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Geomorphic history of low-perched, transgressive dune complexes along the southeastern shore of Lake Michigan

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ABSTRACT

A general geomorphic history of low-perched coastal dunes along southeastern Lake Michigan is developed by combining new chronological data from P.J. Hoffmaster and Warren Dunes State Parks (SP) with published data from Van Buren SP, Silver Lake SP and dunes near Holland, Michigan. Fragmentary evidence of dunes older than 6 ka has been almost obliterated by active dune growth since the mid-Holocene Nipissing transgression of ancestral Lake Michigan. Aeolian activity continued during the drop from peak water levels ~4.7 ka resulting in broad fields of low dunes. Aeolian activity halted during a period of low lake levels but was renewed with the development of large parabolic dune during the Algoma high-water phase of Lake Michigan at ~3.2 ka. This was followed by reduced aeolian activity and development of the Holland Paleosol. Subsequent dune remobilization predates European settlement. High lake levels and land use practices cannot completely account for the pattern of aeolian activity which may be affected by changes in storm winds linked to changes in the paths of extratropical cyclones. Dune field morphology depends on the whether the shore is receding, prograding or stable. Simple lake-plain complexes form along receding shorelines where lakefront erosion exposes sediment to aeolian transport, leading to the preservation of a single set of large parabolic dunes migrating eastward with the shoreline. Compound lake-plain complexes form along stable or prograding shorelines. Here progressively younger dune ridges develop and blowouts migrate inland forming overlapping and nested parabolic dunes.

1. Introduction

One of the largest systems of freshwater coastal dunes in the world occurs along the eastern shore of Lake Michigan (Peterson and Dersch, 1981). These dunes are in response to prevailing westerly winds with a ~70 km fetch across Lake Michigan, analogous to the west coast of North America where large dune complexes occur (Cooper, 1958, 1967). However, Lake Michigan dunes formed in a less complex environment without tectonic activity, tides, or exposed bedrock. In addition, the coast has a relatively limited range of sediment types, sediment supply, wave and wind energy, and a well understood history of lake level change (Baedke and Thompson, 2000). Insights gained from the simpler Lake Michigan dune system could contribute to understanding more complicated oceanic dune systems.

As with coastal dunes in general, the type, size, shape and distribution of aeolian landforms vary greatly within and between coastal dune fields along eastern Lake Michigan (Buckler, 1979). Understanding these variations is one of the basic goals of coastal dune studies. Many attempts concentrated on dunes closest to the shore rather than the dune field as a whole (Psuty, 1992; Hesp, 2002; Saye et al., 2005). In one of the most general models of coastal dune morphology, Short and Hesp (1982) emphasized the role of wave energy. They suggested that high wave energy, dissipative beaches are associated with large transgressive dune fields, intermediate beaches are associated with parabolic dune fields and low wave energy, reflective beaches are associated with small dune fields. Pye (1990) emphasized the role of sediment supply, wind energy and anthropogenic disturbance in determining morphology of coastal dune complexes. He suggested that parabolic dunes and transgressive sand sheets result from high winds, anthropogenic disturbance, and relatively low sediment supply leading to an eroding coastline. High sediment supply, on the other hand, leads to accreting shorelines, that when combined with high wind energy, results in sets of parallel dune ridges.

Like coastal dunes elsewhere, aeolian activity within Lake Michigan coastal dune fields appears to have been episodic (Loope and

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Arbogast, 2000). With the potential of dune mobility serving as a climate proxy (Lancaster and Helm, 2000) the causes of dune mobility has been a major subject in coastal dune research (Arens et al., 2004; Clarke et al., 2002; Clemmensen et al., 2001a, 2009; Hesp, 2002; Wilson et al., 2004). Along Lake Michigan high-perched dunes were explained by high lake levels destabilizing bluff faces exposing sediment to aeolian transport (Dow, 1937). Recently Loope and Arbogast (2000) and Fisher and Loope (2005) applied this idea to Lake Michigan coastal dunes in general, arguing mobilizations during high stands associated with the ~160 year quasi-periodic lake level cycle identified by Thompson and Baedke (1997). This model of dune mobility emphasizes the role of wave erosion in exposing sand. Tsoar and Illenberger (1998) argued that wind energy is the critical factor with several workers in northern Europe arguing for dune mobility coincident with increased storminess and high-water levels (Clemmensen et al., 2001b, 2009; Clarke et al., 2002; Wilson et al., 2004). Increased frequency and energy of storm surges and waves erode foredunes in the back beach, while increased frequency and energy of winds enhances sand transport.

According to Arbogast (2009) most coastal dunes along Lake Michigan are contained within transgressive systems, having

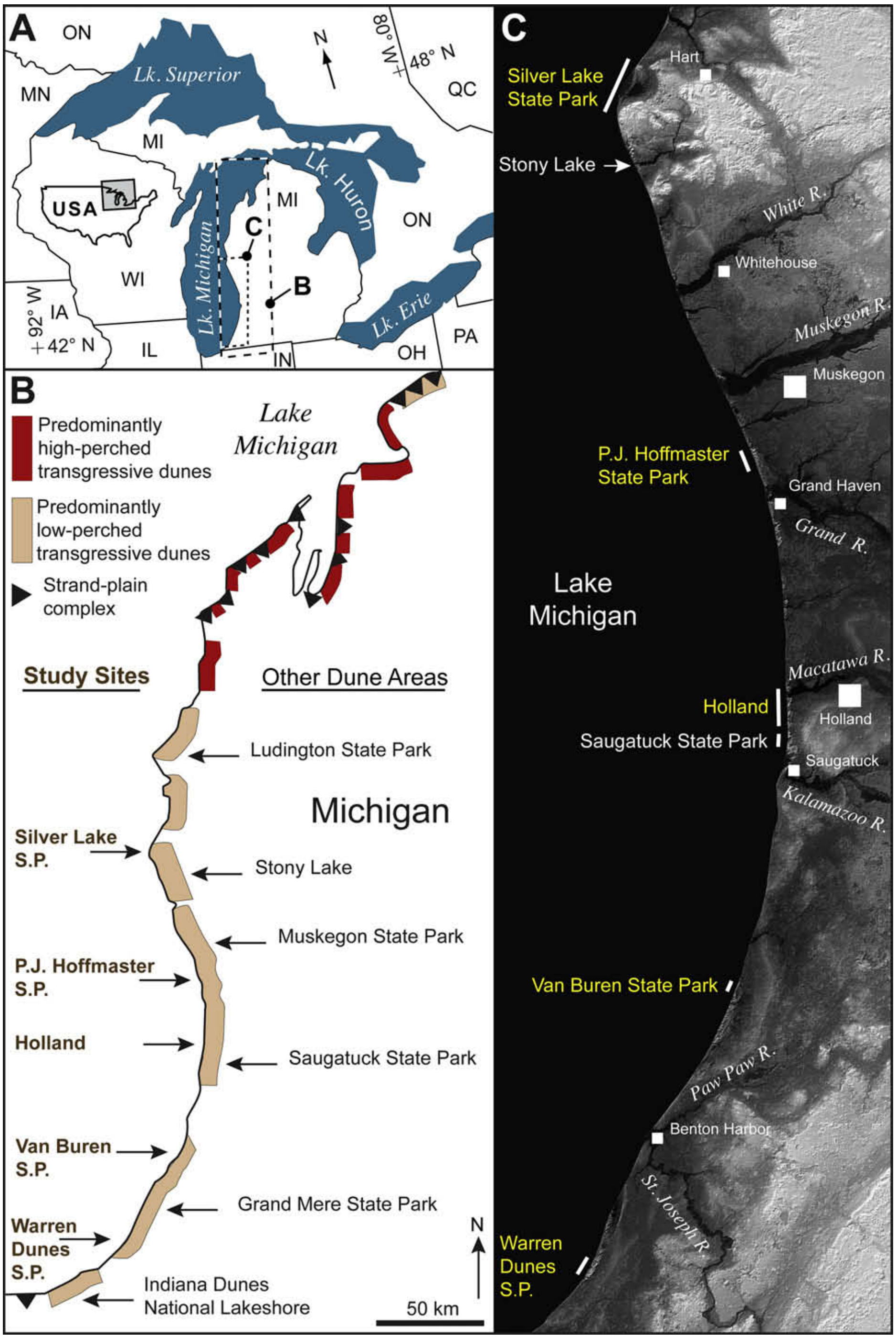

Fig. 1. The study area. (A) Location of the study area in the Great Lakes region of North America. (B) The studied and other dune complexes along the east coast of Lake Michigan. (C) Digital elevation model (DEM) of the study area, where lighter tones correspond to higher elevations.

migrated across previously vegetated or semi-vegetated surfaces (e.g., Hesp and Thorn, 1990). Such aeolian bodies along Lake Michigan can be subdivided into high-perched and low-perched systems (Arbogast, 2009). High-perched dunes are typically tens of meters above current lake levels atop coastal bluffs composed of till or outwash and are particularly common along the northeastern coast of Lake Michigan (Scott, 1942, Fig. 1B). Low-perched dune complexes are typically a few meters above current lake level on lacustrine plains or barrier bars, and are the dominant dune systems along the southeastern shore of Lake Michigan.

Geomorphic histories have recently been developed for individual low-perched dune complexes near Holland (Arbogast et al., 2002; Hansen et al., 2002, 2004; Timmons et al., 2007), Van Buren State Park [SP] (van Oort et al., 2001), and Silver Lake SP (Fisher and Loope, 2005; Fisher et al., 2007). The goal of this paper is to combine data from these previously published studies with new data from Warren Dunes SP and P.J. Hoffmaster SP to develop a general geomorphic history of low-perched dunes in southwestern Michigan. This geomorphic history is then used to yield insights into the underlying causes of coastal dune mobility and the differing morphologies of coastal dune fields.

