–80% of the eolian sand volume along the northwest coast of lower Michigan accumulated during the past 1500 yr rather than during (or immediately after) the Nipissing high stand. Following this study, ARBOGAST *et al.* (2002) conducted detailed chronostratigraphic studies in a reach of very large (>50-m high) dunes near Holland (Figure 1). This research indicated that 1) dune growth was episodic, with most periods of enlargement correlating with high lake levels, 2) periods of stability and growth often occurred at the same general time in all of the dunes, and 3) a major period of stability occurred between ~2000 and 500 cal. Yrs B.P.

As a result of these recent studies (ARBOGAST and LOOPE, 1999; LOOPE and ARBOGAST, 2000; ARBOGAST *et al.*, 2002), a new model now exists for the development of parabolic dunes in transgressive dune fields on topographically low lake terraces along the eastern shore of Lake Michigan. The basis of this model is the perched-dune model (DOW, 1937; SNYDER, 1985; ANDERTON and LOOPE, 1995), which links the growth of large dunes on elevated headlands with periods of high lake level when source bluffs are destabilized by wave erosion and mobilization of eolian sand to the adjacent plateau occurs. Dunes subsequently stabilize when the supply of sand stops as lake level falls and bluffs stabilize.

In addition to increasing our overall understanding of coastal dune evolution, this model is a potential management tool for the numerous coastal parks along Lake Michigan where sand dunes exist. In many of these parks, a continuing stress exists between recreational needs and efforts to maintain dune stability. One such park is Petoskey State Park (PSP; Figure 2), where active dunes are encroaching on the "Dunes Campground". In order to maintain the viability of the campground, the Michigan Department of Natural Resources (MDNR) regularly invests resources in an attempt to stabilize the dunes, educate park users, and remove sand (MACLEAN, T., personal communication, 1999). Despite these efforts, several camp sites have recently been closed due to burial by eolian sand. In light of the existing conflicts, MDNR indicated the need to better understand eolian processes in the park through a geomorphic reconstruction of the dunes. This paper describes the results of this study.

## STUDY AREA

Petoskey State Park is located 5 km northeast of the city of Petoskey and 8 km southeast of the city of Harbor Springs in northwestern lower Michigan (Figure 1). Relative to many other coastal state parks, PSP is small, covering an area of approximately 2 km$^2$. The study area is bounded by highway M-131 to the east and south, Little Traverse Bay to the west, and urban development to the north (Figure 2a).

Active and inactive sand dunes occur in PSP between the landward margin of the beach up to 600 m from the Lake Michigan shoreline. The size of the dunes increases with distance to the shoreline, with the smallest dunes represented by a nearshore foredune that is about 2 m in height. The largest dunes are generally farthest from the shore and, in some cases, almost border M-131. These inland dunes are parabolic and vary in height between 30 and 40 m.

## METHODS

Mapping of geomorphic units provides a valuable characterization of the landscape that can be used to assist inter-

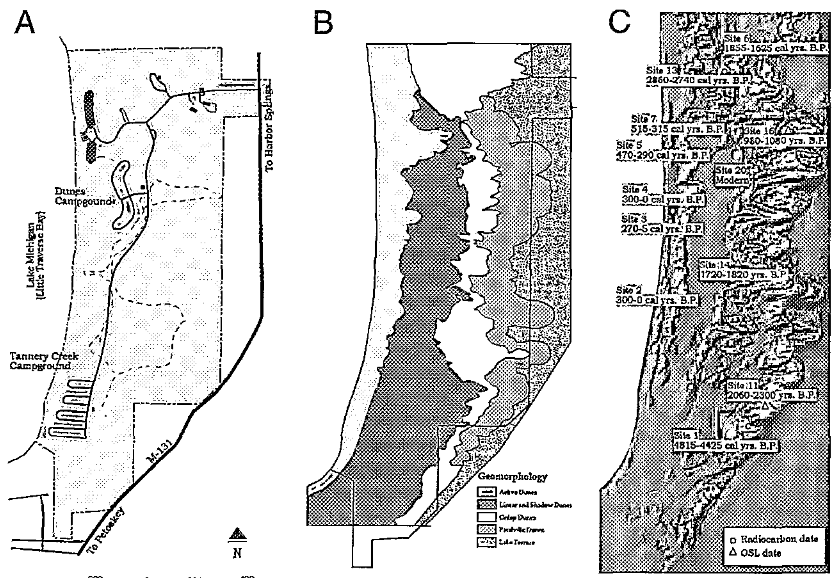


Figure 2. (A) Location of major campgrounds, roads and trails within PSP. (B) Geomorphic units in PSP. (C) Digital elevation model of PSP and the location of study sites and associated radiometric dates.

pretations and reconstruct the geomorphic history of an area. For this reason, detailed geomorphic mapping was conducted at PSP through stereoscopic interpretation of 1998 aerial photography. Delimitation of the geomorphic units was aided by qualitative comparison with the Emmet county soil survey (ALFRED *et al.,* 1973), especially in areas of low relief, where canopy density impaired photo-interpretation. This initial mapping was later refined based on field observations and visual interpretation of a Digital Elevation Model (DEM). This DEM was constructed in ArcInfo from contour lines digitized from a detailed map (scale 1:500) based on a topographic survey of the park conducted by MDNR in 1964.

