Canadian Journal of Earth Sciences

Aeolian activity during Late Glacial time, with an example from Mongo, Indiana, USA

Journal:	<i>Canadian Journal of Earth Sciences</i>
Manuscript ID	cjes-2018-0127.R2
Manuscript Type:	Article
Date Submitted by the Author:	26-Oct-2018
Complete List of Authors:	Fisher, Timothy G.; University of Toledo, Dept. of Environmental Sciences Horton, Jennifer; University of Toledo, Dept. of Environmental Sciences; Minnesota Geological Survey Lepper, Kenneth; North Dakota State University Loope, Henry; Indiana University, Indiana Geological and Water Survey
Keyword:	Aeolian; Mongo Dune field; Younger Dryas; Older Dryas; OSL
Is the invited manuscript for consideration in a Special Issue? :	Not applicable (regular submission)

SCHOLARONE™
Manuscripts

1
2 Aeolian activity during Late Glacial time, with an example from Mongo, Indiana, USA
3
4

5 Timothy G. Fisher
6 Department of Environmental Sciences
7 University of Toledo
8

9 Jennifer Horton
10 Department of Environmental Sciences
11 University of Toledo
12 Current Address: Minnesota Geological Survey, University of Minnesota
13

14 Kenneth Lepper
15 Department of Geosciences
16 North Dakota State University
17

18 Henry Loope
19 Indiana Geological and Water Survey
20 Indiana University
21
22

Abstract:

The last aeolian activity of a significant number of inland sand dunes in the southern Great Lakes region (SGLR) was several thousands of years after deglaciation. At Mongo, Indiana, a field of parabolic sand dunes with a variety of morphologies are within the channel bottom of the Pigeon River meltwater channel, with some dunes having climbed up the channel wall onto the adjacent upland surface. The OSL samples from the channel-bottom dunes have a mean age of 14.2 ± 1.6 ka ($n = 2$) and the OSL samples from upland dunes have a mean age of 12.3 ± 1.6 ka ($n = 4$). Dunes and outwash ages and geomorphic setting constrain both the position of the Huron-Erie and Saginaw lobes. The oldest dune age is also a minimum age for cessation of local meltwater flow from the Huron-Erie Lobe of the Laurentide Ice Sheet and formation of the adjacent Sturgis Moraine of the Saginaw Lobe. The final activity of the dunes is coincident with late glacial stadial and interstadial events as recorded in the Greenland ice core records, a similar finding to all other studies of dunes in the SGLR. It is now well recognized that many dunes were last active before, during and after the Younger Dryas stadial, presumably in response to a climate that was windier and less favorable for vegetation.

Keywords

Aeolian; Mongo Dune field; Younger Dryas; Older Dryas; OSL

43 Introduction

44 Recent work dating at least 60 inland sand dunes with the optically stimulated
45 luminescence (OSL) method in the southern Great Lakes region (SGLR) has determined that a
46 majority of now stabilized dunes were last active during Late Glacial time (Rawling et al. 2008;
47 Kilibarda and Blockland 2011; Campbell et al. 2011; Arbogast et al. 2015; Fisher et al. 2015;
48 Colgan et al. 2017; Arbogast et al. 2017; Fig. 1B). OSL dating of aeolian sand dunes record
49 periods of past climate change, with dunes serving as proxies for presumably drier, windier,
50 and/or cooler conditions and potentially enhanced seasonality—conditions less favorable for
51 stabilizing vegetation. The oldest dated dune can also serve as minimum-limiting ages for
52 deglaciation, especially in the absence of other chronologies. Studies of inland dunes in the
53 SGLR have revealed that the majority of dunes were last active during the Younger Dryas (YD)
54 chronozone (12.9–11.7 ka). Older dunes were last active in Wisconsin and northwest Ohio
55 (Rawling et al. 2008; Campbell et al. 2011; Fisher et al. 2015) and younger dunes were last
56 active into Preboreal time (ca. <11.7 ka) (Campbell et al. 2011; Arbogast et al. 2015). High
57 concentrations of dust in the Greenland ice cores (Rasmussen et al. 2014; Seierstad et al. 2014)
58 correspond in time with the YD and episodically before the YD during the Allerød and Older
59 Dryas, but not during Preboreal time. Thus, as a general statement, it appears that cooler and
60 dustier conditions recorded in the Greenland ice cores as stadial events (the North Atlantic Event
61 Stratigraphy [Björck et al. 1998]) are chronologically similar to sand dune ages in the SGLR.
62 Many other dunes yield ages younger than the YD, and were last active ~11.5–8 ka during the
63 early Holocene. A possible correlation of last activity of early Holocene dunes with the
64 Greenland stadials was suggested by Campbell et al. (2011), but the number of available ages
65 and the error resolution of luminescence dating inhibits firm correlation. Curiously, from central

Wisconsin (Rawling et al. 2008) and northwest Ohio (Fisher et al. 2015), optical ages of approximately 14 ka suggest an earlier period of aeolian dune activity (Fig. 1B) during the Bølling and Allerød interstadials (BA) and Older Dryas stadial, a ~150-year long event at ~14 ka (Björck 2010).

