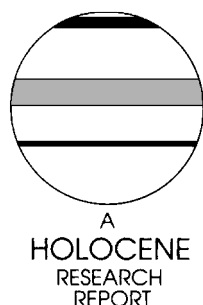


Middle-Holocene mobilization of aeolian sand in western upper Michigan and the potential relationship with climate and fire

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Abstract: A forested dunefield covers the Baraga Plains in western upper Michigan. The ages of five dunes, from across the dunefield, were determined by optically stimulated luminescence (OSL), employing the single-aliquot regenerative-dose (SAR) method on quartz grains. The results indicate that sand mobilization was restricted to the middle Holocene, at around 7 ka. Four environmental variables, rapid climatic oscillations, fire, strong winds and a dry climate are invoked as a combined cause of dune formation. This study provides further evidence for the wide extent of aeolian activity in the upper Midwest of North America during the middle Holocene.

Key words: Dunes, Michigan, middle Holocene, optically stimulated luminescence, OSL dating fire, aeolian sand.

Introduction

Sand dunes are common in central and eastern North America. In the past 25 years there has been a great deal of research on the age and origin of these landforms and related dunefields/sand sheets (e.g., Grigal *et al.*, 1976; Muhs, 1985; Madole, 1995; Keen and Shane, 1990; Arbogast, 1996; Ivester *et al.*, 2001). Much of this work is associated with regional palaeoenvironmental reconstruction because dunes are sensitive landforms that are good indicators of climate change (Heidinga, 1984). While most dunes are presently stable, there is evidence of frequent and often widespread mobilization of aeolian sand during the late Quaternary.

In general, dunes in the humid northern and eastern parts of North America are covered by forest (Keen and Shane, 1990; Ivester *et al.*, 2001), whereas those in the semi-arid/sub-humid regions (e.g., the Great Plains) are stabilized by grass (Arbogast, 1996). This vegetation association is especially important when viewed in the context of the inherent ease with which any particular dunefield mobilizes. Muhs and Maat (1993), for example, demonstrated that dunes in the Great Plains could become active even with a subtle decrease in annual precipitation. This ease of mobilization is supported through widespread findings that dunes in the Great Plains activated frequently in the late Holocene (Muhs, 1985; Madole, 1995; Arbogast, 1996). In contrast to grassland dunefields,

dunes in forested regions are farther from the threshold of activity because they lie within more humid climates. For example, Ivester *et al.* (2001) demonstrated that riverine dunes in Georgia were mostly formed by westerly winds during the Wisconsin glaciation, specifically during oxygen isotope stage 2. These dunes have been essentially stable throughout the Holocene, with only crests being reworked in a minor way.

In the upper Midwest of the USA and in south-central Canada, forested dunefields occupy deglaciated terrain close to the prairie/forest boundary (Webb *et al.*, 1983). In semi-arid/sub-humid Manitoba, dunes in the Brandon sand hills became active several times in the late Holocene due to recurring drought (Wolfe *et al.*, 2000). Dunes in the Minot dunefield in North Dakota have a similar late-Holocene history (Muhs *et al.*, 1997). Forested dunes to the east, in the more humid region of the upper Midwest, generally appear to be older. Dunes in central Minnesota formed during the dry, warm Altithermal/Hypsithermal interval of the middle Holocene (~8000–5000 yrs BP) when small lakes dried and lacustrine sediments were deflated (Grigal *et al.*, 1976; Keen and Shane, 1990). During this period, the vegetation shifted from coniferous/hardwood forest to grass (Bartlein and Whitlock, 1993). The dunes have been stable throughout the late Holocene because the environment became more mesic, lake levels rose, and forest migrated back into the region (Grigal *et al.*, 1976; Keen and Shane, 1990). Dunes also formed in the Newberry dunefield in eastern upper Michigan during the middle Holocene (Arbogast *et al.*, 2002). In contrast to

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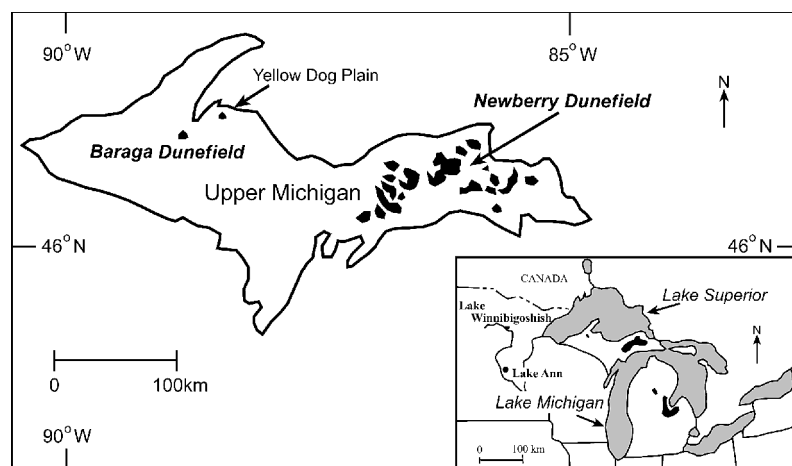