Determination of the chronology of dune formation was based on radiocarbon and optically stimulated luminescence (OSL) dating. In order to establish the maximum limiting age of the dunes, samples for radiocarbon dating were collected at the base of 6 dunes, as well as from five tree stumps rooted on buried paleosols on active blowouts. Samples were taken from well defined A horizons that displayed lateral continuity and abundant pieces of charcoal. The basic assumption behind this sampling strategy is that soil development occurred during periods of landscape stability and subsequent dune growth buried the soil. Samples from organic materials at the core of the parabolic dunes could not be collected due to the size of the dunes and the absence of outcrops. These characteristics would require clear cutting of trees and use of a drill rig, which were not permitted by MDNR. Eleven samples of organic materials were sent to Beta Analytic Inc. in Miami, FL, for radiocarbon dating. The dates reported by the lab were later calibrated to calendar years BP using the method suggested by STUIVER and REIMER (1993).

Samples for OSL dating were collected from the crest of three stabilized dunes in order to determine the minimum-limiting age of dune construction. This sampling strategy assumes that the crest is the last part of the dune to stabilize (MCKEE, 1979). The OSL samples were sent to the Luminescence Laboratory, Institute of Geography and Earth Science, University of Wales, Aberystwyth, (UK), for age determination where they were dated via the single-aliquot regenerative-dose (SAR; MURRAY and WINTLE, 2000) technique. This method incorporates a test dose to monitor changes in luminescence sensitivity, and has provided OSL ages that correlate with calibrated radiocarbon ages for the past 5000 yrs (MURRAY and CLEMMENSEN, 2001).

## Geomorphic History of Dunes at Petoskey State Park

Geomorphic mapping provided a generalization of the landscape that assisted interpretation of the geomorphic history of the park and sample site location. Landforms at PSP were carefully described and grouped into 5 geomorphic units (Figure 2b), each of which has distinctive morphologic characteristics and histories. Figure 2c shows the position of the study sites and age data within the context of the DEM.

### Lake Terrace

This map unit is located in the eastern margin of the park (Figure 2b) and is a low lying area of limited relief. The elevation of this terrace, approximately 186–189 m, suggests that it formed during the Nipissing I transgression of Lake Michigan (HOUGH, 1958). The unit is composed primarily of beach and nearshore sands and gravels.

### Parabolic Dunes Unit

This map unit occurs along the eastern part of the park (Figure 2b) and consists of heavily forested parabolic dunes with arms generally oriented in a westerly direction (270° azimuth). These dunes are the largest dunes in the park and are predominantly lobate according to PYE's (1982) classification. Qualitative examination of the park DEM (Figure 3) shows that the dunes in the northern part of the unit are more lobate in planform and are generally larger than the dunes in the southern part of the unit.

In order to establish the maximum-limiting age of dunes in this map unit, a sample for radiocarbon dating was collected from the A horizon of a well developed Spodosol at the toe of a dune at site 1 (Figures 2c, 3). This sample yielded an age of 4815–4425 cal. yr B.P. (Table 1), suggesting that the soil was buried at the time of the Nipissing II transgression (HOUGH, 1958).

Stabilization of the parabolic dunes, according to OSL dates at sites 11 and 16 (Figures 2c, 3; Table 1), occurred about 2180 $\pm$ 120 ka. in the southern site (site 11) and about 1030 $\pm$ 50 ka in the northern site (site 16). This evidence, together with the difference in size and shape between the northern and the southern dunes, suggests that eolian activity may have ceased in the southern part of the unit about 1000 years earlier than in the northern part. Incomplete bleaching of sands before burial is a possible cause of uncertainty with OSL dating. However, this problem is not common on eolian sand; thus, these dates are considered accurate for the purpose of this study. Unfortunately, the geomorphic processes that caused this dichotomy cannot be established based on the evidence available. However, this difference could be related to colonization of the southern dunes by pioneer vegetation (OLSON, 1958a), formation of protective foredunes (LICHTER, 1995), or a lower sediment supply in this area. This latter hypothesis is supported by the fact that the composition of the present shoreline is gravelly in the southern portion of the park.

