



The loess cover of northeastern Wisconsin

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ABSTRACT

We present the first study of the distribution, genesis and paleoenvironmental significance of late Pleistocene loess in northeastern Wisconsin and adjacent parts of Michigan's Upper Peninsula. Loess here is commonly 25–70 cm thick. Upland areas that were deglaciated early and remained geomorphically stable preferentially accumulated loess by providing sites that were efficient at trapping and retaining eolian sediment. Data from 419 such sites indicate that the loess was mainly derived from proglacial outwash plains and, to a lesser extent, hummocky end moraines within and near the region, particularly those toward the east of the loess deposits. Most of the loess was transported on katabatic winds coming off the ice sheet, which entrained and transported both silt and fine sands. The loess fines markedly, and is better sorted, distal to these source regions. Only minimal amounts of loess were deposited in this area via westerly winds. This research (1) reinforces the observation that outwash plains and end moraines can be significant loess sources, (2) provides evidence for katabatic winds as significant eolian transport vectors, and (3) demonstrates that the loess record may be variously preserved across landscapes, depending on where and when geomorphically stable sites became available for loess accumulation.

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Introduction

Loess is widespread across much of the central United States, especially in the Midwest, on the Great Plains, and near major river valleys that carried outwash (Fehrenbacher et al., 1965; Flint, 1971; Ruhe, 1984; Fehrenbacher et al., 1986; Mason et al., 1994; Pye, 1995; Bettis et al., 2003; Roberts et al., 2003; Fig. 1). Many of these valley trains generated tremendous amounts of eolian sediment, with thick sequences of relatively pure, silty loess on nearby uplands (Hole, 1950 (reprinted, 1968); Flint, 1971; Hole, 1976; Ruhe, 1984; Leigh and Knox, 1994). Justifiably, most early research on loess in the midcontinent area was focused on loess from these main sources (Chamberlin, 1897; Smith, 1942; Leighton and Willman, 1950; Caldwell and White, 1956; Fehrenbacher et al., 1965; Barnhisel et al., 1971; Ruhe et al., 1971), as this loess is thick and dominates the landscape.

However, recent work has documented new, often localized, loess sources, on other deglaciated landscapes, or those nearby (Aleinikoff et al., 2008; Grimley, 2000; Muhs et al., 2008). Studies of these more localized and often thinner loess deposits have expanded the range of options for loess sources, caused many researchers to rethink former ideas about eolian processes, and added to the understanding of the environments and geomorphology of recently deglaciated landscapes. For example, Schaetzl and Loope (2008) documented that loess on uplands in Michigan's eastern Upper Peninsula was sourced

from the plain of Glacial Lake Algonquin. They used geochemistry to link upland loess to dune systems on the nearby lake plain that helped mobilize and deflate silt from silty-sandy glaciolacustrine sediments. Stanley and Schaetzl (2011) used textural and thickness data from loess in central Wisconsin to suggest that it had not one, but two, unique sources: (1) the late Wisconsin terminal moraine, a landform rich in silty tills and with numerous ice-walled lake plains (Attig, 1994; Clayton et al., 2008); and (2) unglaciated, sandy, bedrock-controlled terrain, rendered unstable by thawing permafrost and solifluction (Clayton et al., 2001). In northern Lower Michigan, Schaetzl (2008) hypothesized that the Port Huron outwash plain was the source of a thin silty mantle on nearby uplands. Here, permafrost so controlled the depositional setting that only the flattest sites retained eolian silt; on most other sites the loess was eroded off. Schaetzl and Hook (2008) demonstrated that the comparatively small outwash valley of the Manistee River was a source for the thin loess on nearby uplands, perched far above the valley. Loess was neither continuous nor detected on other, less geomorphically stable areas nearby. Finally, actively eroding surfaces may also have been loess sources during glacial episodes, such as the Iowan Erosion Surface (IES) in southeastern Minnesota and northeastern Iowa (Ruhe, 1969; Hallberg et al., 1978; Mason et al., 1994, 1999). During the last glacial maximum, the IES was ice-free and subject to eolian and fluvial erosion, making it a likely loess source. Thick loess is present here mainly on stable uplands known as paha (Mason et al., 1999) and on downwind areas.

Unlike upland areas near small meltwater rivers such as the Manistee in Michigan, upland surfaces near major outwash valleys

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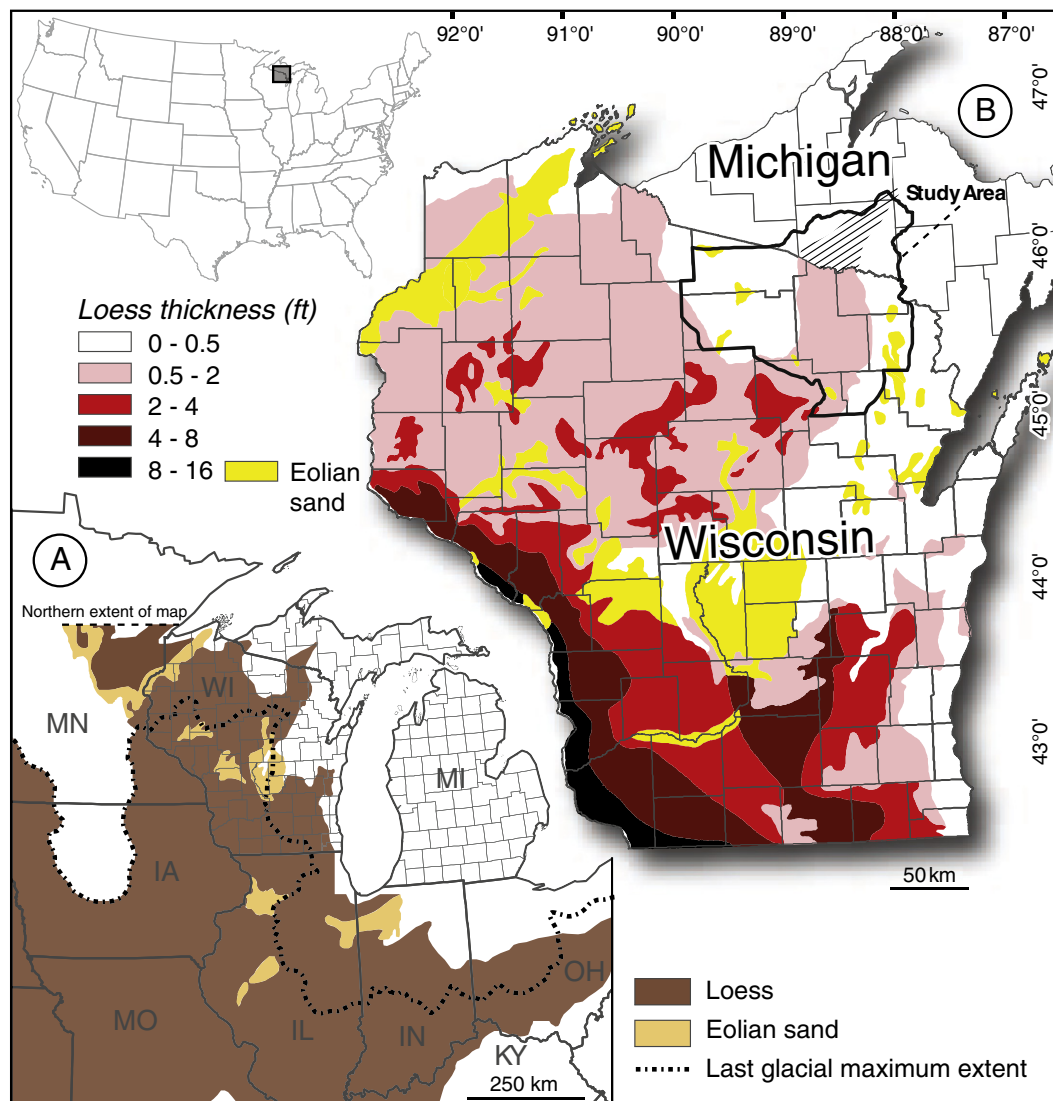