The dunes described in this paper, and studied at the other sites referenced above, record the presence of anchoring vegetation, westerly winds, and a source of sand. Parabolic dunes can originate from blow-outs of older dunes (Pye 1993). Paleosols beneath YD dunes have not been described from the SGLR. However, reactivation during the YD is known from a buried paleosol within a YD-aged dune (Fisher et al. 2015), from geomorphic evidence of overridden dunes (Fisher et al. 2015), and spatial relationships between loess and dunes (Kilibarda and Blockland 2011). Not all dunes may document climate change (related to reduction in vegetation cover), others may be controlled by sediment supply linked to fluvial incision. For example, perched dunes from the northern Lower Peninsula of Michigan (#4 in Fig. 1B) are interpreted as most likely resulting from local fluvial incision activity rather than a changing climate (Arbogast et al. 2017). The original source of sand for many inland parabolic dune fields is outwash and sandy glaciolacustrine deposits. Thus, OSL dates from sand dunes sourced from outwash or glaciolacustrine sediments can be used as minimum-limiting ages for cessation of meltwater flow or glacial lake drainage that can be tied to ice margin position(s). Here we examine dunes within a large deglacial meltwater channel near the town of Mongo, in northeast Indiana (Figs. 1, 2) with outwash as the source of sand for the dunes. The purpose of this study is to evaluate the first optical ages on dunes from northeast Indiana within the context of other inland dunes in the SGLR, and to evaluate the oldest OSL dune age as a minimum limiting age for local deglaciation.

89

90 **Methods**

91 Descriptive terminology of the dunes is after Pye (1993). The samples for OSL dating are
92 from hand-dug pits where well-developed A and B soil horizons were present. Samples are from
93 the C-horizon, below at least 1.3-m depth to avoid the effects of pedogenesis (e.g. Rawling and
94 Hanson 2014; Argyilan et al. 2014; Hanson et al. 2015). Dune crests were targeted to determine
95 the period of last activity. OSL dating was conducted at the Optical Dating and Dosimetry Lab at
96 North Dakota State University. OSL measurements were made on clean, etched quartz in the fine
97 sand fraction (150–250 μm) using single-aliquot regenerative (SAR) procedures (Murray and
98 Wintle 2000; Wintle and Murray 2006) and a Risø DA-15 integrated TL/OSL reader system.
99 Additional information on sample processing, OSL measurement equipment, and procedures can
100 be found in the supplement to Lepper et al. (2007). Water content was assessed from field
101 samples, but because the sample on that one particular day was not considered representative of
102 the past ~14,000 years, values used were modeled from sediment texture, soil structure, and
103 landscape position, as in other studies (cf. Lepper et al. 2011). Dose rates were calculated
104 following the methods presented in Aitken (1985, 1998) and Prescott and Hutton (1988, 1994).
105 All equivalent dose (D_e) distributions in this study were symmetric ($M/m < 1.05$), therefore, ages
106 were calculated based on the mean of the D_e data set. Age errors ($\pm$) are propagated uncertainty
107 (Aitken 1985, 1998). The mean and averaged standard error of each dune grouping was also
108 calculated.

109

110 **Study area, geomorphology and sampling sites**

The Mongo sand dunes are associated with the Pigeon River meltwater channel (Figs. 1A, 2). Most of the dunes are in the channel bottom with a smaller number having climbed out of the valley onto the adjacent upland surface (warm colors, Fig. 1A). The meltwater originated from the eastward receding Huron-Erie glacial lobe after the Saginaw Lobe (Fig. 2) (Brown et al. 1998) retreated approximately 16–18 kyr cal BP (Horton 2015). The dunes and outwash are mapped as part of the Atherton Formation in Indiana, consisting of sand and some silt (Wayne 1963; Johnson and Keller 1972). However, detailed investigation into the dunes has not occurred. Site locations are in Table 1.

The Mongo dunes are composed of well-sorted, fine-to-medium-grained aeolian sand with arms of the parabolic dunes open to the west recording a westerly wind during formation (Figs. 1A, 3). Local relief of the dunes is up to ~7 m. The dunes on the west side of Highway 3 (Fig. 1A), south and west of the town of Mongo, consist of numerous large elongated parabolic dunes, some with smaller nested forms. Isolated, small lunate and lobate parabolic dunes are scattered across the outwash surface with some merged forms having a rake-like morphology (David 1981; Pye 1993). Kilometer-long wind-rift dunes are common along the south side of the dune field. Some wind-rift dunes and arms of parabolic dunes appear to have been remobilized where the linear ridge is segmented by small superimposed parabolic forms or blow-outs (Fig. 3C).

The crest of a broad, parabolic dune that migrated about 20 m upslope out of the channel is sample site 1 (Fig. 3A). Sites 2 and 3 are ~15 m above the channel on two parallel wind-rift dunes. Care was taken to avoid the numerous small borrow pits evident on the LiDAR DEM (Fig. 3B). The thin-A/C horizons at site 2 above a paleo A/B profile suggest recent aeolian activity at the site (Figs. 3E). Sites 4 and 5 are from the channel bottom. Both the B- and C-

horizons were mottled suggesting a fluctuating water table and slightly higher water contents were applied for these sites (Table 2). Site 5 is a high point along a wind-rift dune that appears to have been remobilized into small parabolic segments (Fig. 3C). Site 4 is 1 km east of site 5, and may be a continuation of the same wind-rift ridge, now separated from the western section by cutbank erosion along the Pigeon River (Figs. 3A, C). Site 7 is in an upland position where dunes migrated to the east and climbed 23 m up the channel wall onto the upland (Fig. 3D). The site is along an arm of a parabolic dune that is part of a larger nested compound dune. Clay lamellae were observed within the soil profile, and higher water content was applied for this site (Fig. 3E, Table 2).

Results

The OSL dosimetric and age results for the six sample sites are shown in Tables 2 and 3 and plotted on Figure 4G. The OSL age results offer a minimum-limiting deglacial age of 14.2 ± 1.6 ka for the Sturgis Moraine (Fig. 2), the closest moraine of the Saginaw Lobe to the north, because the Pigeon River meltwater channel crosscuts outwash fans heading at the Sturgis Moraine. The oldest dune age also serves as minimum age for cessation of outwash deposition within the Pigeon River meltwater channel sourced from the Huron-Erie Lobe.