The stratigraphy at site 1 (Figure 3) suggests that the sequence of events was probably as follows: The gravelly unit I and sandy unit II probably represent lacustrian shorezone deposits accumulated during the Nipissing transgression. Subaerial exposure of these deposits allowed soil formation to occur before these units were buried by the eolian unit III sometime during the Nipissing II transgression. Whether Unit III is lacustrine or eolian in origin is not clear based on the available evidence; however, the complete preservation of the soil suggests that an eolian origin is more likely since a transgression of the lake over this deposit would have probably caused erosion of Unit III. After the lake level dropped from the Nipissing II high stand a soil developed, which was later buried by deposition of eolian sand (Unit IV; Figure 3).

### Onlap Dunes

This map unit lies in the center of the park and consists of heavily forested parabolic dunes that lap on to the parabolic

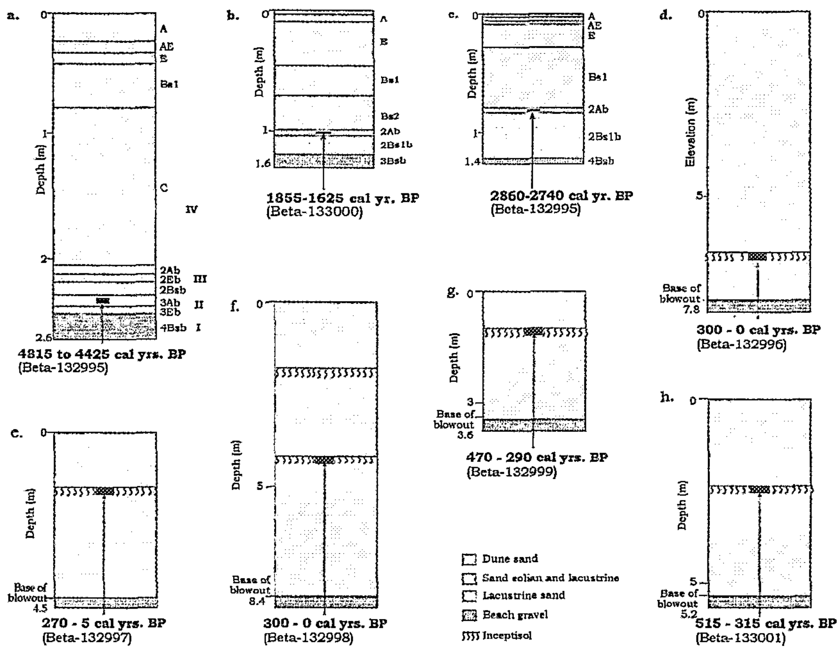


Figure 3. Chronostratigraphy of the investigated portions of dunes at PSP.

dunes (Figures 2b, 2c). The dunes range in height between 10–15 m and are hemicyclic according to PYE's (1982) classification. This plan form, as well as the smaller size of the dunes, suggests that the onlap dunes formed in a shorter period of time than the lobate parabolic dunes to the east.

Four sites were investigated in the onlap dunes (Figure 2c): three at the toe of dunes (site 6, 13, and 20) and one at the crest of a dune (site 14). The stratigraphy of sites 6 and 13 is very similar (Figure 3) and field observations suggest that both radiocarbon samples were collected from the same paleosurface. However radiocarbon dates revealed significantly different dates of burial: 1740 ± 115 cal. yr B.P. and 2800 ± 60 cal. yr B.P., respectively (Table 1; Figures 2c, 3). Considering that the paleosol dated at these two sites appears to be continuous and no significant difference in elevation exists between the sites, these dates present an apparent contradiction. However, given that both radiocarbon dates were obtained from the A horizons of well developed Spodosols with abundant charcoal, we feel they are accurate estimates of soil burial at each site.

At first glance the dates indicate that burial at the lakeward site 13 occurred before burial at the inland site 6. This apparent geographic dichotomy can be explained in terms of sand dune dynamics. At the time of their formation, these dunes were probably transgressive (CARTER, 1988), as suggested by the lack of connectivity among dunes. If this hypothesis is correct, eolian activity could have initiated close to site 13, burying the soil around 2800 cal. yr B.P. Inland migration of the dunes probably reached the location of site 6 sometime around 1700 cal. yr B.P. as suggested by the radiocarbon dates.

Site 20 was located at the toe of one of the dunes (Figure 2c). The radiocarbon sample at this site, which yielded a *modern* age, was regarded as contaminated and useless for this

