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ARTICLE

Holocene, silty-sand loess downwind of dunes in Northern Michigan, USA

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ABSTRACT

In Michigan's Upper Peninsula, sand dunes are widespread on the sandy floor of former Glacial Lake Algonquin, and many of the nearby uplands also have thin mantles of loess. Previous work concluded that these dunes formed during the early Holocene, long after the lake had drained. Where these dunes have migrated against bedrock uplands, many have accreted into larger dune complexes. South and east of these complexes, uplands are mantled with well-sorted sediment, comparatively rich in finer sands and much like the thin, locally sourced loess deposits in Wisconsin and Michigan. Near the dunes, this loess is typically 50–75 cm thick, and rich in very fine sands; presumably much of this sand was deposited as short-range "blow-over" while the dunes were forming. The loess thins to ≈45 cm and becomes siltier on sites farther downwind, to the southeast. Because the dune complexes contain almost no silt, the silt in the loess was likely generated by deflation of saltating sands on the lake plain, transported in suspension, and deposited generally uniformly across the forested uplands, as indicated by spatial trends in silt contents. Periodic Holocene drought may have thinned the forest and helped to intermittently facilitate this type of eolian activity.

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Introduction

Research on sand dunes often focuses on processes of eolian transport and deposition, including identification of the sand source(s) and geochronometric assessment of the eolian interval to better interpret paleoenvironments (e.g. Anderson & Walker, 2006; Arbogast & Loope, 1999; Colgan, Amidon, & Thurkettle, 2017; Johnson et al., 2019; Kilibarda & Kilibarda, 2016; Miao, Hanson, Wang, & Young, 2010; Rawling, Hanson, Young, & Attig, 2008). The sandy bed of Glacial Lake Algonquin (GLA) in Michigan's Upper Peninsula (UP) is dotted with hundreds, if not thousands, of small dunes; most rise less than 3–4 m above the former lake floor. The origin of the lacustrine sands, and subsequently, the dunes, can be traced to the crystalline bedrock of the Canadian Shield

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and the Cambrian sandstones of the Lake Superior area, both of which were eroded by the Laurentide Ice Sheet and deposited into GLA. The last sands were deposited into the lake and nearby areas by meltwater when the ice margin was at the Munising moraine, immediately south of the modern Lake Superior shoreline, at ≈11.4 ka BP (Blewett, 1994; Blewett, Drzyzga, Sherrod, & Wang, 2014; Blewett & Rieck, 1987; Lowell, Larson, Hughes, & Denton, 1999). Today, much of this landscape is the vast, sandy plain known as the Seney Swamp, with its myriad scattered, relict and stabilized, dunes (Arbogast, Wintle, & Packman, 2002; Drobyshev, Goebel, Hix, Corace, & Semko-Duncan, 2008; Heinselman, 1965; Schaetzl et al., 2013).

Studies that have reported ages for the dunes disagree as to their period of final stabilization. An early study of eight dunes by Arbogast et al. (2002) suggested final stabilization in the mid Holocene, between 5.1 and 6.8 ka. A more extensive study by Loope et al. (2012) on 57 dunes established an earlier period of eolian activity, generally between 8 and 10 ka. Pollen data from nearby lakes indicate that, around this (later) time, the lake floor was variously forested with xeric forest species (Delcourt, Nester, Delcourt, Mora, & Orvis, 2002). Dune morphologies indicate that the dunes formed on dominantly WNW winds; other research on similarly-aged and older eolian features in the region also support this interpretation (Arbogast et al., 2015, 1997; Johnson, 2000; Rawling et al., 2008; Schaetzl et al., 2018b). Together, these studies point to a GLA plain that, during dry periods, became geomorphically unstable, due to eolian activity.

Previous research has demonstrated that eolian transport can continue well downwind of dunes, often as fine-sandy or silty deposits, which are often interpreted as loess. Such sediments point to the influence of the eolian system beyond that of the dunes proper (Crouvi, Amit, Enzel, & Gillespie, 2010; Mason, Nater, Zanner, & Bell, 1999). This process is also important in deserts, where generation, deflation, and transport of silt is often intimately linked to saltating sand, i.e. the processes that formed the dunes also generated and transported the silt downwind and subsequently deposited it as loess (Amit et al., 2011; Assallay, Rogers, Smalley, & Jefferson, 1998; McTainsh, 1987; Smalley & Krinsley, 1978; Smith, Wright, & Whalley, 2002; Yaalon, 1969). Alternatively, many sandy flats with migrating dunes simply act as winnowing mechanisms and vehicles of transport for finer sediment, leading to accumulations of loess downwind but playing only a minimal role in *forming* silt-sized particles, e.g. Mason (2001), Roberts, Muhs, Wintle, Duller, and Bettis (2003), Schaetzl and Loope (2008), Mason, Jacobs, and Leigh (2019). In sum, the various pathways of loess generation and transport continue to be a topic of interest and debate within the eolian community (Schaetzl et al., 2018a, 2018b; Wright, 2001).

Establishing silt/loess provenance is typically accomplished by interpreting spatial trends ingeochemistry, grain size, and/or thickness across landscapes (Schaetzl et al., 2018a). In the geochemical approach, elemental and/or mineralogical data from loess are compared to similar data from potential source areas, e.g. Muhs and Bettis (2000), Buggle et al. (2008). The textural approach evaluates grain size data with distance from a presumed source, relying on the assumption that loess gets finer textured downwind from its source, e.g. Ruhe (1954), Rutledge, Holowaychuk, Hall, and Wilding (1975), Muhs, McGeehin, Beann, and Fisher (2004). Thickness trends are also used to establish loess source areas, assuming that loess deposits thin downwind, e.g. Fehrenbacher, Olson, and Jansen (1986). Using these approaches, loess researchers can identify regional silt sources(s) and determine the nature of the transport environment (Nyland, Schaetzl, Ignatov, & Miller, 2018; Schaetzl & Attig, 2013; Ujvari, Kok, Vargara, & Kovacs, 2016). Few studies, however, have focused on sediments *immediately downwind* of dunes (Anderson, 1988) or other obstructions (Goossens, 2006). Almost no work has been reported for areas with rapid changes in grain size, such as loess deposits near a source region.

Study area and theoretical background

Our study examined eolian deposits associated with dunes on the GLA plain, near the town of Germfask in Michigan's eastern UP (Figure 1). These dunes are part of a larger