Discussion

The OSL dated sand dunes near Mongo, Indiana, are useful as climate proxies locally, and can be added to a growing collection of ages for dunes recording the last period of aeolian activity within the SGLR. The oldest OSL age at Mongo, IN of 14.2 ± 1.6 ka is a minimum age for the

Sturgis Moraine to the north (Fig. 2), and cessation of meltwater activity within the channel. Older, minimum-limiting radiocarbon ages are from 1) basal sediment of Meteor Lake, a kettle lake 12 km west of the study area (Fig. 2) dated at 16.1–16.3 cal ka BP (Dziekan 2017); and 2) basal sediment of Fennel and Wall lakes, both only a few kilometers north of the Mongo dunes (Fig. 2) dated at 16.3–16.8 cal ka BP (Horton 2015). Based on these age estimates, a minimum of 2000 years of time is available for dune activity before 14.2 ± 1.6 ka.

The landscape position of the dunes suggests that there may be two populations of dunes present. One set is within the meltwater channel bottom, and another set that has migrated from the channel bottom to the upland edge, assuming the outwash was the sediment source for the dunes. Preservation of older dunes in the channel bottom could be explained by greater water-table sensitivity of upland edges compared with the channel bottoms. For example, a drought during the YD would result in lowered water tables along upland edges and higher outwash surfaces. New or remobilized dunes in upland positions record last activity at 12.3 ± 1.3 ka. At the same time, water tables in the channel bottom would not have dropped as much, and the channel-bottom dunes would have been less likely to remobilize. The channel bottom dunes show blow-outs along the wind-rift dunes (Fig. 3C), and OSL samples 4 and 5 record last activity at 14.2 ± 1.6 ka, opening up the possibility for earlier aeolian activity responsible for the wind-rift dunes. When the Mongo dune ages are combined with all OSL ages from elsewhere in the SGLR (Figs. 4A–G) and plotted as a probability density function plot (Fig. 4H), a central peak reflects considerable dune activity associated in time with the YD, a broad shoulder extends into the Preboreal, and a smaller shoulder overlaps in time with the BA and OD.

The aeolian ages from this study, when pooled with data across the SGLR result in 65% of the ages overlapping the Younger Dryas stadial (Fig. 4). The Younger Dryas stadial (Alley

2000) has been described as cooler and windier in North America (Thorson and Schile 1995; Leavitt et al. 2006; Gonzalez et al. 2009). The SGLR aeolian dune record is in good agreement with pollen, Zr/AL ratios (proxy for aeolian activity) and charcoal climate proxies from regional area lacustrine sediment records during YD time (Shane 1987; Lutz et al. 2007; Gonzales et al. 2009; Gill et al. 2012). Three separate ice cores in Greenland (Fig. 4J) record a rapid decrease in dust levels in the Northern Hemisphere at the beginning of the Bølling, an increase during the OD, variability during the Allerød and a return to high amounts during the YD. To the extent possible, the OSL ages from the SGLR are aligned with the dust record until the end of the YD. These data support an interpretation that inland sand dunes, like pollen records from lakes, record climate change that is coeval with changes in the North Atlantic Event Stratigraphy (Björck et al. 1998).

The duration of the OD is similar to stadials after the YD (grey vertical bars in Fig. 4), but it is difficult to correlate short-lived stadials with dune activity reconstructed from OSL dating alone. A causal relationship between YD and dune activity in the SGLR is accepted because the duration of the YD stadial is similar to the measurement error of OSL. While many of the OD age ($n = 7$) or Preboreal, early Holocene-aged dunes ($n = 27$) may similarly be linked to short-lived stadials, acceptance of such a hypothesis is hampered because the ~100–200 year-long stadials are well within the measurement error of OSL. Supporting data for aeolian activity in the SGLR during short-lived stadials includes increased dust activity within the Greenland ice cores (Fig. 4J), decline in spruce and increase in ash in Ohio at 14 ka (Gill et al. 2012), and loess deposited in a northeast Ohio lake recording the 8.2 event (Lutz et al. 2007). Gonzales et al. (2009) noted a 300–400 year lag between vegetation change in northeast Illinois and isotopic shifts in the Greenland ice core record. It is unknown if a similar lag also existed during the OD.

Beyond developing dune chronologies, knowing the environmental conditions that led to dune initiation or reactivation continues to be an important challenge for understanding sand dune history in the SGLR. Dune work along Great Lake coastlines has suggested a relationship between lake level (usually rising) and renewed coastal dune activity covering the past ~5000 years (e.g., Loope and Arbogast 2000; Arbogast et al. 2002; Loope et al. 2004; Hansen et al. 2010; Fisher et al. 2012; Baca et al. 2014; Hanes et al. 2014). The only late glacial age SGLR dune study site along the coast with source sand controlled directly by water level changes is on the glaciolacustrine plain of glacial Lake Chicago in Ottawa County, Michigan (Colgan et al. 2017). All other study sites are further inland in Michigan (Arbogast et al. 2015; 2017), upwind of Lake Michigan (Rawling et al. 2008), or far enough south of Lake Michigan that changes in sediment supply at the coast would not affect the inland dunes in Indiana (Kilibarda and Blockland 2011; this study) or in Ohio (Campbell et al. 2011; Fisher et al. 2015).

At the Ottawa County site, the oldest dune postdates lake level rise to the Calumet and Algonquin levels by 700 years (Figs. 4A, I), making it uncertain if dune activity was initiated by lake level rise or not, or whether lake level fluctuations between the Calumet and Algonquin levels resulted in a new sediment supply. The other dates from this site correspond with lowering of Lake Algonquin in the lakes Michigan and Huron basin when the North Bay outlet opened and lake level fell to the Chippewa Low (Fisher et al. 2012). This fall in lake level may have resulted in an abundant supply of sand, and today the plethora of stable dunes in Ottawa County make this site a good candidate for further testing relationships between aeolian activity and lake level change (cf. Colgan et al. 2017).