Figure 1. Distribution of loess in the Midwest and in Wisconsin. A. After Flint (1971), which is a generalized version of a map by Thorp and Smith (1952). The original extent of this map extended far beyond the limits shown here. Original scale in Flint: $\approx 1:154,000,000$. B. After Hole (1950, reprinted 1968) and Thorp and Smith (1952). The hatched area in Michigan represents the extent of loess as mapped by Thorp and Smith. The extent of the study area is also shown.

tend to be covered with thick loess deposits, because these rivers were often prodigious and recurrent loess sources (Smith, 1942; Smalley, 1972; West et al., 1980). Loess deposits tend to be concentrated in 50–200 km wide belts alongside these rivers (Smith, 1942; Leighton and Willman, 1950; Thorp and Smith, 1952; Ruhe, 1969; Smalley, 1972), and they tend to be thicker, more continuous and more extensive to the east of these rivers. These patterns clearly suggest that loess transport from them was driven dominantly (but certainly not exclusively) by westerly winds (Fehrenbacher et al., 1986; Mason et al., 1994; Muhs and Bettis, 2000; Bettis et al., 2003). Farther from the rivers, loess deposits are often discontinuous, and in places the loess is so thin as to have been completely incorporated into the underlying soil materials (Schaetzl and Luehmann, 2013). The present study focuses on just such an area.

In northeastern Wisconsin, loess occurs as discontinuous deposits across the landscape, often only on uplands and sideslopes; most lowlands lack loess entirely, as do many upland areas that show evidence of late glacial geomorphic instability, such as ice-contact landforms including hummocky moraines. Although these loess deposits have been previously documented on regional and state-wide maps of surficial deposits, for example Hole (1950, reprinted 1968)

and Figure 1, as well as within Natural Resources Conservation Service (NRCS) county soil surveys, our research focuses in detail on the distribution and origin(s) of this loess. This research contributes to the explanation of the origins of thin, patchy and discontinuous loess deposits that are especially common in the Midwest, north of the late Wisconsin terminal moraine (Hole, 1950 (reprinted, 1968); Thorp and Smith, 1952; Scull and Schaetzl, 2011). The purpose of this study is to map, characterize and interpret the loess deposits of northeastern Wisconsin, the northern extent of which continues into the western Upper Peninsula of Michigan.

Study area

Quaternary history

Northeastern Wisconsin and Michigan's western Upper Peninsula were glaciated several times during the Quaternary Period. Within the study area (Fig. 2), the topography and near-surface sediments are dominantly the result of the advance and subsequent retreat of the southern margin of the Laurentide Ice Sheet (LIS) between about 30,000 and 11,000 cal yr BP (Syverson and Colgan, 2004;

