

# Inland dunes on the abandoned bed of Glacial Lake Chicago indicate eolian activity during the Pleistocene-Holocene transition, southwestern Michigan, USA

Patrick M. Colgan<sup>a\*</sup>, William H. Amidon<sup>b</sup>, Sara A. Thurkettle<sup>a</sup>

<sup>a</sup>Department of Geology, Grand Valley State University, Padnos Hall of Science, 1 Campus Drive, Allendale, MI 49401, United States

<sup>b</sup>Department of Geology, Middlebury College, McCardell Bicentennial Hall, 276 Bicentennial Way, Middlebury, VT 05753, United States

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## Abstract

Inland dune fields have recently emerged as a source of data for reconstructing paleoenvironments and climate in the western Great Lakes region of North America during the Pleistocene-Holocene transition. We employ optically stimulated luminescence (OSL) methods, radiocarbon ages, soils, and landform relationships to determine the age of inland dunes in Ottawa County, Michigan. These dunes rest on the abandoned bed of Glacial Lake Chicago, which is thought to have been exposed after ~13.6 ka. OSL analyses from two inland dunes yield ages ranging from  $13.3 \pm 1.1$  to  $11.6 \pm 0.9$  ka (uncertainty =  $2\sigma$ ). Fine sand in the parabolic dunes suggests deflation of exposed glaciolacustrine nearshore sand by northwesterly and westerly winds. These new data add to a growing number of studies that demonstrate widespread eolian activity in the western Great Lakes region during the Pleistocene-Holocene transition. OSL ages from dune fields in the western Great Lakes indicate peak eolian activity and dune stabilization occurred during or following the Younger Dryas and Preboreal events. Northwesterly and westerly winds suggest the limited effect of hypothesized easterly anticyclonic winds during the Pleistocene-Holocene transition. Rapidly changing climate and newly deglaciated surfaces provided an ideal environment for dune formation.

**Keywords:** Early Holocene; Late Pleistocene; Wisconsin Episode; Younger Dryas; Bølling-Allerød; Eolian; Optically stimulated luminescence; Radiocarbon; Glacial Lake Chicago; Michigan

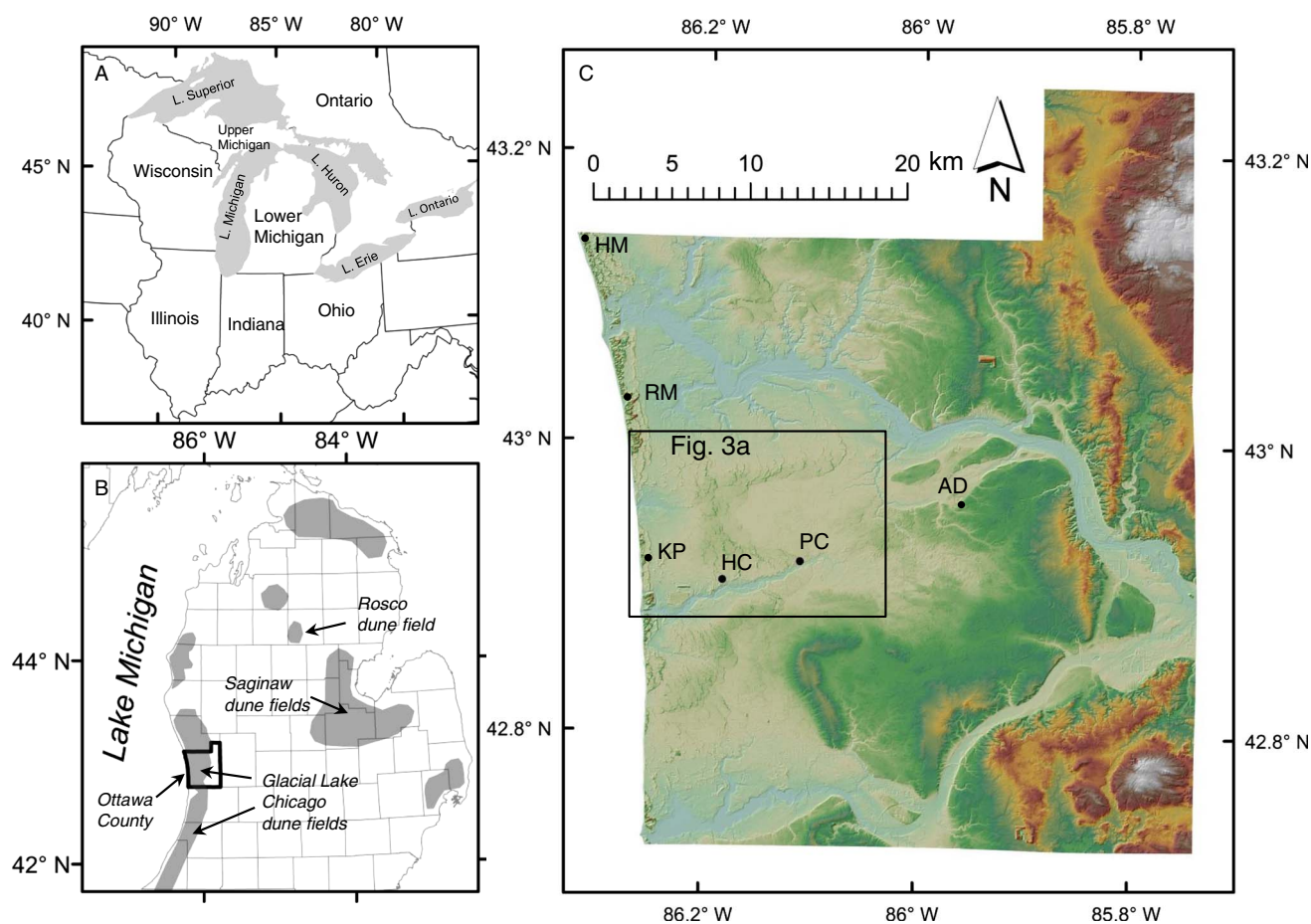
## INTRODUCTION

Late Pleistocene and Holocene eolian dunes in the western Great Lakes region of North America (Fig. 1A) are increasingly being used as a source of evidence for paleolake levels, glaciofluvial sedimentation events, climate changes, and past atmospheric circulation patterns. A growing number of studies hypothesize causal links between coastal dune activity and lake level changes (e.g., Arbogast and Loope, 1999; Loope and Arbogast, 2000; Arbogast et al., 2002a, 2010; Hansen et al., 2003, 2006, 2010; Blumer et al., 2012). Newly constructed inland dune chronologies have been recently utilized to infer eolian activity during the Pleistocene-Holocene transition and early Holocene (Arbogast et al., 2002b, 2015; Rawling et al., 2008; Loope et al., 2010; Miao et al., 2010; Campbell et al., 2011; Kilibarda and Blockland,

2011; Loope et al., 2012). Coastal spits and dunes have also been employed to reconstruct paleowind patterns associated with a hypothesized anticyclone, which may have persisted over a retreating Laurentide Ice Sheet (Krist and Schaeztl, 2001; Kilibarda and Blockland, 2011; Vader et al., 2012). Nearly all of these studies use optically stimulated luminescence (OSL) to estimate the age of eolian sediments as this method is well suited to quartz-dominated loess and dune sand.

Two distinct populations of dunes have been recognized in Michigan as a result of previous studies: coastal dunes and inland dunes (Arbogast et al., 1997; Arbogast and Jameson, 1998; Arbogast, 2009). Coastal dunes are found along the shores of the western Great Lakes (Fig. 1B) and are primarily middle to late Holocene phenomena, related to coastal evolution and lake level changes following the Nipissing transgression (e.g., Arbogast and Loope, 1999; Arbogast et al., 2002a, 2010; Hansen et al., 2010). Coastal dunes are large parabolic dunes up to 50 m in relief, and sometimes perched up to 100 m above the current lake

\*Corresponding author at: Department of Geology, Grand Valley State University, Padnos Hall of Science, 1 Campus Drive, Allendale, MI 49401, United States. E-mail address: colganp@gvsu.edu (P.M. Colgan).



**Figure 1.** (color online) (A) Location map of the western Great Lakes region of North America. (B) Location of the study area in Ottawa County, Michigan, and areas of inland dunes in Lower Michigan (shaded areas are after Arbogast and Jameson [1998]). (C) Shaded relief image derived from a 2004 LIDAR (light detection and ranging) digital elevation model of Ottawa County, Michigan. Location of our two optically stimulated luminescence (OSL) sample sites at Hemlock Crossing Park (HC) and Pigeon Creek Park (PC). Previous radiocarbon and OSL dune studies at Rosy Mound Natural Area (RM) and Hoffmaster State Park (HM). Coastal dune sediment samples from Kirk Park (KP). Allendale delta sediment samples from near Allendale, Michigan (AD).

surface (Arbogast, 2009). A back dune complex of lower-relief parabolic dunes and dune ridges is also present up to a few kilometers inland (e.g., Arbogast and Loope, 1999; Arbogast et al., 2002a, 2010; Hansen et al., 2010). Radiocarbon and OSL analyses for coastal dunes in Lower Michigan yield ages less than  $\sim 6.0$  ka, although a few dunes have produced slightly older ages (Hansen et al., 2010).

Dunes are also found on abandoned outwash and lacustrine plains, well inland from coastal dunes (Fig. 1B). Inland dunes have much lower relief ( $\sim 10$  m) than coastal dunes and are part of extensive sand sheets, which cover abandoned outwash and lacustrine plains (e.g., Arbogast et al., 1997, 2015; Arbogast and Jameson, 1998; Loope et al., 2010, 2012). Only three OSL studies estimate the age of inland dunes on abandoned outwash and glacial lacustrine plains in Michigan, and these studies have produced late Pleistocene and early Holocene ages for these dunes (Loope et al., 2010, 2012; Arbogast et al., 2015). Notably, there are no OSL studies for inland dunes found on the former bed of Glacial Lake

Chicago in western Lower Michigan (Fig. 1B), even though inland dunes are common in this area and cover an estimated area greater than  $200 \text{ km}^2$  in Ottawa County, Michigan, alone (Fig. 1C).