If it is assumed that sand sources were controlled by coastal and fluvial activity for the Ottawa County and Au Sable dune fields in Michigan, respectively, then climate change must

have led to some combination of reduced vegetation cover, drier conditions, and increased wind to explain the inland dune activity elsewhere in the SGLR. While the precise mechanisms that resulted in aeolian activity are uncertain, thousands of years of time was available since deglaciation and initial sediment availability, and last aeolian activity. Figure 4H shows a distribution of OSL ages that is skewed towards younger ages. The majority of OSL ages are between 12.5 to 9.5 ka. Initially all dunes formed from non-aeolian sediments, but through time it is more likely that existing dunes were remobilized or scavenged, versus new dunes forming. For the Mongo dunes, it appears that large wind-rift dunes on the channel bottom record an earlier period of aeolian activity, and reworking of the ridge into a series of blow-out dunes records aeolian activity around 14.2 ± 1.6 . The youngest dunes on the edges of the uplands record renewed aeolian activity of dunes at 12.3 ± 1.3 that had already climbed out of the meltwater channel during earlier aeolian activity, or were in a higher position along the channel bottom.

Fisher et al. (2015) suggested that some dune activity in northwest Ohio may have been caused by water level drops of the proglacial lake within the Lake Erie basin. However, the dated Mongo dunes are not located close to a deglacial lake shoreline, suggesting that regional climate was the driving factor in dune mobility in northeast Indiana.

Summary

The Mongo dunes are short (<7 m height) parabolic forms with small lunate, lobate, nested and rake-like forms, with many wind-rift ridges up to a kilometer long, especially along the dune field's southern boundary. The oldest OSL dates (average 14.2 ± 1.6 ka) are a minimum-limiting age for local deglaciation and cessation of meltwater activity in the Pigeon River meltwater

channel linked to the Huron-Erie lobe. Radiocarbon dated wood from nearby lakes is ~2 ka older—which is a minimum duration for earlier aeolian activity. The age of the Mongo dunes have the same ages as dunes 80 km downwind to the east in northwest Ohio, and contribute to a growing database of inland dune activity in the southern Great Lakes region. From this region, over half of the dated dunes fall within the Younger Dryas chronozone, establishing aeolian dunes as climate proxies in agreement with the North Atlantic Event Stratigraphy during Late Glacial time. At Mongo, Indiana, landscape position of dunes (upland vs. lowland) is suggestive of at least two generations of dune activity and a probability density function plot of all ages within the southern Great Lakes region reveals aeolian activity before, during and after the Younger Dryas stadial.

Acknowledgements

Funding was provided through the USGS Great Lakes Geologic Mapping Coalition (cooperative agreement G13AC00254) to Loope and The University of Toledo Department of Environmental Sciences. John Dilworth assisted with sampling the Mongo Dunes. Cheyanne Jacobs contributed to OSL sample preparation and data collection at NDSU, and Thomas Valachovics at UT assisted with the PDF plot in Figure 4. We acknowledge the support of The Ohio State University Nuclear Reactor Laboratory and the assistance of reactor staff for the neutron irradiation and gamma spectroscopy capabilities as well as Joe Talnagi of Scientific Consulting Services for INAA data reduction. Two anonymous reviewers and Associate Editor Konrad Gajewski are thanked for their helpful suggestions for improving the manuscript.

References

- Aitken, M.J. 1985. Thermoluminescence Dating. Academic Press, London.
- Aitken, M.J. 1998. An Introduction to Optical Dating: The dating of Quaternary sediments by the use of photon-stimulated luminescence. Oxford University Press, New York.
- Alley, R.B. 2000. The Younger Dryas cold interval as viewed from central Greenland. *Quaternary Science Reviews*, **19**: 213–226.
- Arbogast, A.F., Hansen, E.G., and van Oort, M.D. 2002. Reconstructing the geomorphic evolution of large coastal dunes along the southeastern shore of Lake Michigan. *Geomorphology*, **46**: 241–255.
- Arbogast, A.F., Luehmann, M.D., Monaghan, G.W., Lovis, W.A., and Wang, H. 2017. Paleoenvironmental and geomorphic significance of bluff-top dunes along the Au Sable River in northeastern Lower Michigan, USA. *Geomorphology*, **297**: 112–121.
- Arbogast, A.F., Luehmann, M.D., Miller, B.A., Wernette, P.A., Adams, K.M., Waha, J.D., O'Neil, G.A., Tang, Y., Boothroyd, J.J., Babcock, C.R., Hanson, P.R., and Young, A.R. 2015. Late-Pleistocene paleowinds and aeolian sand mobilization in north-central Lower Michigan. *Aeolian Research*, **16**: 109–116.
- Argyilan, E.P., Lepper, K., and Thompson, T.A. 2014. Late Holocene coastal development along the southern shore of Lake Michigan determined by strategic dating of stabilized parabolic dunes and wetlands of the Tolleston Beach, in: Fisher, T.G., Hansen, E.C. (Eds.), *Coastline and Dune Evolution Along the Great Lakes*. Geological Society of America, Special Paper 508 Boulder, CO, pp. 31–46.
- Baca, K.J., Fisher, T.G., and Gottgens, J.F. 2014. Temporally constrained eolian sand signals and their relationship to climate, Oxbow Lake, Saugatuck, Michigan, in: Fisher, T.G., Hansen, E.C. (Eds.), *Coastline and Dune Evolution Along the Great Lakes*. Geological Society of America Special Paper 508, Boulder, CO, pp. 151–165.
- Björck, S. 2010. Bio- and chronostratigraphic significance of the Older Dryas Chronozone — on the basis of new radiocarbon dates. *Geologiska Föreningen i Stockholm Förhandlingar*. **106**: 81–91.
- Björck, S., Walker, M.C., Cwynar, L.C., Johnsen, S., Knudsen K.L., Lowe, J., Wohlfarth, C. and INTIMATE Members. 1998. *Journal of Quaternary Sciences*. **13**: 283–292.
- Brown, S.E., Fleming, A.H., Jones, H., and Schrader, T.L. 1998. Glacial terrains of the Mongo, Wolcottville, and the Indiana part of the Burr Oak 7.5-Minute Quadrangles, LaGrange and Noble Counties, Indiana. *Indiana Geological Survey Open-File Study* 98-6.
- Campbell, M.C., Fisher, T.G., and Goble, R.J. 2011. Terrestrial sensitivity to abrupt cooling recorded by aeolian activity in northwest Ohio, USA. *Quaternary Research*, **75**: 411–416.
- Capps, D.K., Thompson, T.A., and Booth, R.K. 2007. A post-Calumet shoreline along southern Lake Michigan. *Journal of Paleolimnology*, **37**: 395–409.