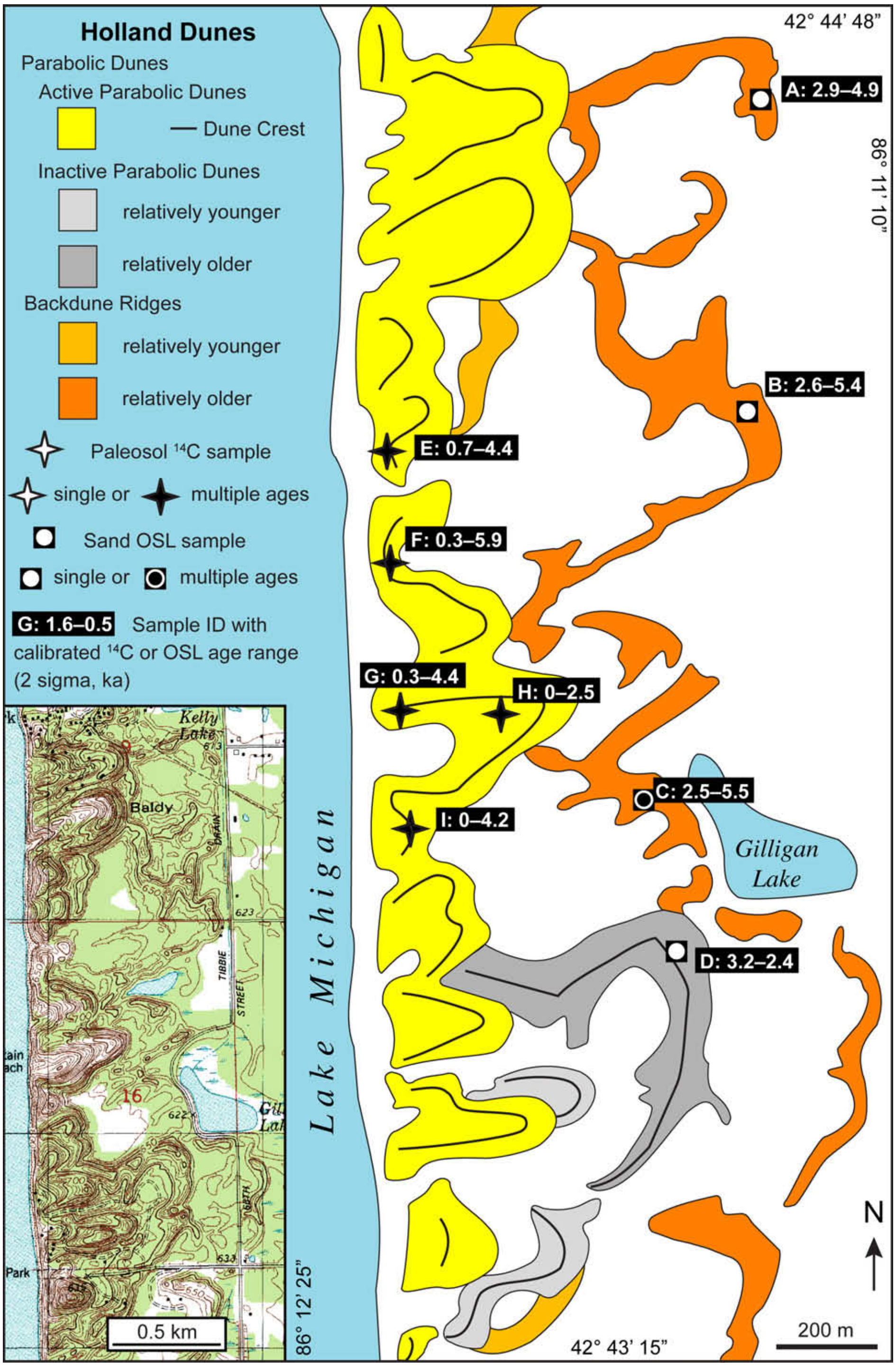

Fig. 2. Geomorphic map with chronology of the dune complex southwest of Holland, Michigan with corresponding topographic map. Radiocarbon ages from Arbogast et al. (2002) and Hansen et al. (2004); OSL ages are from Hansen et al. (2002) and Timmons et al. (2007).

2. Methods

Geomorphic maps of coastal dune complexes at Warren Dunes SP, P.J. Hoffmaster SP, Silver Lake SP, Van Buren SP and near Holland (Fig. 1C) were made with a combination of USGS 7.5 topographic maps, aerial photographs, direct field observations, and previously published work (e.g., Tague, 1946). Dunes were grouped into geomorphic sets based on their geometry, physical continuity, position relative to the coastline and otherdunes, and extent of surface soil development.

Absolute chronologies for dune activity have been determined using radiocarbon ages from wood or charcoal in paleosols (e.g., Arbogast et al., 2002), optically stimulated luminescence (OSL) ages from sand within dunes (e.g., Hansen et al., 2002), and peaks in aeolian sand concentrations in sediment cores from lakes adjacent to dunes (e.g., Fisher and Loope, 2005). Paleosol ages are used with the assumption that dated organic remains accumulated when the soil was at the surface. In this context, previous workers (e.g., Loope and Arbogast, 2000; Arbogast et al., 2002, 2004) have assumed that the ages derived from this material estimate the timing of soil burial by additional deposits of aeolian sand. The assumption with OSL dating is that the sample estimates the time since aeolian sand was finally buried, and the dune began to stabilize at the sample site. The assumption associated with sand peaks in lake sediments is that sand blown into the lake corresponds with periods of dune activity (Fisher and Loope, 2005; Weyer, 2005; Timmons et al., 2007). Sand peak ages are obtained from radiocarbon-derived sedimentation models from individual sediment cores. In this paper new OSL and radiocarbon ages from Warren Dunes SP and P.J. Hoffmaster SP are combined with previously published data from dunes along Lake Michigan (Fig. 1B) to create a general geomorphic history of the low perched, transgressive dune complexes along the southwestern shore of Lake Michigan.

OSL samples were collected from Warren Dunes SP and Hoffmaster SP by driving an opaque PVC pipe into the base of pits or augur holes in the modern dune surface or laterally into pit walls. OSL analyses were conducted at the Sheffield Centre for International Drylands Research. Quartz was extracted and cleaned under subdued red lighting using the procedure outlined in Bateman and Catt (1996). Concentrations of potassium (K), thorium (Th), and uranium (U) in sand from each sample were determined by ICP and converted to effective dose rates using data from Adamiec and Aitken (1998), Marsh et al. (2002), and Aitken (1998) incorporating attenuation for sediment size, density, and paleomoisture (based on present-day values). The contributions to dose rates from cosmic sources were calculated using the expression published in Prescott and Hutton (1994).

OSL analyses were made with an upgraded DA-12 Risø luminescence reader with a 150 W Filtered (GG-420) halogen lamp and a Hoya-340 filter in front of the photomultiplier tube. A single aliquot regenerative dose protocol (cf. Murray and Wintle, 2000) was used to measure the paleodose (D_e) with an experimentally derived preheat of 200 °C for 10 s prior to OSL measurement used to remove unstable signals generated by laboratory irradiations (after Murray and Wintle, 2003). Between 12 and 29 aliquots were analyzed per sample with aliquots only accepted for data analysis where the recycling ratios were within the range of 1 ± 0.1. Most samples showed a highly reproducible normal distribution of D_e with over-dispersion <20%. However, some samples had a wide range of D_e values, large over-dispersion values (>30%) and a multimodal distribution. Most of these samples had both high and low outliers. Taking this into account together with the nature of the samples (dune sand with a low probability of incorporating unbleached material), the most likely explanation is post-depositional mixing due to bioturbation (Bateman et al., 2003, 2007). In the light of this, aliquots that fell outside two standard deviations of the mean were excluded as statistical outliers from subsequent age calculations. The D_e used in the final age calculation was based on a single weighted (by inverse variance) mean D_e and standard error of the replicate data with ages reported from year of sampling (2003 for samples designated with Shfd03 in Table 1 and 2005 for samples designated with Shfd05) as kiloyears (ka). In the text all ages are reported with a range of 2σ. OSL data is given in Table 1.

Outcroppings of paleosols at Warren Dunes SP and P.J. Hoffmaster SP were mapped and AMS radiocarbon ages determined at the Lawrence Livermore National Laboratories and Beta Analytic, Inc. Radiocarbon ages were calibrated using calib V5.0.1 (Stuiver and Reimer, 1993) using the Reimer et al. (2004) calibration curve and reported as kilo calendar years before present (cal. ka BP) with a range of two standard deviations. With calibrated radiocarbon years referenced to 1950 AD, and OSL years to the year of analysis,

Table 1
OSL data.

Sample details			Dose rate data						Paleodose data		Age estimate (years)
Locality	Lab #	Depth (cm)	Moisture (%)	K (%)	U (ppm)	Th (ppm)	Cosmic dose rate (μGy/a^{-1})	Total dose rate (μGy/a^{-1})	n	D_e (Gy)	
Hoff. A	Shfd03078	130	2.3	1.18	0.4	1.2	183 ± 9	1510 ± 84	15	3.39 ± 0.2	2250 ± 500
Hoff. B	Shfd03079	130	3	1.1	0.43	1.5	183 ± 9	1433 ± 77	14	4.05 ± 0.16	2830 ± 380
Hoff. C	Shfd03080	122	2.5	1.09	0.36	1.3	185 ± 9	1386 ± 75	14	3.87 ± 0.29	2790 ± 520
Hoff. D	Shfd03081	115	1.9	1.11	0.41	1.4	186 ± 9	1434 ± 77	10	10.28 ± 0.40	7170 ± 960
Hoff. E	Shfd03082	130	2.7	0.98	0.41	1.3	182 ± 9	1289 ± 68	11	5.57 ± 0.22	4320 ± 560
Hoff. F	Shfd03083	125	2.1	1.05	0.38	1.3	184 ± 9	1391 ± 75	12	3.06 ± 0.14	2200 ± 260
Hoff. G	Shfd03084	135	2.5	1.04	0.43	1.6	182 ± 9	1374 ± 72	14	2.61 ± 0.11	1900 ± 260
Hoff. H	Shfd05052	100	2.6	1.07	0.34	1.35	190 ± 10	1359 ± 77	21	2.7 ± 0.06	1990 ± 240
Hoff. I	Shfd05053	180	2.9	1.19	0.35	1.4	170 ± 9	1457 ± 85	19	5.40 ± 0.14	3710 ± 480
Hoff. J	Shfd05054	180	3.3	1.44	0.34	1.4	171 ± 9	1674 ± 101	18	4.73 ± 0.17	2830 ± 400
Hoff. K	Shfd05055	180	3	1.1	0.39	1.3	171 ± 9	1369 ± 79	19	5.18 ± 0.13	3780 ± 480
Hoff. L	Shfd05056	180	2.7	1.23	0.38	1.3	171 ± 9	1499 ± 98	19	4.19 ± 0.12	2800 ± 360
Hoff. M	Shfd05057	180	2.6	1.05	0.36	1.4	171 ± 9	1335 ± 76	18	3.55 ± 0.11	2660 ± 340
Hoff. N	Shfd05105	160	1.1	0.97	0.39	1.2	176 ± 9	1293 ± 72	15	0.92 ± 0.09	710 ± 160
Hoff. N	Shfd05106	400	3.1	0.94	0.40	3.3	129 ± 6	1327 ± 71	10	1.28 ± 0.06	960 ± 280
Hoff. N	Shfd05107	600	2.2	1.04	0.41	1.3	102 ± 5	1322 ± 89	13	1.12 ± 0.06	880 ± 240
Hoff. O	Shfd05108	160	2.2	1.23	0.36	1.2	176 ± 9	1505 ± 89	13	6.56 ± 0.22	4360 ± 580
Hoff. O	Shfd05109	400	2.9	1.18	0.34	1.3	129 ± 6	1396 ± 84	14	4.6 ± 0.17	3290 ± 460
Warren A	Shfd05058	180	2.7	1.07	0.37	1.5	172 ± 9	1361 ± 78	16	5.24 ± 0.25	3850 ± 580
Warren B	Shfd05059	180	2	1.14	0.47	1.8	171 ± 9	1476 ± 84	16	3.34 ± 0.1	2260 ± 300
Warren C	Shfd05060	180	2.4	1.04	0.39	1.2	172 ± 9	1316 ± 75	16	5.30 ± 0.19	4030 ± 540
Warren D	Shfd05061	180	2.9	1.18	0.49	2.2	171 ± 9	1537 ± 86	10	16.12 ± 0.64	10,490 ± 1440

there is a ~0.05 ka offset between the OSL ages and the calibrated radiocarbon ages reported in the text.