In this article, we present the first OSL ages for inland dunes on the abandoned bed of Glacial Lake Chicago in western Lower Michigan (Fig. 1C). Our new ages demonstrate that these inland dunes were active during the latest part of the Bølling-Allerød and the subsequent Younger Dryas and Preboreal events immediately following final drainage of Glacial Lake Chicago after  $\sim 13.6$  ka (Larson, 2011). Our OSL ages add to a growing number of OSL studies of inland dune fields in the western Great Lakes region and demonstrate a peak in eolian activity during, and slightly after, the end of the Younger Dryas event. Additionally, all of these studies demonstrate northwesterly or westerly winds and do not support the hypothesis of easterly anticyclonic winds along the retreating ice margin of the Laurentide Ice Sheet during the Pleistocene to Holocene transition.

## Geomorphic setting of inland dunes

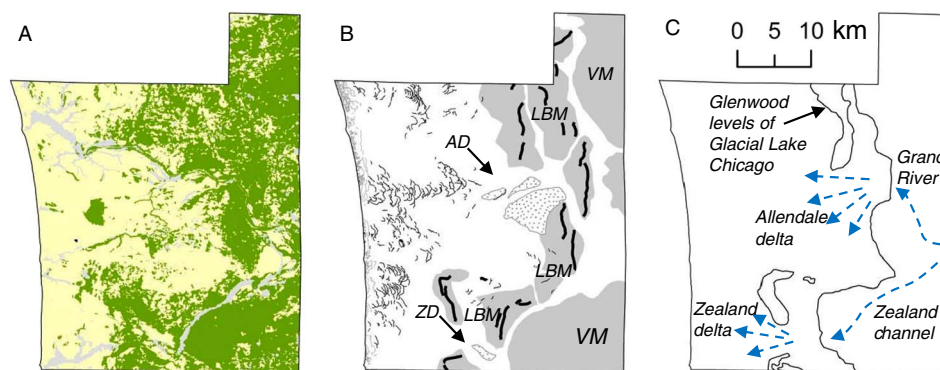
Landforms and sediments in Ottawa County, Michigan, are predominately late Pleistocene glaciolacustrine plains of gravelly nearshore sand, moraines and till plains composed of silt-rich diamicton, and valley trains of sand and gravel between end moraines (Fig. 2). Wisconsin Episode (formerly late Wisconsinan) and older glaciogenic sediments vary from ~10 to >100 m thick and cover late Mississippian bedrock of shale, sandstone, and limestone (Colgan et al., 2015). In eastern Ottawa County, there are end moraines, till plains, uplands, and associated valley trains of the Valparaiso and Lake Border moraine systems (Fig. 2) formed during the Crown Point Phase ~18,200 to 16,800 cal yr BP (Leverett and Taylor, 1915; Curry et al., 2011; Larson, 2011). The western half of Ottawa County is a sandy lacustrine plain abandoned by Glacial Lake Chicago after ~13,600 yr BP (Larson, 2011) and subsequently modified by eolian, fluvial, and coastal processes (Figs. 1C and 2).

Inland dunes on the abandoned bed of Glacial Lake Chicago are covered in forest where not disturbed or heavily modified by humans. Before European settlement in the early 1800s, the area around Pigeon River in western Ottawa County (Fig. 3A) was composed of sandy uplands, covered by a dry-mesic northern forest of *Pinus strobus*, *Quercus albus*, *Quercus rubra*, *Acer rubrum*, *Fagus grandifolia*, *Prunus serotina*, *Populus grandidentata*, and *Tsuga canadensis*. The river valleys were dominated by marsh, wet meadows, floodplain forests, and hardwood conifer swamps (William Martinus & Associates, 2000). Most of the inland dunes in Ottawa County show evidence of wind reworking and human disturbance. Small blowouts in the dunes indicate deflation following intensive logging in the nineteenth century. Heavily disturbed dune areas were planted with *Pinus resinosa* by the Civilian Conservation Corp in the 1930s (William Martinus &

Associates, 2000). These eroded, inland dune sites are easy to identify because soil profiles are absent in blowouts, and downwind areas are buried in eroded soils, which commonly bury preserved soil profiles.

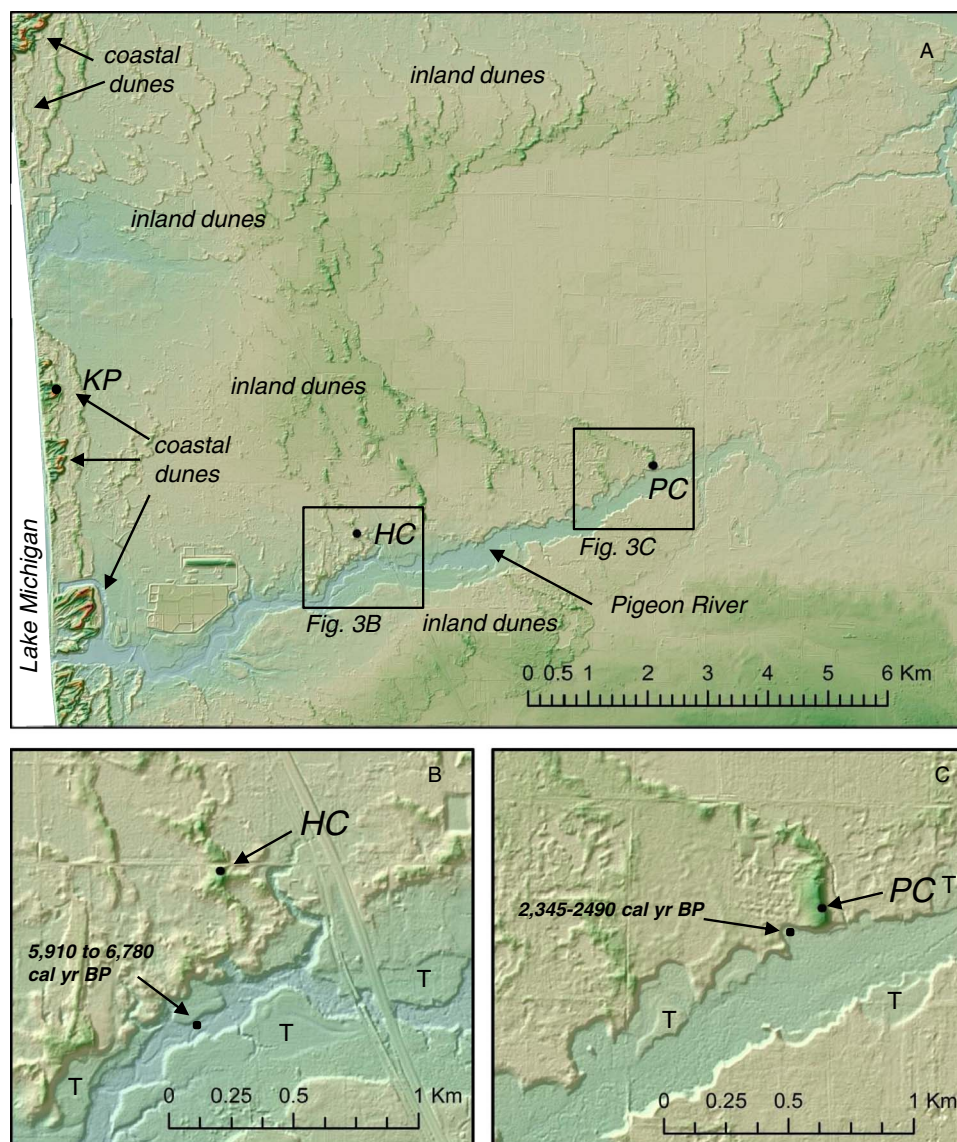
## Glacial and postglacial lakes of the Lake Michigan basin

Glacial Lake Chicago occupied the Lake Michigan basin between ~17,000 and ~13,600 cal yr BP (Table 1, Fig. 2C) based on the existing calibrated radiocarbon chronology (Larson and Schaetzl, 2001; Kincare and Larson, 2009; Curry et al., 2011; Larson, 2011). At its highest levels (Glenwood and Calumet Phases), Glacial Lake Chicago drained southward through an outlet near Chicago into the Mississippi drainage basin (Bretz, 1951). The historical mean level of modern Lake Michigan is ~176.6 m above mean sea level (amsl). Glacial Lake Chicago rose to a maximum level of between 202 and 204 m amsl in the study area (Fig. 2C) based on the highest elevations of the Allendale and Zeeland deltas (Fig. 2C) as mapped by Leverett and Taylor (1915). The Glenwood I level (Table 1) occurred during and after the retreat of the Lake Michigan lobe following the Crown Point Phase after ~17,000 cal yr BP (Curry et al., 2011; Larson, 2011). The Mackinaw Phase (~16,500 to 15,800 cal yr BP) marked a period of low lake level when ice retreated north opening a spillway in the Straits of Mackinaw (Hansel et al., 1985; Hansel and Mickelson, 1988). The Lake Michigan lobe then readvanced during the Port Huron Phase (~15,800 to 15,200 cal yr BP) as far south as Grand Haven, Michigan, and causing Glacial Lake Chicago to rise again to the Glenwood II level (Larson, 2011). The Calumet level of Glacial Lake Chicago (Table 1) occurred during the Two Rivers Phase ~15,200 to ~13,600 cal yr BP (Larson, 2011).