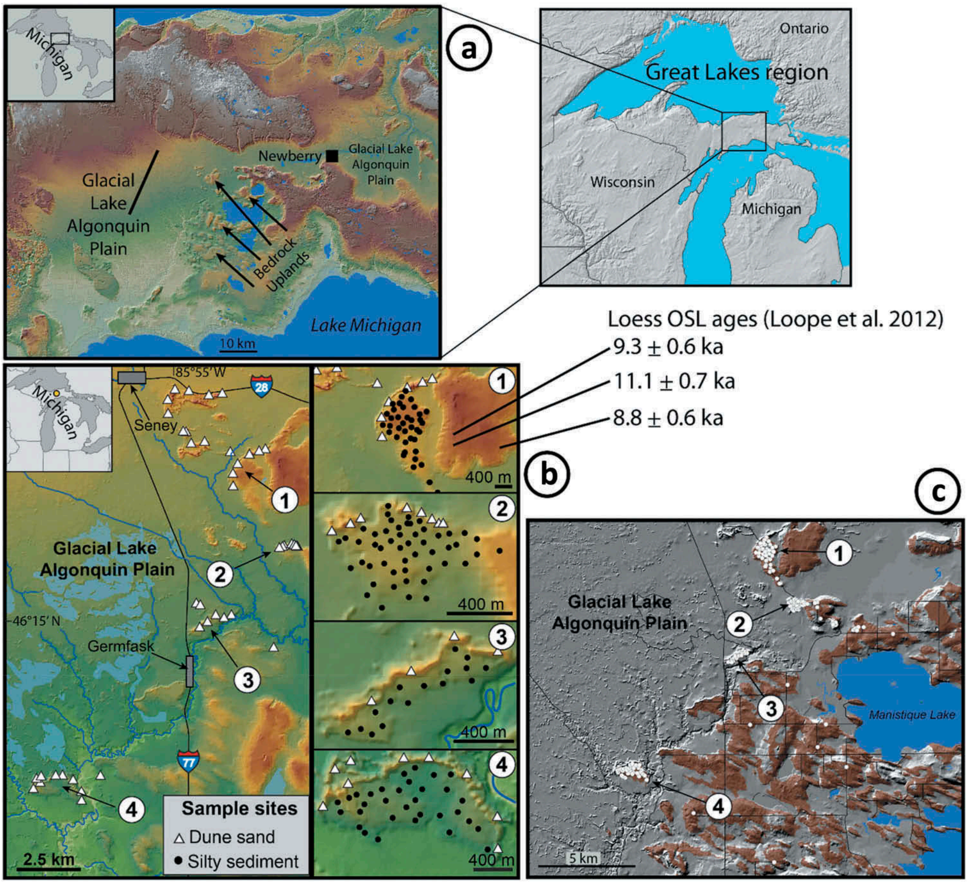

Figure 1. Study area maps. (a) Relief/topography of the eastern Upper Peninsula, showing the low-relief plain of Glacial Lake Algonquin and the locations of prominent bedrock uplands. Note the NE-SW line that is used later as the hypothetical center of the lake plain, for statistical purposes (see below). (b) A smaller extent map, focusing on the locations of the four core study sites. Locations of dune sand samples are shown on all the maps, whereas loess samples within the core areas are shown only on the four inset maps. The locations of the loess sites, dated by Loope et al. (2012), are shown as well. (c) The wider study area, showing the distribution of soils with fine-loamy mantles in brown, and the entire suite of our sample sites, including those farther downwind, to the southeast.

complex known locally as the Newberry Dune Field, named for the City of Newberry, ≈35 km to the northeast (Figure 1(a)). Bedrock uplands near Germfask (Figure 1(b)), typically 3–15 m higher than the lake floor, are mantled with fine-textured and often very sandy-silty sediment. Schaetzl and Loope (2008) and Loope et al. (2012) described similar sediments on other uplands in the UP as loess. Soil maps produced by Natural Resources Conservation Service (NRCS) personnel (Whitney, 1997; Whitney & Calus, 2012; Whitney & Rodock, 2006) have also noted and described fine-sandy and silty mantles in the soils on these uplands, associated with the Graveraet (coarse-loamy, mixed, active, frigid Alfic Oxyaquic Fragiorthods), Greylock (coarse-loamy, mixed, active, frigid Alfic Haplorthods) and McMillan (sandy, mixed, frigid Lamellic Haplorthods) soil series (Figure 1(c)). These types of mantles have been consistently interpreted as loess elsewhere in Michigan (Luehmann, Schaetzl, Miller, & Bigsby, 2013; Schaetzl, 2008; Schaetzl & Luehmann, 2013).

Especially pertinent to our study is a model by Mason et al. (1999), in which saltation is linked to silt deflation and mobilization, and consequently, loess generation and distribution. In this model, saltating sand deflates silt particles from the surface across which they are migrating, thereby facilitating the entrainment of silt into the wind column. As long as sand can saltate across a surface, silts continue to deflate and therefore, cannot accumulate as loess. Should the saltating sand become arrested at a topographic obstruction such as within a deep valley or at a steep escarpment, silts that fall out of the wind column downwind may accumulate as loess. This process leads to loess deposits in the immediate lee of topographic obstructions (Mason et al., 2019; Schaetzl et al., 2018b). In essence, migrating sands form a transportation surface for silts – simultaneously facilitating their deflation and limiting their deposition, as long as the sands continue to be saltated. In support of this model, Schaetzl and Loope (2008) showed that the loess deposits on bedrock uplands (only 40–60 km to the NE of our study area) were mainly generated as dunes migrated across the sandy GLA floor.

Dune sands formed by grinding and abrasion in deserts, where saltating sands physically comminute sand-sized quartz grains, are likewise often associated with downwind loess deposits (Crouvi et al., 2010; Crouvi, Amit, Enzel, Porat, & Sandler, 2008; Wright, 2001). That said, the GLA plain was not a "sand sea" – a type of desert geomorphic system that has been linked to the production of silt via abrasion by saltating sand (Crouvi et al., 2010). Instead, the GLA plain inherited its sand from glacial meltwater. We emphasize that the model of Mason et al. (1999) focuses on the effect of saltating sand and its ability to deflate *preexisting* silt grains – a scenario that we envision for the GLA dunes and their downwind loess deposits.

Study purpose and contributions

The purpose of our study is to report on, and explain, the geomorphic origins of, the fine-textured, presumably eolian, mantle that covers uplands near Germfask, Michigan. Field investigations confirmed that Graveraet, Greylock, and McMillan soil series mapped in these core areas (Figure 1(c)) are rich in silts and fine sands in their upper profiles. We hypothesize that this sediment is likely of eolian origin, because it is similar to other loess deposits identified in northern Michigan (Luehmann et al., 2013; Nyland et al., 2018; Schaetzl, 2008; Schaetzl & Loope, 2008).

In addition to being among the first to report on Holocene loess in the upper Midwest (see also Schaetzl, Forman, & Attig, 2014; Miao, Hanson, Stohr, & Wang, 2018), our work bridges the two main foci of eolian research: sand dunes and loess. Data presented here add important new insights into the geomorphic history of the Newberry Dune Field and therefore elaborate on Schaetzl and Loope's (2008) work by drawing on the models of both Mason et al. (1999) and Pye (1995) to explain loess deposits in the lee of sand dunes near low bedrock uplands that rise above the GLA plain. Lastly, our work provides data and geomorphic context to similar "silty-sand" eolian deposits elsewhere.

Materials and methods

Four sites at the northwestern margin of the bedrock uplands near Germfask, each with fine-loamy mantles in the lee of dunes, were selected for study (Figure 1(b)). We refer to the suites of samples in the immediate lee of each of these dune complexes as "core" areas, numbered 1 through 4, from north to south (Figure 1(b)). We collected samples of sediment from different environments within the study area: (1) from the summits of the dunes immediately upwind of each "core" study area; (2) from the summits of 15 other dunes, upwind and farther out on the lake plain; (3) on stable uplands (in the core areas) in the lee of the dunes, at fairly dense (40–200 m) intervals; and, (4) on upland sites farther downwind (SE) of the core areas, representative of more distal eolian facies (Figure 1). We will refer to the four dune complexes in (1) above as "walling dunes", because they form a conspicuous wall or topographic barrier between the open lake plain and the bedrock uplands to their south and east. For the last two environments, we took care to sample only fine-textured, gravel-free sediment, i.e. sediment that was likely of eolian origin, avoiding any gravelly sediment below. We sampled sediment at each site and plotted each sample location on a GIS using a GPS-enabled laptop. Typically, samples in the dunes were recovered from below the solum, in deep C horizons. The silty mantle in the lee of the dunes was commonly within the E and upper B horizons of the modern soil, as A horizons here are very thin. Clay contents in these Spodosols are low; clay translocation is not a prominent process, thereby essentially negating the effects of pedogenesis on the texture of the eolian sediment. As we have done in the past (Luehmann et al., 2013; Nyland et al., 2018), our samples were collected by bucket auger across the entire sediment column, until the underlying sediment was encountered. We then homogenized the upper (eolian) sediment in the field and retained a ≈ 175 g sample for further analysis. Evaluating the thickness of the eolian mantle in the field, and obtaining a sample of that material, was relatively straightforward; the underlying sediment was usually more clay- or gravel-rich, or exhibited a dramatic increase in medium and coarse sands, as compared to the sediment above. Sites previously affected by bioturbation, such as tree uprooting (Šamonil et al., 2016), were avoided while sampling. At all but the dune sites, we recorded the thickness of the perceived eolian mantle, i.e. the depth to the contact between upper eolian material and the underlying sediment, which was usually residuum and/or clayey lake sediment.

Samples were air-dried, lightly crushed, and passed through a 2-mm sieve to remove coarse fragments. The fine earth fraction was then thoroughly mixed. Particle size analysis (PSA) was performed using a Malvern Mastersizer 2000E laser particle size analyzer, after dispersal for 15 minutes in a solution of $(NaPO_3)_{13}{\cdot}Na_2O$. To provide the most accurate data, we implemented a quality control protocol by comparing multiple measurements from each sample and using the mean of the most comparable data for further analyses (Miller & Schaetzl, 2012).