3. Results and discussion

3.1. Dune geometry

Geomorphic maps of the study sites are presented in Figs. 2–6. Most dunes in these fields are parabolic dunes. Sparsely vegetated, actively migrating parabolic dunes occur on the lakeward side of these complexes. Densely vegetated, stable parabolic dunes usually occur further inland in the lee of active dunes. Some dune fields contain several sets of overlapping vegetated dunes. Dune ridges, prominent in many dune complexes, are usually elongated parallel to the coast, ranging in height from ~5 to 15 m. Such dunes are termed coastal dune ridges where they occur lakeward of large parabolic dunes, and back dune ridges where they occur inland of large parabolic dunes. Parabolic dunes often originate as blowouts in dune ridges (Carter et al., 1990), and sinuous dune ridges are a combination of the two forms in which small parabolic dunes are attached to a dune ridge. Most back dune ridges are sinuous dune ridges. A few dune fields contain large sand sheets bounded on one or more sides by steep sand ridges. Smaller dunes occur within these sheets, similar to transgressive dune fields from South Africa (Hesp et al., 1989).

3.2. Dune geometry at study sites

3.2.1. Holland and Van Buren SP

Dune forms at these two localities are similar (Figs. 2 and 3) in that both complexes consist of back dune assemblages and massive parabolic dune assemblages dominated by large (up to 50 m high and 400 m long) active or recently active parabolic dunes. Older stabilized parabolic dunes consist of only one or two generations of overlapping dunes, but are rare. Although ephemeral foredunes develop on the back beach during low water levels, these complexes lack a permanent coastal dune ridge, and arms of the parabolic dunes are eroded during high-water levels. During these periods paleosols are commonly exposed in dune faces by slumping and removal of vegetation (Arbogast et al., 2002; Hansen et al., 2004).

3.2.2. Hoffmaster SP and Warren Dunes SP

The geomorphology of the permanent dunes at P.J. Hoffmaster SP (Fig. 4) and Warren Dunes SP (Fig. 5) are similar. A continuous coastal dune ridge lies between low foredunes to the west and parabolic dunes to the east. In places blowouts occur along the coastal

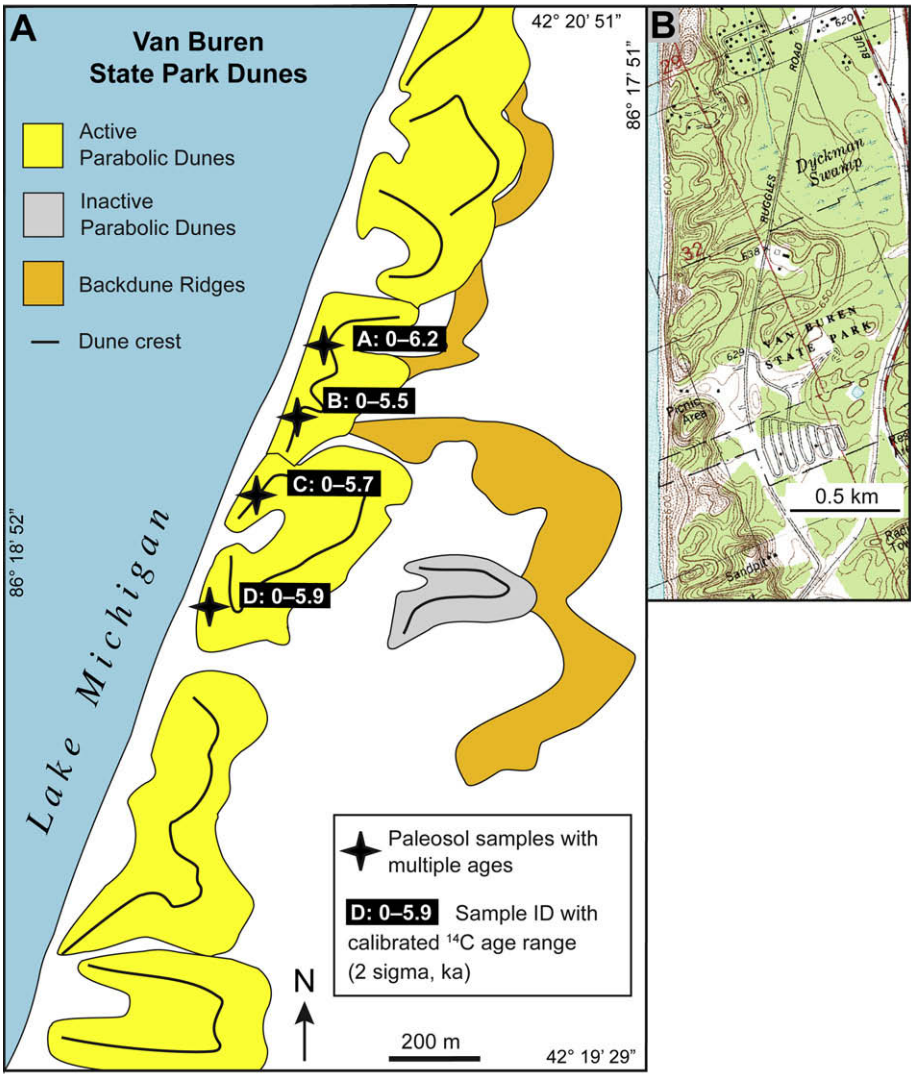

Fig. 3. (A) Geomorphic map with chronology of the dune complex at Van Buren SP with (B) corresponding topographic map. Radiocarbon ages are from van Oort et al. (2001).

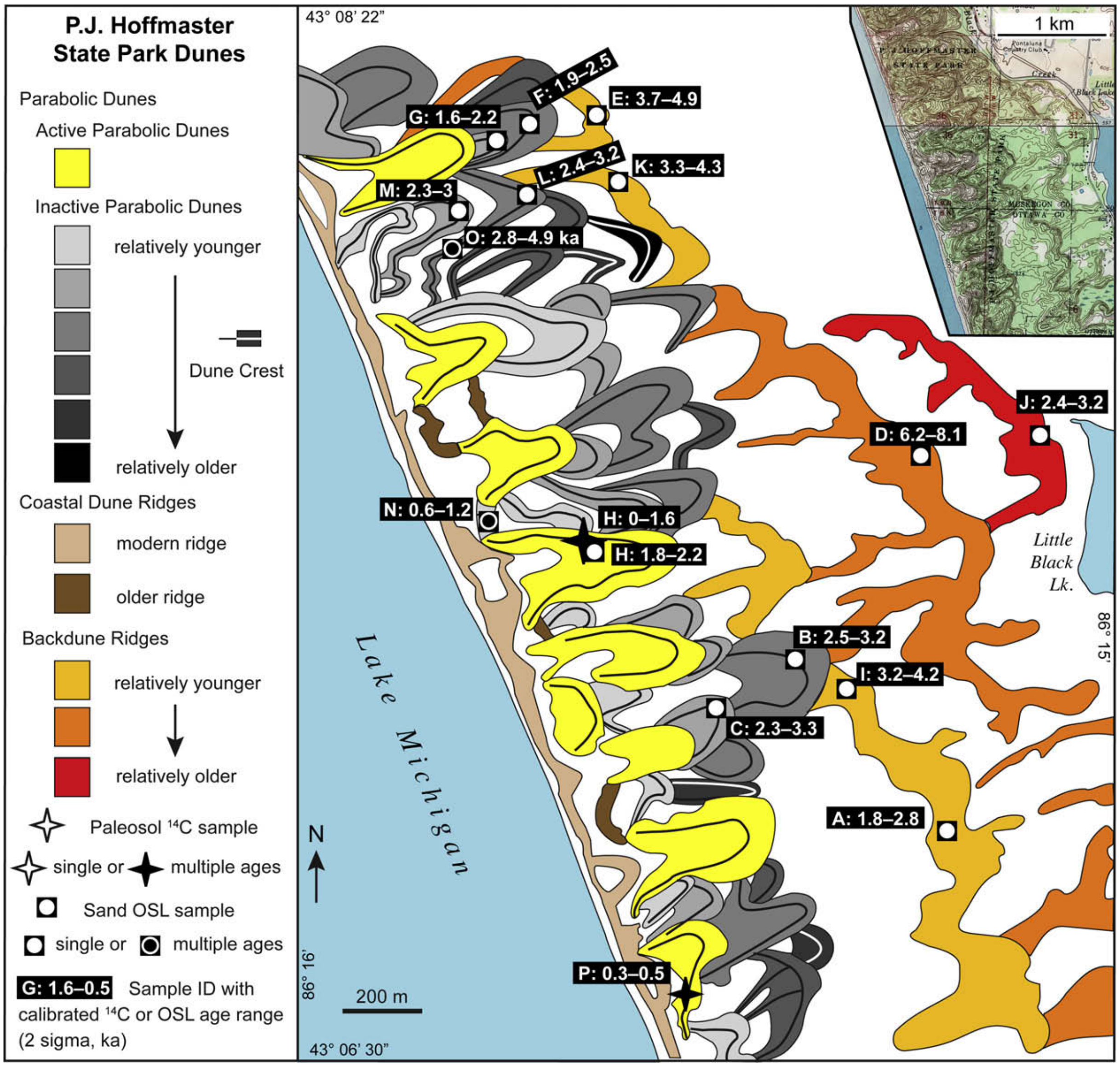

Fig. 4. Geomorphic map of the dune complex at P.J. Hoffmaster SP with corresponding topographic map. Radiocarbon and OSL ages are from this study.

dune ridge and may develop into smaller parabolic dunes migrating into larger parabolic dunes. At P.J. Hoffmaster SP, short ridges parallel to and to the east of the modern coastal ridge occur between large parabolic dunes. These are mapped as older coastal dune ridges (Fig. 4). Our assumption is that these ridges predate the modern coastal ridge. Parabolic dunes immediately east of the modern coastal dune ridge are up to 600 m in length and 55 m in height, and are actively migrating over lower, stable parabolic dunes. The stable parabolic complex consists of up to six generations of overlapping vegetated dunes at P.J. Hoffmaster SP and up to five generations at Warren Dunes SP. Back dune complexes east of the stable parabolic dunes consist of sinuous ridges roughly parallel to each other and to the coast. At P.J. Hoffmaster SP three dune ridges have an average height decreasing from 14 to 6 m eastward. At Warren Dunes SP (Fig. 5) there is only one back dune ridge, however, fragments of two more dune ridges exist northeast of the park (Tague, 1946).

3.2.3. Silver Lake SP

The dune complex at Silver Lake SP is located on Little Sable Point, which is a barrier bar that has prograded into Lake Michigan (Fig. 6). Coastal dune ridges and parabolic dunes occur on the western side of the barrier, while an active, sparsely vegetated sand sheet contains transverse dunes on the eastern side. The western boundary of the sand sheet is the beach ridge from the Nipissing high-water stage of ancestral Lake Michigan (Fig. 6, inset map). A continuous ridge marks the eastern and northern boundaries where the sand sheet is expanding into Silver Lake and the forest north of Silver Lake. Fisher et al. (2007) report that since 1938 dunes north of Silver Lake migrated ~250 m while those west of the lake migrated ~150 m. Dune ridges within the sand sheet are oriented east–west at a high angle to the shore, thus resembling transverse dunes (Fig. 7). Sand transport from the north is supported by the occurrence of steep southward-facing slopes, direct observation of sand on the frozen surface of Silver Lake (Fisher and Loope, 2005; Weyer, 2005), and direct observation of slipface avalanching in February 2004 by T.G. Fisher. In contrast, sand transport from the south is recorded by steep, northward-facing slopes; often steeper than the southward-facing slopes. Thus, under modern conditions the dunes are reversing with a north–south vector, most likely on a seasonal basis with a net eastward migration.