**Figure 2.** (color online) (A) Map of soil textures of parent materials in Ottawa County. Sand textured soils are shown in yellow, and loam textured soils are shown in green (data are from the US Department of Agriculture's SSURGO Database—[https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2\\_053627](https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_053627), accessed March 1, 2016). (B) Landforms of Ottawa County, Michigan. Gray areas are end moraines and till plains of the Lake Border (LBM) and Valparaiso (VM) moraine systems, which were deposited by the Lake Michigan lobe as it advanced out of Lake Michigan basin and flowed to the east and southeast (distal sides of moraines are on the east). Thick dark lines are moraine ridge crests. Thin black lines are inland dune crests, and thin gray lines are coastal dune crests. Allendale delta (AD) and Zeeland delta (ZD) sediments are shown in stippled pattern. (C) The highest shoreline of Glacial Lake Chicago during the Glenwood I and II levels is shown with a dark line based on the descriptions of Leverett and Taylor (1915), and highest elevations of the Allendale (~204 m amsl) and Zeeland (~202 m amsl) deltas. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)





**Figure 3.** (color online) (A) Map showing sampling sites for optically stimulated luminescence (OSL) and radiocarbon analyses. Hemlock Crossing County Park (HC) and Pigeon Creek County Park (PC). (B) Hemlock Crossing OSL site ( $42^{\circ} 55.2624' \text{ N}$ ;  $86^{\circ} 9.1608' \text{ W}$ ; World Geodetic System of 1984 [WGS 84]). (C) Pigeon Creek Park OSL site ( $42^{\circ} 55.9110' \text{ N}$ ;  $86^{\circ} 5.5494' \text{ W}$ ; WGS84 = World Geodetic System of 1984). OSL sample sites are shown with black circles, and radiocarbon samples from vibracores in alluvial are shown with black squares. “T” indicates Lake Nipissing age terraces along the Pigeon River.

After  $\sim 13,600$  cal yr BP, Glacial Lake Chicago ceased to exist as ice retreated north and the lake merged with early Glacial Lake Algonquin to form the larger main Algonquin Phase at a level probably lower than the present lake level in the study area (Larson, 2011).

Following Glacial Lake Algonquin, postglacial Lake Chippewa formed at a much lower level (as low as  $\sim 70\text{--}90$  m amsl) because of opening of drainage paths to the north and east (Larson and Schaetzl, 2001; Kincare, 2007). The lowest level of Lake Chippewa is thought to have occurred at  $\sim 11,000$  cal yr BP (Kincare, 2007). As a result of this large drop in lake level, rivers in western Michigan incised deeply in response to lowered base levels (Kincare, 2007). The Grand, Pigeon, and Macatawa Rivers all have morphologies and valley fills consistent with this hypothesis. Lake level

then rose gradually because of rebound of the outlet of Lake Chippewa to the north and east, finally reaching high stands of Lake Nipissing at  $\sim 5500$  and  $\sim 4500$  cal yr BP (Baedke and Thompson, 2000). Lake Nipissing probably reached its highest elevation in the study area of  $\sim 186$  to  $187$  m masl based on a prominent wave-cut cliff near Holland, Michigan, and well-developed stream terraces along the Grand, Pigeon, and Macatawa Rivers.

### Previous dune research in western Michigan

Coastal dunes have been well studied in and adjacent to Ottawa County, Michigan. Arbogast and Loope (1999) examined coastal dunes at Rosy Mound Natural Area (Fig. 1C)

**Table 1.** Glacial and postglacial lake levels in the Lake Michigan basin.

Lake name	Lake level phase	Maximum elevation (amsl) <sup>a</sup>	Estimated Age (cal yr BP) <sup>b</sup>
Glacial Lake Chicago	Glenwood I	202–204	17,000–16,500
Lake Mackinaw <sup>c</sup>	Mackinaw	<177	16,000–15,800
Glacial Lake Chicago	Glenwood II	202–204	15,800–15,200
Glacial Lake Chicago <sup>d</sup>	Calumet	195	15,200–13,600
Glacial Lake Algonquin <sup>c</sup>	Algonquin	<177	13,600–12,500
Lake Chippewa <sup>c</sup>	Chippewa	70–90	11,000–9000
Lake Nipissing	Nipissing I, II	186–187	5500–4500
Lake Algoma	Algoma	181	~3000
Lake Michigan	Michigan	177	2500–present

<sup>a</sup>Our estimates of lake level elevations for Ottawa County based on sediments and landforms. amsl, above mean sea level.

<sup>b</sup>Age estimates for lake levels are from Kincare and Larson (2009), Larson (2011), and Baedke and Thompson (2000). Age range is possible time of lake level.

<sup>c</sup>There is no evidence for these lakes in Ottawa County as both levels are thought to have been lower than current level of Lake Michigan (Kincare, 2007).

<sup>d</sup>The final phase of Glacial Lake Chicago (Calumet level) occurred after the Two Rivers–Onaway Phase estimated by Larson (2011) as occurring at ~11,700 <sup>14</sup>C yr BP (~13,600 ± 150 cal yr BP).

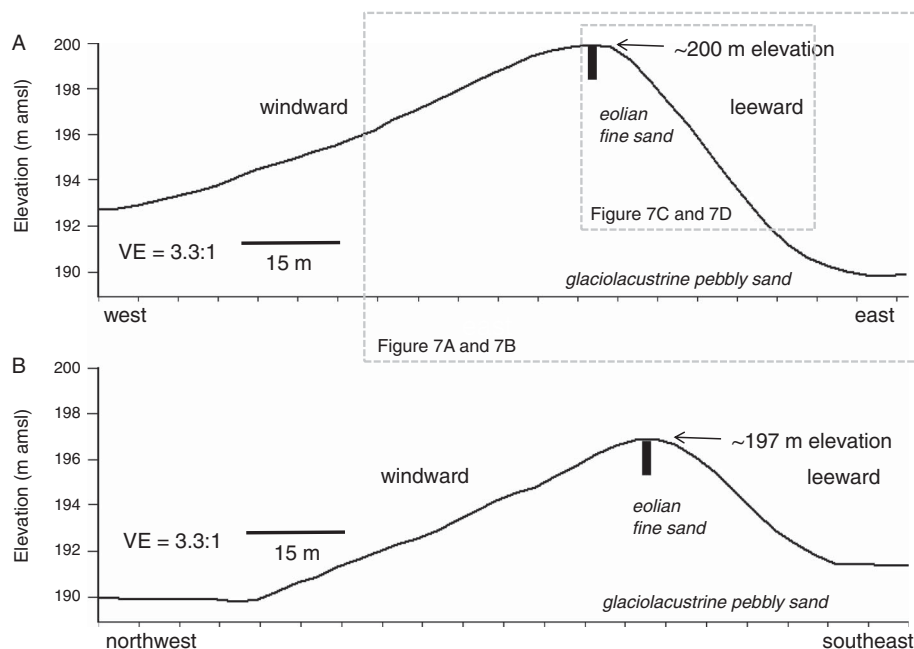
in northwestern Ottawa County as part of a larger study of dunes along the eastern shoreline of Lake Michigan. They provided the first radiocarbon ages of buried soils to demonstrate that coastal dunes are post-Nipissing features younger than ~6000 cal yr BP. Coastal dunes have also been studied just south of Holland, Michigan, in northwestern Allegan County, and at P.J. Hoffmaster State Park (Fig. 1C) in northwestern Ottawa County and southwestern Muskegon County (Loope and Arbogast, 2000; Arbogast et al., 2002a; Hansen et al., 2003, 2006, 2010). The Holland dune complex contains active and inactive parabolic dunes up to 50 m high, and lower-relief inactive back dune ridges. These dunes produced calibrated radiocarbon and OSL ages varying from ~0.3 to 5.9 ka (Hansen et al., 2010). The dune complex at Hoffmaster State Park (Fig. 1C) has a more varied assemblage of dune types with several overlapping generations of large active and inactive parabolic dunes, and several generations of overlapping back dune ridges (Hansen et al., 2010). OSL ages for these dunes produced ages from ~0.3 to ~7.2 ka (Hansen et al., 2010). Interestingly, the oldest OSL age at Hoffmaster State Park ( $7.2 \pm 1.0$  ka) was from a back dune ridge about 1 km inland from Lake Michigan. Another anomalously old OSL age ( $10.5 \pm 1.4$  ka) was reported from a large parabolic dune in Warren Dunes State Park, Indiana (Hansen et al., 2010). Both of these ages suggest that pre-Nipissing age dunes may have been reworked and later buried during the late Holocene. These previous studies confirm that coastal dunes in the study area are Nipissing or younger in age (<6 ka). None of these previous studies discuss or provide ages for the small inland dunes that we focus on in this article.

## MATERIALS AND METHODS

We carefully selected our two inland dune OSL sampling sites (Figs. 3 and 4) based on them having a preserved dune crest

and soil profiles suggesting long-term stability. Finding suitable OSL sampling sites was facilitated by use of a digital elevation model (DEM) derived from LIDAR (light detection and ranging) data collected by Ottawa County, Michigan, in 2004. The DEM has a horizontal resolution of ~3 m and a vertical accuracy of ~0.1 m. The DEM greatly enhanced our ability to pick suitable OSL sampling sites that were not eroded or reworked. Both of the dunes we sampled have preserved dune crests with gentle windward sides and steeper lee sides (Figs. 3 and 4). The sample sites are covered in forest. Most importantly, both dune crests have well-developed O/A/E/B horizons with sesquioxides and translocated humus (Bhs)/C soil horizons with sola depths of ~60 to 70 cm developed on their dune crests (Figs. 5 and 6). Additionally, ground-penetrating radar (GPR) profiles run across the dune crest at the Pigeon Creek OSL sampling site indicate eastward-dipping slip faces in the dune (Fig. 7). The preserved soil profiles, history of forest cover during the Holocene, and eastward-dipping slip faces in a GPR profiles, suggest that our OSL sampling sites have been stable during the Holocene.

Samples for OSL dating were collected in soil pits roughly 1.5 m × 1.5 m and 1.7 m deep (Fig. 5). All of our OSL samples were taken from below 1.2 m depth, below the sola depth and root zone that extends to ~0.6–0.7 m. Aluminum sample tubes were driven into the pit wall and then carefully excavated. Tube ends were packed with Styrofoam to avoid sample movement during transport. One sample (HC-3) was collected below the bottom of the pit using a bucket auger, ~10 cm in diameter, in order to obtain a deeper sample (~2.45 m depth). A sample tube was then driven into the bucket of the auger and then treated as described previously. Samples for moisture content were collected from within ~20 cm of the tube samples. Soil profiles were described for horizon thickness, organic matter, texture, Munsell soil color, and any special characteristics (Buol et al., 1989). Sediment



**Figure 4.** Topographic profiles of dune sample sites at Pigeon Creek Park (A) and Hemlock Crossing Park (B). Profiles run across the dune crest where soil pits for optically stimulated luminescence samples were dug (black bars). Note that the total relief of each dune is less than 10 m. Vertical exaggeration is  $\sim 3.3:1$  in both profiles. The dashed boxes are approximate coverages of the two ground-penetrating radar profiles shown in Figure 7.

grain-size distributions were determined using dry-sieving methods (Lewis and McConchie, 1994). We did not wash samples before sieving because they contained less than 1% fines (Table 2). Grain-size statistics were calculated using GRADISTAT v. 8.0 (Blott and Pye, 2001). When citing ages, we use “ka” for all OSL age dates and “cal yr BP” for ages estimated using the radiocarbon method or the existing radiocarbon chronology.

