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Short Paper

Terrestrial sensitivity to abrupt cooling recorded by aeolian activity in northwest Ohio, USA

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ABSTRACT

Optically stimulated luminescence dated sand dunes and Pleistocene beach ridges in northwest Ohio are used to reconstruct landscape modification more than 5000 yr after deglaciation. Four of the OSL ages (13.3–11.1 ka) cluster around the Younger Dryas cold event, five ages (10.8–8.2 ka) cluster around the Preboreal, one young age (0.9–0.7 ka) records more recent aeolian activity, and one age of 15.1–13.1 ka dates a barrier spit in Lake Warren. In northwest Ohio, both landscape instability recorded by aeolian activity and a vegetation response recorded by pollen are coeval with the Younger Dryas. However, the climate conditions during the Preboreal resulting in aeolian activity are not recorded in the available pollen records. From this, we conclude that aeolian dunes and surfaces susceptible to deflation are sensitive to cooler, drier episodes of climate and can complement pollen data. Younger Dryas and Preboreal aged aeolian activity in northwestern Ohio coincides with aeolian records elsewhere in the Great Lakes region east of the prairie–forest ecotone.

Introduction

Proxies of landscape stability and environmental change recording abrupt climate fluctuations commonly reside within high-resolution ice, cave, coral, marine or lacustrine sediment stratigraphies. With such climate proxies unavailable in northwest Ohio, we instead use the ages of aeolian dunes and deflation surfaces coeval with stadial events during the Pleistocene/Holocene transition to reconstruct past sensitivity of the landscape. On the western Great Plains aeolian dunes are often regarded as indicators of past aridity associated with warmer and drier intervals of climate (Forman et al., 2001; Mason et al., 2004; Wolfe et al., 2004; Miao et al., 2007; Muhs et al., 2008; Wolfe and Hugenholtz, 2009) wherein vegetation cover becomes the critical factor determining mobility. Such biogeomorphic models (Hugenholtz and Wolfe, 2005) work well for the plains of North America, but farther east in the Great Lakes region, most dune histories have focused on coastal dunes (e.g., Loope and Arbogast, 2000; Arbogast et al., 2004; Timmons et al., 2007; Hansen et al., 2010) whose triggering mechanisms are often associated with cyclical lake level changes. The chronology of inland, forested dunes has received little attention. Inland dunes in Wisconsin (Keen and Shane, 1990; Rawling et al., 2008) and the Upper Peninsula of Michigan (Arbogast et al., 2002; Arbogast and Packman, 2004; Loope et al., 2010) have been explained by changes in sediment availability driven by fire, fluctuating water tables and lake levels (Michigan) or rivers, and ameliorating climate (Wisconsin). From a recent review of various climate proxies of late Pleistocene–early Holocene age in the North American midcontinent region, Williams et al. (2010:136) suggested that "aeolian records do not show a significant time-transgressive trend, perhaps due to the narrow longitudinal range of most eolian sites." Here, we expand the longitudinal range by including sites elsewhere in the Great Lakes region, specifically a series of OSL-dated stabilized aeolian dunes and surfaces across northwest Ohio, USA, that with other sites in the Great Lakes region, serve as proxies for dry, cold and windy events at the close of the last ice age. Our results of last dune activity ~4.0–8.0 ka after deglaciation reveal that climate rather than sediment availability controlled aeolian activity.

Study area

During retreat of the Laurentide Ice Sheet from the Fort Wayne Moraine, a sequence of lake stages of ancestral Lake Erie (Figs. 1 and 2, Table 1) formed at decreasing elevations in response to changing outlets during progressive retreat of the Huron-Erie Lobe (Leverett and Taylor, 1915; Forsyth, 1959; Dreimanis, 1977; Calkin and Feenstra, 1985). Recession after the Port Bruce Stade was underway by 18.0–17.1 cal ka BP (14.5 ± 0.15 ^{14}C ka BP: Calkin and Feenstra, 1985), a maximum age for the strandlines. A minimum age for the strandlines is 15.7–14.1 cal ka BP (12.65 ± 0.17 ^{14}C ka BP: Lewis, 1969) based on radiocarbon ages from wood in peat now submerged in the Lake Erie basin. These ages effectively bracket the age of the strandline complex to 18.0–14.1 cal ka BP. Sand dunes and raised beach ridges form a patchy distribution across northwest Ohio, and

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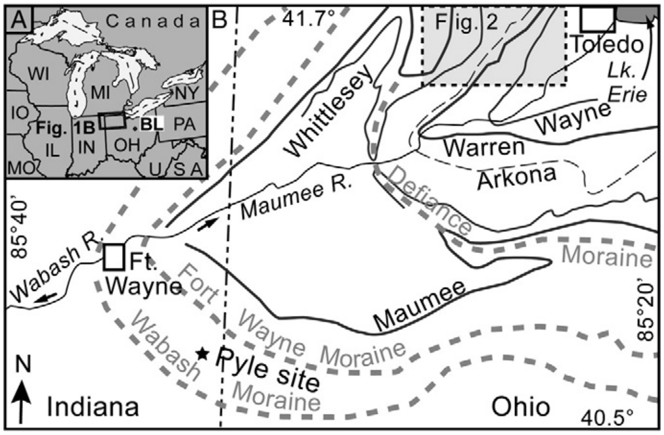

Figure 1. (A) Location of the study area in northwest Ohio. BL refers to Brown Lake in north central Ohio. (B) Moraines and lake levels of ancestral Lake Erie. Shoreline position is generalized after Forsyth (1959).