The data were statistically evaluated with respect to their distance from (A) the nearest large dune, and (B) a NE-SW site (line; see Figure 1) near the center of the lake plain, ≈12–18 km NW of the study area. We drew this line to be representative of the general center of the relict dune field on the lake plain proper and directly upwind from our main study area. Relationships between the sediment characteristics (texture and thickness) and distance to the nearest dune ridgeline were intended to inform us about the influence of the dunes proper on the loess downwind. Relationships of the loess and the dune sand to the center of the lake plain were intended to inform us about longer-distance transport processes. Using these data, we developed linear regression models for a number of sediment attributes and derivatives, using both untransformed and log-transformed data. R^2 and P values were used to determine relative degrees of sorting, with distance from likely eolian sources.

Results

Dune morphologies, ages, and textures

GLA dunes are generally small and parabolic in form, with most having <4 m relief and with limbs oriented to the west and northwest. Nonetheless, some of the larger dunes at the upwind margins of the core areas, abutting bedrock uplands, are much larger (Figures 1(b) and 2) and have more complex ridgeline morphologies. For example, the dunes at Site 4 are

Figure 2. The lee side of the dune at Site 3.

≈10–20 m in height, sometimes with complex, multiple crests, suggestive of dunes migrating and agglomerating into each other. Even the smallest dune complex in this study, Site 2, has ≈15 m of relief in places. The morphology, size, and distribution of these features suggest that they formed while (initially) small dunes migrated to the SE across the sandy floor of the lake plain, coalescing at the northwestern margins of the uplands and accreting into large dune complexes. Other sides of the same bedrock uplands lack such large dune complexes. Data from other late Pleistocene and Holocene sand dunes in the upper Midwest also indicate transport on WNW winds (Johnson, 2000; Rawling et al., 2008; Arbogast et al., 2015; Schaetzl et al., 2018b; Colgan et al., 2017).

Previous research on these dunes has focused on the conditions under which sand could have mobilized in what is now a wet and fully vegetated landscape (Arbogast et al., 2002; Loope et al., 2012). Holocene dune ages, as reported by Arbogast et al. (2002) and Loope et al. (2012), coupled with palynological data from nearby lakes (Delcourt et al., 2002), suggest that the dunes formed at a time when the eastern Upper Peninsula was forested. Pollen spectra and charcoal data from Nelson Lake, ≈37 km east of our study area also suggest that after ca. 7700 cal. yr BP wildfires were common, likely maintaining xeric and open pine forests on sandy uplands (Delcourt et al., 2002; Figure 3), and perhaps on parts of the lake plain. Loope et al. (2012) concluded that the eolian activity on the lake plain occurred within a landscape that was undergoing widespread drought

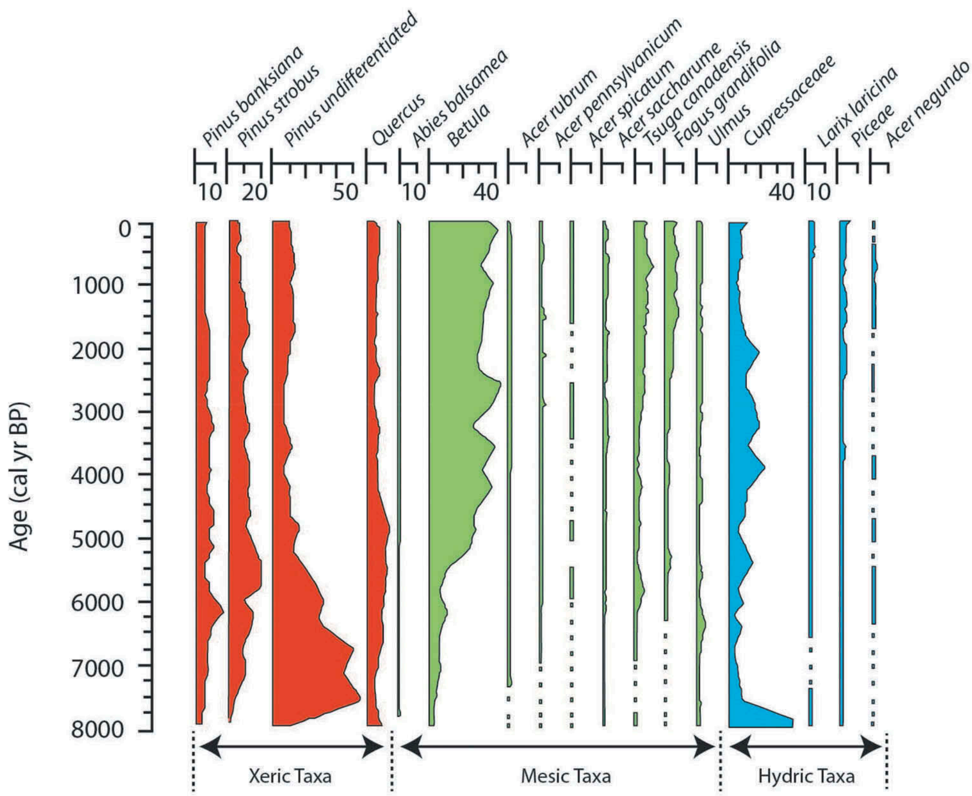

Figure 3. Selected pollen spectra for Nelson Lake, in Michigan's eastern Upper Peninsula. Nelson Lake is ≈37 km east of our study area. After Delcourt et al. (2002).

and/or fire (Kutzbach et al., 1998; McCarthy & McAndrews, 2012), leading to openings in the forest (Loope and Anderton, 1998; Loope et al., 2012). Regionally, water tables were low during the early Holocene, leading to periods of hydrologic closure for the Great Lakes (Lewis, 2016). Cooler and moister climates developed after ca. 5300 cal yr BP, likely putting an end to any eolian activity in the region and allowing the landscape to finally stabilize.

Spatial trends in dune textures across the lake plain support a model of eolian activity within a forested, or at least savanna-like, landscape. Sands from dunes on the lake plain show a strong negative relationship between coarser sand contents and distance, i.e. the contents of medium sand decrease significantly downwind (to the southeast) across even short distances on the lake plain, as the contents of finer sands increase (Figure 4). These data suggest that the lake plain was *not* an open, barren sand landscape, across which sand was being universally supplied to dunes. Rather, it was a vegetated surface, unable to continuously supply new sand to migrating dunes, resulting in loss (winnowing) of the coarser sand fractions downwind. Additionally, because the dunes were migrating within a landscape that mitigated the fastest winds, only the finer sands were able to saltate far downwind. In essence, the vegetative cover on the lake plain facilitated sorting of migrating dune sands; larger sand fractions would have been increasingly trapped *en route*. Finer sands would have been more easily transported, resulting in dunes farther downwind that are composed of increasingly finer sands (Figure 4).

Field observations on eolian sediment downwind (SE) of dunes

Our field data agree with NRCS soil maps, which depict a thin mantle of fine-textured sediment on uplands south and east of the dunes at each of our four core areas (Figure 1 (c)). This mantle continues intermittently as far as 20 km downwind. Based on 197 samples of this sediment, it usually contains almost no coarse (> 2 mm dia.) fragments and is particularly rich in fine and very fine sands. We hypothesized that this sediment is eolian in origin, because (1) evidence of eolian activity is widespread on the lake plain and across the eastern UP, (2) it generally lacks coarse fragments and is fine-sandy/silty, and (3) previous work in the area (Loope et al., 2012; Luehmann et al., 2013; Schaetzl & Loope, 2008) referred to sediments of this type, in similar geomorphic settings, as loess.

Textures and nomenclature

Further evidence for an eolian origin for the sediment that occurs downwind of the dune crests derives from texture data. The sediment is generally uniform in texture, being fine-sandy or fine-loamy, and often very well-sorted, with almost no clay (Figure 5). It contains far more silt than the dunes on the lake plain or the large complex of dunes nearby, implying that it is not simply a downwind extension of the sand in the walling dunes. Nonetheless, the high sand contents in the sediment imply that a significant component of the sediment may have been locally derived (see below).