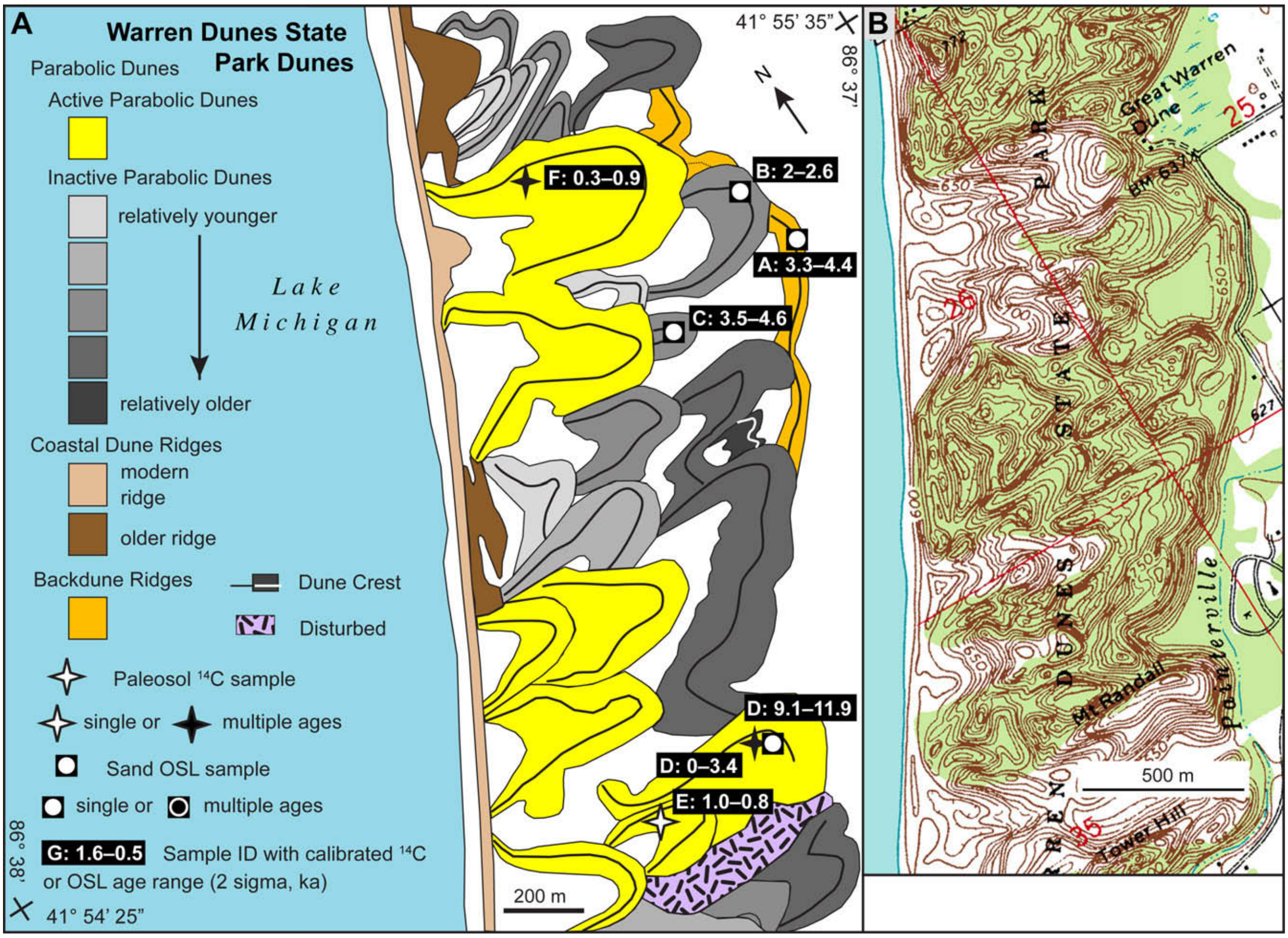

Fig. 5. (A) Geomorphic map with chronology of the dune complex at Warren Dunes SP with (B) corresponding topographic map. Radiocarbon and OSL ages are from this study.

3.3. Dune chronology at P.J. Hoffmaster SP and Warren Dunes SP

Here we report new chronological data obtained from P.J. Hoffmaster SP and Warren Dunes SP. OSL and radiocarbon sample sites are shown on the geomorphic maps (Figs. 4 and 5) with results provided in Tables 1 and 2, respectively, and plotted in Figs. 4, 5, and 7.

3.3.1. Chronology at Hoffmaster SP

Three back dune ridges occur at P.J. Hoffmaster SP. An OSL age of 3.2–2.43 ka was obtained from the easternmost back dune ridge. However, one arm of this ridge is over-ridden by the dune ridge immediately to the west from which an OSL age of 8.13–6.21 ka was obtained (Fig. 4). This age inversion suggests that the easternmost ridge experienced minor remobilization. Three of the four OSL ages from the westernmost dune ridge at P.J. Hoffmaster SP overlap at 2σ recording stabilization at approximately 4 ka while one younger age (2.75–1.75 ka) records more recent activity.

Samples for OSL dating were obtained from pits that penetrated the foreset slopes at the crest above the noses of five large, stable parabolic dunes. The resulting ages should give the age of the last dune mobility but may not distinguish between major dune movement and minor remobilization. The ages range from 2.2–1.44 ka to 3.59–2.07 ka. Most ages statistically overlap within 2σ, and a trend of younger ages closer to the shoreline is not evident. Sand deposited near the nose of a parabolic dune is often sourced from its limbs. Thus OSL ages from the limbs should be older than ages from the nose of the same dune. Two OSL ages from 1.6 and 4.0 m depth from the limb of a parabolic dune overlap within 2σ error at 3.8 ka. This age range is older than the age of 3.16–2.4 ka obtained from the crest of the same dune and can be taken as the younger limit on the beginning of the growth and migration of this dune.

Dune paleosols are exposed in the interior of two actively migrating, large parabolic dunes close to the lake (Fig. 8A and B). Cross-sections of these exposures are given in Fig. 8A and B. A paleosol with a well-developed Bs horizon (enriched in sesquioxides) is exposed at Mount Baldy (locality H: Figs. 4 and 8A) and appears to be part of the Holland Paleosol described by Arbogast et al. (2004). An OSL age of 2.23–1.75 ka was obtained from just below the Holland Paleosol. Three radiocarbon ages were obtained from this soil. The oldest radiocarbon age (1.56–1.39 cal. ka BP) from charcoal does not overlap the other ages (0.96–0.74 cal. ka BP). Radiocarbon ages of 0–0.3 and 0.48–0.31 cal. ka BP were obtained from a paleo-Entisol formed within ~2 m of aeolian sand above the Holland Paleosol. A similar radiocarbon age of 0.48–0.3 cal. ka BP was obtained from a paleo-Entisol exposed in another active P.J. Hoffmaster SP dune (Fig. 8B).

OSL ages were obtained from sand collected at depths of 1.6, 4.0, and 6.0 m in the first short ridge east of the modern coastal dune ridge (Fig. 4). The ages overlap at 2σ suggesting that the upper 6 m of this ridge was deposited between 1.12 and 0.55 ka.

3.3.2. Chronology at Warren Dunes SP

A sample from the easternmost back dune ridge identified by Tague (1946) provided an OSL age of 11.93–9.05 ka. The high range of error in this age is associated with a wide spread in OSL

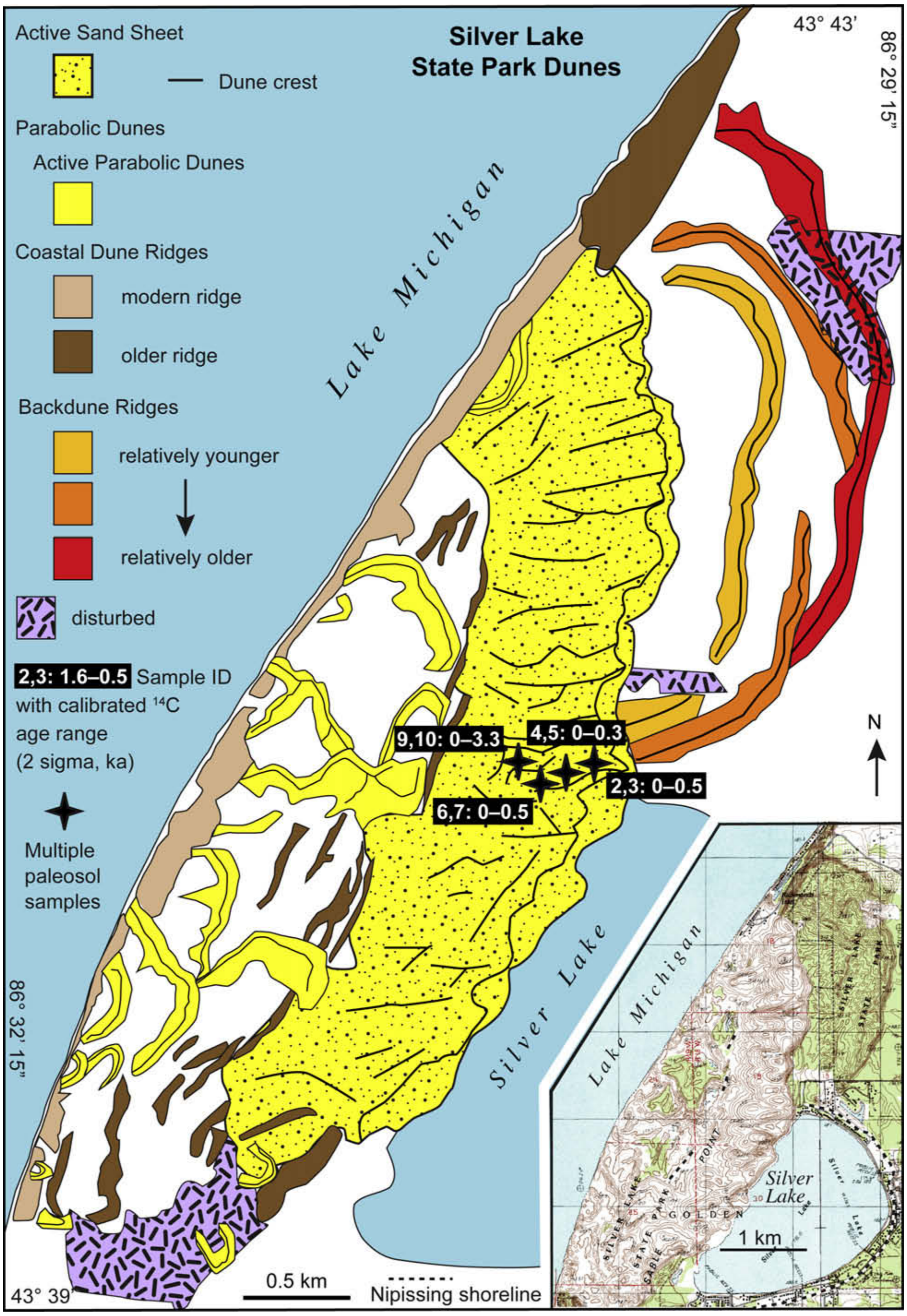

Fig. 6. Geomorphic map with chronology of the dune complex at Silver Lake SP with corresponding DEM. The radiocarbon localities refer to ID numbers in Table 3 of Fisher et al. (2007).

paleodoses and suggests post-depositional disturbance. An OSL age from the westernmost dune ridge in Warren Dunes SP (Fig. 5) indicates stabilization between 4.43 and 3.27 ka. An OSL age of 2.56–1.96 ka is from the crest of the nose of a stable parabolic dune (Figs. 5 and 7B) that had over-ridden the westernmost dune ridge. An age of 4.57–3.49 ka is from a smaller parabolic dune closer to the lake. Mount Randal (locality D: Fig. 5) is an actively migrating parabolic dune in the same geomorphic position as the stable dunes in the park, and may have been remobilized by sand mining on its southern flanks. A series of paleosols are exposed on the stoss slope of Mount Randal (Fig. 8C). Charcoal from the lowest soil dated at 3.36–2.93 cal. ka BP is a minimum age for a dune at this locality. The two overlying paleosols record at least two periods of stability since 3 cal. ka BP. A radiocarbon age of 0.5–0 cal. ka BP from charcoal in the uppermost soil records dune remobilization sometime within the past 500 years.