Table 1. *Summary of radiometric dates.*

| Geomorphic Unit | Site (Fig. 3) | Lab # | Type of Date | Material | Age (yr. BP) |
|---|---|---|---|---|---|
| Massive Parabolic Dunes | 1 | Beta 132995 | Radiocarbon | Charcoal | 4815–4425 cal yr. B.P. |
| Active Dunes | 2 | Beta 132996 | Radiocarbon | Wood | 300–0 cal yr. B.P. |
| Active Dunes | 3 | Beta 132997 | Radiocarbon | Wood | 250–5 cal yr. B.P. |
| Active Dunes | 4 | Beta 132998 | Radiocarbon | Wood | 300–0 cal yr. B.P. |
| Active Dunes | 5 | Beta 132999 | Radiocarbon | Wood | 470–290 cal yr. B.P. |
| Onlap Dunes | 6 | Beta 133000 | Radiocarbon | Charcoal | 1855–1625 cal yr. B.P. |
| Active Dunes | 7 | Beta 133001 | Radiocarbon | Wood | 515–315 cal yr. B.P. |
| Massive Parabolic Dunes | 11 | 31/PP11 | OSL | Sand | 2300–2060 ka |
| Onlap Dunes | 13 | Beta 133003 | Radiocarbon | Charcoal | 2860–2740 cal yr. B.P. |
| Onlap Dunes | 14 | 31/PP14 | OSL | Sand | 1820–1720 ka |
| Massive Parabolic Dunes | 16 | 31/PP16 | OSL | Sand | 1080–980 ka |
| Onlap Dunes | 20 | Beta 1333992 | Radiocarbon | Charcoal | Modern |

study. This sample was collected from a buried A horizon located 5 m south of a cleared forest patch that displayed evidence of a controlled fire. Beta Analytic reported the presence of bomb carbon on the sample, which means that carbon absorbed within the past 40 years was present in the sample. Hence, the charcoal sample was probably part of the root system of a burned tree.

In order to establish the minimum limiting age of the onlap dunes, a sample for OSL dating was collected from the crest of a dune at site 14. This sample yielded an age of 1770 ± 50 ka (Table 1; Figures 2c, 3), indicating that stabilization of the dune occurred at approximately the same time that the dune at site 6 buried the basal Spodosol at that locality.

Investigations in the onlap dunes suggests that the sequence of events was probably as follows: (1) the beach gravel at the base of the dunes was likely deposited during the Nipissing II highstand, (2) when lake level dropped, an eolian cap was deposited on top of the gravel (Unit II), (3) this initial eolian deposition was followed by a period of landscape stability and soil developement, (4) renewed eolian activity around 2800 yr B.P. buried this soil and a transgressive dune field developed, (5) stabilization of the onlap dunes at site 14 occurred around 1700 yr B.P. and probably sometime later in the northern part of the unit (around site 6).

## Linear and Shadow Dunes

This map unit occurs west of the onlap dunes, in the central part of the park (Figure 2b). Contained within this unit are three discontinuous linear dunes (<2 m height), scattered shadow dunes (2–3 m height), and a lake terrace (approximately 180 m elevation). The linear dunes appear to be relict foredunes.

In an effort to determine the age of features within this map unit, several auger sites were investigated to locate datable materials in the swales between the relict foredunes and at the base of shadow dunes. Unfortunately, no buried soils were found during this probing. Instead, this investigation revealed that these dunes overlie beach gravel at an elevation of approximately 180 m. In the area around PSP, the Algoma terrace has been reported to occur around 183 m (LEVERET and TAYLOR, 1915). Hence, this map unit probably formed after lake levels dropped from the Algoma high stand about 3,000 years ago (LARSEN, 1985).

This age hypothesis for the prehistoric foredunes is supported by research conducted by THOMPSON and BAEDKE (1997), who argued that linear dunes at an elevation of approximately 180 m in Sturgeon Bay (approximately 30 km north of PSP) formed between 2600 and 1300 cal. yr B.P. (Figure 4). Due to postglacial isostatic uplift these dates should not be applied directly to other sites in Michigan. That is, landforms of the same age would be found at a higher elevation in Sturgeon Bay than at PSP. Concurrently, lake surfaces that occur at similar elevations in both sites are older around PSP than their counterparts near Sturgeon Bay. However, the data collected by THOMPSON and BAEDKE (1997) can be used as a proxy to provide a reasonable limiting age for nearby sites such as PSP. In this context, we propose a minimum limiting age of 1300 yr. B.P. for the formation of this geomorphic unit.

The scattered distribution of the shadow dunes and the presence of three linear dunes suggest shifting focus of eolian activity within PSP, probably moving lakeward as lake levels fluctuated. These dunes likely formed in a fashion consistent with the model proposed by OLSON (1958c) and THOMPSON and BAEDKE (1997). That is, minor highstands resulted in beach ridge development. As lake level dropped, a wide beach was exposed and the eolian cap on the ridge accumulated. This process was repeated at least 3 times, as evidenced by the three linear dunes preserved.

## Active Dunes

The active dunes map unit occurs in the west part of the park (Figure 2b), close to the lake, and consists of a belt of blowout dunes (MCKEE, 1979) and a foredune that parallels the shoreline. These dunes are absent around and south of the Tannery Creek Campground. The absence of dunes in this part of the park is probably related to the lack of sand along the shoreline in this location.