The sediment averages only 35.0% silt (Figure 5), and thus is sandier than “typical” silt loam-textured loess (Bettis, Muhs, Roberts, & Wintle, 2003; Scull & Schaetzl, 2011). Of the sand fractions, very fine sand was the most abundant (33.8%) – more than double that of fine sand (14.0%). The two most common textures encountered, based on the NRCS

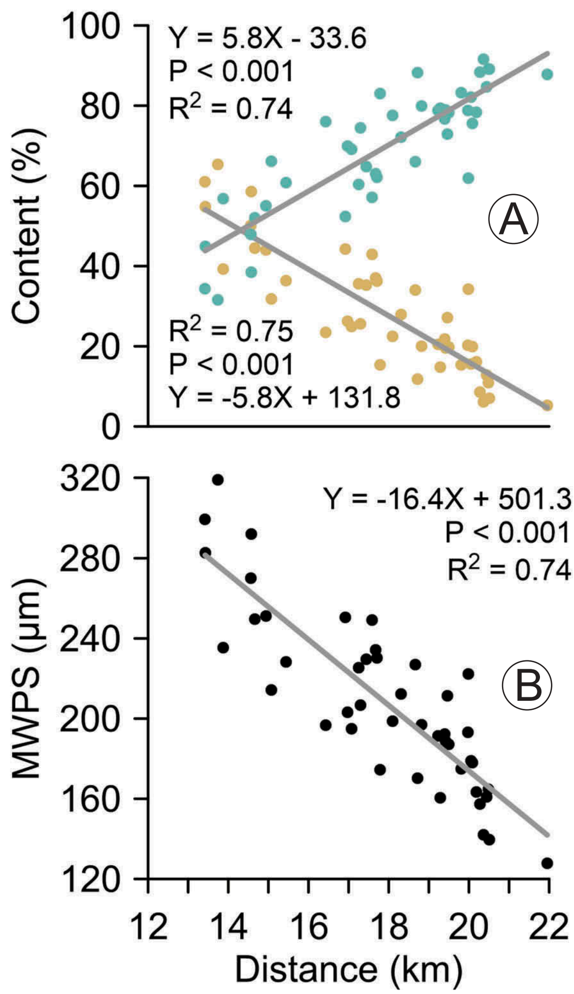

Figure 4. Scatterplots for sand dune grain size vs distance from a point in the center of the lake plain. (a) Decreased contents of medium sand (250–500 µm) shown in brown, alongside increased contents of very fine and fine sand (50–250 µm) shown in green, (b) Mean weighted particle size (MWPS) data for the same dunes.

texture classification system (Soil Survey Division Staff, 1993), were very fine sandy loam (103 samples) and fine sandy loam (47 samples) (Figure 5). Only 11 of the 197 loess samples – all in far downwind locations and most of them at Site 2 – had silt loam textures.

Too fine-textured, with modal particle size values in the 50–65 µm range, and distinctly unstratified, the eolian sediment here has few similarities to traditional European coversands (Kaase, 2002). Lehmkuhl et al. (2014) referred to eolian sediment like that at our study site, with <50% silt+clay, as "silty-sand loess". This description fits well, as this sediment typically has a considerable content of silt but almost no clay (mean 3.2%) (Figure 5). Yaalon and Dan (1974) might have referred to sediment of this type as "loess-like", and Haase et al. (2007) might have described it as "sandy loess". Vandenberghe (2013, p. 21) suggested that eolian sediment with these grain sizes is

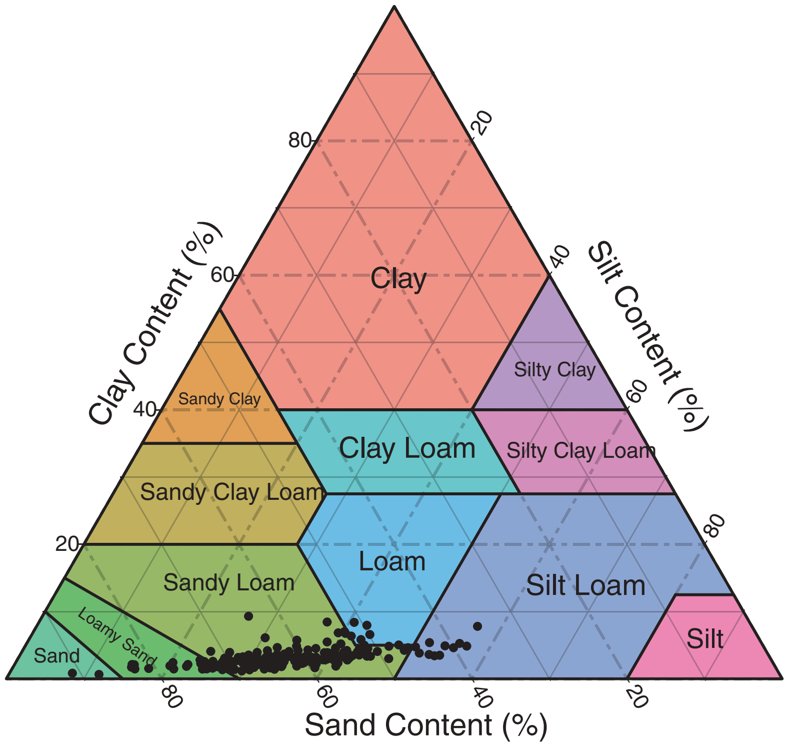

Figure 5. Sand-silt-clay values for all 197 loess samples, plotted on a standard USDA-NRCS textural triangle.

"derived from a nearby, rather sandy source region," and transported only short distances (hundreds of meters or a few kilometers). Collectively, these data support the conclusion that the sediment in the lee of the large dunes is a type of coarse-textured loess, rich in fine sand and not unlike similar sediment reported by Schaetzl and Attig (2013) for sites in northeastern Wisconsin, much of which was derived locally. Likewise, Nyland et al. (2018) reported data for sand-rich loess in Lower Michigan, and as at our study site, their loess was also derived locally. Across the midwest, most loess within a km or two of the source region is less sandy, because the source area is often a deep valley, in which much of the sand gets trapped. At our study site, more sand was able to be transported downwind, and thus, was (locally) mixed into the otherwise silty loess deposit.

Loess thickness and age

Loess in downwind settings averaged 49.5 ± 2 cm thick and, with the exception of a few sites of thicker loess within ≈500–750 m of the dunes, was generally of uniform thickness, decreasing only slightly downwind and exhibiting minimal thickness change beyond ≈4 km (Figure 6 and Table 1). In fact, the overall variation in thicknesses was greater at any given distance than was the change in predicted thickness value across the *entire range* of distances. This trend indicates that local geomorphology and the overall stability

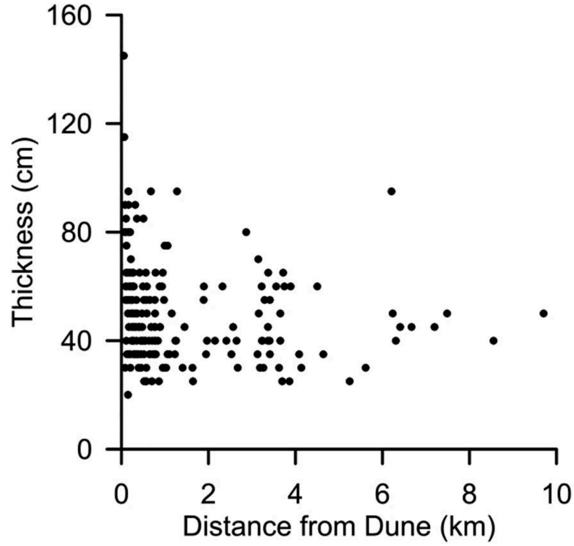

Figure 6. Scatterplot showing the thickness of the eolian (loess) mantle immediately downwind of the dune ridge, using combined data for all four core sites.

Table 1. Grouped texture and thickness data for loess downwind of dunes.

	Group 1	Group 2	Group 3	Group 4
Distance from walling dune	<200 m	200–500 m	500 m – 3 km	3 – 10 km
Number of samples	32	54	71	40
Thickness (cm)[a]	66	48	45	45
Modal particle size (μm)	65.4	60.1	55.1	49.0
Sand content (%)	68.4	63.0	62.4	56.5
Very fine and fine sand (% 50–250 μm)	60.4	50.7	44.5	41.6
Silt content (%)	29.4	34.0	34.3	40.0
Fine silt (% 6–20 μm)	7.2	9.4	10.6	11.8
Medium silt (% 20–40 μm)	14.8	17.2	17.0	20.5
Fine silt/Coarse silt	1.09	1.31	1.77	1.66
Silt/Sand	0.44	0.55	0.59	0.76

[a]Data for this and successive variables in the Table reflect mean values

of surfaces was as important as total influx of eolian sediment in determining the thickness of the eolian mantle (Figure 6). Although thicknesses ranged from 20 to 145 cm, the eolian mantle thickness on only two of the 197 sites exceeded 100 cm, and these two sites were within 25 m of a walling dune.