Table 1
Generalized[a] lake names and elevation for Ancestral Lake Erie.

Lake	Elevation
Maumee	760–800′ (223–244 m)
Whittlesey	735′ (224 m)
Arkona	690–710′ (210–216 m)
Warren	665–680′ (203–207 m)

[a] Simplified from Forsyth (1959).

here we focus on those below the highest Lake Maumee strandline to just below the Lake Warren strandline (Fig. 2).

Methods

Sample sites were selected along the Lake Warren strandline, at higher elevation strandlines, and on dunes at elevations above, below, and on the Lake Warren barrier spit. OSL samples were collected from soil pits into sand dunes or strandlines (Table S1) by pounding 7.5-cm diameter aluminum tubes into the soil C-horizon during Autumn 2007 and Summer 2008, following methodology in Aitken (1998). For details of the OSL methodology, see the supplemental information. OSL samples were processed at the Luminescence Geochronology Laboratory at the University of Nebraska-Lincoln. One new radiocarbon age was obtained from wood fragments from a sand pit in the Lake Warren strandline. Radiocarbon ages were calibrated using Calib V6.0 (Stuiver and Reimer, 1993) with the IntCal 09 terrestrial calibration curve (Reimer et al., 2009) reported as the 2σ range. OSL ages in the text are reported with 1σ error before 2000 A.D.

Results

Sand dunes are distributed throughout northwest Ohio in close proximity to glacial lake strandlines. At many sites, dunes are observed bowing eastward from beach ridges (e.g., #5, Fig. 2), indicating a deflation process between beach ridges with a beach ridge sediment source and short migration distance (Fig. 2). Elsewhere, extensive dune complexes such as between the Maumee and Whittlesey beaches north of I-80/90 (Fig. 2) have transgressed up to 6 km across the lake plain. Morphologically, the dunes have parabolic forms from hundreds of meters to a few kilometers in length, hundreds of meters in width, and usually <5 m, but occasionally ~7 m in height. Parabolic dunes often form dune complexes, for example on either side of the Maumee strand (Fig. 2). Parabolic dunes that extend across and eastward of the Lake Warren barrier spit have masked the

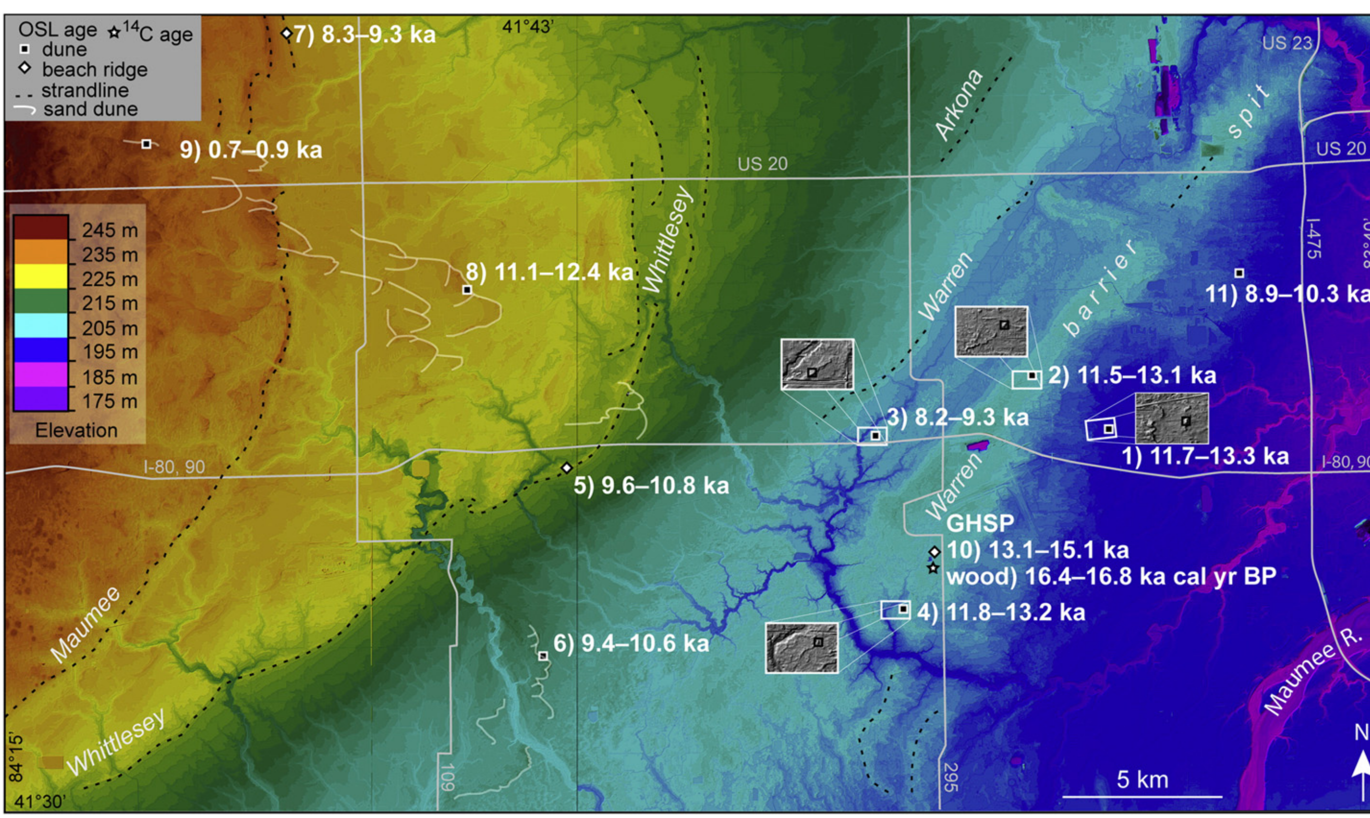

Figure 2. LiDAR based digital elevation model of the study area with locations of the OSL-dated sand dunes and beach ridges. Sample sites are labeled from 1 to 11 and correspond with site numbers in Tables 1 (S1–3) and Figure 4A. OSL ages are in kilo years before 2000 A.D. with 1 sigma error. GHSP: Griffith Hines sand pit.