The set of large parabolic dunes closest to Lake Michigan are actively migrating inland over stable parabolic dunes. A paleosol with a well-developed Bs horizon is exposed in the interior of two active dunes, and appears to be part of the Holland Paleosol described by Arbogast et al. (2004). Three radiocarbon ages were obtained from plant material within the Holland Paleosol at Great Warren Dune (locality F: Figs. 5 and 8D). The oldest age (0.93–0.78 cal. ka BP) does not overlap at the 2σ range with the youngest age (0.69–0.56 cal. ka BP). A younger age of 0.49–0.31 cal. ka BP was obtained from wood in a paleo-Entisol overlying the Holland

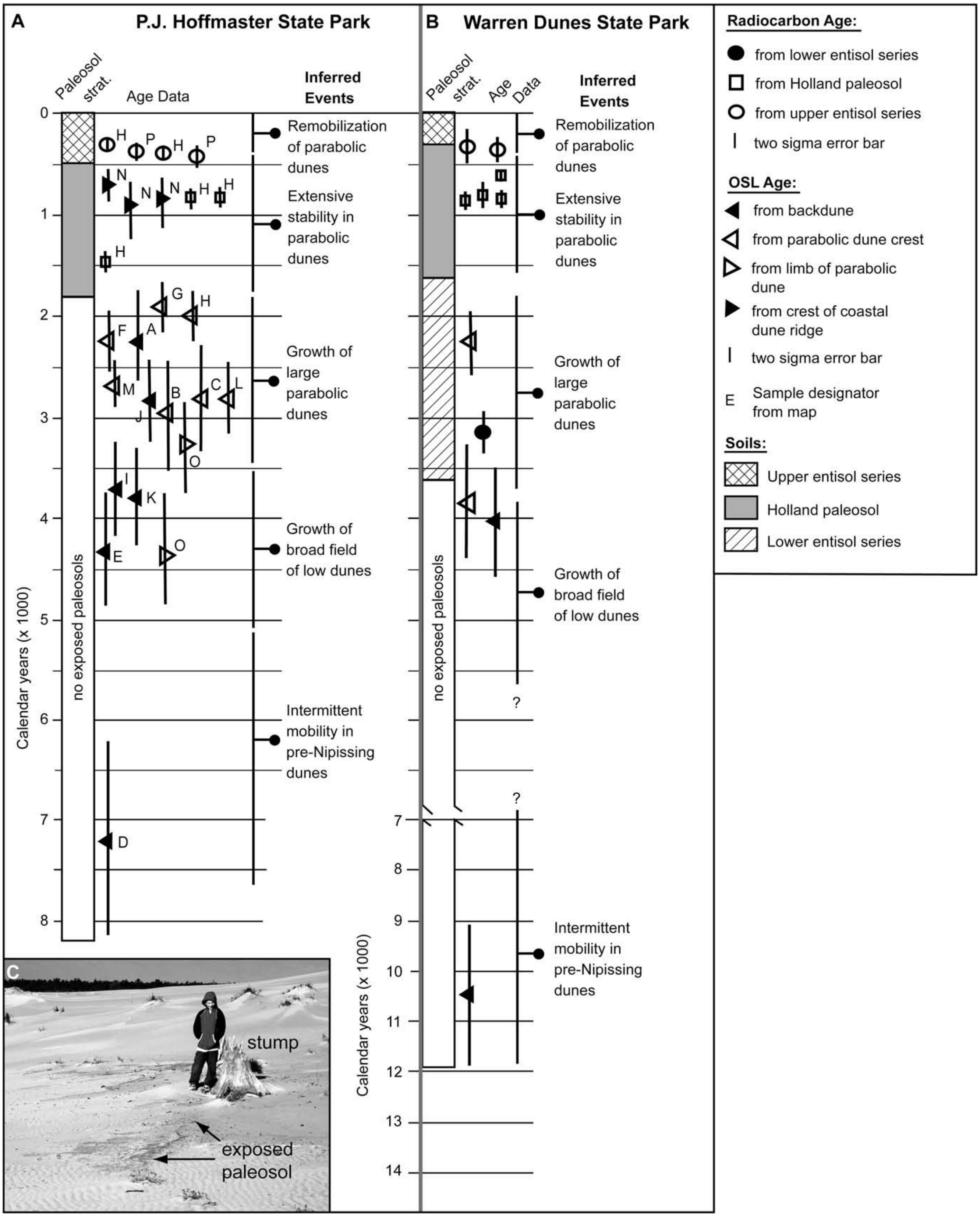

Fig. 7. New chronological data from coastal dune complexes based on paleosol stratigraphy, radiocarbon ages, and OSL ages from aeolian sand. (A) Hoffmaster SP, note letters adjacent to the paleosol and OSL ages refer to the localities shown in Fig. 4. (B) Warren Dunes SP, note letters adjacent to the paleosol and OSL ages refer to the localities shown in Fig. 5. (C) Example of exposed paleosol and stump, person is 1.5 m tall.

Paleosol. The Holland Paleosol is also exposed at the base of the dune east of Mount Randal (locality E: Fig. 5). The dune migrated into this area sometime after 0.96–0.79 cal. ka BP as recorded by a charred stump rooted in this soil.

Table 2
Radiocarbon data.

Location	Soil	Lab #	Material	Radiocarbon age	Calibrated age	Probability	Calibrated age	Probability	Calibrated age	Probability	Calibrated age	Probability	Calibrated age	Probability
Warren D	1Ab	Beta 156730	Charcoal	290 ± 60	270–500	0.918	208–210	0.001	149–187	0.065	−1 to 12	0.012		
Warren D	3Ab	Beta 156731	Charcoal	2970 ± 80	2929–3358	1								
Warren F	2Ab	Cams 108781	Wood	865 ± 35	854–905	0.18	808–831	0.06	693–803	0.76				
Warren F	1Ab	Cams 108897	Wood	345 ± 40	310–490	1								
Warren F	2Ab	Cams 116835	Charcoal	940 ± 35	780–929	1								
Warren F	2Ab	Cams 116837	Wood	685 ± 35	631–688	0.645	560–599	0.355						
Warren E	1Ab	Cams 108893	Wood	970 ± 40	791–955	1								
Hoffmaster H	1Ab	Cams 108778	Charcoal	330 ± 35	307–479	1								
Hoffmaster H	2Ab	Cams 108779	Wood	925 ± 35	765–925	0.994	745–747	0.006						
Hoffmaster H	2Ab	Cams 108780	Charcoal	915 ± 35	760–920	0.97	743–753	0.027						
Hoffmaster H	1Ab	Cams 108892	Wood	180 ± 40	244–301	0.21	131–230	0.501	125–126	0.002	67–118	0.1	−3 to 36	0.183
Hoffmaster H	2Ab	Cams 108895	Charcoal	1580 ± 40	1389–1557	1								
Hoffmaster P	1Ab	Cams 108777	Charcoal	310 ± 40	297–478	1								
Hoffmaster P	1Ab	Cams 108896	Charcoal	420 ± 40	427–530	0.823	389–390	0.0012	321–378	0.176				

4. Discussion

4.1. General geomorphic history

Summaries of the new chronological data from P.J. Hoffmaster SP and Warren Dunes SP and data from Silver Lake SP, Van Buren SP, and Holland dune complexes are shown in Figs. 7 and 9, respectively. A summary of the dune geomorphic history is plotted in Fig. 10 along with the record of lake levels in Lake Michigan, previously considered to be the major control on dune history (Loope and Arbogast, 2000). The chronologies from the five dune complexes can be combined to create a general geomorphic history of the low-perched dune complexes along the southeastern shore of Lake Michigan.

4.1.1. The interpretation of radiocarbon ages from paleosols

Previous studies (Arbogast and Loope, 1999; Loope and Arbogast, 2000; van Oort et al., 2001; Arbogast et al., 2002; Hansen et al., 2004) assumed that the dated organics from paleosols accumulated in the soil shortly before burial by windblown sand. Thus, the resulting radiocarbon ages were thought to estimate the timing of soil burial by additional deposits of aeolian sand. This assumption is more valid for buried Entisols in which the relatively simple A/C horizonations and thin A horizons record relatively brief periods of time for organic accumulation. However disparate ages were obtained in this study (Fig. 8A and D) from buried soils with more developed (A/E/Bs/C) profiles. It is possible that in these cases the soils were buried, uncovered and then reburied. It is also possible that organic matter, especially charcoal, can persist in these soils for extended periods of time. In either case it appears that radiocarbon ages do not always record the time of the latest burial of the soil. The age of burial of a dune paleosol cannot be older that the youngest radiocarbon ages. Similarly, the age of burial cannot be younger than the oldest radiocarbon age obtained on the soil above it, except in cases where older organic material has been eroded and redeposited. Ideally then, a series of radiocarbon ages from a sequence of paleosols will bracket the onset of dune mobility.