Loope et al. (2012) reported luminescence ages on loess at three locations downwind of Site 1 as 11.1 ± 0.7 ka, 9.3 ± 0.6 ka, and 8.8 ± 0.6 ka (Figure 1(b)). These data generally agree with the luminescence ages reported by Loope et al. (2012) for 11 dunes in nearby and/or upwind locations on the lake plain; these dunes ranged in age from 10.2 to 8.2 ka. Of these dunes, six have ages that lie within a narrow window (8.2 to 8.6 ka), suggesting that the main eolian activity on this part of the lake plain occurred in the early Holocene. Because the ages reported for the dunes reflect only their final period of stabilization, it appears that loess was accumulating during a longer time interval, probably while the dunefield migrated across the lake plain.

Loess spatial trends

In our examination of the downwind trends in the loess, we first parsed the sample data into four groups, based on distance from the walling dune: (1) sediment from sites within 200 m, (2) sediment from sites 200–500 m downwind, (3) sediment from sites 500 m to 3 km downwind, and (4) sediment from sites 3 km to 10 km downwind (Table 1). The loess mantle near the dunes displays trends characteristic of eolian sediments, e.g. gradual thinning as distance increases (Luehmann et al., 2013; Schaetzl et al., 2018; Table 1). The thinning trend changes more slowly as distance increases – typical for eolian sediment (Luehmann et al., 2013; Schaetzl et al., 2018; Table 1). Modal particle sizes decrease downwind, in concert with sand contents. Conversely, silt contents increase downwind, and particularly noteworthy are the increases in fine silt in the most distant sites, indicative of a generally uniform fallout of silt from high suspension clouds, coupled with decreasing amounts of sand in this previously forested landscape.

Statistical analyses

Given the clear downwind trends observed in this grouping analysis, we conducted a more detailed statistical analysis, using a suite of linear regressions for the fine-textured mantles downwind of the four dune complexes. We examined 38 different texture and thickness variables against (1) distance from the closest dune and (2) from the generalized center of the plain, using both linear and log-transformed data (Table 2). Of the 152 different regression equations, 96 were significant at $P < 0.01$, and 106 were significant at $P < 0.05$, again pointing to the well-sorted (by distance) nature of this sediment, and supporting our hypothesis that the sediment is eolian. Other systems that could have spatially sorted sediment to this degree, e.g. fluvial or (perhaps) glacifluvial, could not have been operating on Holocene-aged, upland sites.

The greatest number of highly significant ($P < 0.01$) equations, plotted against distance from the dune complex, were linear regressions. In contrast, relationships were often more statistically significant when plotted against the distance from the lake plain as log-transformed equations (Table 2). This apparent juxtaposition probably occurs because at greater distances, i.e. to the lake plain center, the slopes on the regression equations of the log-transformed data are nearly linear; the greatest rate of change occurs much farther upwind. Although compositional sediment data for eolian systems are typically log-transformed (Aitchison, 1986; Sitzia et al., 2017), our data suggest that over short distances, the eolian system here is best modeled using linear trends. The following discussion focuses on the interpretation of linear models on native (untransformed) data for the combined data from the four dune complexes.

Loess textures and transport direction

Spatial trends in loess textures for each of the four core areas indicated that the loess rapidly becomes finer with distance from the dune ridgeline; illustrative data are provided for sites 2 and 4 in Figure 7. Therefore, we combined the data for the four core sites and hereafter report only amalgamated data.

Table 2. The statistical strength of relationships for the loess deposits near Germfask, as a function of distance (as determined by R^2 and P value).

		Linear regressions[a]		Log-transformed regressions[1]	
Variable	Units	Variable vs distance to dune	Variable vs distance to lake plain	Variable vs distance to dune	Variable vs distance to lake plain
Thickness	(cm)	*0.02*	0.00	0.00	0.02
Trask sorting coefficient[b]	–	***0.08***	0.00	0.01	***0.09***
Mean weighted particle size	(μm)	*0.03*	0.00	0.01	0.01
Silt	(2–50 μm)	***0.13***	***0.10***	***0.08***	***0.10***
Sand	(50–2000 μm)	***0.13***	***0.10***	***0.11***	***0.14***
Coarse sand	(500–1000 μm)	***0.09***	0.00	0.00	***0.06***
Medium sand	(250–500 μm)	0.01	0.00	0.00	*0.03*
Fine sand	(125–250 μm)	***0.09***	***0.08***	***0.10***	***0.10***
Very fine sand	(50–125 μm)	***0.16***	0.02	0.01	***0.14***
Fine silt	(2–20 μm)	***0.18***	***0.06***	***0.07***	***0.16***
Medium silt	(20–40 μm)	***0.11***	***0.09***	***0.07***	***0.08***
Fine + medium silt	(2–40 μm)	***0.18***	***0.11***	***0.09***	***0.14***
Coarse silt	(40–50 μm)	0.00	*0.03*	0.02	0.00
Medium + coarse silt	(20–50 μm)	***0.06***	***0.07***	***0.05***	***0.05***
Silt + very very fine sand[3]	(2–60 μm)	***0.08***	***0.08***	***0.06***	***0.06***
Medium silt, coarse silt, + very very fine sand[c]	(20–60 μm)	0.01	***0.04***	*0.03*	0.01
Coarse silt through fine very fine sand[3]	(40–75 μm)	*0.03*	0.00	0.00	*0.02*
Medium very fine sand[c]	(60–75 μm)	***0.10***	0.00	0.00	***0.08***
Fine very fine sand[c]	(50–75 μm)	***0.06***	0.00	0.00	***0.04***
Coarse very fine sand[c]	(75–125 μm)	***0.27***	***0.06***	***0.06***	***0.27***
Medium silt + coarse silt + very fine sand	(20–125 μm)	***0.03***	0.00	0.00	*0.02*
Coarse silt + very fine sand	(40–125 μm)	***0.11***	0.01	0.00	***0.09***
Very fine + fine sand	(50–250 μm)	***0.30***	***0.08***	***0.09***	***0.33***
Fine fine sand[c]	(125–175 μm)	***0.20***	***0.10***	***0.13***	***0.21***
Coarse fine sand[c]	(175–250 μm)	0.01	***0.04***	***0.06***	*0.02*
Very fine, fine and medium sand	(50–500 μm)	***0.25***	***0.13***	***0.14***	***0.27***
Fine and medium sand	(125–500 μm)	0.01	***0.04***	***0.06***	0.02
Medium and coarse sand	(500–1000 μm)	***0.04***	0.00	0.00	***0.04***
Silt/sand	–	***0.15***	***0.11***	***0.09***	***0.12***
Fine silt/medium silt	–	*0.03*	0.00	0.00	***0.03***
Fine silt/coarse silt	–	***0.08***	0.01	0.01	***0.08***
Medium silt/very fine sand	–	***0.41***	***0.14***	***0.11***	***0.33***
Medium silt/fine sand	–	*0.02*	***0.04***	***0.10***	***0.10***
Fine and medium silt/ coarse silt	–	***0.19***	***0.03***	***0.03***	***0.18***
Very fine sand/fine sand	–	***0.04***	0.00	0.00	***0.06***
Silt/Very fine and medium sand		***0.20***	***0.12***	***0.10***	***0.17***
Sand in 1 cm^2 column	g	***0.06***	0.01	0.01	***0.08***
Silt in 1 cm^2 column	g	0.01	***0.04***	***0.04***	0.01

[a]Data shown in the Table are the R^2 values of regression equations for various texture and thickness variables. Regressions that are statistically significant at $P < 0.05$ are in italics. Regressions that are statistically significant at $P < 0.01$ are in bold italics.
[b]After Trask (1932).
[c]Most of the names for the various grain size groups follows the Soil Survey Manual (Soil Survey Division Staff, 1993), except for those indicated here; these names are internal and have been chosen so as to better describe more narrowly defined grain size groupings.