Figure 1 Location of the Baraga dunefield in the western upper peninsula of Michigan. This dunefield is one of several that are found in non-coastal regions within the state.

the Minnesota dunes, which activated solely due to increased middle-Holocene aridity (Keen and Shane, 1990), the Newberry dunefield may have mobilized because of the combined effects of a slightly drier climate and a groundwater decline brought about by isostatically driven adjustments in Lake Michigan and Lake Superior (Arbogast *et al.*, 2002). In both Minnesota and eastern upper Michigan, prevailing winds were northwesterly during dune construction (Grigal *et al.*, 1976; Keen and Shane, 1990; Arbogast *et al.*, 2002).

The Baraga dunefield, in western upper Michigan (Figure 1), is a potential source of important palaeoenvironmental information because it lies between the Newberry dunefield (Arbogast *et al.*, 2002) and the Minnesota dunefields (Grigal *et al.*, 1976; Keen and Shane, 1990). This paper focuses on the history of the Baraga dunefield, and presents a chronology of aeolian activity in the dunefield established by dating sand samples using optically stimulated luminescence (OSL).

Study area

The Baraga dunefield is located in Baraga County, western upper Michigan (Figure 1), and covers about 20 km² (~ about 60%) of a broad upland that is locally called the 'Baraga Plains'. The Sturgeon River borders the southern and western side of the Plains (Figure 2), and occupies a deep gorge (~61 m) along the western boundary. The origin of the Baraga Plains has not been thoroughly reconstructed, but appears to be linked to glacial/lacustrine processes. The region was last glaciated ~11850 yrs BP during the Greatlakean advance by the Keweenaw Bay sublobe of the Superior lobe (Peterson, 1986). Subsequently, outwash may have been deposited in the study area near the ice margin as it retreated into the Superior basin between ~11 ka and 10.7 ka BP. Following this retreat, ice readvanced to a point immediately north/northeast of the Baraga Plains during the Marquette advance at ~10 ka BP (Lowell *et al.*, 1999). Although this ice advance was short-lived (~200 yrs?), it was sufficiently long for a small proglacial lake, glacial Lake Baraga, to develop. This lake apparently covered the study area (Doonan and Byerlay, 1973), and lacustrine sediments were probably deposited until the lake drained about 9.8 ka BP. Sometime later the dunes formed, which, according to the northwest orientation of their parabolic form, must have resulted from northwesterly winds.

The climate of the Baraga region is classified as cool, humid continental (Barrett *et al.*, 1995), and it is affected by its close proximity to Lake Superior. The 'lake effect' predominantly

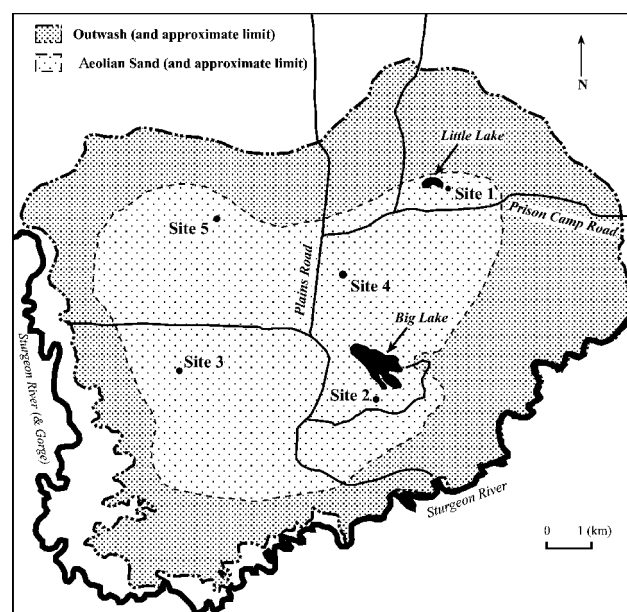


Figure 2 Surface geology and study site locations in the Baraga dunefield.

results in abundant snowfall, but also moderates annual temperatures relative to more inland locations (Sommers, 1984). During the winter the average high temperature is -9.4°C, whereas the mean summer maximum is 24.5°C. Average precipitation is ~86 cm, of which ~52 cm falls between April and September (NOAA/NCDC, 1961–90). Although modern winds are multidirectional due to seasonal variation, the dominant wind is from the northwest (Eichenlaub *et al.*, 1990). According to the general land office survey conducted from 1846 to 1853, the Baraga Plains were covered with jack pine (*Pinus banksiana*) immediately prior to settlement. The soils of the region belong to the Grayling series, which is a Typic Udipsamment (i.e., weakly developed in a seasonal temperature regime; Barrett *et al.*, 1995).