### OSL laboratory methods

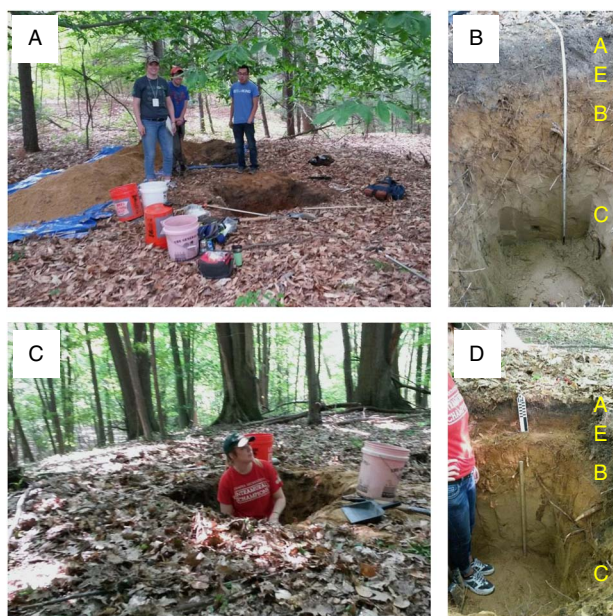
OSL analyses were performed at the Middlebury College Luminescence Laboratory. Full analytical details are available in the Supplementary Materials. All luminescence samples were processed under a 589 nm sodium vapor lamp further filtered with a Lee 101 filter. Following overnight treatments in 10% HCl and bleach, modal size fractions (165 to 250  $\mu\text{m}$ ) of each luminescence sample underwent multiple density separations in solutions of lithium heteropolytungstate to obtain a pure quartz fraction ( $\rho = 2.58$  to 2.66 g/mL). Quartz samples then underwent two 30-minute etches in concentrated HF before a final 30-minute etching in concentrated HCl. All samples were then hand-rubbed and resieved through an 80  $\mu\text{m}$  cloth to break apart low-quality fragments and ensure measurement of intact, high-quality grains.

Signals were measured on small aliquots ( $\sim 20$  to 100 grains per disk) following the standard single aliquot regenerative (SAR) procedure (Murray and Wintle, 2000). Strict rejection criteria were applied, including 10% rejection

thresholds for the recycling, recuperation, and test dose repeatability tests. Postanalysis IR checks were used to verify sample purity. Fast ratios suggest that shine-down curves were dominated by the fast component and a rejection threshold of aliquots with fast ratios less than 12 (Durcan and Duller, 2011). Early background correction was employed to further minimize the potential impact of slow and medium components (Cunningham and Wallinga, 2010). This involved subtraction of the mean signal over the 4- to 5-second interval from the mean signal over the 0- to 0.5-second interval. Equivalent dose ( $D_e$ ) for individual disks was estimated using a quadratic fit to all of the measured SAR steps. Burial dose for samples was estimated using the central age model, which is justified given that overdispersion was always  $<20\%$ , skew was  $<1$ , and kurtosis was between  $-1$  and 1 (Galbraith et al., 1999).

Dose rates were calculated from the inductively coupled plasma mass spectrometry (ICP-MS) bulk geochemistry of representative samples collected within a 20 cm radius of each sample’s location (Guerin et al., 2011). Chemical analyses were performed by ALS Minerals in Reno, Nevada, using a lithium metaborate fusion followed by ICP-MS analysis for both trace and major elements. Dose rates and ages were then computed using the online DRAC (dose rate and age calculator) v. 1.1 (Durcan et al., 2015). Water contents were computed on samples collected from a 20 cm sphere using a mass difference calculation after drying in an oven for 2 days at 60°C (wet weight – dry weight at room temperature).





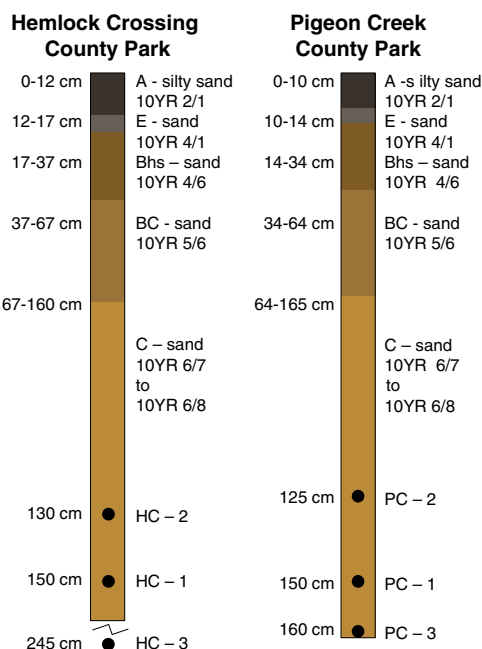
**Figure 5.** (color online) Photographs of the dune sampling sites and soil pits. (A) Hemlock Crossing sampling site looking to the southwest along the crest of the dune. The leeward side of the dune is to the left, and the windward side is to the right. (B) Soil pit at Hemlock Crossing Park site (northwest pit wall). (C) Pigeon Creek sampling site looking to the southeast; the leeward side of the dune is visible in the background sloping to the east. (D) Soil pit and profile at Pigeon Creek Park (north pit wall). The soil master horizons are labeled with A, E, B, and C.

## RESULTS

### Dune distribution, morphology, and sedimentology

Inland dunes in the study area occur as far as ~15 km inland from Lake Michigan (Figs. 1C and 3A). The highest elevation of the lacustrine plain on which inland dunes are developed is ~200 m amsl (~23 m above current level of Lake Michigan), and the lowest elevation is ~185 m amsl (~8 m above lake level). The highest inland dunes have a relief of ~10 m and vary from ~50 to 100 m wide with dune ridges commonly traceable for more than a kilometer (Fig. 3A). Inland dune morphologies are classified as compound and complex parabolic dunes (Cooke et al., 1993). The dune sampled at Hemlock Crossing Park (Fig. 3B) is part of a compound parabolic dune with arms oriented to the northwest (~340°). The dune at Pigeon Creek is part of a raketlike compound parabolic dune that is oriented to winds coming from the west (Fig. 3C). Both of the inland dunes we sampled are part of an extensive sand sheet, and a series of imbricate ridges so must have formed and stabilized at roughly the same time (Fig. 3A).

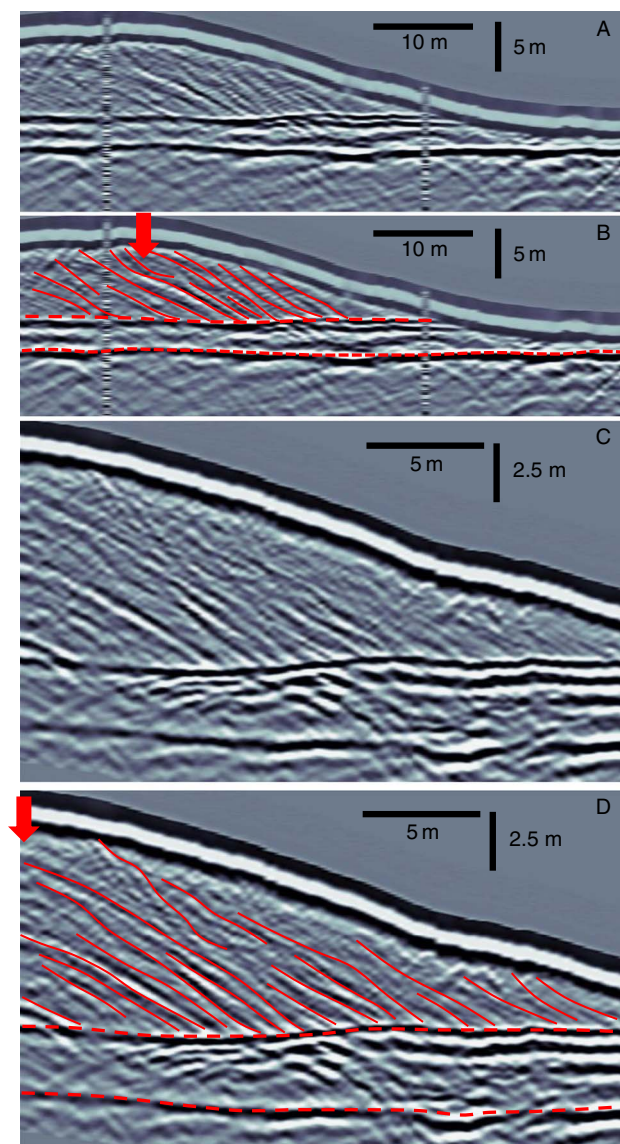
The two inland dunes we sampled for OSL dating are composed of fine sand (Table 2) with a mean  $D_{50}$  of  $209 \pm 19 \mu\text{m}$ , and with fines much less than 1% ( $n = 6$ , 2-sigma). Inland dune sand is significantly finer than coastal dune samples collected just west of our sites (Fig. 1C,



**Figure 6.** (color online) Graphic soil profiles from Hemlock Crossing and Pigeon Creek Parks on dune crest optically stimulated luminescence (OSL) sampling sites. Both soils are weakly developed Spodosols. Black dots indicate depths where OSL samples were taken. Bhs, B horizons with sesquioxides and translocated humus.

site KP) on the crests of two large parabolic dunes at Kirk Park ( $D_{50}$  of  $270 \pm 28 \mu\text{m}$ ,  $n = 6$ ). Sediments of the Allendale delta deposited in Glacial Lake Chicago in the area (Fig. 1C, site AD; Table 2) are composed of moderately to poorly sorted, gravelly medium sands with a mean  $D_{50}$  of  $294 \pm 17 \mu\text{m}$  ( $n = 3$ ). This and other lacustrine units cover large areas of Ottawa, Muskegon, Allegan, and other coastal counties in western Michigan. The sediment has been mapped and interpreted as nearshore lacustrine sand and gravel deposited during the Glenwood and Calumet levels of Glacial Lake Chicago (Leverett and Taylor, 1915; Martin, 1955; Farrand, 1982). The lacustrine sand and gravel varies from a few meters thick to well over 20 m thick based on mapping and water well records in Ottawa and Muskegon Counties. At depth, offshore silt and clay beds are commonly interbedded with or underlie the lacustrine sand and gravel (Colgan and Stark, 2005a, 2005b; Colgan and Tort, 2006; Colgan et al., 2015). Seven near-surface samples of Glacial Lake Chicago nearshore sediment collected in southeastern Muskegon County (Table 2) are moderately to poorly sorted, gravelly medium sand and have a  $D_{50}$  of  $307 \pm 26 \mu\text{m}$  ( $n = 7$ ).