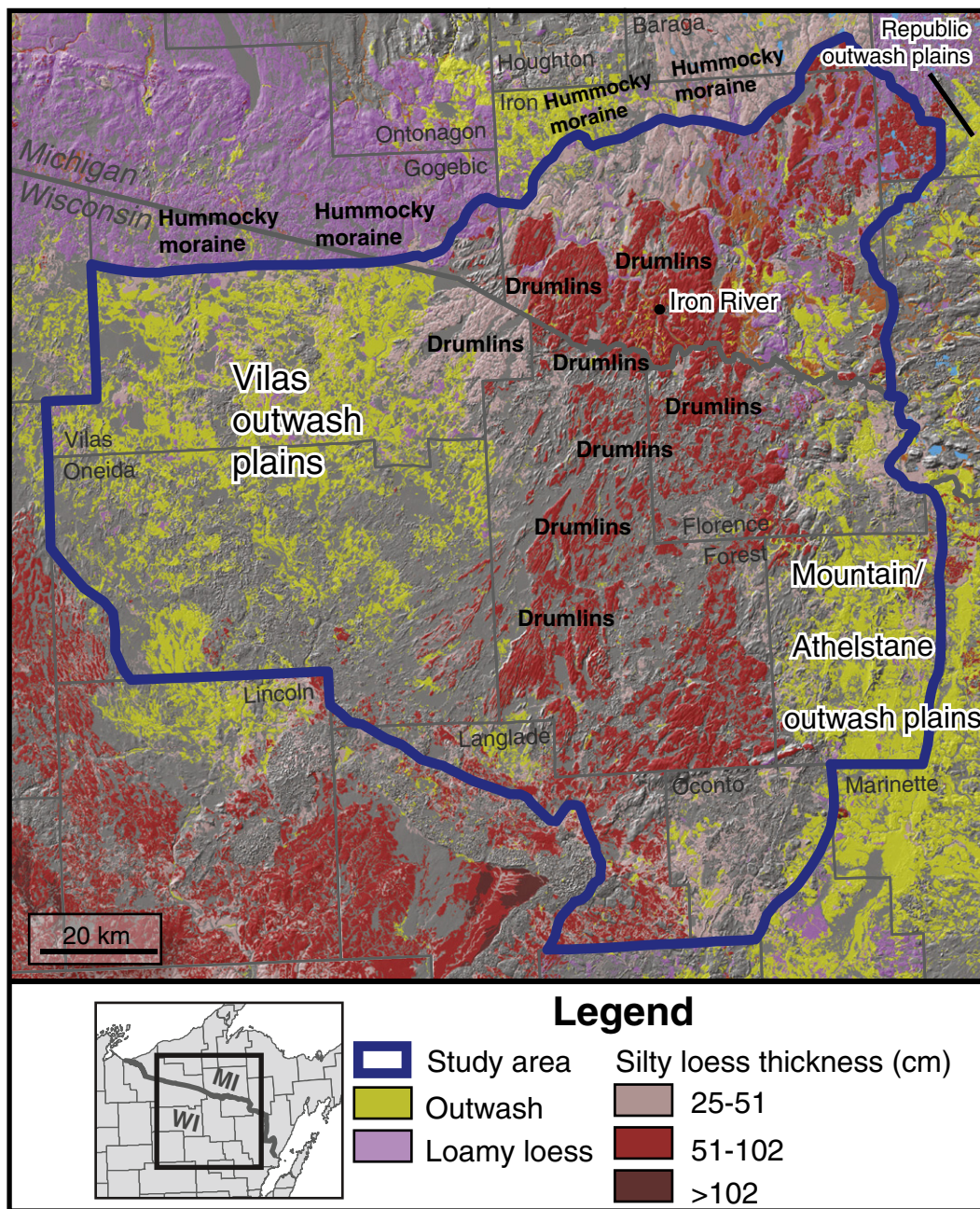


Figure 2. Outline of the study area, overlain onto a map of surficial sediment distribution (including loess thicknesses), as indicated on NRCS county soil surveys. Topography is illustrated by use of a hillshade DEM. Prominent cultural features (e.g., county and city names) also appear.

Attig et al., 2011a). Areas of bedrock-controlled topography do occur, however, in the eastern part of the study area, particularly in Iron County, Michigan.

By about 30,000 cal yr BP, the Green Bay, Langlade, and Wisconsin Valley lobes of the LIS had advanced into Wisconsin, reaching their maximum extent several thousand years later at the Hancock–Almond, Parrish, and Harrison moraines, respectively (Fig. 3; Clayton and Moran, 1982; Attig et al., 1985; Mickelson, 1986; Attig et al., 1998; Syverson and Colgan, 2004; Attig et al., 2011a). Ice recession was interrupted by several significant stillstands and readvances. Because of the configuration of the ice lobes in the study area, during ice retreat the high drumlin crests in the central part of the area (which also is higher than areas to its east and west) probably became ice-free early (Simpkins et al., 1987). These areas remained ice-free during subsequent readvances. Although ice margin recession in the

north occurred mainly by downwasting and widespread stagnation, retreat in the eastern parts of the study area was associated with a much more well-defined ice margin (Thwaites, 1943; Mickelson, 1986).

In the north, the east–west trending ice margin receded far enough north of the drainage divide for lakes to form between it and the bedrock highlands along the Wisconsin–Michigan border. Ice then readvanced into northern Wisconsin, depositing the Winegar moraine (Fig. 3). The sediment in the Winegar moraine contains more silt than that of earlier advances, as a result of the glacier overriding and incorporating silt-rich lake sediment (Attig, 1985). The Winegar readvance, ca. 14,000 cal yr BP (Attig et al., 2011a), resulted in the formation of extensive outwash plains in the northwestern part of the study area. These sandur surfaces are referred to here as the Vilas outwash plains, named for Vilas County which contains the majority of this landscape (Fig. 2). In many areas, this outwash was

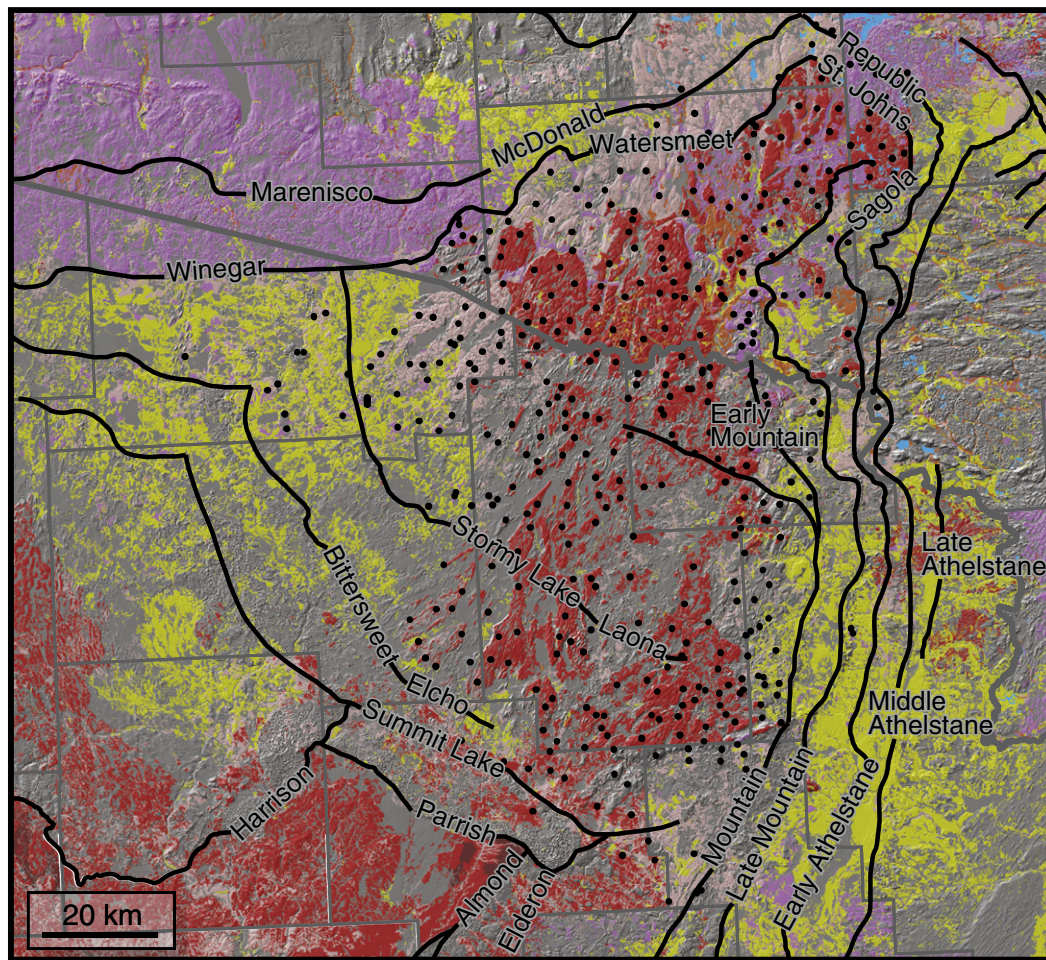


Figure 3. Ice-marginal positions (modified from Clayton et al., 2006) and sample locations used in this study. Ice retreat in this area proceeded from southwest to northeast; hence, the youngest moraines are in the northeastern part of the map. Color legend as in Figure 2.

deposited over remnant ice and outwash from earlier advances (Attig, 1985; Attig and Clayton, 1993; Attig et al., 1998). After recession from the Winegar moraine, the ice readvanced and deposited the Marenisco moraine about 13,000 cal yr BP (Attig, 1985; Peterson, 1986; Fig. 3). Taken together, the distribution of the many lakes and wetlands in the extensive pitted and collapsed outwash plains, coupled with the hummocky morphology of the moraines, indicate that buried ice persisted throughout the period of deglaciation until about the time of the Winegar and Marenisco readvances. This persistence of buried ice resulted in extensive landscape instability, due to melting of shallowly buried ice. Permafrost is thought to have existed in northern Wisconsin and adjacent Michigan until about this time (Clayton et al., 2001).