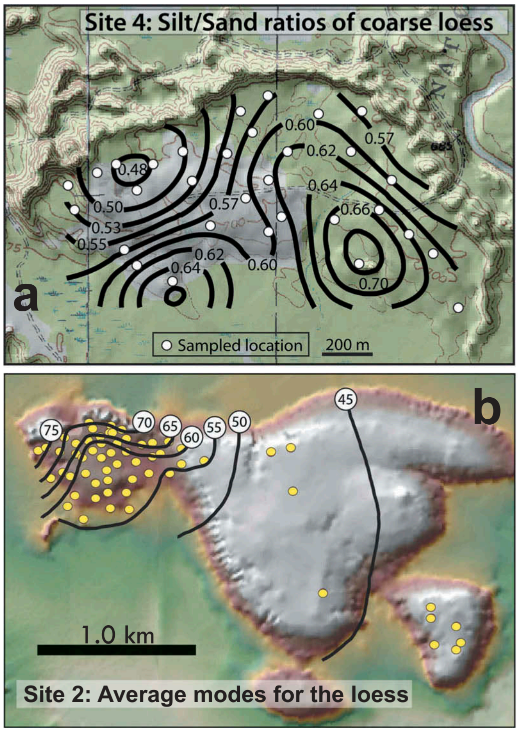

Figure 7. Spatial patterns, derived by ordinary kriging, that indicate dominant west-northwesterly winds during the loess depositional interval at our study areas. (a) Silt/sand ratios for loess samples at site 4. (b) Modal loess particle size values at site 2.

The majority of the regression lines are negative for various sand fractions and positive for silt fractions and various silt/sand ratios (Figure 8). Together, these data point to a clear downwind fining pattern for the loess, which is mainly caused by decreasing sand contributions in the immediate lee of the dunes; this factor then led to comparatively higher contents of silt, especially fine and medium silts, farther downwind (Table 1).

Maximum sand fractions in the loess occur immediately next to the dune and decrease downwind from the dune ridgelines; conversely, silt contents increase downwind (Figure 8 and Table 1). Loess in the immediate lee of the dunes is particularly rich in very fine sand (Figure 8 and Table 1). Regression equations for the fine and very fine sand fractions suggest that most of the sand additions to the loess occur within 1–2 km of the dune ridgeline; this negative trend with distance is especially true for fine sands and fractions coarser than fine sand (Figure 8). We interpret this trend to indicate that most of the sands were derived locally, from the dune proper, transported by saltation and as short-range, low suspension “blow-over”, and eventually fell out of suspension due to flow separation and loss of turbulence. Finer sands were able to be transported slightly farther, possibly because they attain greater elevations during transport.

We contend that almost none of the silt in the loess was derived from the dunes proper. Sand data from the four large dunes (28 total samples) and from 17 smaller dunes on the lake plain had an average of 1.9 ± 1.7% silt. Instead, the silt in the loess was predominantly derived from the lake plain, having been deflated from that surface by

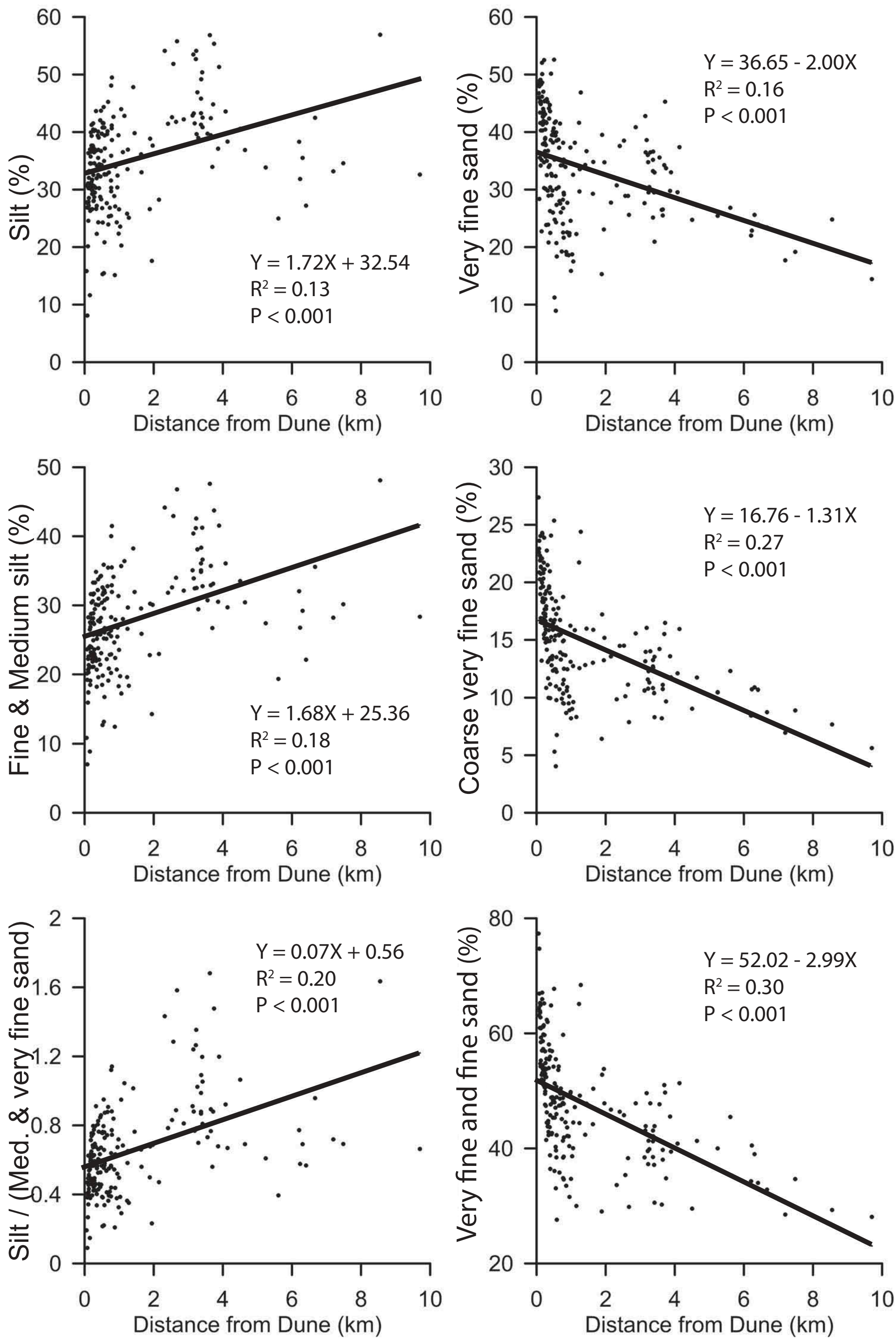

Figure 8. Scatterplots showing the contents of various sand and silt size fractions in the eolian mantle immediately downwind of the dune ridge, combined for all four study sites.

saltating sands, after the model of Mason et al. (1999). Thus, we attribute the downwind increases in silt contents in the loess (Figure 8) to two factors: (1) diminished sand dilution, i.e. fewer sands were transported to downwind locations, and thus the proportion of silts in the loess increased downwind (Figure 8), and (2) a slight increase in deposition of silts in downwind sites (or at least a very minimal dropoff) because of high-altitude transport in suspension, i.e. above and perhaps within the tree canopy. Data on total silt and sand contents (mass values) in the eolian mantle, generated by multiplying the contents of these fractions by the mantle thickness and assuming a bulk density of 1.5 g cm^{-3}, support this interpretation (Figure 9). Total mass of sand in the mantle decreases with distance away from the walling dunes ($P < 0.01$; Table 2; Figure 9). The sand mass data therefore agree with texture data (Figures 8 and 9) that point to the dunes as the main sand source. Total mass of silt (and especially of the finer silt fractions) in the mantle, however, increases slightly downwind, suggestive of fairly homogeneous silt deposition across the landscape (Figure 8 and Table 1). This type of deposition appears to indicate fallout from silts in high-level suspension clouds, and certainly not from a point source like the upwind dune or a suite of dunes. Forest cover on the landscape would have had minimal impact on high-level transport, leading to a more-or-less uniform content of silt in the eolian mantle, regardless of location (Figure 9). Although silts from such a depositional system would have fallen on all parts of the bedrock upland landscape, we did not sample sites in local lowlands or on sloping sites; such locations lack geomorphic stability and the thin deposit of loess that may have existed there would likely have been altered since its original period of formation.