Field observations on the blowout dunes revealed that they overlie beach gravel at an elevation of about 180 m. THOMPSON and BAEDKE's (1997) relative lake level curve for Sturgeon Bay suggests that Lake Michigan was at this elevation for the last time around 1300 yr B.P. (Figure 4). Due to differential isostatic uplift, this date cannot be used directly at PSP; however, it provides an estimate of the maximum limiting age of these dunes, indicating that the blowout dunes begun to form sometime after 1300 yr B.P.

Five sites were examined on the blowout dunes (Figures 2c, 3) and buried Inceptisols (A/C profile) were observed at each of these locations. Samples for radiocarbon dating were collected from dead cedar or pine trees in their growth position at each site (Table 1). The sampled trees appeared to be about 100–150 yr old at the time of their death (LOOPE, W., personal communication, 1999).

Radiocarbon dates and the number of paleosols present in the blowout dunes indicate that at least 3 periods of eolian activity have occurred in the blowout dunes in the past 500 cal. yr B.P. These episodes were separated by periods of landscape stability, as evidenced by buried soils. The weak soil development in these soils (A/C profile) and the type of trees present probably indicate that these episodes of stability were relatively short lived.

Sand accumulation in the blowout dunes probably initiated sometime after 1000 years ago, associated with a fall on the level of Lake Michigan (Figure 4). Approximately a 1–2 m thick sand unit is preserved from this event at the present time in the northern part of the blowout dunes at sites 5 and 7 (Figure 3). A period of stability, evidenced by a buried soil at these sites, followed this initial accumulation of sand. This period of stability was probably short lived based on the degree of development of the paleosol (A/C profile) and the type of trees observed on this surface (white pine). Around 500–300 cal. yr B.P. eolian activity re-initiated and buried this soil. A new period of stability followed the deposition of this second unit. This second soil was buried sometime after 300

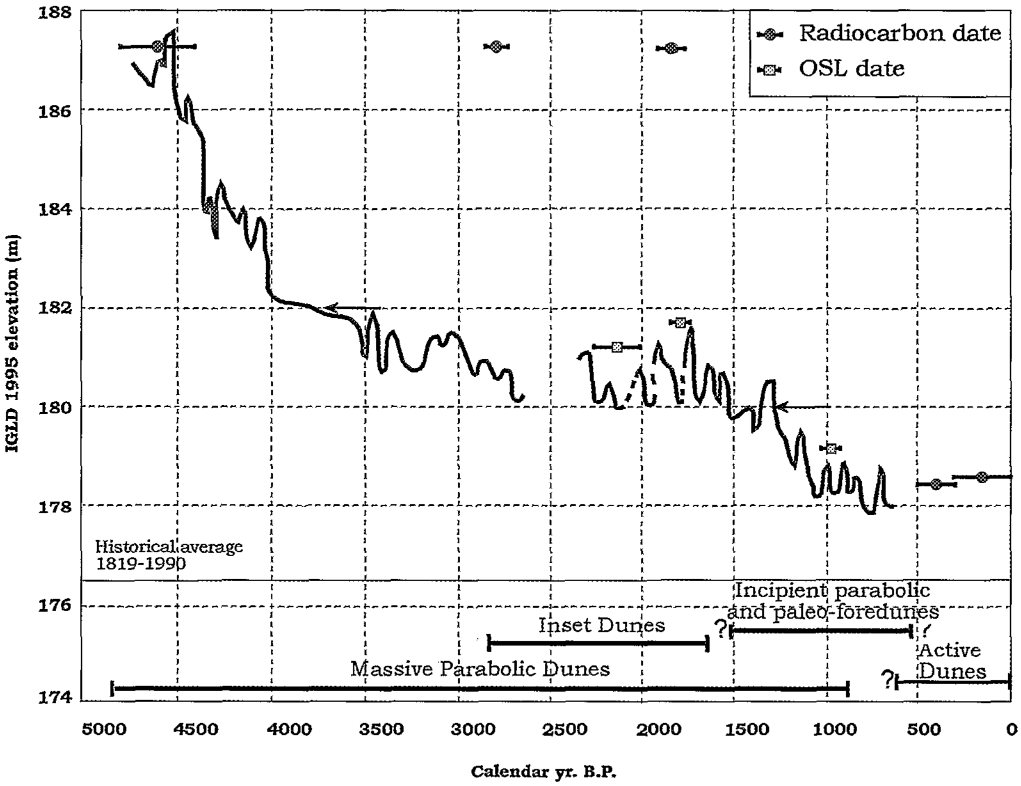


Figure 4. Relative late Holocene lake level for Sturgeon Bay, approximately 30 km north from Petoskey State Park (Modified from THOMPSON and BAEDKE, 1997). Radiocarbon dates are plotted at the elevation at which the samples were obtained. The bars on the lower part show the duration of eolian activity in the different geomorphic units at PSP and represent a 95% confidence interval. Arrows indicate elevation of basal gravel for the incipient parabolic and linear dunes map unit.

yr B.P. at sites 2–4 (Figures 3, 4) due to reactivation of eolian processes. An additional paleosol found at site 4 indicates that at least one more cycle of eolian activity occurred at this site. At the present time these dunes have pervasive active blowouts. The specific causes of this cyclicity of dune aggradation are difficult to assess with the available evidence, but it could be related to a number of factors including storms, minor lake level fluctuations, occasional forest fires, or periods of increased sediment supply along the shoreline.