- 309 Colgan, P.M., Amidon, W.H., and Thurkettle, S.A. 2017. Inland dunes on the abandoned bed of
310 Glacial Lake Chicago indicate eolian activity during the Pleistocene-Holocene
311 transition, southwestern Michigan, USA. *Quaternary Research*, **87**: 66–81.
- 312 Curry, B.B., Lowell, T.V., Wang, H., and Anderson, A.C., 2018. Revised time-distance diagram
313 for the Lake Michigan Lobe, Michigan Subepisode, Wisconsin Episode, Illinois, USA,
314 in: Kehew, A.E., Curry, B.B. (Eds.), *Quaternary Glaciation of the Great Lakes Region:*
315 *Process, Landforms, Sediments, and Chronology*. The Geological Society of America
316 Special Paper 530, pp. 69–101.
- 317 David, P.P. 1981. Stabilized dune ridges in northern Saskatchewan. *Canadian Journal of Earth*
318 *Sciences*, **18**: 286–310.
- 319 Dziekan, M.R. 2017. Origins of basal sediment within kettle lakes in southern Michigan and
320 northern Indiana. Unpublished MS Thesis, Department of Environmental Sciences,
321 Univ. Toledo, Toledo Ohio. 145p.
- 322 Fisher, T.G., Blockland, J.D., Anderson, B., Krantz, D.E., Stierman, D.J., and Goble, R. 2015.
323 Evidence of sequence and age of Ancestral Lake Erie lake-levels, northwest Ohio. *Ohio*
324 *Journal of Science*, **115**: 62–78.
- 325 Fisher, T.G., Weyer, K.A., Boudreau, A.M., Martin-Hayden, J.M., Krantz, D.E., and
326 Breckenridge, A. 2012. Constraining Holocene lake levels and coastal dune activity in
327 the Lake Michigan basin. *Journal of Paleolimnology*, **47**: 373–390.
- 328 Gill, J.L., Williams, J.W., Jackson, S.T., Donnelly, J.P., and Schellinger, G.S. 2012. Climatic and
329 megaherbivory controls on late-glacial vegetation dynamics: a new, high-resolution,
330 multi-proxy record from Silver Lake, Ohio. *Quaternary Science Reviews*, **34**: 66–80.
- 331 Gonzalez, L.M., Williams, J.W., and Grim, E.C. 2009. Expanded response-surfaces: a new
332 method to reconstruct paleoclimates from fossil pollen assemblages that lack modern
333 analogues. *Quaternary Science Reviews*, **28**: 3315–3332.
- 334 Hanes, B.E., Fisher, T.G., Becker, R.H., and Martin-Hayden, J.M. 2014. Elucidating paleo dune
335 activity and timing from wetlands in the lee of coastal sand dunes, Grand Mere Lakes,
336 Michigan, USA, in: Fisher, T.G., Hansen, E.C. (Eds.), *Coastline and dune evolution*
337 *along the Great Lakes*. Geological Society of America Special Paper 508, Boulder, CO,
338 pp. 133–150.
- 339 Hansel, A.K., and Johnson, W.H. 1992. Fluctuations of the Lake Michigan lobe during the late
340 Wisconsin subepisode. *Sveriges Geologiska Undersökning*, **81**: 133–144.
- 341 Hansel, A.K., Mickelson, D.M., Schneider, A.F., and Larsen, C.E. 1985. Late Wisconsinan and
342 Holocene history of the Lake Michigan Basin, in: Karrow, P.F., Calkin, P.E. (Eds.),
343 *Quaternary Evolution of the Great Lakes*. Geological Survey of Canada, Special Paper
344 30, St John's Newfoundland, pp. 39–53.
- 345 Hansen, E.C., Fisher, T.G., Arbogast, A.F., and Bateman, M.D. 2010. Geomorphic history of
346 low-perched, transgressive dune complexes along the southeastern shore of Lake
347 Michigan. *Aeolian Research*, **1**: 111–127.