In northeastern Wisconsin, the pattern of deglaciation associated with the Green Bay Lobe was very different. Rather than widespread stagnation, ice receded downslope, into the Green Bay lowland, as a continuous ice margin. As a result, ice-margin positions are marked by narrow, well-defined moraines and heads-of-outwash (Thwaites, 1943; Clayton, 1986; Attig and Ham, 1999). The timing of the Green Bay Lobe retreat remains uncertain; retreat may have started as early as between 19,000 and 17,000 cal yr BP, or perhaps as much as 2000–3000 years later (Syverson and Colgan, 2004; Attig et al., 2011b). After the ice receded eastward from the Hancock–Almond moraine, it readvanced to the Elderon, Mountain, and Athelstane moraine systems (Fig. 3). Between these moraine systems and higher topography to the west, several north–south trending outwash plains formed, which we refer to as the Mountain/Athelstane outwash plains.

Because of the high and continuous character of these linear moraines, localized and perhaps ephemeral, proglacial ponding was common in areas currently mapped as outwash plains. Here, as in the north, ice buried by outwash or glacial sediment likely persisted until about the time of the Athelstane readvances.

Landscapes and geomorphology of the study area

Most of the study area consists of drumlins and other low hills, broad belts of hummocky moraines that locally contain remnants of many ice-walled lake plains, and nearly flat, locally pitted to extensively pitted and collapsed outwash plains (Fig. 2). The majority of the glacial sediment is sandy; sandy loam tills are common, and outwash is predominantly sand textured. Bedrock is near to the surface in Iron County, Michigan, and as a result, much of the sediment here is very gravelly. Elsewhere, the cover of glacial sediments is thicker, less gravelly, and bedrock outcrops are uncommon. The loess cover in the study area is often restricted to uplands, and is especially thick on high drumlins near the center of the study area (Fig. 2).

Because loess deposits occur at various locations across Wisconsin and have gradual and overlapping boundaries (Hole, 1950 (reprinted, 1968); Scull and Schaetzl, 2011), we chose to precisely define our study area, so as to focus on the loess deposits within. Our goal in defining the study area was to incorporate not only the core, but also the margins, of the northeast Wisconsin loess sheet, even as it extends into Michigan where Scull and Schaetzl (2011) named it the Iron County loess sheet. We included the surrounding glacial

landscapes if we believed that they were associated with the genesis of the loess. Thus, the study area includes neighboring outwash plains and often terminates at distal moraines (Fig. 2).

In northern Wisconsin, the study area includes areas south of the Winegar–Watersmeet moraine, particularly the Vilas outwash plains (Figs. 2, 3). At its southern margin, we delimited the study area at the Oneida–Lincoln County line, approximating the southern limit of the outwash surfaces. In Michigan, the study area border roughly coincides with the distal margins of the Watersmeet, St. Johns, and Sagola moraines, as defined by Peterson (1985, 1986) and modified by Schaetzl et al. (2013). These moraines form a prominent glacial re-entrant in Iron County, MI (Figs. 2, 3), within which the loess cover is particularly thick (Fig. 2; Luehmann et al., 2013). In northeastern Wisconsin, the eastern margin of the study area follows the state border. Farther south, it follows the middle Athelstane moraine (Figs. 2, 3). The southern border of the study area follows the Menominee County line westward, to the late Wisconsin moraine, named the Outer moraine by Thwaites (1943) (Figs. 2, 3). In Langlade County, the border generally follows the proximal slope of this moraine, through the interlobate with the Summit Lake moraine.

Methods

Preliminary data management and mapping

Hole's (1950, reprinted 1968) map of aeolian silt and sand deposits (Fig. 1) identified a broad area of loess in northeastern Wisconsin, which we used as a starting point for sampling. Additional detail on loess thickness and distribution was provided from Natural Resources Conservation Service county soil maps. Data from these maps, for both Wisconsin and western Upper Michigan, were downloaded from the NRCS's Soil Data Mart website (<http://soildatamart.nrcs.usda.gov/>) and imported into a GIS. In the GIS we rasterized the initial vector files and seamed the county-wide coverages together into statewide (Michigan and Wisconsin) mosaics.

In order to make the NRCS soil data more useful for mapping and sampling, we determined the parent material(s) for most of the soil series from the official series description on the NRCS website (<http://soils.usda.gov/technical/classification/osd/index.html>). When the parent material description for a soil series was stated as loess, usually over another sediment type, we also estimated its thickness from the description, entered these data into the GIS attribute table, and coded the map unit symbology in the GIS coverage accordingly (Fig. 2). Although we did not focus on them, soils described in the NRCS official series descriptions as having loamy loess or loamy eolian deposits as parent material, especially common on the Watersmeet/Winegar moraine, were also singled out and uniquely coded (Fig. 2). These GIS data were loaded onto a laptop computer, equipped with a built-in GPS unit, facilitating field navigation to predetermined sites for sampling loess soils.

Field methods and loess sampling

The field-sampling goal was to obtain a large number of representative loess samples from broad upland sites of low-slope gradient, using a repeatable and consistent methodology. Upland sites were deemed the most geomorphically stable areas in the landscape, and thus would have been most likely to have retained loess by limiting its potential erosion, redistribution, and/or burial. A digital elevation model (DEM) with 10-m resolution (USGS, 2009), used in conjunction with the loess map data, helped optimize the sample site targets. Forested areas were preferred for sampling, as many have never been plowed; agricultural fields were lower priority but were, necessarily, sampled in some areas.

Geographically, we sought to sample uniformly across the uplands of the study area. We aimed for a final sample density of at least one

sample every 20–30 km², with slightly higher densities in areas where the loess deposits are more prevalent or where they exhibit rapidly changing textural properties across the landscape. We were particularly interested in sampling upland sites near and within the outwash plains that border the main loess deposit, as these areas contained sediment that appeared to be eolian but with textures that were coarser than expected.