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eastward edge of the strandline (Campbell, 2009). Dune orientations across the region consistently record westerly winds.

The one outcrop examined in this study was along the eastern wall of the Griffins Hines sand pit near the center of the Lake Warren barrier spit (Fig. 2). OSL sample #10 (UNL-2450) is from planar laminated sand in unit A having an OSL age of 14.1 ± 1.0 ka (Fig. 3). Stratigraphically above this unit is cross-bedded, very-fine pebbly sand (unit B) and a thin organic mud (unit C) draped into an erosion channel cut into unit B. Unit C is overlain by ripple drift and trough cross-bedded sand of units D and E, respectively (Fig. 3). A radiocarbon date of 13,430 ± 90 ^{14}C yr BP (Beta-258945, −23.4 δ^{13}C, 16.9–16 cal ka BP) is from wood fragments in unit C.

A longitudinal pattern of OSL ages by elevation is not apparent, instead multiple ages cluster at 13.3–11.1, 10.8–8.2 ka (Fig. 4A). The OSL ages are presented in Table 2, and ten of the eleven OSL ages are at least 3 ka younger than the age of 16.6–16.4 cal ka BP from wood fragments in the Lake Warren barrier spit (Fig. 2, Table 2). The two beach ridges (#5 and #7; Fig. 2) at elevations above Lake Warren are stratigraphically older than Lake Warren, yet they have ages 6–7 ka younger. OSL ages that appear to be too young are difficult to explain except by contamination of younger sand from bioturbation. However, for many of the samples, ages calculated from the maximum observed D_e values are less than the expected age of the strandline complex.

The 14.1 ± 1.0 ka OSL age from the Lake Warren spit littoral sediments overlaps at two-sigma error with the maximum radiocarbon age from the sand pit (Fig. 3). Lake Warren is not reliably or independently dated. The oldest age assigned is 16.4–15.2 cal ka BP (13.1 ± 0.1 ^{14}C ka BP, ISGS-473) by Totten (1985) with younger ages between 15.7 and 12.4 cal ka BP based on ages of 12.0 ± 0.5 (S-30) and 11.4 ± 0.45 ^{14}C BP (S-29) from muck lying directly above Lake Warren sediment (Dreimanis, 1966; Calkin and Feenstra, 1985). Radiocarbon dated wood in littoral settings is subject to redeposition and often provides ages older than the littoral sediment (e.g., Szabo et al., 2003; Fisher et al., 2008); thus, the wood fragment age from the Griffin–Hines sand pit dated to 16.9–16 cal ka BP is considered only a maximum age for Lake Warren.

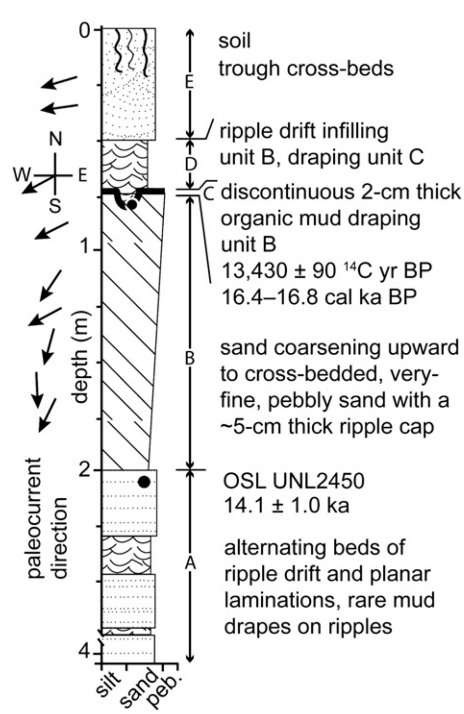

Figure 3. Lithostratigraphic log from the Griffith Hines sand pit located on Figure 2.

We expected sand dunes on or adjacent to glacial lake beaches to be similar in age to the strandlines themselves, not up to 8 ka younger. First we explore the analytical results of the OSL ages and conclude that the ages are not spuriously young, and then second we explore the implications of the young OSL ages for interpreting landscape development.

The analytical results of OSL dating did not provide any reason to suspect that the OSL ages are abnormally young. For example, there is no evidence for radioactive disequilibrium in the gamma ray spectra of UNL2450 or UNL2451. Skewness and kurtosis values (Bailey and Arnold, 2006) calculated for the equivalent dose, D_e, distributions are not consistent with partial bleaching (skewness < $2\sigma_c$) nor are there significantly negatively skewed values as might be expected if they were contaminated with younger sand (Table S3). Values of c/c_{crit}, k/k_{crit}, $c/2\sigma_c$, $k/2\sigma_k$ and overdispersion, where c is skewness and k is kurtosis, indicate that for each sample the D_e value should be calculated using the Central Age Model (Bailey and Arnold, 2006, Fig. 22; Galbraith et al., 1999). D_e values are based on 37–75 aliquots per sample; additional aliquots with unacceptable recycling ratios (>±10% error), $D_e > 2D_o$, low fast to medium component ratio (<20) in the decay curve, or detectable feldspar (IRSL) were discarded prior to averaging. D_e distributions for several of the older samples are significantly overdispersed, with values of σ ranging from 15% to 29%, indicating a source of spread in D_e beyond that associated with statistical error estimation (Olley et al., 2004).