- 348 Hanson, P.R., Mason, J.A., Jacobs, P.M., and Young, A.R. 2015. Evidence for bioturbation of
349 luminescence signals in eolian sand on upland ridgetops, southeastern Minnesota, USA.
350 Quaternary International, **362**: 108–115.
- 351 Horton, J.M. 2015. The Deglacial Chronology of the Sturgis Moraine in South-Central Michigan
352 and Northeast Indiana. Unpublished MS Thesis, Department of Environmental
353 Sciences, Univ. Toledo, Toledo Ohio, p. 100.
- 354 Johnson, G., and Keller, S. 1972. Geologic map of the 1° x 2° Fort Wayne quadrangle, Indiana,
355 Michigan, and Ohio, showing bedrock and unconsolidated deposits. Indiana Geological
356 Survey, Regional Geology Map 08A.
- 357 Kilibarda, Z., and Blockland, J. 2011. Morphology and origin of the Fair Oaks Dunes in NW
358 Indiana, USA. Geomorphology, **125**: 305–318.
- 359 Leavitt, S.W., Panyushkina, I.P., Lange, T., Wiedenhoeft, A., Cheng, L., Hunter, R.D., Hughes,
360 J., Pranschke, F., Schneider, A.F., Moran, J., and Stieglitz, R. 2006. Climate in the
361 Great Lakes region between 14,000 and 4000 years ago from isotopic composition of
362 conifer wood. Radiocarbon, **48**: 205–217.
- 363 Lepper, K., Gorz, K.L., Fisher, T.G., and Lowell, T.V. 2011. Age determinations for Lake
364 Agassiz shorelines west of Fargo, North Dakota, U.S.A. Canadian Journal of Earth
365 Sciences, **48**: 1199–1207.
- 366 Lepper, K., Fisher, T.G., Hajdas, I., and Lowell, T.V. 2007. Ages for the Big Stone moraine and
367 the oldest beaches of glacial Lake Agassiz: Implications for deglaciation chronology.
368 Geology, **35**: 667–670.
- 369 Lepper, K., Wilson, C., Gardner, J., Reneau, S., and Lavine, A. 2003. Comparison of SAR
370 techniques for luminescence dating of sediments derived from volcanic tuff. Quaternary
371 Science Reviews, **22**: 1131–1138.
- 372 Loope, W.L., and Arbogast, A.F. 2000. Dominance of an ~150-year cycle of sand-supply change
373 in Late Holocene dune-building along the eastern shore of Lake Michigan. Quaternary
374 Research, **54**: 414–422.
- 375 Loope, W.L., Fisher, T.G., Jol, H.M., Goble, R.J., Anderton, J.B., and Blewett, W.L. 2004. A
376 Holocene history of dune-mediated landscape change along the southeastern shore of
377 Lake Superior. Geomorphology, **61**: 303–322.
- 378 Lutz, B., Wiles, G., Lowell, T.V., and Michaels, J. 2007. The 8.2-ka abrupt climate change event
379 in Brown's Lake, northeast Ohio. Quaternary Research, **67**: 292–296.
- 380 Murray, A., and Wintle, A.G. 2000. Luminescence dating of quartz using an improved single-
381 aliquot regenerative-dose protocol. Radiation Measurements, **32**: 57–73.
- 382 Prescott, J.R., and Hutton, J.T. 1988. Cosmic-ray and gamma-ray dosimetry for TL and electron-
383 spin-resonance. Nuclear Tracks and Radiation Measurements, **14**: 223–227.
- 384 Prescott, J.R., and Hutton, J.T. 1994. Cosmic ray contributions to dose rates for luminescence
385 and ESR dating: large depths and long-term time variations. Radiation Measurements,
386 **23**: 497–500.

- 387 Pye, K. 1993. Late Quaternary development of coastal parabolic megadune complexes in
388 northwestern Australia, in: Pye, K., Lancaster, N. (Eds.), Special Publication of the
389 International Association of Sedimentologists. Blackwell Scientific, Oxford, pp. 23–44.
- 390 Rasmussen, S.O., Andersen, K.K., Svensson, A.M., Steffensen, J.P., Vinther, B.M., Clausen,
391 H.B., Siggaard-Andersen, M.-L., Johnsen, S.J., Larsen, L.B., Dahl-Jensen, D., Bigler,
392 M., Rothlisberger, R., Fischer, H., Goto-Azuma, K., Hansson, M.E., and Ruth, U. 2006.
393 A new Greenland ice core chronology for the last glacial termination. *Journal of*
394 *Geophysical Research*, **111**: D06102.
- 395 Rasmussen, S.O., Bigler, M., Blockley, S.P., Blunier, T., Buchardt, S.L., Clausen, H.B.,
396 Cvijanovic, I., Dahl-Jensen, D., Johnsen, S.J., Fischer, H., Gkinis, V., Guillevic, M.,
397 Hoek, W.Z., Lowe, J.J., Pedro, J.B., Popp, T., Seierstad, I.K., Steffensen, J.P.,
398 Svensson, A.M., Vallenga, P., Vinther, B.M., Walker, M.J.C., Wheatley, J.J., and
399 Winstrup, M. 2014. A stratigraphic framework for abrupt climatic changes during the
400 Last Glacial period based on three synchronized Greenland ice-core records: refining
401 and extending the INTIMATE event stratigraphy. *Quaternary Science Reviews*, **106**,
402 14–28.
- 403 Rawling, J.E., Hanson, P.R., Young, A.R., and Attig, J.W. 2008. Late Pleistocene dune
404 construction in the Central Sand Plain of Wisconsin, USA. *Geomorphology*, **100**: 494–
405 505.
- 406 Rawling, J.E., and Hanson, P.R. 2014. Dune formation on late Holocene sandy bay barriers
407 along Lake Michigan's Door Peninsula: the importance of increased sediment supply
408 following the Nipissing and Algoma high lake level phases, in: Fisher, T.G., Hansen,
409 E.C. (Eds.), *Coastline and Dune Evolution Along the Great Lakes*. Geological Society
410 of America Special Paper 508, Boulder, CO, pp. 65–84.
- 411 Seierstad, I.K., Abbott, P.M., Bigler, M., Blunier, T., Bourne, A.J., Brook, E., Buchardt, S.L.,
412 Buizert, C., Clausen, H.B., Cook, E., Dahl-Jensen, D., Davies, S.M., Guillevic, M.,
413 Johnsen, S.J., Pedersen, D.S., Popp, T.J., Rasmussen, S.O., Severinghaus, J.P.,
414 Svensson, A., and Vinther, B.M. 2014. Consistently dated records from the Greenland
415 GRIP, GISP2 and NGRIP ice cores for the past 104 ka reveal regional millennial-scale
416 $\delta^{18}\text{O}$ gradients with possible Heinrich event imprint. *Quaternary Science Reviews* **106**:
417 29–46.
- 418 Shane, L.C.K. 1987. Late-glacial vegetational and climatic history of the Allegheny Plateau and
419 the till plains of Ohio and Indiana, U.S.A. *Boreas*, **16**: 1–20.
- 420 SSURGO, 2015. Soil survey geographic database 20150126 last accessed at
421 http://maps.indiana.edu/previewMaps/Environment/Soils_SSURGO_Soil_Survey.html
422 September 19, 2018.
- 423 Thorson, R.M., and Schile, C.A. 1995. Deglacial eolian regimes in New England. *Geological*
424 *Society of America Bulletin*, **107**: 751–761.
- 425 Wayne, W.J. 1963. Pleistocene Formations in Indiana. *Indiana Geological Survey Bulletin*
426 25, 85 p.