At each of 419 sample sites, a few of which lie just outside the study area boundary but are geomorphically related, loess thickness was determined, and a 500–600 g loess sample was taken using a hand auger (Fig. 3). For this reason, all loess thicknesses discussed in this document should be viewed as maximum thicknesses, because we sampled sites where loess should have been optimally preserved. Samples were taken within or below the soil profile but at least ≈ 30 cm from any underlying lithologic discontinuity (Schaetzl, 1998). Our goal was to obtain an amalgamated sample of loess that was representative of the entire loess column at the site, while avoiding the areas immediately above the underlying lithologic discontinuity, and the upper profile (A horizon) (Schaetzl and Luehmann, 2013). Areas of obvious disturbance, such as by tree uprooting (Schaetzl et al., 1990; Kabrick et al., 1997a, 1997b; Phillips and Marion, 2006), were avoided. Loess thickness and textural properties were noted at each site.

Lab analyses

The samples were air dried, lightly ground to pass a 2-mm sieve, and passed through a sample splitter and recombined (four passes total), in order to achieve the high level of homogeneity necessary for analysis on a Malvern Mastersizer 2000E laser particle-size analyzer. We did not remove carbonates or organic matter from the samples prior to further analysis, because the loess was not originally calcareous, and because these lower-profile samples contained almost no organic matter. From each homogenized sample, 2-g subsamples were removed and dispersed in a water-based solution of $(\text{NaPO}_3)_{13} \cdot \text{Na}_2\text{O}$, after shaking for 2 h. As discussed in Miller and Schaetzl (2012), subsamples of soil run in most laser particle-size analyzers are so small that they may not be representative of the larger sample. Thus, in order to optimize the quality of our particle-size data, we analyzed two subsamples from each loess sample and compared the data statistically. When the suite of particle-size data—of which the Mastersizer produces 105 discrete “slices” or bins—were sufficiently “similar,” we used the mean values for all subsequent analyses. However, in cases where the data from the two runs were sufficiently dissimilar (see Miller and Schaetzl, 2012 for details), a third, or sometimes even a fourth subsample was run. In these situations, the two most comparable samples were used to generate the mean particle-size values used in subsequent analyses.

Data analyses

Because these loess deposits are thin (≈ 10 –125 cm) and underlain by sandy glacial sediment, the textural characteristics (i.e., the particle-size distributions) of most samples have been compromised by sand that has been mixed upward by pedogenic processes into the otherwise silty loess (Schaetzl and Luehmann, 2013). Evidence of sand intermixing is clearly illustrated in most of the particle-size distribution curves from loess samples taken within the study area (Fig. 4). The distinct bimodality of the curves shows a silt or very fine sand peak, which we attribute to eolian transport, and a second peak (or mode)—usually in the medium sand fraction—which we attribute to the underlying glacial sediment. Schaetzl and Luehmann (2013) demonstrated that the sand mode in loess samples from this area is often similar to the underlying, sandy glacial sediments, confirming its origin. Note also that the sample directly overlying hard

bedrock lacks a secondary sand mode because there was no sand here to mix into the overlying loess (Fig. 4A).

This type of secondary sand “contamination” occurs in almost every sample recovered from the study area (Fig. 4), and as a result it dramatically skews particle-size distribution data. Therefore, as a necessary next step in the analysis, we followed the practice of Luehmann et al. (2013) by “filtering” the particle-size data; that is, essentially removing those particle sizes that compose the second (or, rightmost) “peak” on the particle-size curves (Fig. 4). Schaetzl and Luehmann (2013) confirmed that the vast majority of the underlying sediment in this area is very sandy, and thus the mixed-in sediment is almost all sand; little or no silt has been mixed upward into the loess. The goal of the filtering process is to restore the particle-size data as close as possible to its presumed original

composition. The filtering procedure runs as a macro in MS-Excel. Details of the procedure are provided elsewhere (Luehmann et al., 2013) and the Excel code is available at <http://www.geo.msu.edu/schaetzl/Links.html>. Examples of pre- and post-filtered data curves are presented in Figure 4.

GIS analyses

We kriged the “filtered” loess particle-size data, as well as thickness and sorting data. Although kriging may be a less-than-optimal interpolation routine in situations where soil properties exhibit spatial dependencies at scales smaller than the scale at which sampling was performed (Pongpattananurak et al., 2012), our dense sampling network, when applied to sediment like loess that has low amounts of