For understanding landscape development in the study area, the implications of young OSL ages are either (1) ancestral Lake Erie is much younger than realized, as recent as ~9 ka, or (2) conditions suitable for aeolian transport of sand ended 4–8 ka after deglaciation. Although the young OSL ages may appear to support the first interpretation, there are three reasons given why they are considered minimum ages only for the Maumee and Whittlesey beach ridges (#7 and #5, respectively). First, sample #10 from within the Lake Warren barrier spit is on a stratigraphically younger position of the landscape but is 4–5 ka older. Second, ages #5 and #7 are well beyond the 2σ range of the accepted age of the ancestral Lake Erie beaches (Calkin and Feenstra, 1985; Villa-Garcia, 1989; Barnett, 1992; Szabo et al., 2003). And third, older sand dunes are found at lower elevations. Consequently, we favor the second implication that episodic dune and deflation processes were active 4–8 ka after deglaciation and that the dated sand from beaches #5 and #7 is assumed to overlie or be a lag deposit on deflated beach ridges.

Discussion

We compare the timing of aeolian activity in northwest Ohio with the ages of stadial events in the NGRIP ice core, discuss the environmental conditions that might have led to the young aeolian activity, and compare the ages with dunes from elsewhere in the Great Lakes region.

Aeolian activity coeval with Greenland stadials

The precision of OSL dating makes it reasonable to assign last activity of the older four dunes to the Younger Dryas cold period (Fig. 4A). After the Younger Dryas, numerous abrupt and short-lived stadials (Fig. 4A) characterize the Preboreal period, including the Preboreal Oscillation (e.g., Fisher et al., 2002), possible events at 10.9 and 10.3 ka (corrected age model for the early Holocene oscillation 1 of Hughen et al., 1996), 9.3 ka (Fleitman et al., 2008; Yu et al., 2010) and the 8.2 ka event (Alley and Agústsdóttir, 2005). However, the same OSL precision prevents associating the Preboreal aged dunes and beach ridge deflation ages to specific Preboreal stadials.

The last activity and stabilization of the latest Pleistocene–early Holocene sand dunes in northwest Ohio predates the early-to-mid-

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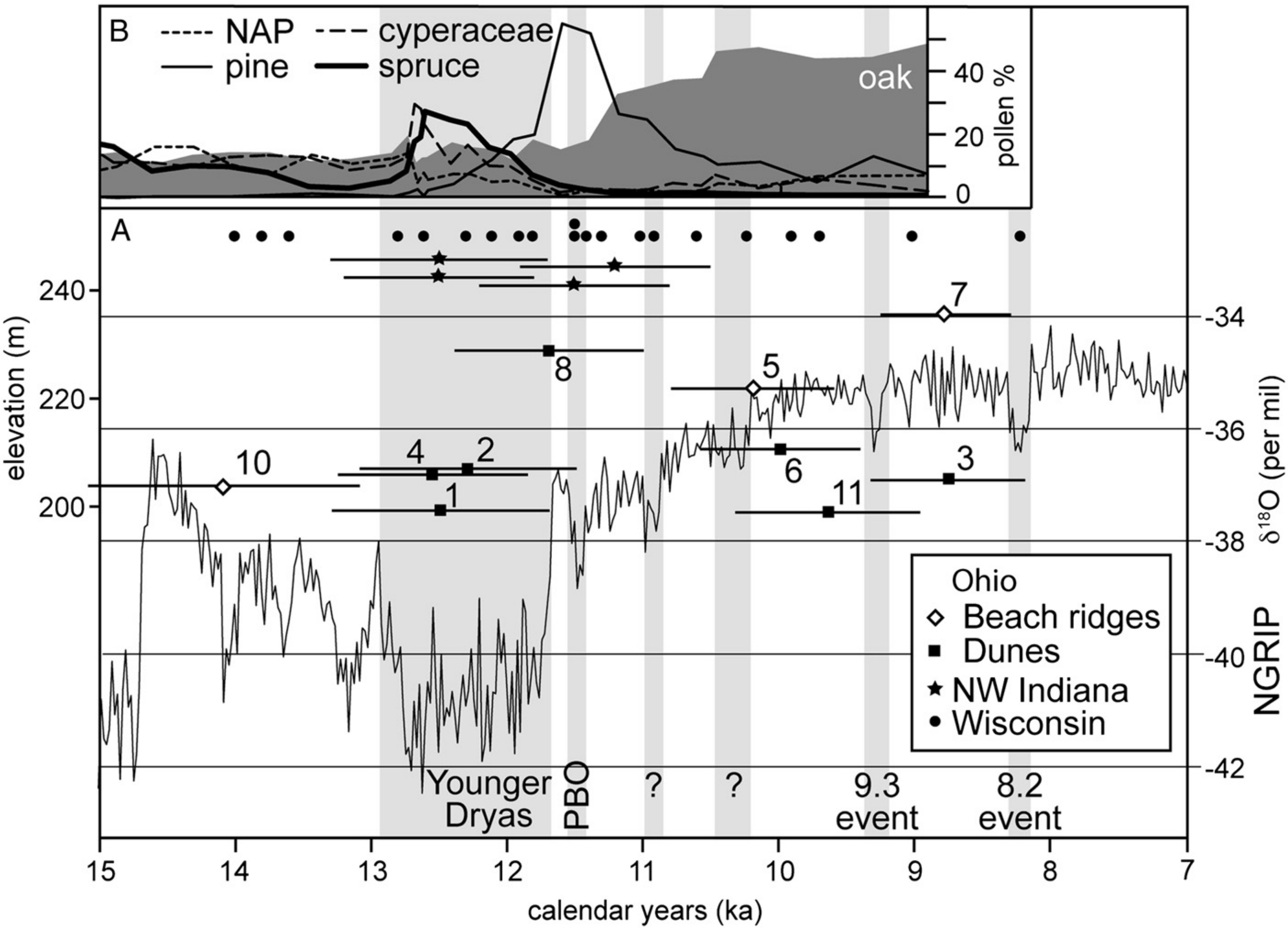