The vegetation on the lee side of the blowout dunes is predominantly coniferous, including northern white cedar (*Thuja occidentalis*), white and red pine (*Pinus resinosa* and *Pinus strobus*), and scattered small red maple (*Acer rubrum*) and deciduous shrubs, such as poison ivy (*Trifolium hybridum*). This composition suggests that stabilization of the blowout dunes probably occurred less than 100–200 yr ago (OLSON, 1958a; LICHTER, 1997). The active blowouts and the foredune display scattered pioneer vegetation (bearberry, sand cherry, baby's breath, and dune grass among others). The occurrence of blowouts indicates that that the foredune is the present focus of sand accumulation and that deposition on the lee side of the blowouts occurs due to erosion of their windward side. The latter process contributes to the enlargement of the blowouts and possibly, to the detachment of the dunes, eventually forming parabolic dunes.

## SUMMARY AND DISCUSSION

Results from this study provide a general picture regarding the evolution of geomorphic units at PSP. The horizontal bars at the bottom of Figure 4 represent the estimated period of eolian activity for the different geomorphic units at PSP. The diagram shows that at times more than one geomorphic unit has been active in the study area. Eolian aggradation of multiple dune units is a common occurrence in coastal dune fields, as suggested by CARTER and WILSON (1990) for a foredune field in Northern Ireland, where multiple foredunes may experience aggradation at any given time.

Dune formation at PSP initiated during the Nipissing II high stand about 4800–4400 cal. yr ago. At this time, the parabolic dunes were active and the shoreline was somewhere west of these dunes, perhaps at the location of the modern onlap dunes. When lake level dropped from the Nipissing level, eolian deposition shifted lakeward and the formation of the onlap dunes begun followed by a period of landscape stability that ended about 2800 cal. yr B.P. Following this period of stability, accumulation of eolian sand occurred and a transgressive dune field developed. Some of the dunes in this field migrated east and partially buried the older parabolic dunes. Several minor fluctuations of Lake Michigan between 2800 and 1300 cal. yr B.P. resulted in the formation

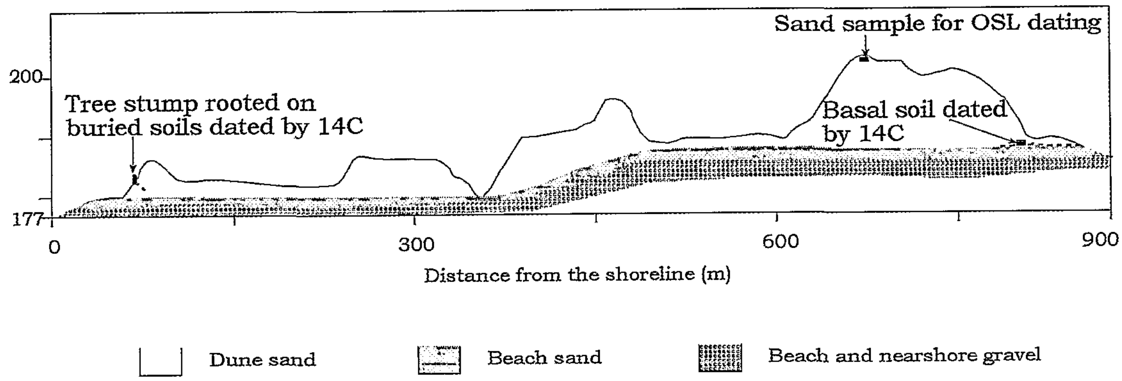


Figure 5. Schematic topographic cross section showing types of radiometric dates and generalized depositional environments. Vertical exaggeration = 3×.

of the linear and shadow dunes unit (Figure 4). Finally, after 1300 cal. yr B.P. lake level dropped close to its present level and accumulation of the active dunes begun, which has episodically continued up to the present time.

As shown in Figure 5, two distinctive lake terraces are present at PSP, occurring around 186, and 180 m above sea level. In general, the dunes at PSP are a regressive sequence with marked periods of vertical aggradation. This regressive sequence of sand dunes is related to the overall long-term level fall in Lake Michigan and postglacial isostatic rebound. Similar regressive sequences have been described in southeast Australia and Northern Ireland in association with mid-late Holocene relative sea level change (THOM, 1983; HESP and THOM, 1990; CARTER and WILSON, 1990).