Finally, our data support previous work in the upper Midwest that the dominant wind direction during this Holocene eolian interval was from the northwest or west-northwest (Bettis et al., 2003; Schaetzl et al., 2018b). Modal particle size values in the loess decrease to the east-southeast (Figures 7(b) and 10). The most silt-rich loess samples were obtained from the farthest east-southeast sites, whereas the sandiest samples are typically in the shadow of the walling dune (Table 1). This conclusion is not drastically different than data on current winds from nearby weather stations, where both northwesterly and southwesterly components are evident (Figure 11). Nonetheless, the strongest modern

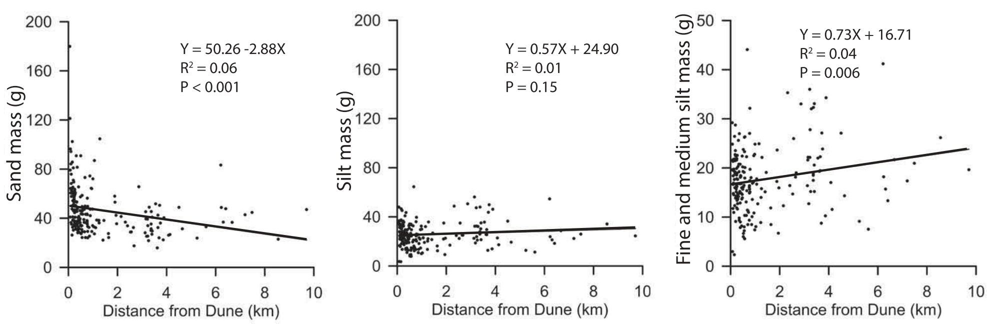

Figure 9. Scatterplots and regression equations for total sand, total silt, and total medium and fine silt in the eolian mantle, vs distance from the upwind dune, combined for all four study sites. Data represent the calculated mass of each sediment type in a column one cm^2 in area, summed across its thickness, as determined in the field, and assuming a bulk density of 1.5 g cm^3.

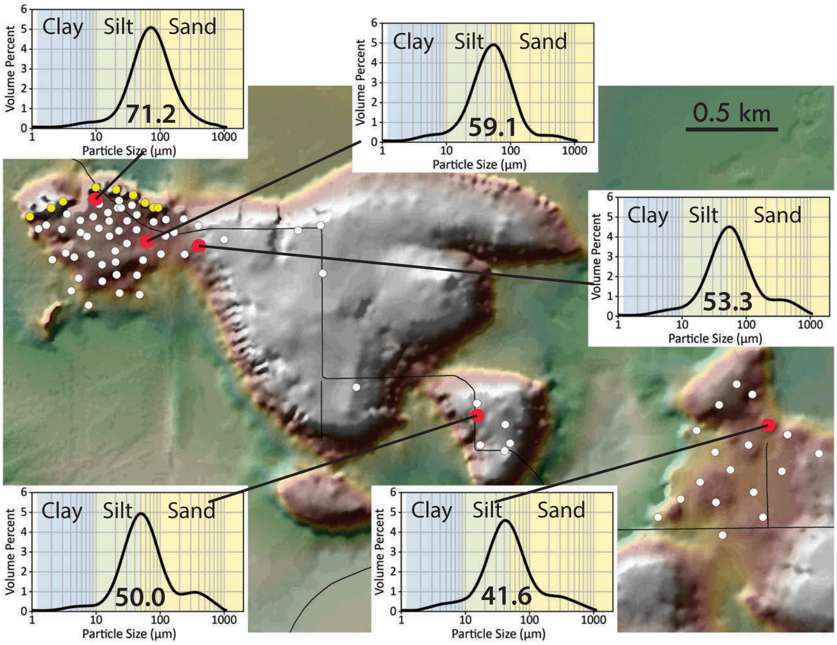

Figure 10. Detailed grain size data and modal values (in μm) for five representative loess samples at Site 2. Yellow symbols are dune sample sites.

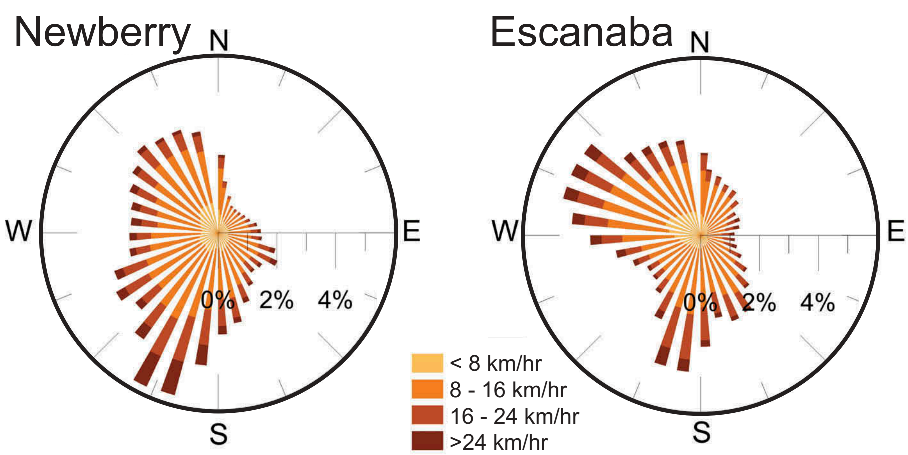

Figure 11. Wind rose data (miles/hr) from January 2007 through December 2016, for two national weather service stations in the Upper Peninsula. Newberry is ≈30 km to the east-northeast, and Escanaba is ≈100 km to the southwest of Germfask.

winds are mainly from the south and southwest, whereas winds that drove the early Holocene eolian system at our study area were mainly from the west-northwest.

Discussion

Contributions to theory

Loess deposits on desert margins, downwind from dunefields and large "sand seas," have caused some researchers to link dune movement to loess generation (Amit et al., 2014; Crouvi et al., 2010; Enzel, Amit, Crouvi, & Porat, 2010). Spatial associations of loess sheets downwind from sand seas confirm this connection is real. Typically, this type of loess has two components: (1) a fine-silt component, which has travelled further in suspension, and (2) a near-source component that is usually dominated by coarse silts and very fine sands (Crouvi et al., 2010, 2008; Enzel et al., 2010). Another topic that has piqued the interest of eolian scientists working in deserts is the extent to which coarser sediment in desert loess was derived from sand grinding and abrasion vis-a-vis from other sources and mechanisms (Bullard, McTainsh, & Pudmenzky, 2004; Yaalon & Dan, 1974). Lastly, the efficacy by which saltation dislodges and entrains silts – in deserts or elsewhere – from the underlying substrate has yet to be fully investigated. Our study provides some insight into these questions because our data derive from an eolian system that mimics loess downwind from desert dunes, but which occurred in a more humid, vegetated landscape.

Pye (1995) described four different scenarios in which loess deposits can form; the one most pertinent to our study has been modified and reproduced in Figure 12 – wherein "a transition between sand dunes, sand sheets, sandy loess and more typical silty loess" is present. Unlike Pye's model, however, our sand-to-silt deposit is extremely short-range and thus was formed entirely within the same climate. Instead of illustrating an arid-to-humid eolian depositional transition, therefore, our loess data are from a rapidly "fining-downwind" eolian system, likely aided by the damping effects of forest vegetation. Thus, we suggest that the model presented by Pye (1995) may also illustrate eolian systems in which vegetation reduces the transportation efficiency of the wind. It seems clear that winds during this eolian interval must have been strong enough to transport sands and silts into and through the Holocene forest; the forest, however, limited how far most of this sediment could be transported. Silts, many of which may have been moving in high suspension clouds, were able to be transported farther downwind, and onto uplands up to 10 km to the southeast of the walling dunes (Figure 1 and Table 1), whereas most sands were deposited closer to the dune. Thus, our data are unique in that they represent eolian transport of a type not typically documented, and also provide information on a type of coarse loess not typically reported.

Because it appears that the large dunes at the upwind margin of the loess deposits contributed some sand to the loess and influenced the downwind depositional patterns of that loess, our work also may be able to inform eolian theory on the effects of obstructions to deposition of dust. Goossens (1996, 2006), working on dust transport in wind tunnels, showed that deposition is clearly affected by obstructions to flow (Figure 13). His work illustrated that when such obstructions impact wind, some sediment is deposited on the upwind side of the obstruction; this sediment is slightly coarser than the overall average grain size. Goossens (2006) also reported "a zone of reduced grain size on the leeside of hills, which extends from just upwind of the summit to a distance of several times the height of the hill", as well as a zone of minimal deposition immediately downwind of the obstruction (Figure 13).