Figure 4. (A) OSL ages with one sigma error plotted by elevation against the NGRIP ^{18}O record (Rasmussen et al., 2006). Episodes of cool climate are highlighted with gray columns. OSL ages plot during either the Younger Dryas or Preboreal (early Holocene), which is characterized by numerous episodes of brief cooling, or stadials. PBO: Preboreal Oscillation. (B) Pollen from the Pyle site (Fig. 1) obtained from the North American Pollen Database that illustrates a brief return to cooler conditions (Shane, 1987) during the Younger Dryas cold period, overlapping in time with the last mobility of four sampled sand dunes. NAP: non-arboreal pollen. OSL-dated dunes from Wisconsin are plotted without the standard deviation error to minimize clutter on the figure, but may be found in Table 1 of Rawlings et al. (2008: 498). Indiana dune ages are from Kilibarda and Blockland (2011).

Holocene warmth of the Altithermal period in the American upper Midwest. Climate reconstructions using pollen-based vegetation reconstructions closest to the study area in southern Michigan, northeastern Indiana and central Ohio, record the Younger Dryas climate reversal (Manny et al., 1978; Shane, 1987; Shane and Anderson, 1993). The Pyle site (Fig. 1B and 4B; Shane, 1987) is the closest and most physiographically similar pollen site to the study area. The pollen data indicate a slight increase in moisture after ~12.9 cal ka BP, but by ~11.5 cal ka BP deciduous trees had replaced coniferous species other than pine (Shane, 1987).

Aeolian activity in the study area during the Preboreal is recorded by the deflation of two beach ridge surfaces and activity of three dunes. The closest pollen records for this time period record a warmer and drier climate dominated by deciduous species after 11.5 ka (OSL),

Table 2
OSL ages.

#	UNL #	Burial depth (m)	H2O (%)[a]	K2O (%)	U (ppm)	Th (ppm)	Cosmic (Gy)	Dose Rate (Gy/ka)	De (Gy)[b]	No. of aliquots	Age (ka)[c]
1	UNL1913	0.96	1.1	1.10	0.6	1.8	0.19	1.35 ± 0.06	16.94 ± 0.72	40	12.5 ± 0.8
2	UNL1914	0.95	1.4	1.14	0.6	1.9	0.19	1.39 ± 0.06	17.11 ± 0.68	41	12.3 ± 0.8
3	UNL1915	0.60	2.3	1.41	0.7	1.8	0.19	1.62 ± 0.07	14.16 ± 0.56	46	8.76 ± 0.56
4	UNL1916	0.90	1.9	1.19	0.6	1.7	0.19	1.41 ± 0.06	17.66 ± 0.66	48	12.5 ± 0.7
5	UNL2102	0.66	5.8	1.42	1.52	2.76	0.2	1.81 ± 0.07	18.35 ± 0.55	48	10.2 ± 0.6
6	UNL2103	0.65	4.2	1.65	0.81	2.05	0.20	1.81 ± 0.07	18.14 ± 0.57	46	10.0 ± 0.6
7	UNL2104	0.80	6.1	1.44	1.10	2.23	0.19	1.68 ± 0.06	14.78 ± 0.39	47	8.78 ± 0.48
8	UNL2105	0.56	7.8	1.55	0.65	1.77	0.20	1.61 ± 0.06	18.91 ± 0.56	39	11.7 ± 0.7
9	UNL2106	0.61	4.6	1.38	0.75	1.87	0.20	1.57 ± 0.06	1.24 ± 0.06	75	0.79 ± 0.06
10	UNL2450	2.05	3.4	1.53	0.99	1.82	0.16	1.38 ± 0.07	19.46 ± 0.65	44	14.1 ± 1.0
11	UNL2451	0.75	3.3	1.16	0.66	1.96	0.19	1.37 ± 0.05	13.16 ± 0.68	37	9.63 ± 0.69

[a] In-situ moisture content; saturation moisture content of 25% assumed for UNL2450.
[b] Error on D_e is 1 standard error.
[c] Error on age includes random and systematic errors calculated in quadrature.

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changing to a more open canopy after ~8.8 ka (OSL) with a 10–30% increase in cyperaceae and non-arboreal pollen (NAP, Fig. 4B). The Preboreal stadials are not recorded in the pollen records. Nevertheless, aeolian activity is also recorded in Brown Lake in north-central Ohio where dated loess was correlated to two events of abrupt climate change between 8.95 and 8.0 ka (OSL), in which drier and windier conditions were called upon to explain the deposition of loess from an adjacent glacial lake plain (Lutz et al., 2007). Further support for our stadial hypothesis is the cessation of dune activity in the study area when the eastward migration of the prairie–forest boundary west of the Great Lakes basin had begun (Baker et al., 1992; Yu and Eicher, 1998; Williams et al., 2010) and when the dunes might have been expected to be active.