Methods

An extensive field survey was conducted after studying aerial photographs of the Baraga region. No exposures were found, and so the sand deposits were investigated at 15 sites using a

bucket auger. On the basis of this work, 11 samples were collected for age determination from five dunes located across the dune field (Figure 2). One sample was a small piece of charcoal (Site 2), which was processed for radiocarbon dating via accelerator mass spectrometry (AMS) by the Institute for Arctic and Alpine Research in Boulder, Colorado. The remaining 10 samples were of sand for dating by OSL (Aitken, 1998) at the Aberystwyth Luminescence Laboratory. Although no obvious unconformities were present in the dunes, two samples were collected from different depths at each site to establish if there was more than one phase of sand deposition (Figure 3). One of these samples was always taken immediately below the solum in a hand-dug pit at ~1.5 m, and collected by driving PVC pipe into the pit wall with a mallet. A lower sample was collected toward the base of the dune using a bucket auger that was covered by an opaque plastic sheet. At one site (Site 5), the lower sample was collected from a soil pit because the deposits were thin.

Preparation of the sand samples for luminescence dating took place in the laboratory under subdued red lighting. The samples were treated with hydrochloric acid (10%vol/vol) to remove carbonates, and with hydrogen peroxide (6%) to remove organic material. After the desired grain-size fraction (180–212µm) had been obtained via dry sieving, mineral separation was performed with heavy liquids (sodium polytungstate) of two densities, 2.63 gcm⁻³ and 2.70 gcm⁻³, thereby removing as many feldspar grains and heavy minerals as possible. The mineral fraction of density >2.63 and <2.70 gcm⁻³ was immersed in 40% hydrofluoric acid (HF) for 60 minutes, and then washed with conc. hydrochloric acid to remove fluorides. The etched material was resieved to extract the grains >180µm, thereby removing the smaller quartz grains and any partially dissolved feldspars. The aim of these procedures is to minimize feldspar contamination and obtain quartz grains for luminescence dating.

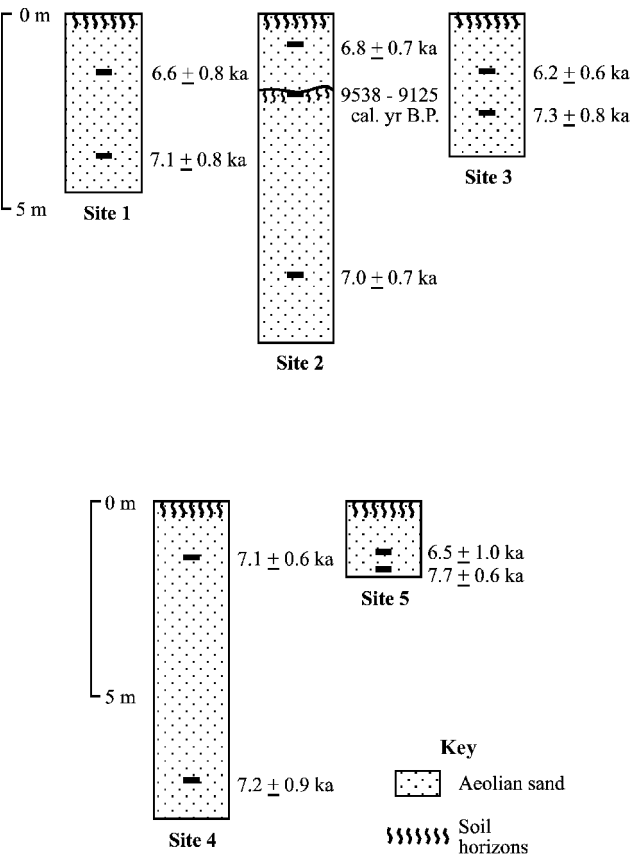


Figure 3 Aeolian sand thickness and OSL ages at the five study sites.

The single-aliquot regenerative-dose (SAR; Murray and Wintle, 2000) technique was employed to date the quartz grains. This method incorporates a test dose to monitor changes in luminescence sensitivity, and has provided OSL ages that correlate with calibrated radiocarbon ages for the past 5000 yrs (Murray and Clemmensen, 2001), and was also employed to determine the age of the Newberry dunefield in the eastern Upper Peninsula (Arbogast *et al.*, 2002). The quartz grains were attached to 1 cm aluminum discs using a silicone oil spray, providing each disc with approximately 1500 grains with a total weight of around 9 mg. The equivalent dose (*D_e*) was determined on 24 separate aliquots for each sample, either using preheats from 160–300°C for 10 s, with three aliquots for each preheat temperature, or with preheats from 160–260°C for 10 s, with four aliquots for each temperature. A cut-heat of 160°C was applied for the test dose signals. The OSL signals were taken on an automated Risø TL/OSL Reader, and irradiations were performed using the integral ⁹⁰Sr-⁹⁰Y beta source. Four regeneration doses of 0, 9.8, 19.6 and 39.2 Gy were used for all samples, and the test dose was 4.9 Gy. Stimulation was provided by blue light-emitting diodes (peak emission 470 ± 30 nm) while the aliquots were held at 125°C, and the signals were detected with an EMI 9635Q photomultiplier tube. UV filters (Hoya U-340) were employed on the detection system to exclude the emission of the diodes and to pass the 365 nm OSL peak emission.