4.1.2. Pre-Nipissing dunes

Early geomorphic histories of the Lake Michigan coastal dunes emphasized their shapes, sizes, elevations, soil profiles, sedimentary compositions, and positions relative to each other, and to relict shoreline features (Scott, 1942). These studies generally attributed dunes to various high-water stages of lakes within the Lake Michigan basin (Glenwood, Calumet, Algonquin, Nipissing, and Algoma) during and since deglaciation (e.g., Tague, 1946). More recent work by Arbogast and Loope (1999), used radiocarbon ages to challenge that view. The evidence now indicates that most dunes in low-perched dune complexes along the southeastern shore of Lake Michigan have been active during or since the Nipissing transgression which reached peak water levels at ∼4.7 ka (Thompson and Baedke, 1997). None of paleosols ages from the five dune complexes included in this study are older than the Nipissing transgression. Eleven of thirteen OSL ages from the back dunes, and all OSL ages from coastal dune ridges and large parabolic dunes are younger than ∼5 ka. These include dunes at Warren Dunes that Tague (1946) attributed to the Algonquin (∼13 ka) stage of ancestral Lake Michigan. Older ages from two sites on eastern back dune ridges do indicate that fragments of pre-Nipissing dunes survived later remobilization. The OSL age from the second back dune ridge at P.J. Hoffmaster SP (locality D: Fig. 4) indicates a stabilization age of 8.13–6.21 ka. An older OSL age (11.93–9.05 ka) from the easternmost dune ridge near Warren Dunes SP more closely corresponds with Lake Algonquin (∼13 ka) then the Glenwood

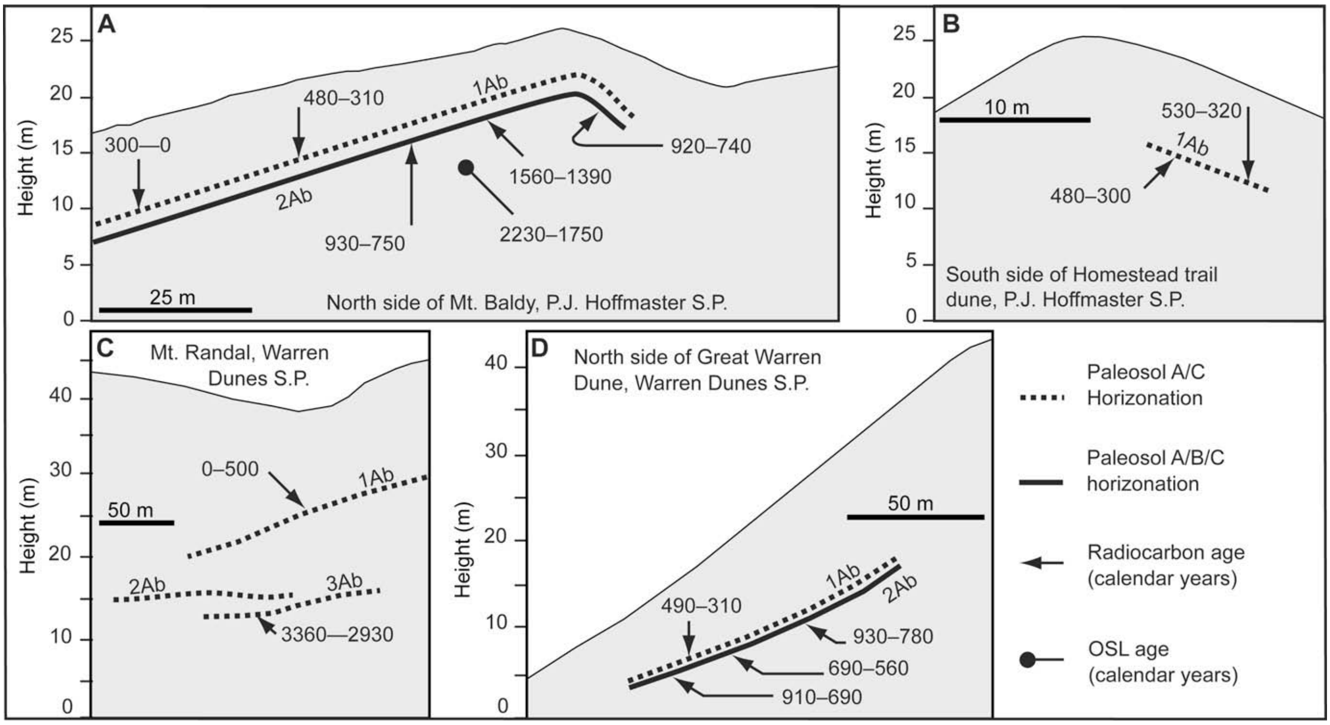

Fig. 8. Cross-sections of dune faces showing the positions of paleosols. (A) Locality H: Fig. 4, (B) Locality P: Fig 4, (C) Locality D: Fig. 5, (D) Locality F: Fig. 5.

stage (~17 ka) of glacial Lake Chicago as suggested by Tague (1946).

4.1.3. Nipissing dunes

Evidence for the initiation of dune growth during the Nipissing transgression occurs in the sequences of paleosols along the lakeshore at Holland (Fig. 9A) and Van Buren SP (Fig. 9B). At both places dated basal soil overlain by aeolian deposits place upper limits on the initiation of dune growth. An age of 5.89–5.31 cal. ka BP from the basal paleosol at Holland is equivalent to the oldest sand peaks in small lakes of the same area (Figs. 2 and 9A). At Van Buren SP the basal peat (Fig. 9B) was deposited between 5.7 and 5.2 cal. ka BP, a maximum age for the overlying dune. Minimum ages for the sand overlying the basal soil are from stratigraphically higher paleosols: 4.85–4.35 cal. ka BP at Holland and 4.34–4.02 cal. ka BP at Van Buren SP. The age of the oldest peak in sand concentration in the Silver Lake sediments is ~5600 ka. Taken together these ages suggest that dunes were active along the southeastern coast of Lake Michigan as water levels rose towards the Nipissing peak (~4.7 ka).

At both Holland and Van Buren SP the basal soils are overlain by thick deposits of aeolian sand containing a sequence of paleo-Entisols collectively referred to as the *lower Entisol series* (Fig. 9). This soils series records brief periods of dune stability and activity, and indicate, that at least on a local scale, dune activity was episodic. Episodic movement is also indicated by distinct peaks in sand concentrations in Silver Lake and the small dune lakes around Holland.

After the fall from the Nipissing high lake level (Fig. 10) dune forms outlined by paleosols of this age have a relatively low relief, suggesting relatively low dunes. This phase ended with a period of dune stability, indicated by gaps in aeolian sand peaks from 3.8 to 3.4 cal. ka BP in the Holland area lakes (Fig. 9A), and from 4.3 to 3.2 cal. ka BP in Silver Lake (Fig. 9C) which correlate to low water levels of Lake Michigan (Fig. 10). OSL ages (Figs. 2 and 9A) indicate that most of the back dunes in the Holland area stabilized shortly before this time. Thus, in the Holland area the first phase of aeolian activity resulted in a relatively broad zone of low dunes that included both the back dunes and the area now occupied by large parabolic dunes. At P.J. Hoffmaster SP half of the OSL ages from back dune ridges, as well as the OSL ages from the limb of a parabolic dune approximately 500 m to the west (Figs. 4 and 7A) fall into this same time period, as does the OSL age from the back dune and a small parabolic dune at Warren Dunes SP (Fig. 7B). Once again these indicate relatively broad dune fields that stabilized after the fall in lake levels from the peak Nipissing stage.

Fisher et al. (2007) mapped a pre-Nipissing baymouth bar west of Silver Lake that was observed in a ground penetrating radar traverse. A set of dune ridges at the edge of this pre-Nipissing bar have bases roughly 6 m above current lake levels and probably represent the Nipissing-stage coastal ridge (Fig. 6). The parabolic dunes that occur between the shore and the Nipissing dune ridge must have formed following lake level lowering after the Nipissing stage. In the southwest portion of the study area the Nipissing ridge is up to 800 m east of the current shoreline indicating that Little Sable Point has prograded westward in response to sediment transport in the littoral zone However, the proportion of the barrier bar and dunes associated with the initial fall in lake level from the peak Nipissing stage is unknown.

4.1.4. Algoma dunes

An increase in aeolian sand in small lakes associated with coastal dune fields at both Holland (Timmons et al., 2007) and Silver Lake SP (Fisher and Loope, 2005) indicates a new phase of dune growth coincident with lake level rise at the beginning of the Algoma phase ~3200 years ago (Fig. 10). Peaks in sand concentration in the Holland area lakes (Fig. 9A) between 3.4 and 1.8 cal. ka BP overlap with radiocarbon ages from paleosols in the upper portion of the lower Entisol series at Holland (Fig. 9A), Van Buren SP (Fig. 9B), and an OSL age from the crest of a large parabolic dune overriding back dunes at Holland (Figs. 4 and 9A). From Holland and Van Buren SP outcrop patterns of paleosols suggests that parabolic dunes grew to their present proportions during this period

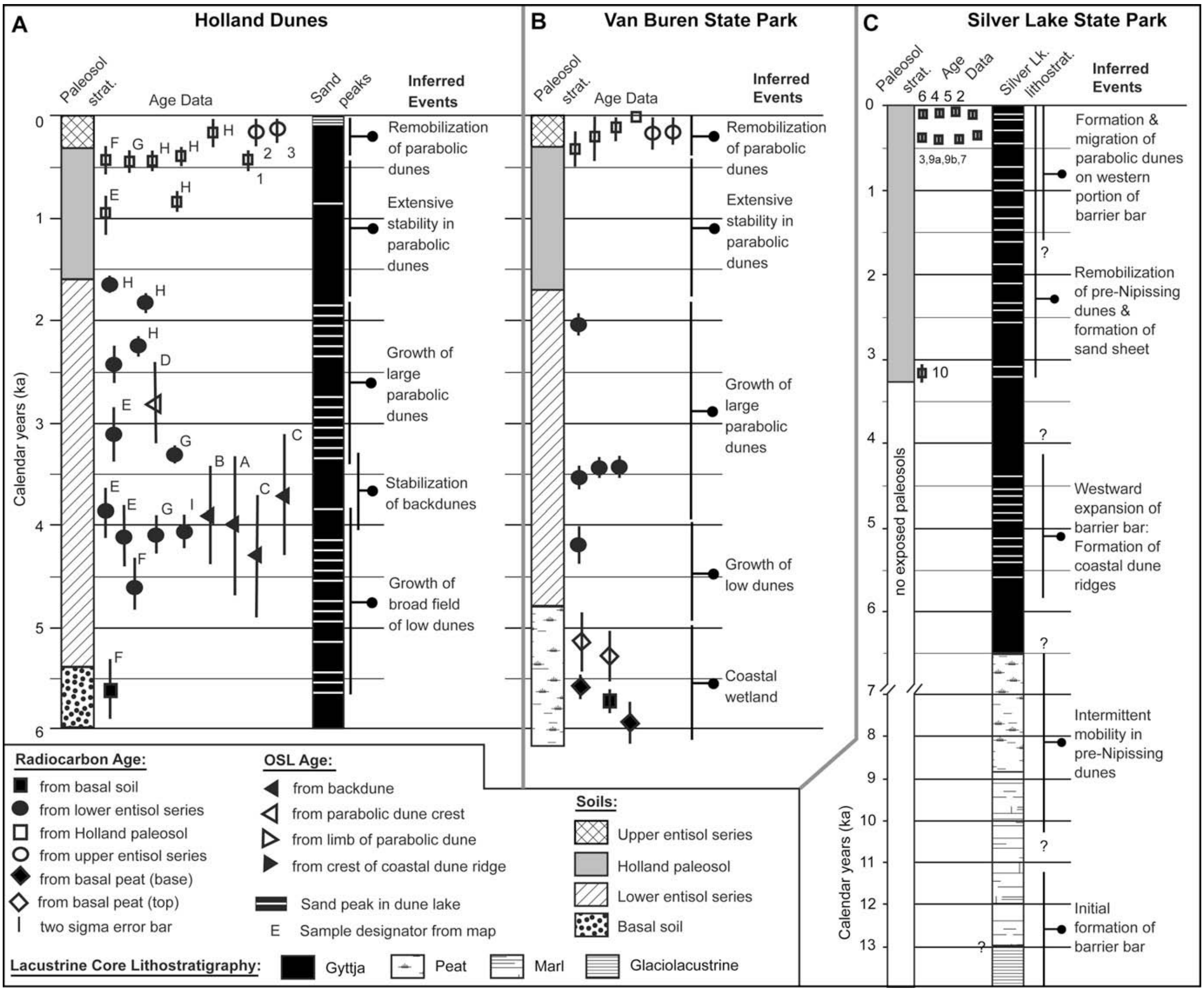

Fig. 9. Summary of previously published chronological data on dune complexes from the southeastern coast of Lake Michigan. (A) Chronology of dune activity in the complex southwest of Holland from Arbogast et al. (2002), Hansen et al. (2004), Hansen et al. (2002), and Timmons et al. (2007). Letters adjacent to the paleosol and OSL ages refer to the localities shown in Fig. 2. (B) Chronology of dune activity in the complex at Van Buren SP from van Oort et al. (2001). Letters adjacent to the paleosol ages refer to the localities shown in Fig. 3. (C) Chronology of dune activity in the complex at Silver Lake SP. Peaks in sand concentrations from Silver Lake adjacent to the dune complex are from Fisher and Loope (2005). The numbers next to paleosol ages are sample identification numbers in Table 3 of Fisher et al. (2007) with locations given in Fig. 6.

of time, with relief locally exceeding 40 m. All OSL ages from crests of stable parabolic dunes from P.J. Hoffmaster SP fall into the interval between 3.5 and 1.6 ka. Less data is available for Warren Dunes SP, but the existing data is consistent with a major period of dune growth at this time. Interestingly, OSL ages from Holland, P.J. Hoffmaster SP, and Warrren Dunes SP suggest that most back dunes were stable during this period, with episodic dune growth and migration largely confined to parabolic dunes close to shore.