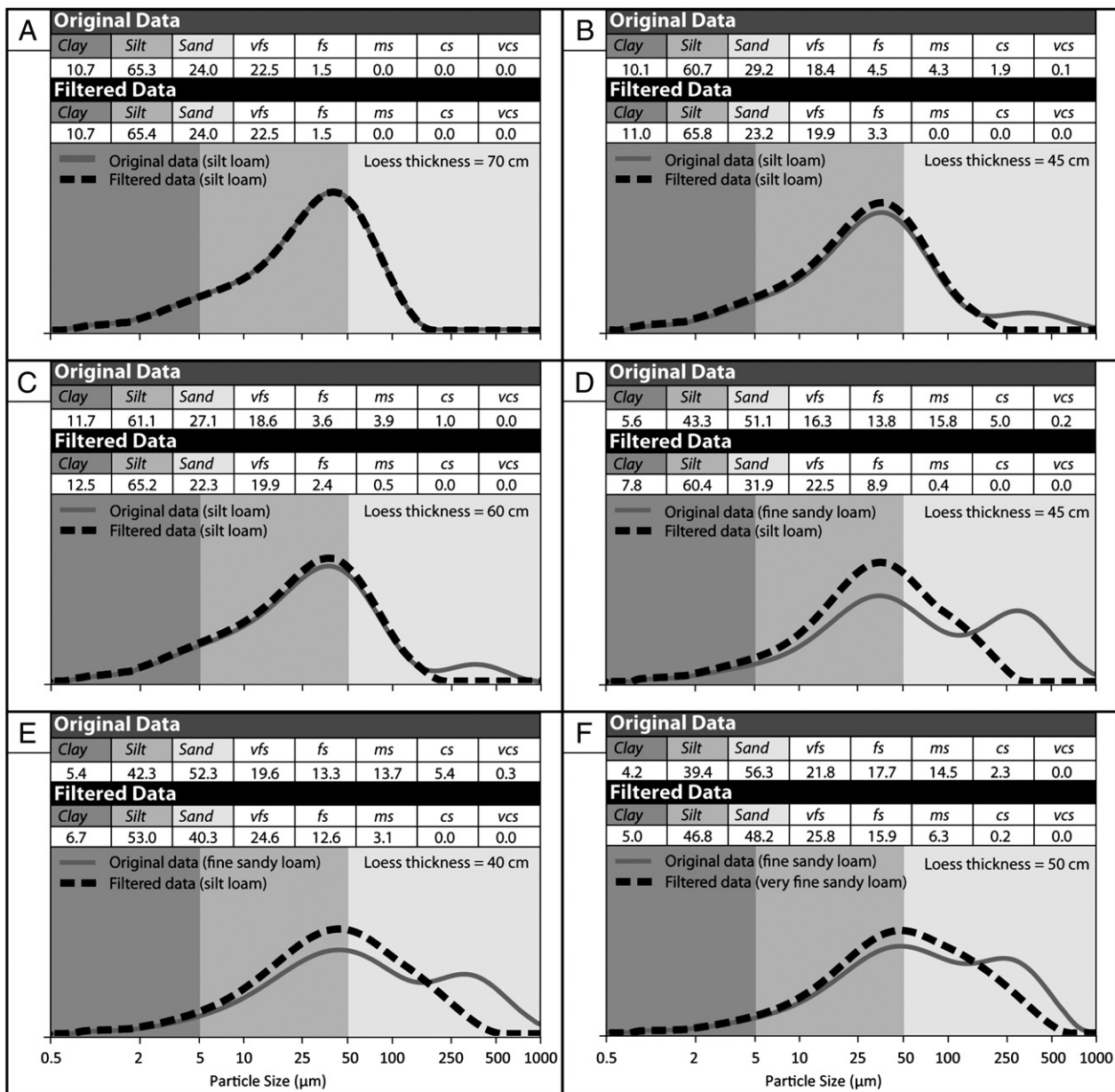


Figure 4. Original particle-size curves (thin gray lines) for various loess samples from the study area, illustrating the bimodality that commonly occurs when sand that underlies the loess is mixed into the initially silty sediment. Also shown (dotted black lines) are the particle-size curves for the same samples after applying a “filtering” operation that removes most of the sand data and recalculates the remaining particle-size fractions. See Luehmann et al. (2013) for details. A. Thick loess on a bedrock knob, northern Florence County, Wisconsin. B. Moderately thick, silty loess in Iron County, Michigan. C. Moderately thick loess in western Florence County, Wisconsin. D. Moderately thick loess on the west-central edge of the loess sheet, Forest County, Wisconsin. E. Thin, coarse-textured loess on the far eastern edge of the loess sheet, Marinette County, Wisconsin. F. Moderately thick and poorly sorted, coarse-textured loess near the Marenisco moraine, Gogebic County, Michigan.

Table 1
The major upland¹ soil series in the study area² that have some type of eolian mantle.

Soil series	NRCS parent material description (upper parent material–lower parent material)	Range of eolian mantle thickness (NRCS OSD) (cm)	Texture class of loess or eolian mantle (NRCS)	Extent within study area (%)
<i>Silty loess</i>				
Wabeno	Loess–loamy and sandy till or glacial mud-flow sediment	30–91	Silt loam	6.34
Stambaugh	Modified silty eolian sediments–gravelly sandy deposits	61–102	Silt loam	2.56
Goodman	Loess–till	30–102	Silt loam	1.58
Goodwit	Loess–till	30–102	Silt loam	0.20
<i>Silty–sandy loess</i>				
Champion	Modified loamy eolian material–gravelly sandy or loamy glacial till	41–61	Silt loam/fine sandy loam	2.52
Sundog	Modified loamy reworked eolian deposits–sandy and gravelly glaciofluvial deposits	Not reported	Very fine sandy loam	1.07
Petticoat	Modified silty eolian material–sandy glacial till	Not reported	Silt loam	0.84
Peavy	Modified loamy eolian material–loamy, dense glacial till	Not reported	Silt loam/very fine sandy loam	0.25
Wakefield	Modified loamy eolian deposits–loamy glacial till	30–46	Silt loam	0.11
Keewaydin	Loamy and silty eolian deposits–till	38–76	Fine sandy loam	0.07
<i>Sandy loess</i>				
Padus	Loamy alluvium–stratified sandy outwash	61–102	Sandy loam	14.15
Pence	Loamy alluvium or eolian deposits–stratified sand or stratified sandy outwash	25–51	Sandy loam	5.93
Keweenaw	Sandy deposits	Not reported	Loamy sand	3.87
Karlin	Sandy deposits	Not reported	Loamy fine sand	1.59
Pemene	Loamy sand glacial till	Not reported	Loamy fine sand	0.11
Lode	Modified loamy eolian deposits–sand and gravel	41–91	Silt loam/loam	0.22

1. Most of the upland soils, formed in loess, also have down-catena associated soils in wetter drainage classes. For the sake of brevity, they are not listed here.

2. The study area spans 14,900 km².

short-term spatial variation, gave us confidence in this method for this application (Matheron, 1963; Scull and Schaetzl, 2011). We used the geostatistical wizard module of ArcGIS to create various kriged maps, symbolizing the data in isoline format. Normally, we set the default parameters in the geostatistical wizard to 15 and 12 maximum and minimum neighbors, respectively. The number of isolines, as well as their spacing (equal interval vs. geometric interval), was adjusted in each map to maximize interpretability. Lastly, we clipped the isolines to the approximate spatial extent of the loess, which is a slightly smaller area than that of the study area boundary.

Results and discussion

Loess distribution and thickness

Maps of parent material determinations, as indicated on each soil series' official description (OSD) on the NRCS website (<http://soils.usda.gov/technical/classification/osd/index.html>), were used as estimates of loess distribution in the study area. We have found the NRCS maps to be excellent predictors of loess presence/absence, as well as thickness (e.g., Stanley and Schaetzl, 2011). That is, when NRCS descriptions indicate that a soil has formed in loess, we have been able to confirm the observation in the field at nearly all sites.

In glaciated regions, however, parent material assessments by the NRCS are usually done conservatively. That is, when NRCS personnel are unsure of the parent material, or when a series can occur on a number of similar materials, OSDs often use only generic descriptors. For example, several soil series in this area are described with "loamy sediment" or "loamy alluvium" parent materials. Many of these series actually have a thin but recognizable eolian mantle, although some of the underlying sediment has usually been mixed into it (Schaetzl and Luehmann, 2013). For this reason, some soils in the study area that have formed in an eolian mantle lack explicit "loess" parent material descriptors in their OSDs. Nonetheless, the dominant upland soils in the region that have formed in loess, are described as such by the NRCS (Natzke and Hvizdak, 1988; Linsemier, 1997; Boelter and Elg, 2004; Boelter et al., 2005; Table 1) and are shown in Figure 2.