No sedimentary structures or unconformities below the base of the sola were observed in either of the two soil pits dug during OSL sampling. Slip faces have been observed in sand pits in other inland dunes in the study area if the bedding is dried out and etched by winds, but it is very difficult to see these slip faces in fine eolian sand, especially when moist and in a small exposure such as a hand-dug soil pit. A GPR profile run across the dune through our sampling site at Pigeon



**Figure 7.** (color online) Ground-penetrating radar (GPR) reflection profiles of the inland dune at Pigeon Creek County Park. These profiles run west to east, the same as the dune profile in Figure 4A. The profile was obtained using a PulseEKKO 100 system. A common midpoint offset survey estimated wave velocity of 0.132 m/ns for the dune sand at the site. (A) GPR profile across dune crest using a 50 MHz frequency antennae with a transmitter receiver separation of 2 m, step size of 0.5 m, and stacking of 128 times; total length of profile is 60 m, and total depth is ~20 m. (B) Our interpretation of the profile in panel A. Red dashed lines mark the interpreted contact of the dune sediment with underlying Glacial Lake Chicago nearshore sediment (highest dashed line) and the groundwater table (lowest dashed line). (C) GPR profile obtained with a 100 MHz frequency antennae with a transmitter receiver separation of 1 m, step size of 0.25 m, and stacking of 128 times; total length of profile is 25 m, and total depth is ~17 m. (D) Our interpretations of buried slip faces in the dune (red solid lines). Interpretations of sediment and groundwater table are the same as in panel B. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Creek Park shows dipping reflectors that we interpret as slip faces (Fig. 7). Two other prominent reflectors at depth in the profiles are interpreted as the contact between dune sand and gravelly nearshore lacustrine sand, and the underlying water table (Fig. 7).

### Soil profiles developed on inland dunes

Soil horizons are present on the inland dunes of western Ottawa County where they are not eroded by blowouts or heavily modified by humans. Many inland dunes are extensively modified by small blowouts that have completely eroded all soil horizons and left depressions from 1 to 5 m deep and from 10 to 50 m in diameter (Fig. 3B and C). Most of the inland dunes of Hemlock Crossing Park and Pigeon Creek Park are mapped as “blown out land” in the *Soil Survey of Ottawa County, Michigan* (US Department of Agriculture, Soil Conservation Service, 1972), even though preserved soils or buried soils are present in numerous locations. Where soils are preserved or buried by blown sand, soils probably correspond to those of the Rubicon Series. Soil profiles in these areas can be classified as Inceptisols or Spodosols with thin O, A, and E horizons over weak B horizons (Bw) or spodic horizons (Bhs) and sometimes contain ort stones developed in the upper part of the B horizon. Figure 6 shows the soil profiles described in the OSL sampling pits at Hemlock Crossing and Pigeon Creek Parks on dune crests. At both sample sites, the soil profiles on the dune crests were O/A/E/Bhs/BC/C, with total sola thickness of ~60 to 70 cm.

### Radiocarbon ages of Pigeon River valley alluvium

Table 3 lists radiocarbon ages from buried organic beds in alluvium filling the Pigeon River valley. Four calibrated accelerator mass spectrometry (AMS) ages vary in age from 5910 to 6780 cal yr BP (2-sigma range for four ages; Colgan and Stevens, 2016). These samples were collected in a series of vibracores taken across the valley and are from depths ranging from 2.5 to 2.8 m below the current floodplain surface (Fig. 3). An additional AMS radiocarbon age was obtained from alluvium sample in a vibracore recovered near the dune sample site at Pigeon Creek Park (Fig. 3). This wood sample is from a depth of 2.3 m and produced a 2-sigma calibrated age of 2345 to 2490 cal yr BP (Table 3).

### OSL ages of dune sediments

Table 4 lists the OSL ages for the six dune samples taken from two sites. The ages (Fig. 8) are well clustered and range from  $11.6 \pm 0.9$  to  $13.3 \pm 1.1$  ka (2-sigma). The oldest OSL age is from a depth of 2.45 m, from the dune at Hemlock Crossing Park. The youngest OSL age is from Pigeon Creek Park from a depth of 1.50 m. All of the ages are within 2-sigma uncertainty of one another, although the mean age of sample HC-3 ( $13.3 \pm 1.1$  ka) is slightly older than the other five samples (Fig. 6). Although not significant at the 2-sigma



**Table 2.** Texture data for eolian and glaciolacustrine sediments in Ottawa and Muskegon Counties, Michigan.

Sample number	Depth (cm)	Mean ( $\mu\text{m}$ )	$D_{10}$ ( $\mu\text{m}$ )	$D_{90}$ ( $\mu\text{m}$ )	Sort <sup>a</sup>	gr %	vcs %	cs %	ms %	fs %	vfs %	Silt %
Inland dune OSL samples from Hemlock Crossing and Pigeon Creek County, Ottawa County												
HC-1	150	199.6	122.0	326.1	2.672	-	-	1.1	24.6	63.7	10.6	0.1
HC-2	130	220.5	130.1	348.4	2.677	-	-	0.6	36.7	55.1	7.5	0.1
HC-3	245	195.3	127.5	333.3	2.613	-	-	0.6	23.3	67.9	8.1	0.1
PC-1	150	219.2	121.4	337.2	2.567	-	-	0.9	34.3	57.6	7.1	0.1
PC-2	125	206.1	129.7	316.1	2.437	-	-	0.2	25.0	67.4	7.4	0.1
PC-3	160	211.9	127.9	337.4	2.638	-	-	0.9	30.7	59.9	8.5	0.0
Mean	-	208.8	126.4	333.1	2.601	-	-	0.6	29.1	62.0	8.2	0.1
2 $\sigma$	-	18.8	6.9	20.1	0.164	-	-	0.4	10.3	9.6	2.3	0.0
Coastal dune samples from the crests of two large parabolic dunes at Kirk Park, Ottawa County												
KP1-1	50	253.4	186.1	333.1	1.790	-	0.1	0.2	51.7	47.5	0.5	0.1
KP1-2	100	263.9	187.3	335.0	1.789	-	-	-	59.1	40.3	0.6	0.1
KP1-3	150	253.4	184.2	332.6	1.805	-	-	0.1	51.9	47.2	0.8	0.0
KP2-1	50	284.9	203.2	343.5	1.690	-	-	0.6	77.4	21.5	0.5	0.1
KP2-2	100	280.1	199.2	339.9	1.706	-	-	0.1	73.4	26.1	0.4	0.0
KP2-3	150	285.6	202.5	348.3	1.720	-	-	2.1	74.7	22.7	0.4	0.1
Mean	-	270.2	193.8	338.7	1.750	-	-	0.5	64.7	34.2	0.5	0.1
2 $\sigma$	-	27.8	16.1	11.5	0.092	-	-	1.5	21.6	22.2	0.3	0.0
Allendale delta sediments from west of Allendale, Ottawa County												
AD-1	150	284.7	139.1	536.0	3.854	2.0	0.7	9.0	60.8	24.7	1.7	1.1
AD-2	150	305.4	252.2	611.6	2.425	2.8	0.9	15.0	73.2	7.1	0.5	0.6
AD-3	150	291.8	148.0	547.9	3.703	0.8	1.9	9.9	66.9	19.5	0.6	0.6
Mean	-	294.0	179.8	565.2	3.327	1.9	1.9	11.3	67.0	17.1	0.9	0.8
2 $\sigma$	-	17.2	102.7	66.4	1.282	1.6	1.2	5.3	10.1	14.8	1.1	0.5
Glacial Lake Chicago nearshore sediments from southwestern Muskegon County												
M-9	150	302.8	167.8	635.4	3.788	3.4	2.6	12.7	69.1	11.8	0.3	0.1
M-10	150	304.6	170.5	647.9	3.801	3.5	2.9	13.8	68.1	11.0	0.3	0.4
M-13	150	328.4	153.4	4735	30.86	22.7	3.8	13.9	43.5	14.0	1.2	0.9
M-14	150	298.6	250.2	514.8	2.058	0.7	0.4	9.7	79.4	9.2	0.4	0.2
M-18	150	293.5	149.9	564.5	3.765	1.5	1.7	10.4	67.1	18.6	0.5	0.2
M-19	150	324.0	162.2	2532	15.61	13.6	6.0	17.6	49.3	12.5	0.5	0.6
M-20	150	295.4	150.3	613.9	4.085	4.4	1.7	9.4	65.8	17.6	0.7	0.6
Mean	-	306.8	172.0	1463	9.138	7.1	2.7	12.5	63.2	13.5	0.6	0.4
2 $\sigma$	-	25.7	65.6	2988	19.6	15.0	3.3	5.4	23.0	6.4	0.6	0.5

Notes: gr = gravel; vcs = very coarse sand; cs = coarse sand; ms = medium sand; fs = fine sand; vfs = very fine sand.

<sup>a</sup>Sorting coefficient =  $D_{90}/D_{10}$ .

level, this is notable given that sample HC-3 is from a greater depth (2.45 m) than the other samples.