The complexity of dune morphologies at PSP may be indicative of variable wave energy over the late Holocene. SHORT and HESP (1982) classified beaches in southeastern Australia as either being reflective, intermediate, or dissipative depending upon their wave energy regime. According to these authors' study, reflective low energy beaches result in the development of small foredunes, while intermediate beaches are characterized by large-scale parabolic dunes, sand sheets, and blowouts. These results suggest that the beach at PSP was predominantly intermediate during the formation of the parabolic and onset dunes, while during the formation of the linear and shadow dunes unit, the beach was probably reflective.

Multiple hypothetical explanations could be drawn to try to explain the morphological diversity of sand dunes at PSP or the differences between linear dune strand plains (*e.g.* Sturgeon Bay) and parabolic dune fields (PSP). Figure 6 attempts to address a possible explanation based on the slope of the nearshore area. This slope controls the magnitude of the horizontal retreat and advance of the lake over the shoreline. In areas such as the linear and incipient dunes map unit, where the slope of the nearshore was very gentle, small lake level fluctuations would cause a significant retreat or advance of the shoreline, favoring processes of linear dune formation as proposed by THOMPSON and BAEDKE (1997). On the other hand, sites such as the parabolic dunes unit, where the slope of the nearshore was more pronounced, a more significant change in lake level is required to significantly shift the focus of erosion or deposition.

At PSP the foredune constitutes a trap for eolian sand from the beach, while the blowout dunes are sediment starved, as suggested by the presence of bearberry and sand cherry. This implies that deposition on the lee side of these dunes occurs at the expense of their windward side, contributing to blowout enlargement. These types of processes are clearly insufficient to account for the large volume of sand necessary to build the large parabolic dunes at PSP. This negative sand supply suggests that vertical aggradation of parabolic dunes is impaired by the presence of a lakeward foredune. Hence, an episode of erosion of the foredune during a highstand is necessary in order for such aggradation to occur, as suggested by multiple coastal dune studies (CARTER and WILSON, 1990; HESP and THOM, 1990; LOOPE and ARBOGAST, 2000; Figure 6).

The controls on cycles of eolian activity and landscape stability are difficult to evaluate based solely on the evidence from this study. Additionally, a straightforward comparison of the radiometric dates obtained in this study with previous studies is problematic due to limitations in temporal resolution of the dating methods used and inconsistencies on the materials dated by different studies. Overall, it appears that the growth of the massive parabolic dunes at PSP occurred during the same interval of time that large dunes grew elsewhere on low surfaces along the shore (*e.g.,* ARBOGAST and LOOPE, 1999; ARBOGAST *et al.,* 2002).

This study also demonstrates that the range of dune morphologies at PSP is much greater than that observed elsewhere along the shore at distinct localities. This wide range of dune morphology at PSP likely occurs because the park is located within an embayment, which 1) serves as a funnel for littoral sediment to accumulate that can later be reworked to form dunes, and 2) protects dunes from the full erosive power of waves during strong storms. At other localities where dunes have recently been studied (*e.g.,* ARBOGAST and LOOPE, 1999; ARBOGAST *et al.,* 2002), the shoreline is comparatively linear and the large dunes front the shore. Thus, any smaller dunes that may have formed windward of the large dunes during a regressive phase were completely eroded dur-