Triggers for dune mobility

Dunes are usually considered diagnostic features in arid and semi-arid regions with reactivation associated with aridity and land use changes. In the Great Lakes region sand dunes are found in either coastal or inland locations. Many inland dues are triggered by falling lake levels revealing broad expanses of sand for transport, for example following episodic lake level lowering along the southern shore of the Superior basin (Loope et al., 2010). The Younger Dryas cold period has been described as cooler and windier (Alley, 2000) in both North America (e.g., Thorson and Schile, 1995; Leavitt et al., 2006) and Europe (e.g., Rebollal and Pérez-González, 2008). In addition to the Younger Dryas aged dunes from this study, similarly aged dunes (Fig. 4A) are reported from central Wisconsin (Rawling et al., 2008), northwest Indiana (Kilibarda and Blockland, 2011), and New England (Thorson and Schile, 1995). These data imply that during stadials in the Great Lakes region landscape instability was driven by more arid conditions and perhaps also more intense winds (cf. Tsoar et al., 2009) to degrade forest cover sufficiently for dunes to become active. The consistent westerly paleowind direction recorded by the dunes in the study area suggests that continental air masses were dominant over warmer and moister maritime air masses from the south during this time. Elsewhere, increased aeolian activity associated with cold periods include the 8.2 ka event in northern Ohio (Lutz et al., 2007), fire initiated dune activity along the shores of Hudson Bay occurring during cold phases (Filion, 1984), and dune activity in the northern Great Plains of Canada during the cooler Little Ice Age (Wolfe and Hugenholtz, 2009).

To explain the reactivations of the dunes, we propose that under cooler, drier and windier conditions, water tables on high points of the landscape (sand dunes and coarse-grained beach ridges) were lowered, stressing the stabilizing vegetation cover. With less precipitation and increasing winds during these cold periods, locally the highest and driest dunes and beach ridges (Fig. 2) were more susceptible to mobility and deflation, respectively. On these exposed surfaces, dune formation can be explained when vegetation cover drops below ~30% (Wasson and Nanninga, 1986). Similar landscape responses including aeolian activity during the Younger Dryas stadial are discussed by Thorson and Schile (1995) for New England states and are well known in Europe (e.g., Pokorny and Ruzickova, 2000; Rebollal and Pérez-González, 2008), and only recently have numerical ages for dunes been available in the Great Lakes regions to register a similar landscape response. Cessation of Preboreal aeolian activity in northwestern Ohio is explained by the well-established climate amelioration initiated after the reorganization of atmospheric circulation following the demise of the Laurentide Ice Sheet in Hudson Bay (Dean et al., 2002; Lewis et al., 2008).

Conclusions

The OSL-dated sand dunes and beach ridges in northwest Ohio record dune mobility and deflation processes overlapping in time with cooler periods and episodes of abrupt climate change as recorded in the Greenland ice cores. While the Younger Dryas cold event is recorded in regional pollen data, the early Holocene events may have been too short to recognize with existing pollen data. To explain aeolian dune activity during these intervals, drier conditions are necessary, which are assumed during the short-lived stadial events. Raised landforms of coarser sediment would be more susceptible to desiccation and loss of vegetation compared to adjacent low-relief, finer-grained glacial lake plains. The results indicate that the geomorphological record of sand dunes and deflated surfaces from northwest Ohio, and likely at many other sites in the Great Lakes region, are sensitive indicators of abrupt and cooler-climate events, and can complement pollen records.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.yqres.2011.01.009.

References

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.

Alley, R.B., Agústsdóttir, A.M., 2005. The 8 k event: cause and consequences of a major Holocene abrupt climate change. Quaternary Science Reviews 24, 1123–1149.

Arbogast, A.F., Packman, S.C., 2004. Middle-Holocene mobilization of aeolian sand in western upper Michigan and the potential relationship with climate and fire. The Holocene 14, 464–471.

Arbogast, A.F., Wintle, A.G., Packman, S.C., 2002. Widespread middle Holocene dune formation in the eastern Upper Peninsula of Michigan and the relationship to climate and outlet-controlled lake level. Geology 30, 55–83.

Arbogast, A., Schaetzl, R.J., Hupy, J.P., Hansen, E.C., 2004. The Holland Paleosol: an informal pedostratigraphic unit in the coastal dunes of southeastern Lake Michigan. Canadian Journal of Earth Sciences 41, 1385–1400.

Bailey, R.M., Arnold, L.J., 2006. Statistical modeling of single grain quartz De distributions and an assessment of procedures for estimating burial dose. Quaternary Science Reviews 25, 2475–2502.

Baker, R.G., Maher, L.J., Chumbley, C.A., Van Zant, K.L., 1992. Patterns of Holocene environmental change in the midwestern United States. Quaternary Research 37, 379–389.

Barnett, P.J., 1992. Quaternary geology of Ontario. In: Thurston, P.C., Williams, H.R., Sutcliffe, R.H., Scott, G.M. (Eds.), Geology of Ontario. Ontario Geological Survey, Toronto, pp. 1010–1088.

Calkin, P.E., Feenstra, B.H., 1985. Evolution of the Erie-basin great lakes. In: Karrow, P.F., Calkin, P.E. (Eds.), Quaternary Evolution of the Great Lakes. Geological Survey of Canada, St. John's, Nfld, pp. 149–170.

Campbell, M.C., 2009. The evolution and chronology of the Lake Warren Shoreline in the Oak Openings Region of Ohio, USA. University of Toledo.