## DISCUSSION

### OSL ages of inland dunes in Ottawa County, Michigan

Our OSL ages from the two inland dunes (Table 4 and Fig. 8) are significantly older than previously published OSL and radiocarbon ages for middle to late Holocene coastal dunes in the study area (see Figs. 1 and 3A for location of coastal dunes in the study area). This indicates that inland dunes in the study area are not associated with the well-documented period of eolian activity in coastal Michigan that occurred following

the fall from Nipissing high stand after ~5500 cal yr BP (e.g., Loope and Arbogast, 2000; Arbogast et al., 2002a; Hansen et al., 2003, 2006, 2010). Alternatively, our OSL ages indicate that inland dunes in the study area formed during the Pleistocene-Holocene transition.

The soil profiles we describe corroborate our new OSL ages (Figs. 5 and 6). The soils developed on inland dune crests are weakly to moderately developed Spodosols similar to soils developed on lacustrine surfaces underlying the younger coastal dunes at Rosy Mound Natural Area (Arbogast and Loope, 1999). This confirms that our two inland dunes are significantly older than coastal dunes, which are mid- to late Holocene age. Additionally, dunes and soil profiles similar to those in the study area have also been described in the Saginaw Lowland in east-central Lower Michigan (Fig. 1B) (Arbogast et al., 1997; Arbogast and

**Table 3.** Radiocarbon ages from the organic material in alluvium of the Pigeon River valley.

Sample number	Laboratory ID	Sample material <sup>a</sup>	Depth (m)	<sup>14</sup> C age ( <sup>14</sup> C yr BP)	<sup>13</sup> C/ <sup>12</sup> C	Calibrated range <sup>b</sup> (2σ cal yr BP)	Mean age (cal yr BP)
HC-8	Beta-353048	Plant fragments	2.7	5680 ± 30	-28.4	6400–6500	6450
HC-9	Beta-353054	Plant fragments	2.8	5890 ± 30	-27.0	6660–6780	6720
HC-10	Beta-353052	Plant fragments	2.7	5220 ± 40	-26.8	5910–6170	6040
HC-11	Beta-353050	Plant fragments	2.5	5750 ± 30	-28.2	6470–6640	6550
PC-1	Beta-424922	Wood	2.3	2390 ± 30	-25.3	2345–2490	2420

<sup>a</sup>All accelerator mass spectrometry samples pretreated with acid/alkali/acid washes.

<sup>b</sup>Radiocarbon calibration uses IntCal09.

Jameson, 1998). Soils developed on these dunes are also Spodosols, or Inceptisols trending toward Spodosols. Dunes in the Saginaw dune field likely formed after the retreat from the Port Huron advance when Glacial Lake Saginaw drained and the lake bed was exposed (Arbogast et al., 1997; Arbogast and Jameson, 1998). This history is very similar to what occurred in the study area.

Radiocarbon ages of Pigeon River valley fill provide additional corroborating evidence and demonstrate the stratigraphic consistency of our OSL ages. The radiocarbon ages are on buried wood and organics from wetland sediment buried ~2.3 to 2.8 m below the current floodplain. The calibrated AMS radiocarbon ages of buried organics in the alluvium in the Pigeon River valley vary from ~2345 to 6780 cal yr BP (Table 3) demonstrating that the valley was incised before 6780 cal yr BP (Colgan and Stevens, 2016). Colgan and Stevens (2016) interpreted the valley fill sequence at Hemlock Crossing Park (Fig. 3) as indicating valley incision during the Chippewa low stand (~11,000 to 9000 cal yr BP), followed by transgression and valley aggradation from ~9000 to ~5500 cal yr BP. The buried alluvial organics formed in wetlands during the Lake Nipissing transgression. Because the inland dunes are cross-cut by the valley, it is clear that the dunes are older as demonstrated by our new OSL ages. Fluvial terraces in the Pigeon River valley vary from ~3 to 10 m above the current level of Lake Michigan and were likely formed during and after the Nipissing transgression. These terraces truncate the inland dunes all along the valley indicating that the dunes are older than the Nipissing high stand (~5500 cal yr BP). If the dunes were younger, we would expect them to cover these

terraces. On the other hand, large coastal dunes have migrated across the valley and partially blocked the mouth of Pigeon Lake, near Lake Michigan.

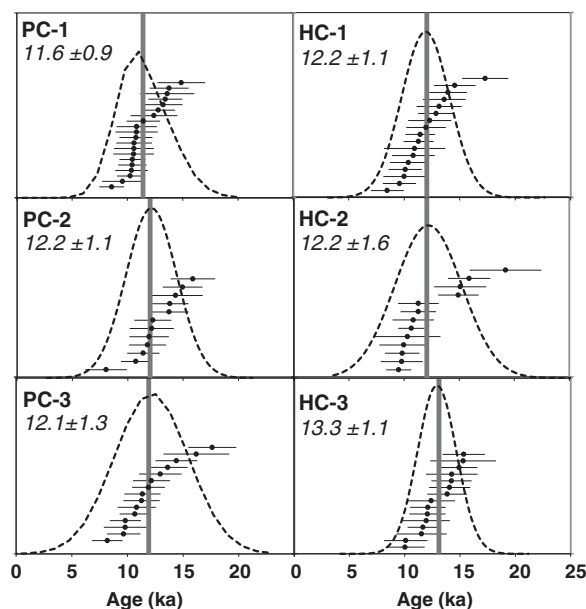
In summary, our OSL ages, soil profiles, radiocarbon ages, and stratigraphic position and geomorphic setting of inland dunes all demonstrate that inland dunes in the study area formed after the estimated time of drainage of Glacial Lake Chicago after ~13.6 ka and before the Nipissing transgression and high stand at ~5500 cal yr BP (Table 1). Based on the range of our OSL ages, dune activity probably began during the late Bølling-Allerød after ~13.6 ka and continued as late as the Preboreal event at ~11.5 ka. The peak of dune activity occurred during the Younger Dryas event.

### Source of inland dune sand

The source of the inland dune sand must have been locally derived and deflated from the exposed bed of Glacial Lake Chicago, which is composed of poorly sorted, gravelly medium sand (Table 2). Inland dunes in the study area are dominated by fine sand, whereas the larger coastal dunes are dominated by medium sand (Table 2). Support for our hypothesis of deflation of exposed lake sediments is found in the availability of abundant fine sand in the sandy nearshore lacustrine sediments of Glacial Lake Chicago (Table 2). These sandy lacustrine sediments could also be a source for some of the recently recognized loess in southeastern Lower Michigan (Schaeztl et al., 2015).

**Table 4.** Optically stimulated luminescence analyses for dune samples from Hemlock Crossing and Pigeon Creek County Parks.

Lab number	Sample number	U (ppm)	Th (ppm)	Rb (ppm)	K <sub>2</sub> O (wt.%)	In situ H <sub>2</sub> O (%)	Depth (m)	Dose rate (Gy/ka)	D <sub>e</sub> (Gy) ± 2σ	Aliquots (n)	Optical age ± 2σ
M046	HC-1	0.44	1.60	31.24	1.12	3.33	1.50	1.43	17.54 ± 1.52	17	12.2 ± 1.1
M047	HC-2	0.43	1.60	28.92	1.02	3.38	1.30	1.34	16.41 ± 2.06	13	12.2 ± 1.6
M048	HC-3	0.43	1.49	30.81	1.11	5.48	2.45	1.36	18.14 ± 1.35	15	13.3 ± 1.1
M049	PC-1	0.45	1.60	27.80	0.98	3.37	1.50	1.30	15.05 ± 1.04	21	11.6 ± 0.9
M050	PC-2	0.54	1.95	29.09	1.04	3.60	1.25	1.40	17.19 ± 1.50	14	12.2 ± 1.1
M051	PC-3	0.61	2.36	28.62	1.03	3.66	1.60	1.43	17.29 ± 1.75	17	12.1 ± 1.3

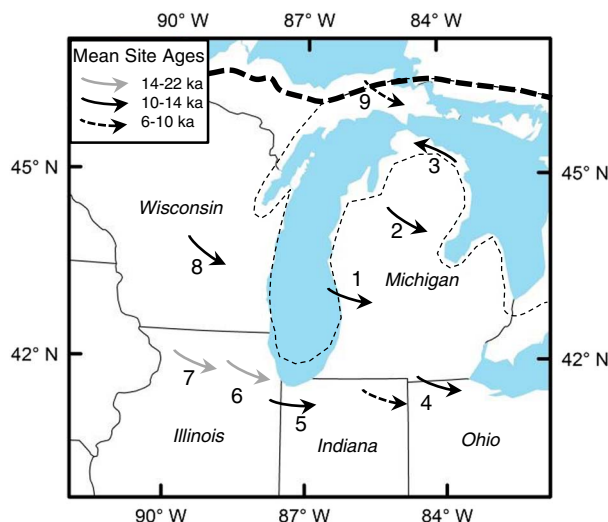


**Figure 8.** Plots showing ages of multiple aliquots for each sample (black dots), 2-sigma uncertainties (thin lines), and the summed probability distribution of all ages accepted for a given sample (dashed black line).

### Inland dune activity in the western Great Lakes region

Our OSL ages add to a growing number of OSL-dated dune studies that show a peak of eolian dune activity in the western Great Lakes centered at near the end of the Younger Dryas event at the Pleistocene-Holocene transition (Fig. 9). A review of OSL-dated inland dunes located around Lake Michigan (Fig. 9) demonstrates that eolian dune activity and stabilization also peaked slightly after the end of the Younger Dryas event in most of these areas (Figs. 10 and 11). These studies and our new data provide a total of 57 OSL age analyses whose mean is centered on the Pleistocene-Holocene transition (Rawling et al., 2008; Campbell et al., 2011; Kilibarda and Blockland, 2011; Arbogast et al., 2015). We assumed (as the original authors did) that all of our probability density distributions represented single events, except for the ages of Campbell et al. (2011), which both the authors and we assume record at least two dune-forming events.