Aliquots were screened for feldspar at the end of the SAR procedure, using infrared stimulated luminescence (IRSL), as suggested by Spooner and Questiaux in 1989. It is necessary to reject contaminated aliquots because any potassium present in the grains leads to a higher dose rate, resulting in higher *D_e*s than quartz grains. However, some feldspars are prone to anomalous fading, resulting in low *D_e*s. Thus, feldspar contamination is likely to produce broader distributions of *D_e* compared with quartz-only samples. Aliquots were given a small dose (4.9 Gy) and the IRSL signals were recorded after a cut-heat of 160°C. If the signal intensity was more than twice the background level the aliquot was rejected from the *D_e* analysis. The response to infrared stimulation varied between samples so that the rejection ranged from 0 to 25%. Narrow *D_e* distributions (illustrated by Aber-38/7; Figure 4a) were obtained for the samples, indicating that the sand was well bleached at deposition and that there was no corruption of the quartz data by feldspar. The aliquots also produced similar OSL test dose intensities (Figure 4b), providing further evidence for aliquot purity.

The OSL age was calculated on the weighted mean *D_e* and error on all quartz aliquots unless there was an obvious pre-heat plateau (the *D_e* remained at the same level over a range of preheat temperatures; Figure 4c), and then only the aliquots within the plateau were accepted. A separate sample was collected in the field for the determination of the environmental dose rate. This was achieved using thick-source alpha counting on a Daybreak 582 Alpha Counter and beta counting on a Risø GM-25-5 multichannel beta counter. Water content was also measured on these samples, and it ranged from 2 to 5% (wt. of water/wt. of dry sediment). A water content of 5 ± 5% was therefore chosen for the calculation of the attenuation in the environmental dose rate in all samples. The data for the dose rates and the *D_e*s are given in Table 1.

Sites, samples and results

The Baraga dunes generally consist of reddish sands, which are relatively well sorted and range in texture from fine to coarse. The deposits underlying the dunes are typically less well sorted

and include coarse sands, granules and pebbles. No buried soils were found below the aeolian sands, and there was no sharp contact between the two types of sand deposits. The lower sands were not studied to determine their origin, but it is inferred from the glacial history of the region (e.g., Doonan and Byerly, 1973), that they are either outwash or lacustrine deposits. It is also assumed, given the gradational nature of the boundary between the sand deposits, that the outwash/lacustrine sands were the source material for the aeolian dunes. The location of the five dunes (Figure 2) and the sample depths (Figure 3) are given below, together with the OSL ages.

Site 1

The dune is ~ 4.5 m high, and is located in the northeastern part of the study area, ~ 100 m east of Little Lake. Sand samples were collected at 1.5 m and ~ 3.5 m depths, and yielded OSL ages of 6.6 ± 0.8 ka and 7.10 ± 0.8 ka respectively (Aber-38/1 and Aber-38/2).

Site 2

The dune is located in the southeastern part of the study area, ~ 200 m south of Big Lake. At 8.5 m high, this is the tallest dune investigated in this study. A poorly developed buried soil was found at a depth of ~ 2 m on the dune slip face. The soil was ~ 5 cm thick with a diffuse 2Ab horizon overlying a 2C horizon. A small piece of charcoal (~ 20 mg) was retrieved from the soil and provided an AMS date of 8370 ± 110 yr BP (CURL-5518; 9538–9125 cal. yr BP).

Sand samples were collected above and below the palaeosol at 1.5 m and ~ 6.5 m depths, and yielded OSL ages of 6.8 ± 0.7 ka and 7.0 ± 0.7 ka respectively (Aber-38/3 and Aber-38/4).

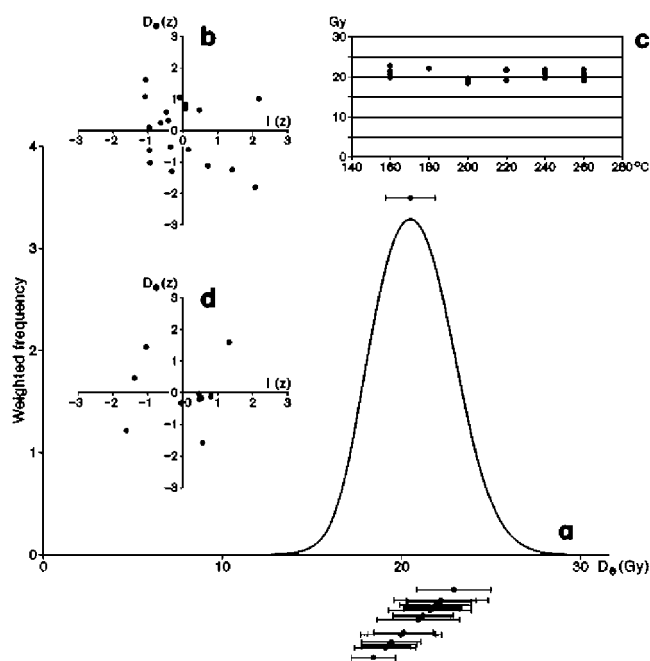


Figure 4 OSL data obtained in this study. (a) Weighted frequency distribution of the D_e for Aber-38/7, with the weighted mean shown above and individual aliquot D_e s shown below in increasing magnitude. (b) Standardized plot of D_e versus test dose OSL intensity for quartz aliquots of sample Aber-38/7; most aliquots (89%) fall within ± 2 standard deviations. (c) D_e plotted against preheat temperature for the same sample, displaying a long plateau from 160 to 260°C. (d) Standardized plot of the weighted mean D_e versus the mean test dose OSL intensity for all samples.