427 Wintle, A.G., and Murray A. 2006. A review of quartz optically stimulated luminescence
428 characteristics and their relevance in single-aliquot regeneration dating protocols.
429 Radiation Measurements, **41**: 369-391.

430

431

Draft

Tables

Table 1. Optically stimulated luminescence sample locations.

Sample ID	Elevation (m)	UTM Coordinates (16T)		Decimal Degrees	
		(E)	(N)	Long°	Lat°
MD1401	301	648997	4613966	-85.2106	41.6635
MD1402	294	646244	4616008	-85.24288	41.6824
MD1403	293	646278	4615946	-85.24493	41.6818
MD1404	284	647839	4615157	-85.22394	41.6744
MD1405	285	648547	4614852	-85.21551	41.6715
MD1407	306	652251	4614362	-85.17117	41.6664

Table 2. Concentration of dosimetrically significant elements¹ and relevant data.

Sample ID	Sample Depth (m)	H ₂ O content %	K (ppm)	Rb (ppm)	Th (ppm)	U (ppm)
MD1401	1.75	10 ± 3	9865 ± 959	28.36 ± 2.94	1.227 ± 0.125	0.447 ± 0.042
MD1402	1.30	10 ± 3	9306 ± 943	27.56 ± 2.40	1.304 ± 0.131	0.497 ± 0.041
MD1403	1.40	10 ± 3	9206 ± 947	28.08 ± 2.93	1.172 ± 0.122	0.367 ± 0.035
MD1404	1.95	15 ± 3	8073 ± 804	26.77 ± 2.27	0.985 ± 0.100	0.519 ± 0.041
MD1405	1.85	15 ± 3	7817 ± 911	23.22 ± 2.61	1.017 ± 0.106	0.371 ± 0.039
MD1407	1.77	12 ± 3	9672 ± 1057	29.63 ± 2.81	1.341 ± 0.138	0.520 ± 0.051

¹Elemental concentrations from instrumental neutron activation analysis (INAA) conducted at The Ohio State University Nuclear Reactor Lab. INAA data reduction by Scientific Consulting Services, Dublin, OH.

Table 3. Optically stimulated luminescence ages and related results.

Sample ID	N ¹	M/m ²	υ ³	Equivalent Dose ⁴ J/Kg	Dose Rate ⁵ (J/Kg/ka)	Age ± Uncertainty ⁶ (ka)
MD1401	91/95	1.01	0.307	14.429 ± 0.465	1.165 ± 0.111	12.4 ± 1.3
MD1402	90/94	0.99	0.337	14.093 ± 0.501	1.144 ± 0.111	12.3 ± 1.3
MD1403	90/95	1.02	0.350	13.555 ± 0.500	1.097 ± 0.111	12.4 ± 1.3
MD1407	95/96	1.02	0.342	13.737 ± 0.482	1.147 ± 0.117	12.0 ± 1.3
Mean age						12.3 ± 1.3
MD1404	86/95	0.97	0.372	13.747 ± 0.551	0.959 ± 0.092	14.3 ± 1.5
MD1405	90/96	0.98	0.353	12.836 ± 0.478	0.911 ± 0.100	14.1 ± 1.6
Mean age						14.2 ± 1.6

¹Number of aliquots used for OSL De calculation/number of aliquots from which OSL data was collected (filtering criteria given in Lepper et al. 2003).

²Mean/median ratio: a measure of dose distribution symmetry (see supplement to Lepper et al. 2007).

³Dose distribution data dispersion (standard deviation/mean)

⁴All data distributions were symmetric in this study; therefore, representative doses were based on the mean of the equivalent dose distribution for all samples (see Lepper et al. 2011)

⁵Dose rates calculated following the methods presented in Aitken (1985; 1998) and Prescott and Hutton (1988; 1994).

⁶Fully propagated age uncertainty (Aitken 1985) for individual samples

Figure Captions

Figure 1. A) Color (online) LiDAR digital elevation model of the Pigeon River meltwater channel and Mongo sand dunes (area within white dashed lines). Of the six sand dunes dated with the optically stimulated luminescence (OSL) method (white dots), four are on the uplands above the meltwater channel (MD1401,-2,-3,-7; Figs 3 A,B,D) and two in the channel (MD1404,-5; Figs 3 A,C). B) Location of the Mongo Dune field (star) and other sites in the southern Great Lakes with OSL-dated inland sand dunes: 1–Rawling et al. (2008); 2–Kilibarda and Blockland (2011); 3–Campbell et al. (2011); Fisher et al. (2015); 4–Arbogast et al. (2015, 2017); 5–Colgan et al. (2017).