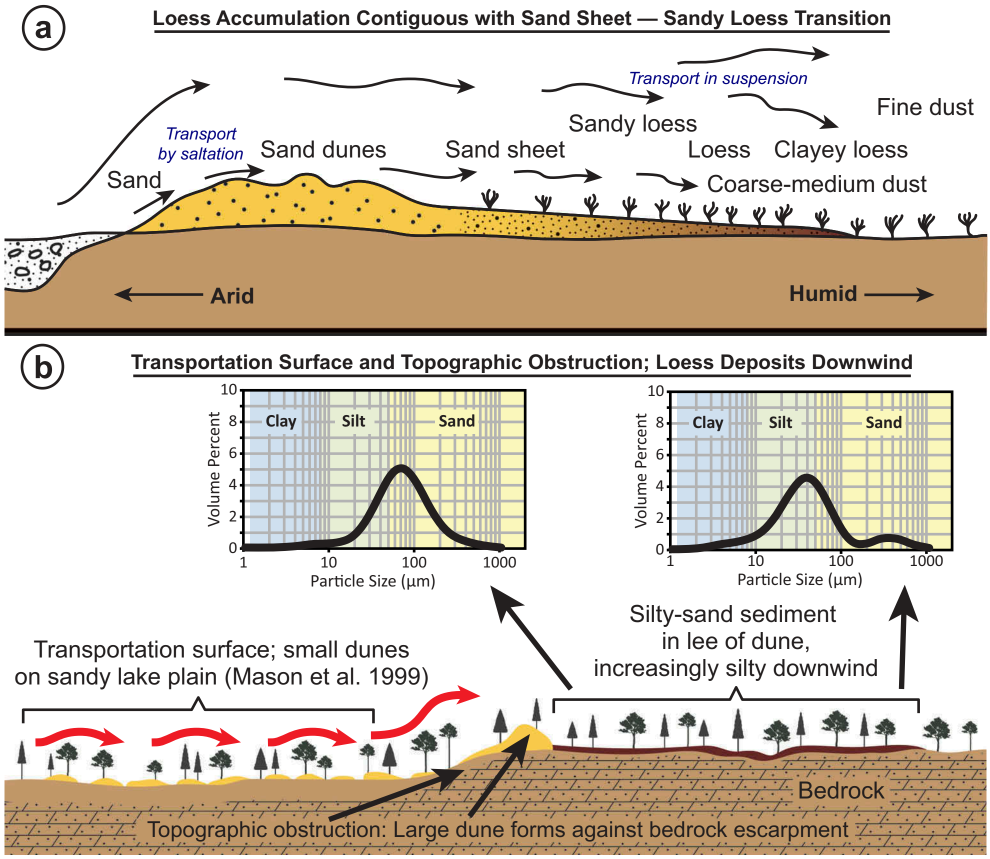

Figure 12. A model of eolian deposition showing the grain size transition from sands to fine loess, in this case along a climatic gradient. Part A: after Pye (1995). Part B: created for our study area.

At our study sites, we saw no evidence of deposition upwind of the dunes, and observed a significant *increase* in eolian deposition immediately downwind of them, especially for the finest sands, akin to the "sand shadows" described by Clemmensen (1986); these shadows formed over several hours during a storm in which wind velocities exceeded 15 m sec^{-1}. We attribute the discrepancy between our deposits and those modelled in wind tunnels to much faster wind speeds at our study site; most of Goossen's wind tunnel experiments were performed using wind speeds of ≈3.8 miles hr^{-1}(1.7 m sec^{-1}), far slower than would have been occurring at our study area. Additionally, Goossen's obstructions were solid objects – unable to contribute sediment to the wind stream, which our dunes would have done. At the slower wind speeds in Goossen's wind tunnels, saltation of sands over the obstruction, leading to sandy-silt eolian sediment in the immediate lee, could not have occurred. Thus, we argue that data from wind tunnel experiments, albeit useful, must be tempered against other factors that might have operated in nature, before findings from one can be translated to the other.

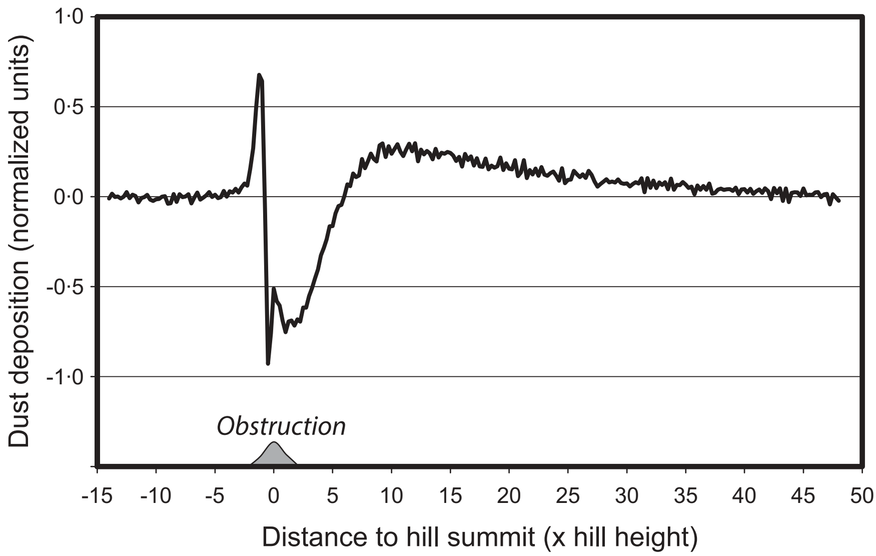

Figure 13. Generalized dust deposition over a symmetrical hill/obstruction in a wind tunnel. After Goossens (1989).

The system of loess deposition

Rapidly decreasing amounts of sand downwind from the walling dunes (Figure 8, Table 1) suggest that much of the fine and very fine sand in the loess was derived directly from the dunes, saltating over the dunes and/or being transported in low suspension as a type of "blow-over" sediment. Silt contents increase downwind due mainly to less sand dilution, but also because some of the silt, transported in high suspension, was able to circumvent most of the effects of the forest. Thus, overall mass of silt increases slightly downwind, as compared to the rapid fallout of sand (Figure 9). This pattern is indicative of eolian transport on very *strong* winds, which likely would have been necessary to (1) deflate sand and allow for dune migration on what would have been a vegetated landscape, (2) transport sand hundreds of meters downwind from dune crests, and (3) transport significant quantities of silt in high suspension, kilometers downwind of its (lake plain) source. The eolian deposits here are thinner than most loess deposits, likely due to the silt-poor nature of the lake plain sediments; similar deposits on uplands in Michigan's Upper Peninsula, with sandy lake beds and outwash plains as sources, are also thin (Luehmann et al., 2013; Schaetzl & Loope, 2008).

Because the eolian mantle on these uplands is texturally uniform from top-to-bottom, we conclude that the silt was deposited contemporaneously with the sand from the dunes, i.e. we envision a system driven by strong winds, with saltating sands nearer to the surface, concurrent with transport of silts in suspension, not entirely dissimilar to the eolian system operative in the Nebraska Sand Hills (Miao et al., 2007). The end result is sandier loess near the dunes and siltier loess at more distant locations. Thus, our data suggest that deposition of eolian sediment on the uplands near Germfask, Michigan was temporally associated with dune migration on the GLA plain. The overall mass of silt in the mantles, as well as their areal extent, also point to a prolonged period of eolian activity and loess generation on the lake plain – supported by luminescence dates on the dunes

(Loope et al., 2012). This type of eolian system matches what was posited by Mason et al. (1999), i.e. saltating sands help to entrain and deflate silts from the landscape, leading to loess deposits downwind. Sediment deflation and transport in our study area during the latest Pleistocene and early Holocene were likely driven by strong northwesterly and west-northwesterly winds across the lake plain, based on (1) dune orientations, (2) previous work in the region (Arbogast et al., 2015; Rawling et al., 2008; Schaetzl et al., 2018b), and (3) loess textural patterns in the lee of large dunes (Figures 7, 8 and 10).

Conclusions

Although the evolution of the Newberry Dune Field remains somewhat enigmatic, data presented here add several important elements to this discussion, pointing to a concurrent period of dune migration and dust generation on the GLA plain, all within what would have been a forested landscape. Textures of dunes get progressively finer to the southeast (downwind), as would be expected for sand driven by strong northwesterly and west-northwesterly winds, across a partially vegetated, drought-influenced landscape. Where migrating dunes were stalled at bedrock obstructions, they developed into large dune complexes. Loess downwind of these large dunes is rich in fine sands, but gets siltier with distance. This pattern points to sand enrichment from the dunes proper, intermingling with silt, transported in high suspension but generated from dunes migrating across the lake floor.

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Disclosure Statement

No potential conflict of interest was reported by the authors.

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