Rawling et al. (2008) provided 24 OSL ages for eolian dune activity in the Central Sand Plain of Wisconsin, which formed after Glacial Lake Wisconsin drained at  $\sim 15,000$  cal yr BP. These OSL ages range from  $19.3 \pm 1.7$  to  $5.8 \pm 0.4$  ka. The peak of the probability density distribution of their ages is  $\sim 11.5$  ka, and the arithmetic mean and 1 standard deviation is  $11.8 \pm 2.7$  ka (Fig. 10). This peak correlates with the end of the Younger Dryas event (Fig. 11). Rawling et al. (2008) proposed three different hypotheses to explain eolian activity and dune stabilization: (1) aridity caused by a climate event, (2) deflation of outwash in the Wisconsin River valley, and (3) melting of permafrost developed on the lake plain, which lowered water tables enabling deflation. They found the most attractive hypotheses to be deflation of outwash or melting of

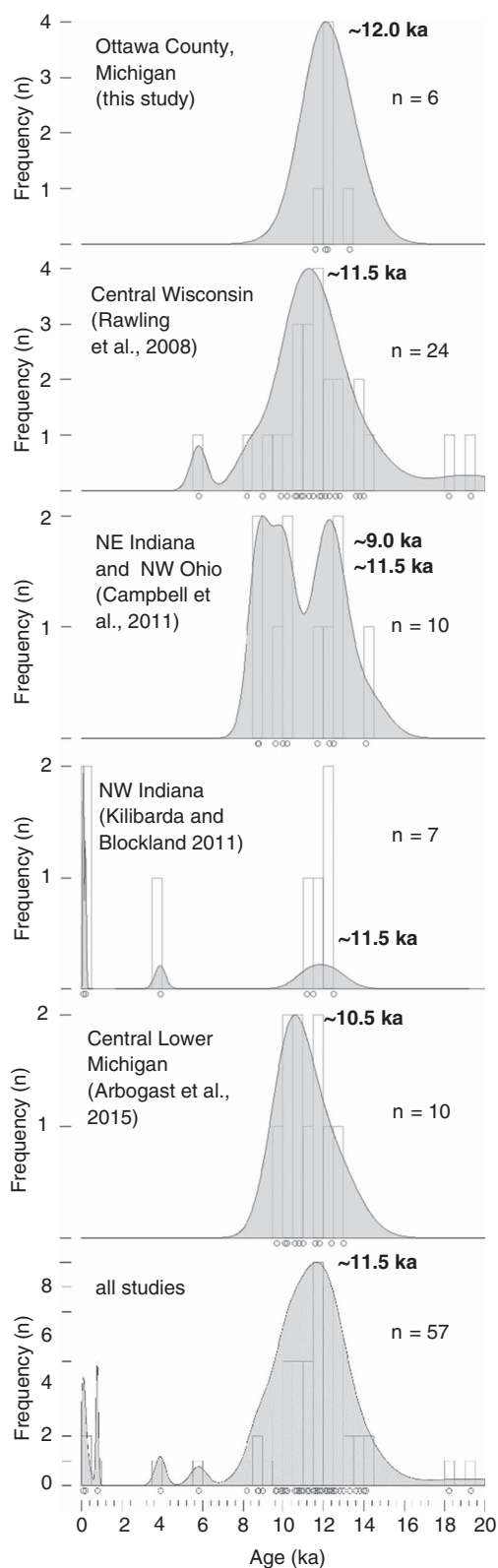


**Figure 9.** (color online) Location of late Pleistocene to early Holocene dune fields in the western Great Lakes region. Arrows indicate the approximate reconstructed wind directions and age ranges in each study. Thick dashed line is the approximate terminus of the retreating Laurentide Ice Sheet at  $\sim 12.9$  ka and during the main phase of Glacial Lake Algonquin, which is shown with the thin dotted line (after fig. 5 of Arbogast et al., 2015). (1) Ottawa County, Michigan, dune field (this study). (2) Roscoe dune field of north-central Lower Michigan (Arbogast et al., 2015). (3) Coastal spits cited by Krist and Schaetzl (2001) as evidence for easterly winds along the front of the retreating Laurentide Ice Sheet. (4) Dune fields of northeastern Indiana and northwestern Ohio (Campbell et al., 2011). (5) Dune fields of northwestern Indiana (Kilibarda and Blockland, 2011). (6) Green River Lowland of northwestern Illinois (Miao et al., 2010). (7) Dunes and elongated ice-walled lake plains used by Allred et al. (2014) to reconstruct paleowind directions at  $\sim 17,000$  cal yr BP. (8) Central Sand Plain of Wisconsin (Rawling et al., 2008). (9) Early Holocene dunes in Upper Michigan (Loope et al., 2010).

permafrost, which then lowered water tables and led to enhanced eolian deflation. This hypothesis is attractive because the peak of the ages occurs at the end of the Younger Dryas event, a time when the climate was changing from cool and dry to a warmer and wetter climate of the early Holocene. Dune activity during the Younger Dryas was then followed by dune stabilization once Holocene climate conditions were established after  $\sim 11.7$  ka and surfaces became stabilized by vegetation cover.

Campbell et al. (2011) examined inland dunes in northeastern Indiana and northwestern Ohio (Fig. 9) and provided 10 OSL ages that range between  $14.1 \pm 1.0$  and  $8.8 \pm 0.5$  ka (excluding a single young age of  $0.79 \pm 0.1$  ka). These 10 OSL ages have two peaks in the probability density distribution, one at  $\sim 12.5$  ka and another at  $\sim 9.0$  ka (Fig. 10). They suggested that eolian activity on susceptible deflation surfaces was enhanced during the cooler and drier Younger Dryas event and the subsequent Preboreal oscillation and can be used to compliment pollen records of climate, which also suggest cooler and drier conditions at this time (Campbell et al., 2011).





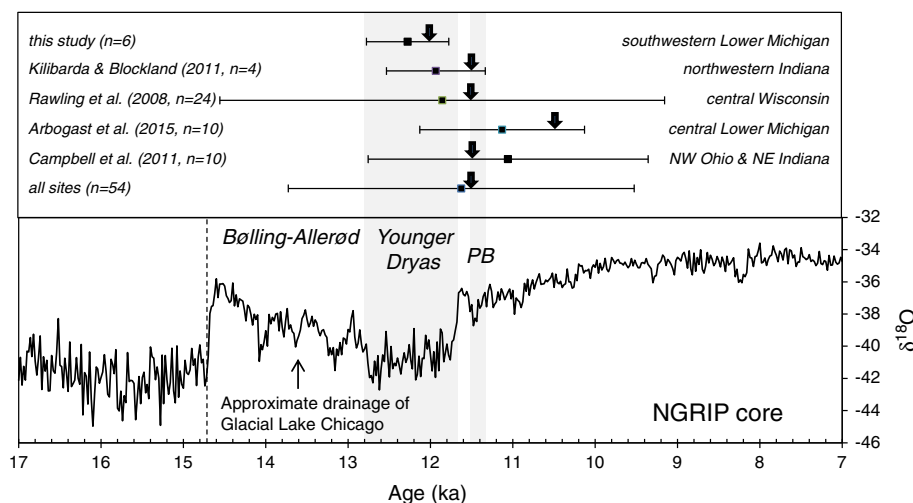
**Figure 10.** Probability density and histogram plots for dune fields formed between ~14 and 10 ka (see Fig. 9 for site locations). The circles under the plots are individual sample means. The y-axis is number of samples in histograms, and the x-axis is ka before present. Ages correspond to approximate peaks in probability density function plots. The plots were constructed using DensityPlotter v. 7.1 (Vermeesch, 2012).

Inland dunes of the Fair Oaks dune field in northeastern Indiana (Fig. 9) yielded four OSL ages ranging from 12.5 to 11.2 ka (Kilibarda and Blockland, 2011). These dunes also yielded three much younger OSL ages less than 4 ka that they interpreted as reflecting late Holocene reworking. Excluding the three younger ages, the probability density distribution shows a peak at ~11.5 ka and mean and standard deviation of  $11.9 \pm 0.6$  ka (Figs. 10 and 11). Kilibarda and Blockland (2011) argue that their observations and OSL ages indicate dune building began during the Bølling-Allerød event when easterly and northeasterly winds, attributable to anticyclonic circulation over the retreating ice sheet, formed transverse and barchan dune ridges. This dune-building event was then followed by reworking of the dunes during the Younger Dryas event by westerly winds that formed a great variety of parabolic dunes.

Most recently, Arbogast et al. (2015) provide 10 OSL ages for eolian dune activity in the Rosco dune field of central Lower Michigan (Figs. 1B and 9). These OSL ages range from  $13.0 \pm 1.2$  to  $9.7 \pm 0.8$  ka. The peak of the probability density distribution is ~10.5 ka, with a mean and standard deviation of  $11.1 \pm 1.0$  ka (Fig. 10). This peak occurs slightly after the Preboreal oscillation (Fig. 11). The probability density distribution of all 57 OSL ages including our 6 new ages shows a peak occurring at ~11.5 ka slightly after the end of the Younger Dryas event during the Preboreal oscillation (Figs. 10 and 11).

### Climate reconstruction based on pollen and permafrost evidence

Reconstructions of paleoenvironments and climate of Lower Michigan during the Bølling-Allerød and Younger Dryas events, based on plant macrofossils and pollen from inland lake sediment cores, indicate cool and dry conditions (Hupy and Yansa, 2009). Black spruce (*Picea mariana*) and sedges were common in low areas because of wet soils attributable to melting buried glacier ice and permafrost, whereas open white spruce (*Picea glauca*) parklands favored the drier uplands (Hupy and Yansa, 2009). Tundra plants and widespread fossil ice-wedge casts and ice-wedge polygons suggest that tundra vegetation and permafrost were present in eastern Wisconsin up to at least 13,000 cal yr BP (Maher and Mickelson, 1996; Maher et al., 1998; Clayton et al., 2001). Relict ice-wedge polygons found on the abandoned surface of Glacial Lake Saginaw in Lower Michigan also indicate that permafrost formed after lake drainage sometime during the Bølling-Allerød warming event and the subsequent Younger Dryas cooling (Lusch et al., 2009). Cool climate, terrestrial gastropods followed by boreal forest indicate ice-free conditions at the Two Creeks site in eastern Wisconsin and the Cheboygan bryophyte site in northern Lower Michigan during the Bølling-Allerød event (Larson, 2011; Rech et al., 2012). All of these observations suggest that Younger Dryas cooling and drying in an area already affected by permafrost provided a suitable environment for eolian deflation of the



**Figure 11.** Comparison of dune field mean ages (black squares) to the oxygen isotope record of the North Greenland Ice Sheet Project (NGRIP) ice core. Drainage of Glacial Lake Chicago occurred at  $\sim 13.6$  ka based on the existing radiocarbon chronology (Larson, 2011). Large arrows show peaks of probability density plots determined from Figure 10. Peaks in dune optically stimulated luminescence ages occur during or shortly after the Younger Dryas event and the Preboreal event (PB). Three outlier samples ( $<4$  ka) shown in Figure 9 were not included in the mean for data from Kilibarda and Blockland (2011). One late Holocene outlier ( $\sim 0.79$  ka) was not included in the mean and standard deviation for data of Campbell et al. (2011).

recently exposed nearshore sediments of Glacial Lake Chicago in the drier uplands of the study area.