Dean, W.E., Forester, R.M., Bradbury, J.P., 2002. Early Holocene change in atmospheric circulation in the Northern Great Plains: an upstream view of the 8.2 ka cold event. Quaternary Science Reviews 21, 1763–1776.

Dreimanis, A., 1966. Lake Arkona-Whittlesey and Post-Warren radiocarbon dates from “Ridgetown Island” in southwestern Ontario. The Ohio Journal of Science 66, 582–586.

Dreimanis, A., 1977. Late Wisconsin glacial retreat in the Great Lakes Region. North America: Annals of the New York Academy of Sciences 288, 70–89.

Filion, L., 1984. A relationship between dunes, fire and climate recorded in the Holocene deposits of Quebec. Nature 309, 543–546.
Fisher, T.G., Smith, D.G., Andrews, J.T., 2002. Preboreal oscillation caused by a glacial Lake Agassiz flood. Quaternary Science Reviews 21, 873–878.
Fisher, T.G., Yansa, C.H., Lowell, T.V., Lepper, K., Hajdas, I., Ashworth, A.C., 2008. The chronology, climate, and confusion of the moorhead phase of glacial lake agassiz: new results from the Ojata Beach, North Dakota, USA. Quaternary Science Reviews 27, 1124–1135.
Fleitman, D., Mudelsee, M., Burns, S.J., Bradley, R.S., Kramers, J., Matter, A., 2008. Evidence for a widespread climatic anomaly at around 9.2 ka before present. Paleoceanography 23, PA1102.
Forman, S.L., Oglesby, R., Webb, R.S., 2001. Temporal and spatial patterns of Holocene dune activity on the Great Plains of North America: megadroughts and climate links. Global and Planetary Change 29, 1–29.
Forsyth, J.L., 1959. The beach ridges of northern Ohio. Ohio Division of Geological Survey, Information Circular 25, 1–10.
Galbraith, R.F., Roberts, R.G., Laslett, G.M., Yoshida, H., Olley, J.M., 1999. Optical dating of single and multiple grains of quartz from Jinmium rock shelter, northern Australia. Archaeometry 41, 339–364.
Hansen, E.C., Fisher, T.G., Arbogast, A.F., Bateman, M.D., 2010. Geomorphic history of low-perched, transgressive dune complexes along the southeastern shore of Lake Michigan. Aeolian Research 1, 111–127.
Hugenholtz, C.H., Wolfe, S.A., 2005. Biogeomorphic model of dunefield activation and stabilization on the northern Great Plains. Geomorphology 70, 53–70.
Hughen, K.A., Overpeck, J.T., Peterson, L.C., Trumbore, S., 1996. Rapid climate changes in the tropical Atlantic region during the last deglaciation. Nature 380, 51–54.
Keen, K.L., Shane, L.C.K., 1990. A continuous record of Holocene eolian activity and vegetation change at Lake Ann, east-central Minnesota. Geological Society of America Bulletin 102, 1646–1657.
Kilibarda, Z., Blockland, J., 2011. Morphology and origin of the Fair Oaks Dunes in NW Indiana, USA. Geomorphology 125, 305–318.
Leavitt, S.W., Panyushkina, I.P., Lange, T., Wiedenhoeft, A., Cheng, L., Hunter, R.D., Hughes, J., Pranschke, F., Schneider, A.F., Moran, J., Stieglitz, R., 2006. Climate in the Great Lakes region between 14, 000 and 4000 years ago from isotopic composition of conifer wood. Radiocarbon 48, 205–217.
Leverett, F., Taylor, F.B., 1915. The Pleistocene of Indiana and Michigan and the history of the Great Lakes. U.S. Geological Survey Monograph, 53. 527 pages.
Lewis, C.F.M., 1969. Late Quaternary history of lake levels in the Huron and Erie basins. Proceedings of the 12th conference on Great Lakes Research International Association of Great Lakes Research, pp. 250–270.
Lewis, C.F.M., King, J.W., Blasco, S.M., Brookes, G.R., Coakley, J.P., Croley, T.E.I., Dettman, D.L., Edwards, T.W.D., Heil, C.W.J., Hubeny, J.B., Laird, K.R., McAndrews, J.H., McCarthy, F.M.G., Medioli, B.E., Moore Jr., T.C., Rea, D.K., Smith, A.J., 2008. Dry climate disconnected the Laurentian Great Lakes. EOS Transactions 89, 541–542.
Loope, H.M., Loope, W.L., Goble, R.J., Fisher, T.G., Jol, H.M., 2010. Early Holocene eolian dune activity linked to stepped-lowering of glacial Lake Minong, eastern Upper Michigan, USA. Quaternary Research 74, 73–81.
Loope, W.L., Arbogast, A.F., 2000. Dominance of an 150-year cycle of sand-supply change in Late Holocene dune-building along the eastern shore of Lake Michigan. Quaternary Research 54, 414–422.
Lutz, B., Wiles, G., Lowell, T.V., Michaels, J., 2007. The 8.2-ka abrupt climate change event in Brown's Lake, northeast Ohio. Quaternary Research 67, 292–296.
Manny, B.A., Wetzel, R.G., Bailey, R.E., 1978. Paleolimnological sedimentation of organic carbon, nitrogen, phosphorous, fossil pigments, pollen, and diatoms in a hypereutrophic, hardwater lake: a case history of eutrophication. Polskie Archiwum Hydrogiologii 25, 243–267.
Mason, J.A., Swinehart, J.B., Goble, R.J., Loope, D.B., 2004. Late-Holocene dune activity linked to hydrological drought, Nebraska Sand Hills, USA. The Holocene 14, 209–217.