4.1.5. Holland Paleosol

An extended period of stability following the Algoma high stand is recorded by the Holland Paleosol, which is a buried soil with an A/E/Bs/C horizonation (Arbogast et al., 2004). The better development of this soil suggests a longer-lived period of stability then the soils of the lower Entisol series. The Holland Paleosol occurs near the top of all dune paleosol exposures at Holland and Van Buren SP, and sporadically in active parabolic dunes at P.J. Hoffmaster SP, Warren Dunes SP (Fig. 8), and Silver Lake SP (Fisher et al., 2007). Soil ages immediately below the Holland Paleosol at Holland and Van Buren SP range from 3.38–3.22 to 1.72–1.54 cal. ka BP. At P.J. Hoffmaster SP an OSL age from the sand beneath the Holland Paleosol is 2.47–1.51 ka (Fig. 8). Thus the available data suggest a slowdown in the pace of dune growth by ~1.6 ka. A sharp drop in the OSL probability curve (Fig. 10) suggests a slowdown in aeolian activity at the same time as does a gap in aeolian sand in small lakes near Holland (Figs. 9A and 10). A similar, although shorter gap, has been observed in a lake associated with the Saugatuck dunes 7 km further south (Fig. 1B, Dean et al., 2006).

Arbogast et al. (2004) used the widespread distribution of the Holland Paleosol as evidence of synchronous dune stability throughout most of the southeastern shore of Lake Michigan. However, the Holland Paleosol crops out in only a small proportion of the active parabolic dunes at P.J. Hoffmaster SP and Warren Dunes SP. Thus it is possible that aeolian activity in these complexes may have been asynchronous (as it is today) with a mix of actively migrating unvegetated, and inactive vegetated dunes. Evidence for this occurs at Silver Lake SP where, despite the widespread occurrence of the Holland Paleosol, aeolian sand deposition within the lake, though variable, was continuous during this time (Fig. 9C). Even if dune mobility did not entirely cease, it appears

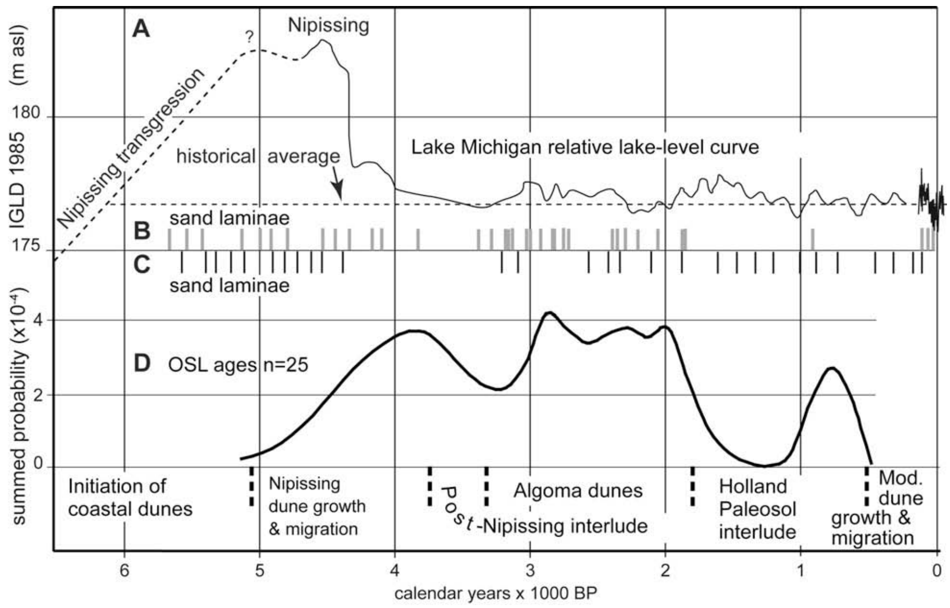

Fig. 10. A summary of geochronological data and dune geomorphic history from the southeastern shore of Lake Michigan plotted against (A) the Lake Michigan water level curve modified from Baedke and Thompson (2000). IGLD refers to the International Great Lakes Datum. (B) Sand peaks from lakes adjacent to dunes near Holland from Timmons et al. (2007). (C) Sand peaks from Silver Lake (Fisher and Loope, 2005). (D) Summed probability distribution curve for the 25 OSL ages from the dunes, plotted using a routine in Lowell (1995).

that the pace of dune growth and migration diminished significantly along the southeastern shore of Lake Michigan after ~2 ka.

4.1.6. Modern dunes

Burial of the Holland Paleosol records another period of dune growth and migration that continues today. Paleo-Entisols forming the *upper Entisol series* overlie the Holland Paleosol in exposures of actively migrating dunes at Warren Dunes SP, Van Buren SP, Holland, and P.J. Hoffmaster SP. Remobilization of the dunes was sometime after the youngest radiocarbon age from the Holland Paleosol, but before the oldest radiocarbon age from the overlying upper Entisol. This method constrains the timing of remobilization to between 0.92–0.74 and 0.48–0.31 cal. ka BP at Hoffmaster SP; 0.69–0.56 and 0.49–0.31 cal. ka BP at Warren Dunes SP; 0.53–0.14 and 0.31–0 cal. ka BP at Holland; and 0.42–0.03 and 0.29–0 cal. ka BP at Van Buren SP. Peaks in sand concentration from lakes near Holland similarly record renewed aeolian activity ~150 years ago. Taken together, these ages suggest that remobilization was asynchronous, occurring earliest at P.J. Hoffmaster SP and Warren Dunes SP, and significantly later at Holland and Van Buren SP. Radiocarbon ages at Silver Lake SP from tree trunks rooted in the Holland Paleosol (Fisher et al., 2007) fall into two clusters; one at 0.3–0 cal. ka BP and another at 0.5–0.3 cal. ka BP. If the trees from which the radiocarbon dates were obtained from Silver Lake SP were killed by sand burial, then remobilization occurred in two phases.

4.2. Morphological variations in dune complexes

The landscapes near Holland and Van Buren SP can be viewed as *simple lake-plain complexes* dominated by a single set of active parabolic dunes but lacking permanent coastal dune ridges (Fig. 11C). The geometries of paleosols in outcrops along the lakeshore indicate formation on the depositional lobes of large parabolic dunes (Hansen et al., 2004). This suggests that the limbs of these dunes, and by implication the shoreline, were once further west indicating net shoreline recession. In this situation coastal dune ridges are not preserved and the western edges of the parabolic dunes are undercut during periods of high-water levels. The resulting slumping removes vegetation, exposing sand that is blown inland by prevailing offshore winds. Thus, as the shoreline retreats the dunes migrate with it, as was suggested by Pye (1990). This telescoping of the western edge of the dune field causes the dunes to form a single set of high parabolic dunes. High-perched dunes (Fig. 11A) also form along retreating shorelines where slumping exposes the sediment to aeolian transport by offshore winds causing dunes at the top of the bluff to grow and migrate inland (cf. Anderton and Loope, 1995).

In contrast to the relatively simple lake-plain complexes, the landscapes at P.J. Hoffmaster SP and Warren Dunes SP are classified as *compound lake-plain complexes* (Fig. 11D). Here there are permanent coastal dune ridges and larger parabolic complexes containing multiple generations of overlapping and nested dunes. Ephemeral foredunes develop lakeward of the coastal dune ridge during periods of low lake levels only to be destroyed during higher lake levels (van Dijk, 2004). During these periods of erosion, wind may transport some of the foredune sand inland to the higher coastal ridge (cf. Olson, 1958). According to Pye (1990) and Hesp (2002) large coastal dune ridges are features of stable coasts, while Hesp (2002) suggests that a series of such ridges will form in prograding coasts. Short, shore-parallel, dune ridges occur between the larger parabolic dunes at P.J. Hoffmaster SP. If these are fragments of former coastal dune ridges (now partially buried by eastward transgressing parabolic dunes), the shoreline has indeed prograded westward through time. The OSL ages obtained on the short ridge immediately inland of the current coastal dune ridge suggests that the shore has migrated 90 m within the last 500–900 years.

Compound lake-plain complexes appear to form in areas with stable or prograding shorelines on which high coastal dune ridges form. Blowouts in these ridges may develop into parabolic dunes; with various stages in this process observable today at both P.J. Hoffmaster SP and Warren Dunes SP. These parabolic dunes migrate inland climbing over, and partially burying, already established dunes. As the shoreline shifts basinward a newly established coastal dune ridge will eventually form. Multiple generations of blowouts, parabolic dunes and coastal dune ridges lead to a compound complex in which fragments of older coastal