Loess occurs mainly on the uplands that lie between the Vilas outwash plains to the west, generally associated with the Winegar moraine, and the outwash plains to the east that are associated with the Mountain and Athelstane moraines. This loess sheet continues into Michigan's western Upper Peninsula, where it lies within the box-shaped, glacial reentrant bordered by the Watersmeet, Ned Lake, St. Johns and Sagola moraines (Fig. 3). Where present, the loess is thickest on upland sites that presumably became geomorphically stable shortly after deglaciation. It thins on side slopes and is often undetectable in lowlands. Most lowlands in the study area carried glacial meltwater and contained ice later than adjacent uplands; loess deposited there may have been buried by, or mixed into, glaciofluvial sediment, or even removed by meltwater, as buried ice melted. Many thin loess deposits have been subsequently disturbed, mixed and buried by tree uprooting, especially in areas of high water tables (Schaetzl et al., 1990). In the few lowlands that have loess, it is often buried beneath thick mats of decaying organic matter.

Across the study area, extensive areas of thick loess occur as a nearly continuous mantle on the high drumlins of Iron County, Michigan, and northern Florence County, Wisconsin (Habecker et al., 1990; Kabrick et al., 1997a, 1997b; Fig. 5). The sediment on these uplands is typically silty and well sorted, with particle-size modal values of 31–38 μm and thicknesses between 50 and 75 cm. In the NRCS soil survey (Linsemier, 1997) soils on these uplands are mapped within the Wabeno soil series, described as having formed in 30–90 cm of silty loess over gravelly sandy loam till (Table 1). Thick, silty loess is especially noteworthy on hilltops north and east of Sunset Lake, in Iron County. Other nodes of particularly thick loess also occur in northwestern and extreme southern Florence County, and in southeastern Forest County (Fig. 2). Within any particular area, loess is usually thickest on broad summits of high elevation. Because all of these areas are high in elevation, it suggests that, during deglaciation, they became ice-free and stable earlier than did other, lower areas that contained native outwash rivers and abundant buried ice. As a result, they would have been open for loess accumulation longer than at other sites. Importantly, these sites may also have become vegetated earlier, increasing surface roughness and enhancing their ability to trap dust more efficiently than would

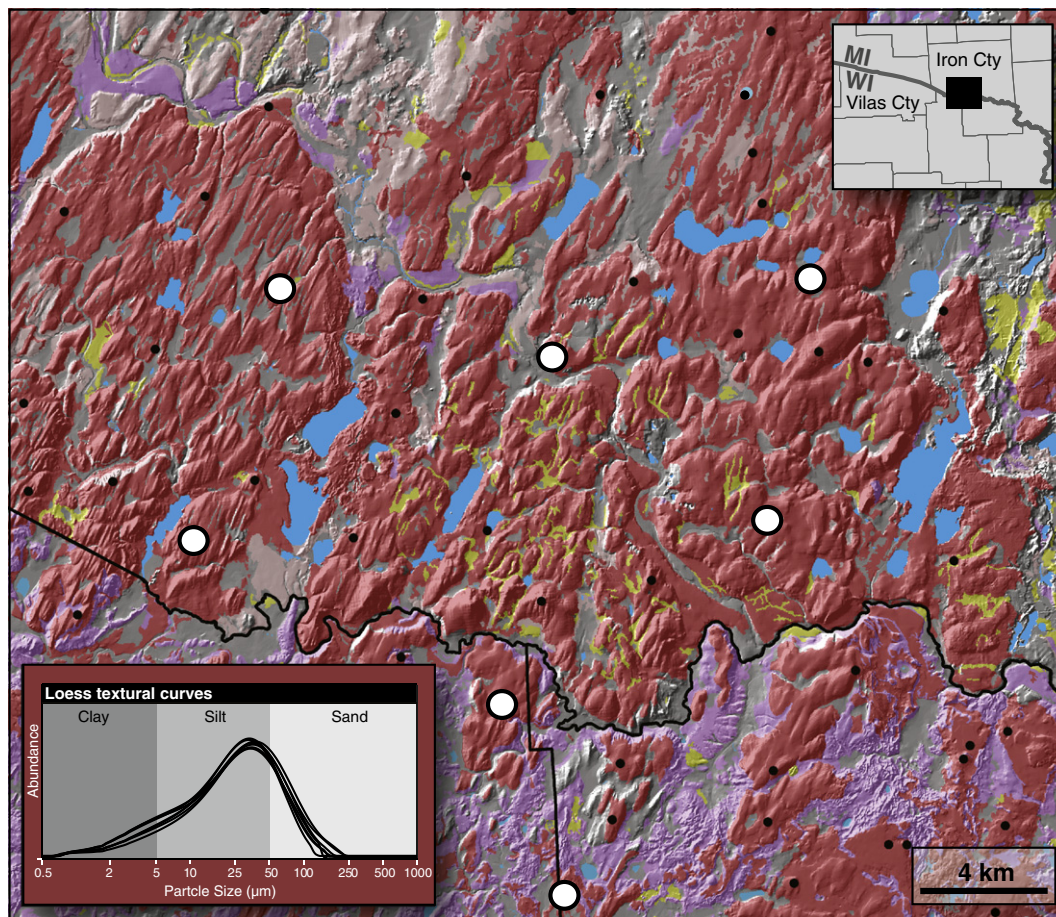


Figure 5. Shaded relief map of southern Iron County, Michigan, and adjacent parts of Wisconsin, showing loess distributions. This figure illustrates the drumlinized topography of the region, where silty loess with thicknesses of 55–70 cm covers most uplands. Loess soils in this area are usually mapped within the Wabeno series (Linsemier, 1997) and are shown on this diagram in red. Areas of thinner loess show as pink (Champion or Pence soils). Sample locations are shown as white and black dots. Filtered particle-size data for only seven of these are shown below; these sample locations are shown as white dots. Mapping units with “loamy loess” parent materials are colored purple, and outwash-derived soils are shown in yellow.

have other, less vegetated sites (Trainer, 1961; Tsoar and Pye, 1987; Pye, 1995; Lehmkuhl et al., 2000; Sweeney et al., 2007).

Loess is also noticeably absent in some upland areas within the core of the study area, particularly those areas that may have been geomorphically unstable for longer periods of time, due to abundant buried ice and thawing permafrost; these areas are readily identified because of high densities of kettles, hummocky topography, and the widespread occurrence of coarse-textured, ice-contact stratified drift (Clayton, 1986). Where loess is found in areas of collapse and instability, it is patchy and highly spatially discontinuous. These areas contrast with the high, stable drumlins of Iron County, which do not show evidence of collapse and have thick loess mantles. Many areas identified as collapse topography in Florence County were mapped by NRCS personnel as within the Padus series, formed in 60–100 cm of sandy loam sediment over stratified sandy and gravelly sediment. We interpret much of the coarseness of the upper profile to mixing of loess and the underlying, sandy sediment, or to erosion and redeposition, rather than to the initial texture of the eolian material.