Figure 2. Location of the Pigeon River meltwater channel south of the Sturgis Moraine. On the digital elevation model basemap, lighter greys are higher elevation. Black arrows indicate meltwater flow direction from the Huron-Erie Lobe to the west. The boundary between the Saginaw and Huron-Erie lobes is uncertain, represented by the dashed line.

Figure 3. Sample site locations on a LiDAR digital elevation model and optically stimulated luminescence (OSL) ages of sampled sand dunes. Note the two dated dunes within the outwash channel (A, C; samples MD1404 and MD1405) are older than dunes on the uplands above the channel (A, B, D; samples MD1401-1403 and MD1407). See Figure 1 for locations. E) Soil profiles at the sample sites with corresponding OSL age below the log. F) Soil pit at MD1401 showing well-developed soil horizons and OSL sampling location (circle). [Colour online.]

Figure 4. Optically stimulated luminescence (OSL) ages from sand dunes in the southern Great Lakes region with one sigma error, relationship between water levels in the Lake

509 Michigan basin, and climate records from Greenland ice cores. Broad gray column is
510 Younger Dryas time and narrow gray columns are shorter stadial events. OSL dates from
511 sand dunes at: A) Ottawa County, Michigan (Colgan et al. 2017); B) central sand plains of
512 Wisconsin, note error bars are not shown on all samples due to space limitation (Rawling
513 et al. 2008); C) Fair Oaks dune field, northwest Indiana (Kilibarda and Blockland 2011); D)
514 Rosco dune field, northern Lower Peninsula of Michigan (Arbogast et al. 2015); E)
515 northwest Ohio (Fisher et al. 2015); F) northwest Ohio (Campbell et al. 2011); G) Mongo
516 dune field (this study). H) Probability density function plot of 59 OSL ages on dunes in B
517 through G. Note shoulder centered on 14 ka (Older Dryas), the main peak towards the end
518 of the Younger Dryas, and a shoulder during the Preboreal. I) Relative water levels in Lake
519 Michigan basin from data in Hansel et al. (1985), Hansel and Johnson (1992), Capps et al.
520 (2007), Fisher et al. (2012), Curry et al. (2018); TCL is Two Creeks lowstand. J) Fifty-year
521 means of dust records from Greenland ice cores (Rasmussen et al. 2014; Seierstad et al.
522 2014). K) Greenland climate ^{18}O record from NGRIP ice core (Rasmussen et al. 2006).

523

Figure 1. A) Color (online) LiDAR digital elevation model of the Pigeon River meltwater channel and Mongo sand dunes (area within white dashed lines). Of the six sand dunes dated with the optically stimulated luminescence (OSL) method (white dots), four are on the uplands above the meltwater channel (MD1401,-2,-3,-7; Figs 3 A,B,D) and two in the channel (MD1404,-5; Figs 3 A,C). B) Location of the Mongo Dune field (star) and other sites in the southern Great Lakes with OSL-dated inland sand dunes: 1–Rawling et al. (2008); 2–Kilibarda and Blockland (2011); 3–Campbell et al. (2011); Fisher et al. (2015); 4–Arbogast et al. (2015, 2017); 5–Colgan et al. (2017).

240x83mm (600 x 600 DPI)

Figure 2. Location of the Pigeon River meltwater channel south of the Sturgis Moraine. On the digital elevation model basemap, lighter greys are higher elevation. Black arrows indicate meltwater flow direction from the Huron-Erie Lobe to the west. The boundary between the Saginaw and Huron-Erie lobes is uncertain, represented by the dashed line.

190x75mm (600 x 600 DPI)

Figure 3. Sample site locations on a LiDAR digital elevation model and optically stimulated luminescence (OSL) ages of sampled sand dunes. Note the two dated dunes within the outwash channel (A, C; samples MD1404 and MD1405) are older than dunes on the uplands above the channel (A, B, D; samples MD1401-1403 and MD1407). See Figure 1 for locations. E) Soil profiles at the sample sites with corresponding OSL age below the log. F) Soil pit at MD1401 showing well-developed soil horizons and OSL sampling location (circle). [Colour online.]

190x195mm (600 x 600 DPI)

Figure 4. Optically stimulated luminescence (OSL) ages from sand dunes in the southern Great Lakes region with one sigma error, relationship between water levels in the Lake Michigan basin, and climate records from Greenland ice cores. Broad gray column is Younger Dryas time and narrow gray columns are shorter stadial events. OSL dates from sand dunes at: A) Ottawa County, Michigan (Colgan et al. 2017); B) central sand plains of Wisconsin, note error bars are not shown on all samples due to space limitation (Rawling et al. 2008); C) Fair Oaks dune field, northwest Indiana (Kilibarda and Blockland 2011); D) Rosco dune field, northern Lower Peninsula of Michigan (Arbogast et al. 2015); E) northwest Ohio (Fisher et al. 2015); F) northwest Ohio (Campbell et al. 2011); G) Mongo dune field (this study). H) Probability density function plot of 59 OSL ages on dunes in B through G. Note shoulder centered on 14 ka (Older Dryas), the main peak towards the end of the Younger Dryas, and a shoulder during the Preboreal. I) Relative water levels in Lake Michigan basin from data in Hansel et al. (1985), Hansel and Johnson (1992), Capps et al. (2007), Fisher et al. (2012), Curry et al. (2018); TCL is Two Creeks lowstand. J) Fifty-year means of dust records from Greenland ice cores (Rasmussen et al. 2014; Seierstad et al. 2014). K) Greenland climate 18O record from NGRIP ice core (Rasmussen et al. 2006).

180x203mm (600 x 600 DPI)