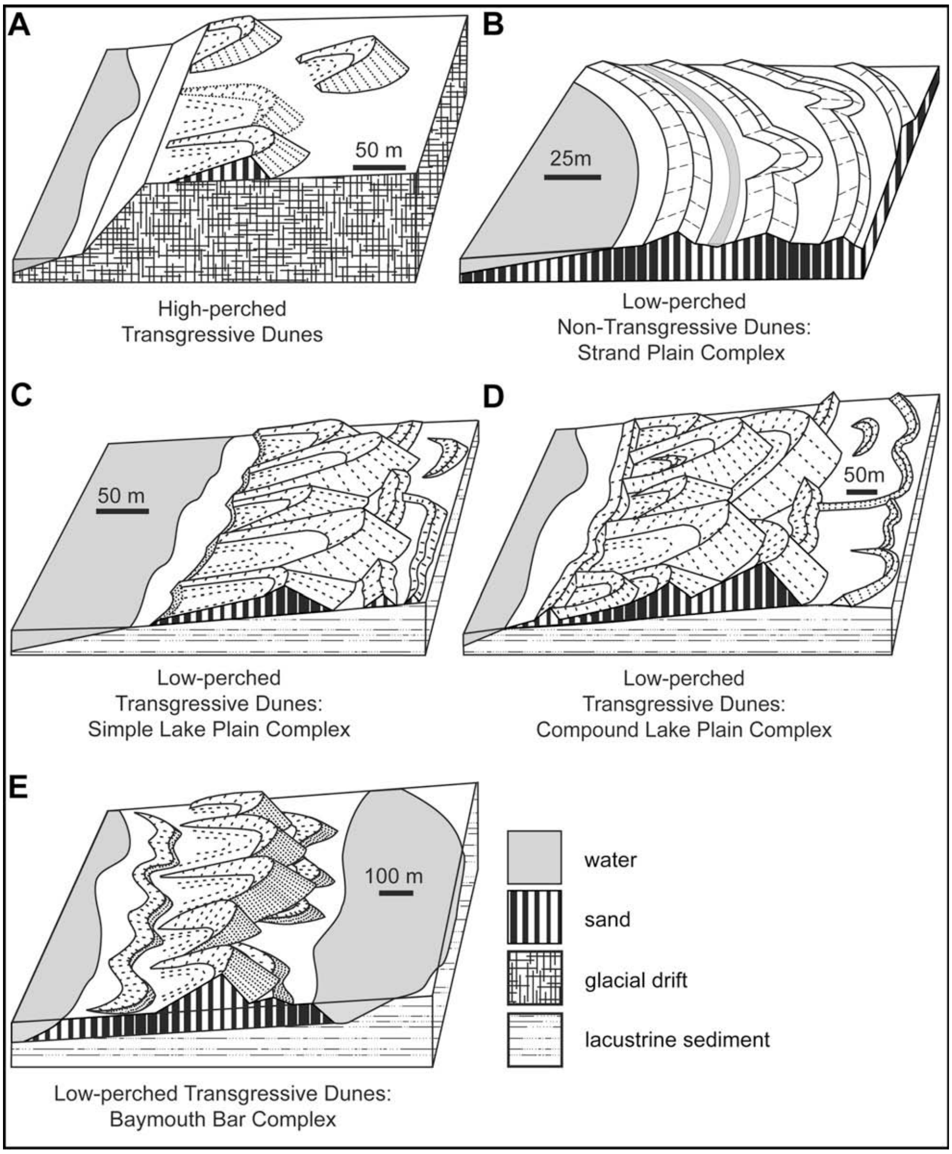

Fig. 11. Types of dune complexes along the eastern shore of Lake Michigan. The classification scheme used here is an extension of the system introduced by Arbogast (2009). (A) High-perched transgressive dunes occur on high coastal bluffs and are commonly parabolic. (B) Strand plain complexes form in coastal embayments that trap large amounts of littoral sediment. The complexes consist of a series of parallel coastal ridges marking successive positions of the prograding shoreline. These may be modified by blowouts forming small parabolic dunes. (C) Simple lake-plain complexes occur on lake-plain sediments only a few meters above current lake levels. They lack a coastal dune ridge and typically consist of one or two generations of large parabolic dunes to the west of low sinuous back dune ridges. (D) Compound lake-plain complexes occur on lake-plain sediments only a few meters above current lake levels. From west to east they consist of a coastal dune ridge, multiple generations of overlapping and nested parabolic dunes and several sets of parallel sinuous back dune ridges. (E) Barrier bar complexes form at the mouths of coastal embayments. On narrower barriers, like the one pictured here, barriers are dominated by dune ridges and parabolic dunes. Wider barriers may contain a more complex assemblage of dune types including sand sheets and transverse dunes.

ridges are preserved between overlapping and nested parabolic dunes. A similar process occurs when sediment trapped in embayments forms strand plain complexes (Fig. 11B) with numerous, parallel beach ridges with aeolian caps containing blowouts that can develop into small parabolic dunes (Thompson, 1992).

Barrier bar complexes (Fig. 11E) form in areas where longshore transport leads to the formation of, or expansion of, a barrier across a coastal embayment. Narrower barrier bars, like the one at Stony Lake (Fig. 1B), tend to be dominated by large parabolic dunes. At Silver Lake SP where the barrier is wider, the dune geometries are more complex and include a large sand sheet with reversing transverse dunes.

Our model for the morphological development of dune fields along the southeastern coast of Lake Michigan is somewhat similar to the model developed for the northwestern coast of England (Pye, 1990). In both models morphological differences are related to shifts in the position of the coastline (progradation vs. recession). Pye (1990) emphasizes the role of sediment supply. In determining this along Lake Michigan, the offshore accommodation space is also important. In shallow embayments or areas with gently dipping predepositional surfaces, sediment accumulation will result in progradation. Conversely, in areas with steeper predepositional surfaces, shorelines may recede despite the supply of sediment to the nearshore environment.

4.3. The timing and causes of dune growth and mobility

There is a limited correlation between levels of Lake Michigan and large-scale history of the low-perched dunes along the southeastern shore (Fig. 10). Widespread dune growth was initiated as lake levels rose during the Nipissing transgression. Broad fields of relatively low dunes formed during the fall from the Nipissing level, followed by inactivity during low water levels. Renewed aeolian activity recorded by the growth of large parabolic dunes at about 3.5 ka correlates with an increase in lake level. However, as noted by Arbogast et al. (2004), the slowdown in aeolian activity recorded by the Holland Paleosol after ~2 ka lasted through a major cycle of lake level fluctuation. Dune mobility along Lake Michigan can be initiated by anthropogenic disturbances removing sand from the stoss face of dunes, and there is a widespread assumption that dune mobility in the historical period is a consequence of land use practices introduced by European settlers. While some impact on the dunes undoubtedly occurred following European settlement, the new data presented here supports Arbogast et al. (2004) who suggested that remobilization of the dunes preceded arrival of large numbers of European settlers in western Michigan in the mid-1800s.

It appears that some factor or factors in addition to lake level and modern land use practices must be responsible for controlling dune activity. Arbogast et al. (2004) suggested that an influx of sediment to the southern part of Lake Michigan could have been responsible for initiating the period of reduced dune mobility represented by the Holland Paleosol. They argued that this influx hypothetically led to the formation of extensive foredunes at the inland edge of broad beaches that protected the permanent dunes from wave erosion. However, data from compound lake-plain complexes suggests that even with prograding shorelines, blowouts in coastal dune ridges can evolve into parabolic dunes that migrate inland (previous section). Wind energy is one of the critical factors in dune mobility (Tsoar and Illenberger, 1998), and for our study area this is reinforced by contemporary observations that almost all dune growth and migration occurs in the late autumn and winter when the westerly winds are the strongest (van Dijk, 2004; Hansen et al., 2009). A study of a large parabolic dune at Holland, MI showed that nearly half the annual sand transport was associated with the two strongest storms (Hansen et al., 2009). An extended decrease in the frequency or intensity of storm winds could be responsible for a period of reduced dune activity. Such changes in storminess were invoked to explain extended periods of dune stability along the European Atlantic Coast (Clemmensen et al., 2001; Clarke et al., 2002; Wilson et al., 2004). The north–south elongation of Lake Michigan (Fig. 1) means that fetch, and hence wind energy along the coast, is strongly influenced by wind direction. Thus shifts in the direction of storm winds should also influence dune mobility. In the Great Lakes region changes in storm winds could be associated with changes in the average tracks of extratropical cyclones (Wang et al., 2006; Eichler and Higgins, 2006). In a recent study, Clemmensen et al. (2009) found that extended periods of mobility identified in the dune fields along the west coast of Jutland, Denmark correlated with periods of relatively cool, and wet summers identified in peat bog sediments from southwestern Sweden. This correlation suggests that increased dune mobility resulted from increased summer storminess linked to varying extra tropical cyclone pathways.

Multiple paleosols within dunes and distinct aeolian sand peaks in lakes adjacent to dunes indicate that aeolian activity was episodic, at least on a local scale. This suggests that shorter cycles of aeolian activity may exist within the longer periods discussed above. Some workers (Loope and Arbogast, 2000; Fisher and Loope, 2005; Fisher et al., 2007) have suggested that dune mobility corresponds to high lake levels recorded by the ~160 year quasi-periodic lake level cycle of Thompson and Baedke (1997). Unfortunately, the number of paleosols from a dune is only a minimum estimate for episodes of activity, and the error of our OSL ages is too large to detect ~160 year cycles. Thus, aeolian sand peaks in sediment cores from small lakes adjacent to coastal dunes is probably our best chance at obtaining a complete, high-resolution chronology of dune activity. Fisher and Loope (2005) found a correlation between sand peaks in Silver Lake and peaks in Lake Michigan lake levels. Conversely, Timmons et al. (2007) found that sand peaks in small lakes adjacent to dunes southwest of Holland were just as likely to correlate with falling lake levels as they were with rising lake levels. These differing results may be due to the combined uncertainties in age models for lake levels and sedimentation rates in cores. It is still worthwhile to pursue these relationships because both dune activity and lake level fluctuations are driven by fluctuations in climate.

5. Conclusions

Although differences occur in details, there are common elements in the geomorphic history of the five dune complexes studied here that allow for the reconstruction of a general history of the coastal dunes along the southeastern shore of Lake Michigan.

Stage 1: *Pre-Nipissing dune complexes (deglaciation – ca. 5.7 ka).* Coastal dunes developed from earlier high-water stages in ancestral Lake Michigan, but were interior dunes during the low stand preceded the Nipissing peak.

Stage 2: *Nipissing dune growth and migration (~5.7–3.8 ka).* Aeolian activity began towards the end of the Nipissing transgression and continued during the fall from the Nipissing peak resulting in broad fields of low coastal dunes.

Stage 3: *Post-Nipissing interlude (~3.8–3.3 ka).* A short period of relative dune stability corresponding roughly to a prolonged period of low lake levels.

Stage 4: *Algoma dune growth and migration (~3.3–1.6 ka).* Episodic reactivation of dunes roughly synchronous with a rise in lake level to the Algoma stage, and the formation of large parabolic dunes along the shoreline.

Stage 5: *Holland Paleosol interlude (~1.6–0.5 ka).* A slowdown in dune activity marked in many places by a relatively well-developed spodic paleosol (Arbogast et al., 2004).

Stage 6: *Modern dune growth and migration (~0.5–0 ka).* A renewal in dune growth and migration that appears to predate the arrival of European settlers and continues today.

The morphologies of dune complexes depend largely on whether the shoreline is receding, stable, or prograding. Simple lake-plain complexes, like high-perched complexes, form in areas of shoreline recession. The result is a relatively narrow dune complex with a simple geometry of parabolic dunes migrating inland with the shoreline. Compound lake-plain complexes, like strand plain complexes, form where the shoreline is stable or prograding. The result is a relatively large dune field with overlapping and nested parabolic dunes formed from blowouts in a succession of coastal dune ridges. Barrier bar complexes form in areas where longshore transport results in barriers built across coastal embayments. Narrow barriers have relatively simple complexes of coastal dune ridges and parabolic dunes, while wider barriers may also contain sand sheets and transverse dunes.

There is a tendency for periods of relatively high lake levels to be periods of active dune growth and migration, and for periods of relatively low lake levels to be periods of dune stability. However, the extensive period of dune stability from ~1.6 to 0.5 ka is a notable exception. The recent remobilization of coastal dunes predates European land use patterns, thus, at least one factor in addition to lake level and modern land use patterns must be responsible for mobilizing the coastal dunes. Variations in storminess, associated with shifts in the paths of extratropical cyclones are one possibility.

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