Site 3

This site is located in the western area of the dunefield, ~ 3 km east of the Sturgeon River. The dune is 3.5 m tall at the crest, and samples were collected at 1.5 m and ~ 2.5 m depths. The OSL ages were 6.2 ± 0.6 ka for the upper sample (Aber-38/5) and 7.3 ± 0.8 ka for the lower sample (Aber-38/6).

Site 4

This dune is one of the larger dunes in this study, at ~ 8 m tall. It is located near the centre of the dunefield, less than 2 km N/NW of Big Lake. Sand samples were collected at 1.5 m and 7.0 m depths, and yielded OSL ages of 7.1 ± 0.6 ka and 7.2 ± 0.8 ka respectively (Aber-38/7 and Aber-38/8).

Site 5

The site is located in the northwest area of the dunefield, ~ 3 km W/NW of Site 4. This was the smallest dune that was investigated, being only ~ 2 m tall. Both sand samples were therefore collected from a soil pit, at depths of 1.5 m and 1.75 m. The OSL age for the upper sample was 6.5 ± 1.0 ka, and the lower sample yielded an age of 7.7 ± 0.6 ka (Aber-38/9 and Aber-38/10).

Discussion

The dunefield is contained within the area of outwash/lacustrine deposits, and there is no sharp contact, or buried soil, between the lower deposit and the aeolian sands. Since dune height generally increases across the dune field from NW to SE, this supports the assumption that the aeolian sand was derived from the underlying outwash/lacustrine deposits.

The OSL ages for the Baraga dunes indicate that aeolian activity occurred during the middle Holocene from 7 to 6 ka. Table 1 and Figure 4d show that there is very little difference in the D_e from sample to sample and from dune to dune, giving a mean D_e of 20.6 ± 1.2 Gy. The dose rates are also very similar, and this also indicates a similar mineralogy for all the dunes. Thus, it appears that our dates reflect a restricted period of dune formation at ~ 7 ka. A discrepancy exists between the OSL ages and the AMS date (~ 9.2 ka) on the charcoal from the palaeosol at Site 2. The OSL ages for the sand above and below this palaeosol are virtually identical, suggesting that the charcoal could have been derived from older deposits and was blown onto the dune; thus, it would not represent *in-situ* material and should not be used to date the palaeosol. Such a pattern of reworked charcoal has been seen elsewhere in palaeosols within interior dunes within Michigan. Arbogast (unpublished data) obtained an age of ~ 39 ka from charcoal at a depth of ~ 1.5 m in a dune in northern lower Michigan. This date clearly implies reworking of 'old' charcoal by the wind, otherwise it implies that the dune was overridden by ice and not modified during the late-Wisconsin glacial advance. The palaeosol at Site 2 in the Baraga dunes is nevertheless significant because it clearly indicates that a period of stability occurred at this site as the dune formed. This period of stability was clearly of short duration, as the palaeosol is weakly developed. Such a conclusion is supported by the finding that similar levels of palaeosol development occurred in ~ 150 yrs in coastal sand dunes along Lake Michigan (Loope and Arbogast, 2000).

Overall, the evidence suggests that the Baraga dunes were constructed in the middle Holocene and there was no remobilization of aeolian sand in the late Holocene. The period of aeolian activity falls within the range of OSL ages obtained for the Newberry dunes (7–5.5 ka) in the eastern Upper Peninsula