Miao, X., Mason, J.A., Swinehart, J.B., Loope, D.B., Hanson, P.R., Goble, R.J., Liu, X., 2007. A 10, 000-year record of dune activity, dust storms, and severe drought in the central Great Plains. Geology 35, 119–122.
Muhs, D.R., Bettis, E.A.I., Aleinikoff, J.N., McGeehin, J.P., Beann, J., Skipp, G., Marshall, B.D., Roberts, H.M., Johnson, W.C., Benton, R., 2008. Origin and paleoclimatic signifi cance of late Quaternary loess in Nebraska: evidence from stratigraphy, chronology, sedimentology, and geochemistry. Geological Society of America Bulletin 120, 1378–1407.
Olley, J.M., Pietsch, T., Roberts, R.G., 2004. Optical dating of Holocene sediments from a variety of geomorphic settings using single grains of quartz. Geomorphology 60, 337–358.
Pokorny, P., Ruzickova, E., 2000. Changing environments during the Younger Dryas climatic deterioration: correlation of aeolian and lacustrine deposits in southern Czech republic. GeoLines 11, 89–92.
Rasmussen, S.O., Andersen, K.K., Svensson, A.M., Steffensen, J.P., Vinther, B.M., Clausen, H.B., Siggaard-Andersen, M.-L., Johnsen, S.J., Larsen, L.B., Dahl-Jensen, D., Bigler, M., Rothlisberger, R., Fischer, H., Goto-Azuma, K., Hansson, M.E., Ruth, U., 2006. A new Greenland ice core chronology for the last glacial termination. Journal of Geophysical Research 111.
Rawlings III, J.E., Hanson, P.R., Young, A.R., Attig, J.W., 2008. Late Pleistocene dune construction in the Central Sand Plain of Wisconsin, USA. Geomorphology 100, 494–505.
Rebollal, M.B., Pérez-González, A., 2008. Inland aeolian deposits of the Iberian Peninsula: sand dunes and clay dunes of the Duero Basin and the Manchega Plain, Palaeoclimatic considerations. Geomorphology 102, 207–220.
Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J., Weyhenmeyer, C.E., 2009. IntCal09 and marine09 radiocarbon age calibration curves, 0–50, 000 years cal BP. Radiocarbon 51, 1111–1150.
Shane, L.C.K., 1987. Late-glacial vegetational and climatic history of the Allegheny Plateau and the till plains of Ohio and Indiana, USA. Boreas 16, 1–20.
Shane, L.C.K., Anderson, K.H., 1993. Intensity, gradients and reversals in late glacial environmental change in east-central North America. Quaternary Science Reviews 12, 307–320.
Stuiver, M., Reimer, P.J., 1993. Extended 14 C data base and revised CALIB 3.0 14 C age calibration program. Radiocarbon 35, 215–230.
Szabo, J.P., Bradley, K., Tevesz, M.J.S., 2003. Foundations from the past: clues to understanding late Quaternary stratigraphy beneath Cleveland, Ohio. Journal of Great Lakes Research 29, 566–580.
Thorson, R.M., Schile, C.A., 1995. Deglacial eolian regimes in New England. Geological Society of America Bulletin 107, 751–761.
Timmons, E.A., Fisher, T.G., Hansen, E.C., Eiasman, E., Daly, T., Kashgarian, M., 2007. Elucidating eolian dune history from lacustrine sand records in the Lake Michigan coastal zone, USA. The Holocene 17, 789–801.
Totten, S.M., 1985. Chronology and nature of the Pleistocene beaches and wave-cut cliffs and terraces, Northwestern Ohio. In: Karrow, P.F., Calkin, P.E. (Eds.), Quaternary Evolution of the Great Lakes: Geological Association of Canada Special Paper, 30, pp. 171–184.
Tsoar, H., Levin, N., Porat, N., Maia, L.P., Herrmann, H.J., Tatumi, S.H., Claudino-Sales, V., 1989. The effect of climate change on the mobility and stability of coastal sand dunes in Ceará State (NE Brazil). Quaternary Research 71, 217–226.
Villa-Garcia, R.A.R. 1989. Termino-glacial/proglacial depositional environments in Late Pleistocene sediments of Erie County, Pennsylvania. M.S. thesis, University of Akron, Akron, OH, 101 p.
Wasson, R.J., Nanninga, P.M., 1986. Estimating wind transport of sand on vegetated surfaces. Earth Surface Processes and Landforms 11, 505–514.
Williams, J.W., Shman, B., Bartlein, P.J., Diffenbaugh, N.S., Webb III, T., 2010. Rapid, time transgressive, and variable responses to early Holocene midcontinental drying in North America. Geology 38, 135–138.
Wolfe, S.A., Hugenholtz, C.H., 2009. Barchan dunes stabilized under recent climate warming on the northern Great Plains. Geology 37, 1039–1042.
Wolfe, S.A., Huntley, D.A., Ollerhead, J., 2004. Relict Late Wisconsinan dune fields of the northern Great Plains. Canada Geographie physique et Quaternaire 58, 323–326.
Yu, Z., Eicher, U., 1998. Abrupt Climate Oscillations during the last deglaciation in central North America. Science 282, 2235–2238.
Yu, S.-Y., Colman, S.M., Lowell, T.V., Milne, G.A., Fisher, T.G., Breckenridge, A., Boyd, M., Teller, J.T., 2010. Freshwater outburst from Lake Superior as a trigger for the cold event 9300 years ago. Science 328, 1262–1266.