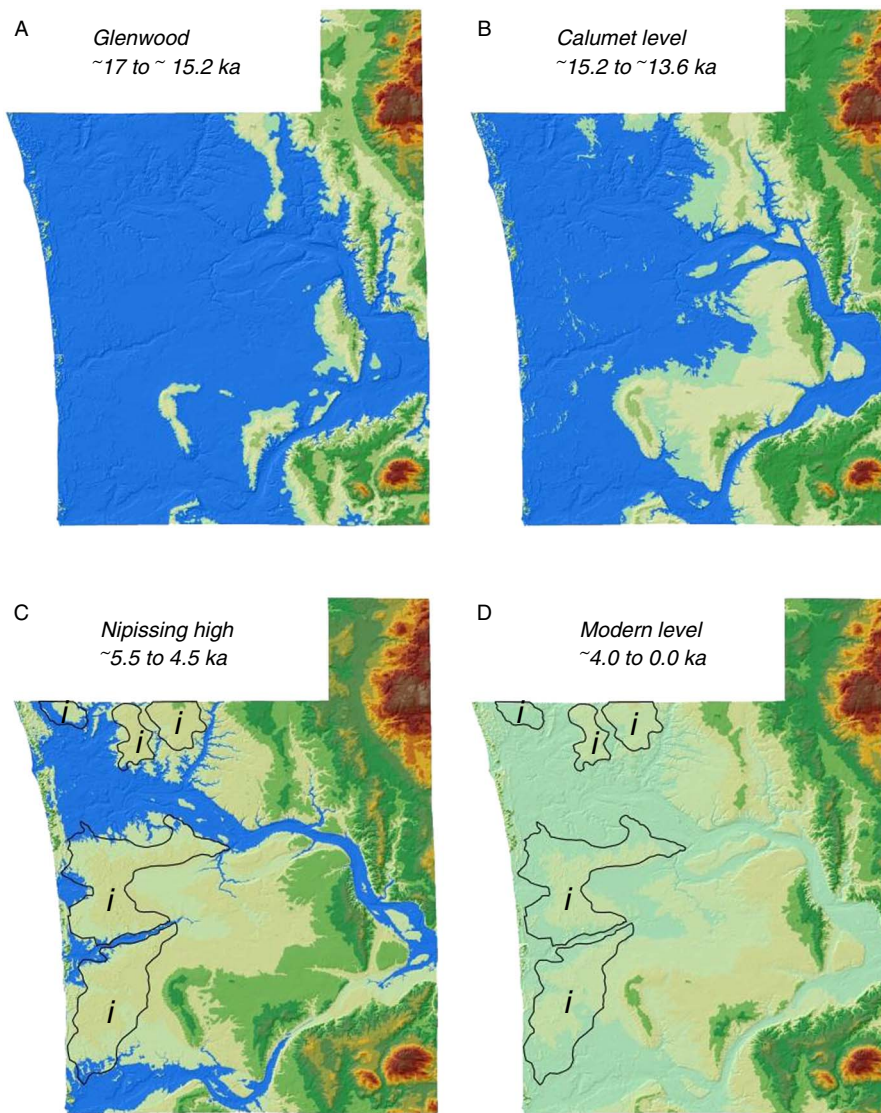
### Implications for paleolake level history in western Michigan

Figure 12 illustrates our reconstructions of paleolake levels in the study area (Table 1). Glacial Lake Chicago reached elevations of between  $\sim 202$  and  $\sim 204$  m amsl, sometime between  $\sim 17,000$  and  $\sim 15,200$  cal yr BP (Table 1 and Fig. 12A). It is notable that the areas covered by inland dunes in the study area were still covered by Glacial Lake Chicago until after the end of the Calumet Phase at  $\sim 13,600$  cal yr BP (Fig. 12), and therefore, dunes could not have been formed before then. Our OSL ages are compatible with this conclusion because our oldest age is  $13.3 \pm 1.1$  ka and must have formed after drainage of Glacial Lake Chicago, inland of the shorelines of Glacial Lake Algonquin and postglacial Lake Chippewa (Table 1, Fig. 12C). The abandoned bed of Glacial Lake Chicago in the study area was exposed during the Glacial Lake Algonquin and Lake Chippewa levels and up until the present time. Inland dunes formed and stabilized during the Younger Dryas event and perhaps as late as the Preboreal event. During the early Holocene, dunes were stabilized by vegetation and crosscut by erosion of the Pigeon River and other rivers in the study area. The mid-Holocene Nipissing high stand was reached sometime after about 5500 cal yr BP (Baedke and Thompson, 2000). This supports our interpretation that the inland dunes are older than the Nipissing high because terraces in the Pigeon River valley both truncate dunes and do not have dunes on terrace surfaces (Fig. 12C). Most of the large, relatively young coastal dunes lie on the surface flooded by Lake Nipissing and have constricted the Pigeon River by encroachment of dune sand at the river mouth.

### Paleowinds in the western Great Lakes region

Studies in the western Great Lakes region have provided new information on paleowinds reconstructed from OSL-dated inland dunes during the Pleistocene-Holocene transition (Fig. 9). Easterly winds are inferred from spits that developed in glacial Lake Algonquin between  $\sim 13.6$  and 11 ka (Krist and Schaetzl, 2001; Vader et al., 2012) and from dunes in northwestern Indiana (Kilibarda and Blockland, 2011). These studies hypothesize that easterly winds were the result of anticyclonic circulation above the retreating Laurentide Ice Sheet as predicted in atmospheric models of late Pleistocene circulation (Kutzbach and Guetter, 1986; Broccoli and Manabe, 1987; COHMAP Members, 1988).

All of the recently OSL-dated inland dune fields cited in the previous section indicate northwesterly and westerly winds during the late part of the Bølling-Allerød, Younger Dryas event, and the Preboreal oscillation (Fig. 9). Undated inland dunes in the Saginaw dune field of Lower Michigan (Fig. 9) also indicate winds from the northwest and west after about  $\sim 15,000$  cal yr BP (Arbogast et al., 1997; Arbogast and Jameson, 1998). The northwesterly and westerly directions confirm previous interpretations that the anticyclonic circulation must have been limited in its effects after the late part of the Bølling-Allerød event and during the Younger Dryas event (Arbogast et al., 2015; Kilibarda and Blockland, 2011). This was also the interpretation of Rawling et al. (2008) for the inland dunes that formed in the Central Sand Plain of Wisconsin as no evidence was found there for easterly winds even though some of these dunes were older than the Bølling-Allerød. Arbogast et al. (2015) proposed that there must have been a very steep energy gradient to the winds because easterly wind directions were apparently occurring less than



**Figure 12.** (color online) Time-series reconstructions of lake levels during the late Pleistocene and Holocene mapped using a digital elevation model and estimates of lake levels from landforms and sediments in the county. (A) Glenwood I and II levels of Glacial Lake Chicago (~203 m amsl). (B) Calumet level of Glacial Lake Chicago (~195 m amsl). (C) Postglacial Lake Nipissing at its maximum level in Ottawa County (~186 m amsl) and the location of inland parabolic dune fields outlined in fine black lines (i). (D) Modern lake level of Lake Michigan with areas of inland parabolic dune fields outlined with black lines (i). The lake bed of Glacial lake Chicago would have been exposed after the fall from the Calumet level after ~13.6 ka (panel B).

150 km from northwesterly winds (Fig. 5 of Arbogast et al., 2015). Our observations provide no evidence for easterly anticyclonic winds nor evidence against a steep energy gradient hypothesis. In summary, inland dunes in this study, and three of four sites with OSL ages reviewed previously, provide no support for anticyclonic easterly and northeasterly winds during the latest part of the Bølling-Allerød event and the subsequent Younger Dryas event.

## CONCLUSIONS

1. Inland dunes are common on the abandoned bed of Glacial Lake Chicago in Ottawa County and surrounding coastal counties in western Lower Michigan. Inland dunes have parabolic forms and are modified by blowouts and human disturbance.
2. Six new OSL ages indicate that inland dunes formed and stabilized between  $13.3 \pm 1.1$  and  $11.6 \pm 0.9$  ka (2-sigma uncertainty). Soils developed on the inland dunes, radiocarbon ages on buried organics in the Pigeon River valley, and stratigraphic and landform relationships all corroborate our OSL ages.
3. The inland dunes in the study area formed and stabilized after drainage of Glacial Lake Chicago at ~13,600 cal yr BP during the late Bølling-Allerød, Younger Dryas, and Preboreal events.
4. The source of inland dune sand was the gravelly, medium to fine nearshore sand on the abandoned bed of Glacial Lake Chicago. Sand was deflated by northwesterly and



westerly winds, before vegetation was able to completely stabilize sandy nearshore lake sediments.

5. Four other OSL-dated dune fields in the western Great Lakes region also show that eolian activity driven by northwesterly and westerly winds was a widespread phenomenon during the Pleistocene-Holocene transition. This supports a hypothesis that changing climatic conditions at the Pleistocene-Holocene transition and the availability of recently deglaciated surfaces provided an ideal environment for eolian activity.
6. Evidence of northwesterly and westerly winds at all of these sites supports previous interpretations of the limited effect of an anticyclone developed over the retreating Laurentide Ice Sheet.

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## Supplementary material

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