Table 1 Dosimetry and calculated OSL ages

Sample number (Aber-)	Sample depth (m)	α count rate (cts/ks/cm ²)	U (ppm)	Th (ppm)	Sealed/unsealed α count	K %	β dose rate (Gy/ka)	γ dose rate (Gy/ka)	Cosmic ray dose rate (Gy/ka)	Total dose rate (Gy/ka)	D _e (Gy)	OSL age (ka)
38/1	1.5	0.320 ± 0.005	1.50 ± 0.14	4.01 ± 0.45	1.01 ± 0.03	2.55	2.07 ± 0.13	0.95 ± 0.06	0.17 ± 0.02	3.19 ± 0.14	21.1 ± 2.4	6.6 ± 0.8
38/2	3.5	0.250 ± 0.005	1.27 ± 0.12	2.82 ± 0.39	1.04 ± 0.03	2.42	1.92 ± 0.12	0.83 ± 0.05	0.14 ± 0.01	2.89 ± 0.13	20.5 ± 2.1	7.1 ± 0.8
38/3	1.5	0.431 ± 0.007	1.88 ± 0.20	5.86 ± 0.64	1.02 ± 0.04	2.38	2.04 ± 0.13	1.04 ± 0.07	0.17 ± 0.02	3.25 ± 0.14	22.2 ± 2.1	6.8 ± 0.7
38/4	6.5	0.286 ± 0.005	1.49 ± 0.14	3.08 ± 0.44	1.05 ± 0.04	2.43	1.96 ± 0.12	0.87 ± 0.06	0.10 ± 0.03	2.94 ± 0.14	20.4 ± 2.0	7.0 ± 0.7
38/5	1.5	0.340 ± 0.006	1.29 ± 0.19	5.29 ± 0.61	0.96 ± 0.03	2.41	1.97 ± 0.12	0.95 ± 0.06	0.17 ± 0.02	3.10 ± 0.14	19.2 ± 1.7	6.2 ± 0.6
38/6	2.5	0.263 ± 0.005	1.41 ± 0.12	2.70 ± 0.39	1.03 ± 0.04	2.24	1.81 ± 0.11	0.80 ± 0.05	0.15 ± 0.02	2.77 ± 0.12	20.2 ± 1.9	7.3 ± 0.8
38/7	1.5	0.264 ± 0.004	1.03 ± 0.13	4.00 ± 0.42	1.00 ± 0.04	2.34	1.86 ± 0.12	0.85 ± 0.05	0.17 ± 0.02	2.89 ± 0.13	20.4 ± 1.4	7.1 ± 0.6
38/8	7.0	0.302 ± 0.005	1.47 ± 0.15	3.60 ± 0.47	1.02 ± 0.04	2.27	1.86 ± 0.12	0.86 ± 0.06	0.09 ± 0.02	2.81 ± 0.13	20.3 ± 2.2	7.2 ± 0.8
38/9	1.5	0.267 ± 0.005	1.22 ± 0.14	3.42 ± 0.43	0.97 ± 0.03	2.36	1.88 ± 0.12	0.84 ± 0.05	0.17 ± 0.02	2.90 ± 0.13	18.7 ± 2.9	6.5 ± 1.0
38/10 ¹	1.75								0.17 ± 0.02	2.90 ± 0.13	22.4 ± 1.6	7.7 ± 0.6

¹ No dosimetry sample was collected for Aber-38/10, and so the dosimetry data from Aber-38/9 was used to allow for an age to be determined.

(Arbogast *et al.*, 2002), as well as corresponding with dune formation in Minnesota (Grigal *et al.*, 1976; Keen and Shane, 1990). Given that the Baraga dunefield lies between these regions, these correlations suggest that there was a previously unreported arc of dune formation across the upper Midwest into the core of the Great Lakes region during the middle Holocene.

Although the OSL ages indicate that the Baraga dunes formed during the middle Holocene, the cause for their mobilization is far less clear because they lie within a long-recognized humid and geomorphically stable region. Most importantly, there is no distinctive environmental ‘smoking gun’, such as intensive drought or deglaciation, which can be directly linked to dune formation. It is possible that the dunes began to form shortly after glacial Lake Baraga drained ~9.8 ka BP (Doonan and Byerlay, 1973). The AMS date of ~9.3 cal. ka BP derived from a small piece of charcoal in the palaeosol at site 2 appears to support a deglacial theory for sand mobilization. However, this isolated charcoal fragment only indicates that fire occurred during the early Holocene, while all 10 OSL ages indicate that dunes formed from 7 to 6 ka. A deglacial hypothesis would require the continuation of aeolian activity for nearly 4 ka. Such a long duration seems unlikely in the context of a forested environment, and so we reject a deglacial/early-Holocene hypothesis for the origin of the dunefield.

One variable that may be related to the formation of the Baraga dunefield is the increased warming and drying that is widely recognized in the upper Midwest during the middle Holocene. In central Minnesota, for example, average July temperature was apparently ~2°C higher and annual precipitation was ~100 mm less (Bartlein and Whitlock, 1993). This kind of climate change is linked to the formation of dunefields in Minnesota (Grigal *et al.*, 1976; Keen and Shane, 1990), which formed in the lee of small lake basins between 8000 and 5000 yrs BP when their lacustrine sediments were exposed and deflated during the warmer/drier interval. These dunefields subsequently stabilized when the climate became more mesic, lake levels rose, and forest migrated back into the region.