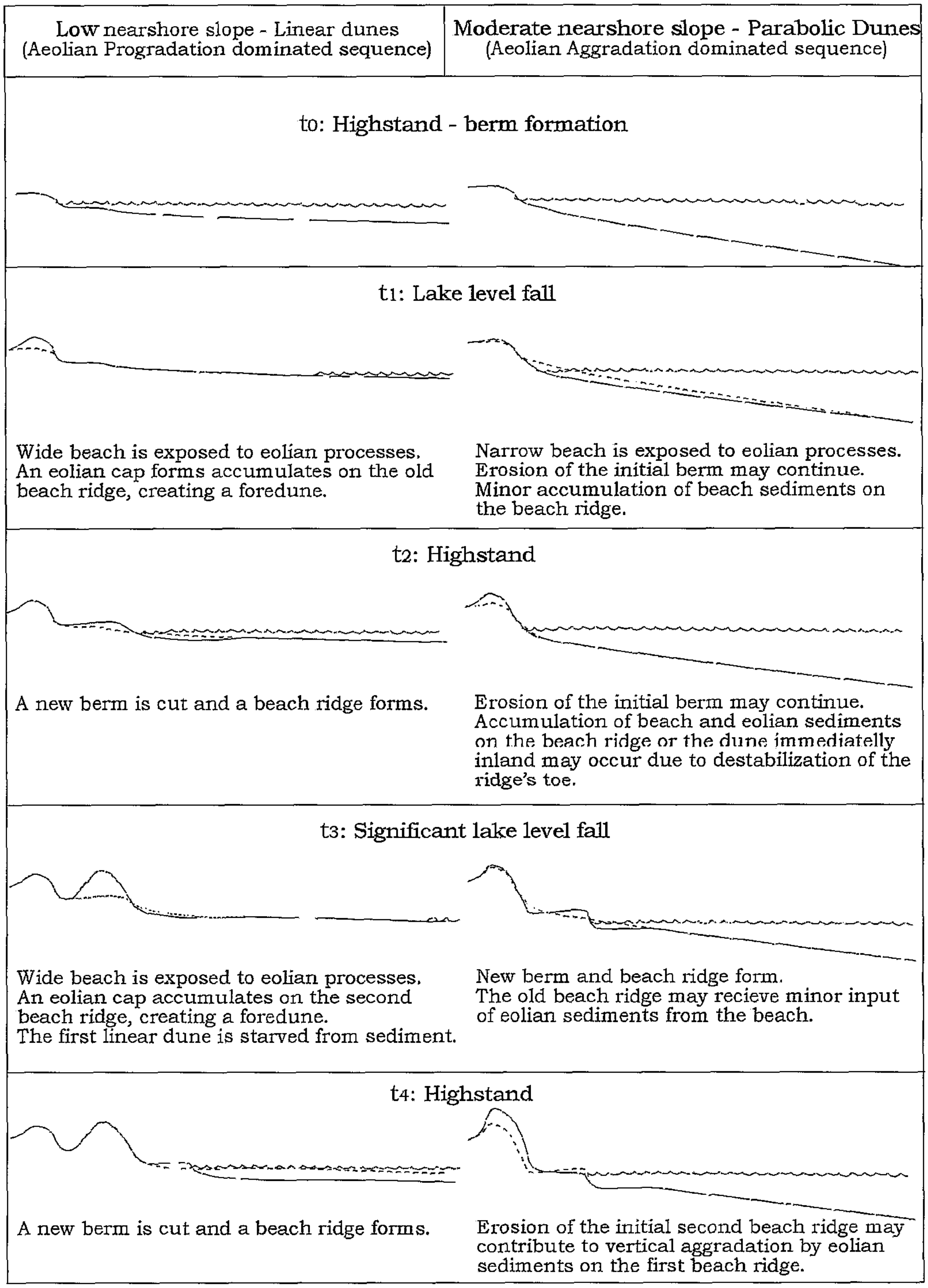


Figure 6. Schematic diagram showing the effect of the nearshore slope on dune aggradational and progradational sequences. Dashed lines show the profile of the previous stage. Repetition of these cycles over time may yield to linear dunes sequences (left) or parabolic dune fields (right).

ing a subsequent lake-level increase. From the standpoint of park management, this study clearly shows that eolian processes have been active in PSP for the past ~4800 cal. yr and that, most importantly, they will continue to be in the area of the campground for the foreseeable future.

## CONCLUSIONS

The purpose of this study was to reconstruct the geomorphic history of Petoskey State Park and evaluate possible implications of our findings to current models of dune formation along lake Michigan. The results from this study indicate that large volumes of sand have been added to this system in the past 5000 yr, with significant aggradation over relatively short periods of time. During this time, multiple cycles of eolian activity and stability have occurred and the focus of deposition has generally migrated lakeward.

Several questions about coastal dune formation are unclear after decades of study, which provides great potential for future studies. Aspects such as the local controlling factors of eolian processes, modern analogs to the currently accepted models of Lake Michigan dune evolution (OLSON, 1958b; THOMPSON, 1992; LICHTER, 1995, 1997; THOMPSON and BAEDKE, 1995, 1997; PETTY *et al.,* 1996; ARBOGAST and LOOPE, 1999; LOOPE and ARBOGAST, 2000), timing of blowout initiation and growth, among others.

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☐ RESUMEN ☐

La presencia de dunas costeras es común a lo largo del litoral este del Lago Michigan. El presente estudio se dedica a establecer la hisoria del campo de dunas en el Parque Estatal de Petoskey, en la parte noroeste de la península inferior del estado de Michigan. Los resultados obtenidos revelan que en este sitio existen cinco unidades geomorfológicas con características y edades de formación independientes: una terraza lacustre, las dunas parabólicas, las dunas superpuestas, las dunas lineales y parabólicas incipientes, y las dunas activas. Edades radiométricas obtenidas a través de carbono catorce y luminiscencia estimulada ópticamente sugieren que la formación de las dunas en esta localidad comenzó alrededor de 4.800 años antes del presente. En general, las dunas en este parque son más recientes y de menor tamaño cerca a la costa y su tamaño y edad aumentan hacia el interior. La progradación y agradación vertical de las dunas en este parque ha occurido durante el Holoceno Medio y Superior, asociado con las fluctuacions del nivel del Lago Michigan. Los resultados obtenidos en este estudio indican además que una pendiente infralitoral suave favorece la progradación de la línea de costa y formación de cordones dunares, mientras que una pendiente infralitoral moderada a fuerte favorece la agradación vertical de las dunas parabolicas.