There is evidence that the middle-Holocene climate in upper Michigan was drier than it is today, and that this drying had a more pronounced effect on coarse-textured substrates such as the Baraga Plains. According to Booth *et al.* (2002), for example, plant and macrofossil data from Mud Lake in the Keewenaw Peninsula (Figure 1) indicate that the lake was surrounded by a jack pine and spruce forest from 9.6 to 8.3 cal. ka BP. Subsequently, there was a dramatic increase in the abundance of eastern white pine (*P. strobus*), which is a species that is adapted to drier climates and occupies sandy surfaces. This species dominated the vegetation around Mud Lake until 4.8 cal. ka BP when the climate became more mesic (Booth *et al.*, 2002). Additional evidence for a drier middle-Holocene climate exists at the Yellow Dog Plains, which are ~50 km northeast of the Baraga dunefield (Figure 1). According to Brubaker (1975), the dominant vegetation in this region has been jack pine since ~9 ka BP; this species represents an edaphic climax on coarse sandy substrates that are relatively dry and sterile. On-finer textured, sandy substrates near the plains (tills, for example), eastern white pine dominated the vegetation from ~8 to 5 ka BP in a manner consistent with Mud Lake (Booth *et al.*, 2002). Brubaker (1975) also noted a quantitative increase in grass pollen on the Yellow Dog Plains at ~8.4 ka BP, suggesting that there were fewer trees between 9 and 5 ka BP than in the modern forest. Recent research by Delcourt *et al.* (2002) indicates that middle-Holocene drying in upper Michigan was probably caused by the more frequent influx of dry Pacific air, resulting from zonal atmospheric flow.

Although the pollen data clearly indicate that the middle-Holocene climate of western upper Michigan was drier than

the modern one, the question remains: was it sufficiently dry to cause extensive mobilization of aeolian sand through a massive reduction in vegetation? The evidence seems to suggest that it was not. Davis *et al.* (2000), for example, employed modern pollen analogues and their relationship with climatic variables to reconstruct Holocene climate in the Great Lakes region. Results from this study supported earlier research by Bartlein *et al.* (1984) indicating that the middle-Holocene climate of upper Michigan was only $\sim 1^{\circ}\text{C}$ warmer with $\sim 9\%$ less annual precipitation than the modern climate. Although this slightly drier climate caused some adjustments in the vegetation of western upper Michigan, the region was nevertheless sufficiently humid to support forest (Brubaker, 1975; Booth *et al.*, 2002). Moreover, the middle-Holocene climate of upper Michigan was apparently more mesic than the modern climate of central Minnesota where dunes are now stable. In this context, it is important to note that the Minnesota dunes formed only because sandy lacustrine sediments were exposed and deflated when the adjacent lakes dried (Grigal *et al.*, 1976; Keen and Shane, 1990). The Baraga Plains, in contrast, have been an upland outwash plane that has apparently been surrounded by forest (Brubaker, 1975; Booth *et al.*, 2002) since glacial Lake Baraga drained ~ 9.8 ka BP (Doonan and Byerly, 1973). Overall, it is difficult to imagine that only a subtle change to a slightly warmer and drier climate reduced vegetation sufficiently on the Baraga Plains to cause extensive mobilization of aeolian sand. Thus, we reject increased middle-Holocene warming and drying as the sole cause for dune formation on the Baraga Plains; nevertheless, it probably contributed to the mobilization of aeolian sand.

An additional climatic variable may have aided landscape destabilization during the early-to middle-Holocene transition. A rapid climate oscillation produced a major cold and dry event in the circum-North Atlantic region at ~ 8.2 cal. ka BP (Alley *et al.*, 1997; Klitgaard-Kristensen *et al.*, 1998; von Grafenstein *et al.*, 1998). This event is hypothetically linked to the rapid discharge of fresh glacial meltwater from proglacial Lakes Agassiz and Ojibway through Hudson Bay into the Labrador Sea (Barber *et al.*, 1999). According to Dean *et al.* (2002), this short-lived event has been identified at Elk Lake in Minnesota through various palaeoclimate proxies (e.g., dust as % Al and % Si, increased varve thickness) that also indicate a rapid and dramatic increase in wind activity, particularly westerly winds. This period of strong winds is partially consistent with palaeoclimate simulations (Kutzbach and Guetter, 1986; Kutzbach, 1987; COHMAP members, 1988) and it persisted until about 5.3 cal. ka BP at Elk Lake (Bradbury *et al.*, 1993). Given the obvious connection between dune formation on the Baraga Plains and westerly air flow, the OSL ages from the Baraga dunefield suggest that mobilization of aeolian sand in this region is somehow related to the windy period documented at Elk Lake (Dean *et al.*, 2002). The Baraga Plains are perched above the adjacent Sturgeon Gorge (Figure 1), which would have allowed the strong westerlies unimpeded access into the region (Barrett *et al.*, 1995).

Before strong winds can mobilize aeolian sand, however, vegetation must somehow be reduced beyond a critical threshold. A potential destabilizing variable in forested dunefields is fire (e.g., Filion *et al.*, 1991). Although there is no direct proof supporting the role of fire in the Baraga dunefield in the middle Holocene, there is circumstantial evidence suggesting that fire may have played a role in the mobilization of aeolian sand. According to Jacobson *et al.* (1987), the dominance of pine and birch within the upper Midwest in the early Holocene suggests that fire was more prevalent during that period of time than it was later. Evidence for fire in the early and mid-

dle Holocene in the western Upper Peninsula is found in the deposits of Mud Lake (Figure 1). Macroscopic charcoal fragments and charred macrofossils occur at the base of pollen zone P-1 (jack pine-spruce zone, ~ 9.6 cal. ka BP) and charred macrofossils in pollen zone P-2 (eastern white pine zone, ~ 8.3 cal. ka BP), suggesting local fires at these times (Booth *et al.*, 2002). Microscopic charcoal was also extracted from these sediments, with increased amounts found in the deposits of ~ 9 cal. ka BP and between 7 and 6 cal. ka BP. The latter period correlates with the OSL ages for the Baraga dunes. Additional evidence for increased incidence of middle-Holocene fire is reported by Delcourt *et al.* (2002), who discovered high concentrations of charcoal in pond sediments between 8000 and 5300 cal. yr BP in eastern upper Michigan. According to Delcourt *et al.* (2002), fire occurred more frequently during the middle Holocene because fire-adapted, xeric tree species such as jack (*P. banksiana*) and/or red pine (*P. resinosa*) occupied upland sandy sites at that time.

This relationship between fire and vegetation is significant in the context of the Baraga dunefield because jack pine covered the dunes immediately prior to settlement; indeed, it was the only substantial area of jack pine in Baraga County (Barrett *et al.*, 1995). Given that jack pine has existed on the Yellow Dog Plains (Figure 1) throughout the Holocene (Brubaker, 1975), which is geomorphically and texturally consistent with the Baraga Plains, it has probably been the dominant vegetation on the Baraga Plains as well in the past 10000 yrs. If this association is valid, and fire was indeed more common in the upper Midwest during the drier middle Holocene as research (Jacobson *et al.*, 1987; Delcourt *et al.*, 2002) suggests, then the Baraga Plains would have been a prime locale for frequent, intense fires.

The role of fire as a destabilizing variable on the Baraga Plains is questionable because, according to W.L. Loope (personal communication), fires in contemporary forests increase ground cover through sprouting and rapid establishment of seedlings associated with fire-adapted species. However, activation of dunes east of Hudson Bay in the late Holocene is linked to fires that occurred during cold/dry intervals that precluded establishment of stabilizing seedlings and assorted ground cover (Filion *et al.* 1991). Given the apparent intensity of the 8.2 cal. ka BP event, perhaps this cold/dry interval contributed to an initial destabilization of the Baraga landscape in a similar manner. The impact of rapid, short-term climate changes, such as those described by Broecker and Hemming (2001), is not generally observed in the pollen record, because the scale of resolution is insufficient. Although the pollen records for upper Michigan indicate a forested environment in the early and middle Holocene, the 8.2 cal. ka BP event, in combination with fire, may have caused a reduction in the vegetation cover. Following this event, the region was apparently warmer, drier and windier until ~ 5 cal. ka BP (Dean *et al.*, 2002), with an increased incidence of fire (Booth *et al.*, 2002; Delcourt *et al.*, 2002). The strong winds may also have caused devastation by windthrow (e.g., Schaetzl, 1986), resulting in bare hollows, thus providing the winds with easy access to the dry sands. We therefore propose that a combination of rapid climate change, fire, strong winds and a drier middle-Holocene climate may have led to sand mobilization and the formation of dunes.

Conclusion

OSL dating of five dunes from the Baraga Plains in western upper Michigan provides evidence for a limited period of sand movement in the middle Holocene. Parabolic dunes were

constructed by northwesterly winds around 7 ka, and the local outwash/lacustrine deposits were the most probable source material. The cause for this mobilization of aeolian sand is not obvious because no direct evidence exists for a primary destabilizing environmental variable. Although the middle-Holocene climate was somewhat warmer and drier, it does not appear to have been sufficiently so to have reduced vegetation cover in a landscape that lay within a documented forested region. The Baraga dunefield, therefore, appears to be an example of geomorphic activity related to ephemeral environmental conditions that leave no trace in regional pollen records.

Our hypothesis for dune formation relies on palaeoenvironmental evidence from other sites. Elk Lake in Minnesota indicates that strong winds occurred in the middle Holocene beginning with the 8.2 cal. ka BP cold/dry event. Sites in the Upper Peninsula attest to increased fire activity during the middle Holocene, associated with jack pine vegetation on sandy substrates. The Baraga Plains were probably covered by jack pine, and were probably subject to fire too. We propose that rapid climate change at the end of the early Holocene may have initiated landscape instability, and, in combination with fire and windthrow, resulted in vegetation reduction. Deflation may have started at this time, and the warmer and drier climate that followed may have continued to support sand mobilization alongside the influences of fire and strong winds. These influences decreased by ~6 ka and vegetation was able to recover sufficiently to stabilize the dunes. This hypothesis is based on circumstantial evidence, but we can see no other way of explaining sand mobilization in the middle Holocene. It implies that the Baraga Plains, and similar sandy sites, are vulnerable to any future rapid environmental changes. We hope our research stimulates others to investigate the dynamic evolution of the Michigan landscape in the Holocene, and to produce conclusive evidence to either support or refute the conjectures offered in this paper.

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