Simpkins et al. (1987, 18) described “wind-blown sediment consisting of fine sand and silt” throughout the uplands of Forest County, Wisconsin. Just as they stated that in this area it approaches a meter in thickness, we found that loess thickness here typically is between 70 and 90 cm (Fig. 2). Field observations indicated that this loess cover varies in thickness, even on uplands, largely because of disturbances by tree uprooting and burrowing mammals (Clayton,

1986; Kabrick et al., 1997b). On sideslopes, much of the loess cover that may have existed has been transported downslope by colluvial processes, leaving behind a thin, mixed layer of loess and the underlying glacial sediment (Simpkins et al., 1987). Such non-summit areas were not sampled as part of the present research.

In general, the loess cover across the region is thickest along a N–S axis, running from south-central Iron County, MI, through west-central Florence County, WI, and into southeastern Forest County, WI (Fig. 6A). Here, the area of thickest loess is shifted east of center, toward the Mountain/Athelstane outwash plains. A second node of thick loess occurs in southeastern Vilas County, although this may be a statistical artifact driven by thick loess at two points. The loess thickness gradient is remarkably steep along the eastern edge of the loess sheet, in central Florence County and in southeastern Forest County. And, notably, loess thickness thins in parallel with the major ice margin locations in the Upper Peninsula (Fig. 6A).

Loess is generally thin or undetectable on the flat and pitted surfaces of the outwash plains of the study area. However, a loamy mantle, which we interpret as eolian sediment, is commonly found on many of the “flatter” uplands that rise above many of the broader outwash surfaces (Natzke and Hvizdak, 1988). Many of these uplands are outwash fans that became isolated and stable when the ice block that supplied water and sediment to them melted, even as meltwater continued to flow across broad, adjoining surfaces below. Loess is present on these uplands because they provided stable sites for eolian

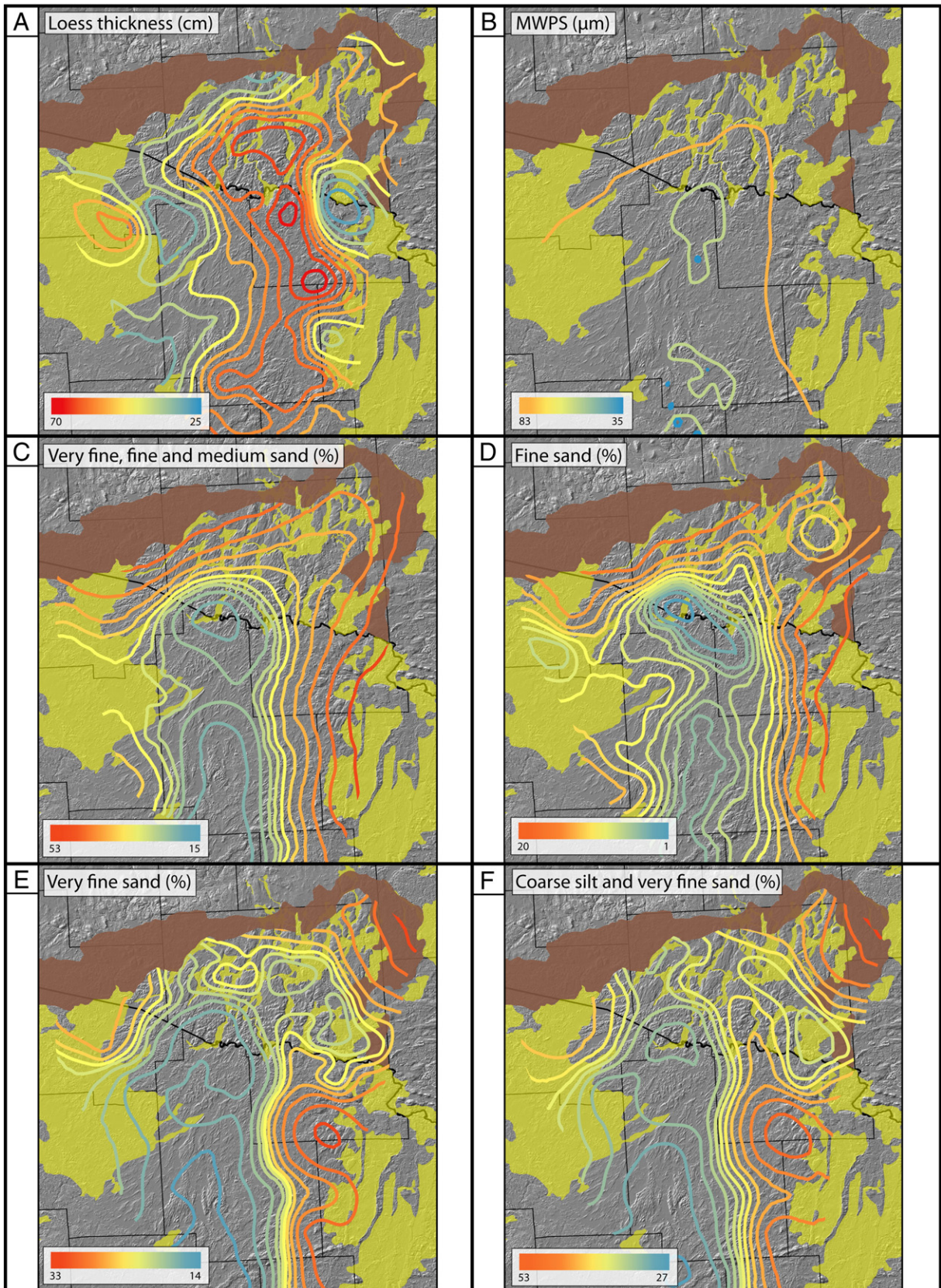


Figure 6. Kriged isoline maps of loess characteristics across the study area, set on a gray hillshade background. Yellow areas are outwash plains and meltwater sluiceways. Brown areas are wide, hummocky moraine tracts. Isoline values do not occur at equal intervals, as per the default mapping routine in ArcGIS. A. Loess thickness (cm). B. Mean weighted particle size (μm). C. Content of very fine, fine and medium sand (50–500 μm). D. Content of fine sand (125–250 μm). E. Content of very fine sand (50–125 μm). F. Content of coarse silt and very fine sand (40–125 μm). G. Content of medium silt (20–35 μm). H. Content of fine and medium silt (12–35 μm). I. Content of fine silt (12–25 μm). J. Mode of the 0–1000 μm particle-size fraction (μm).

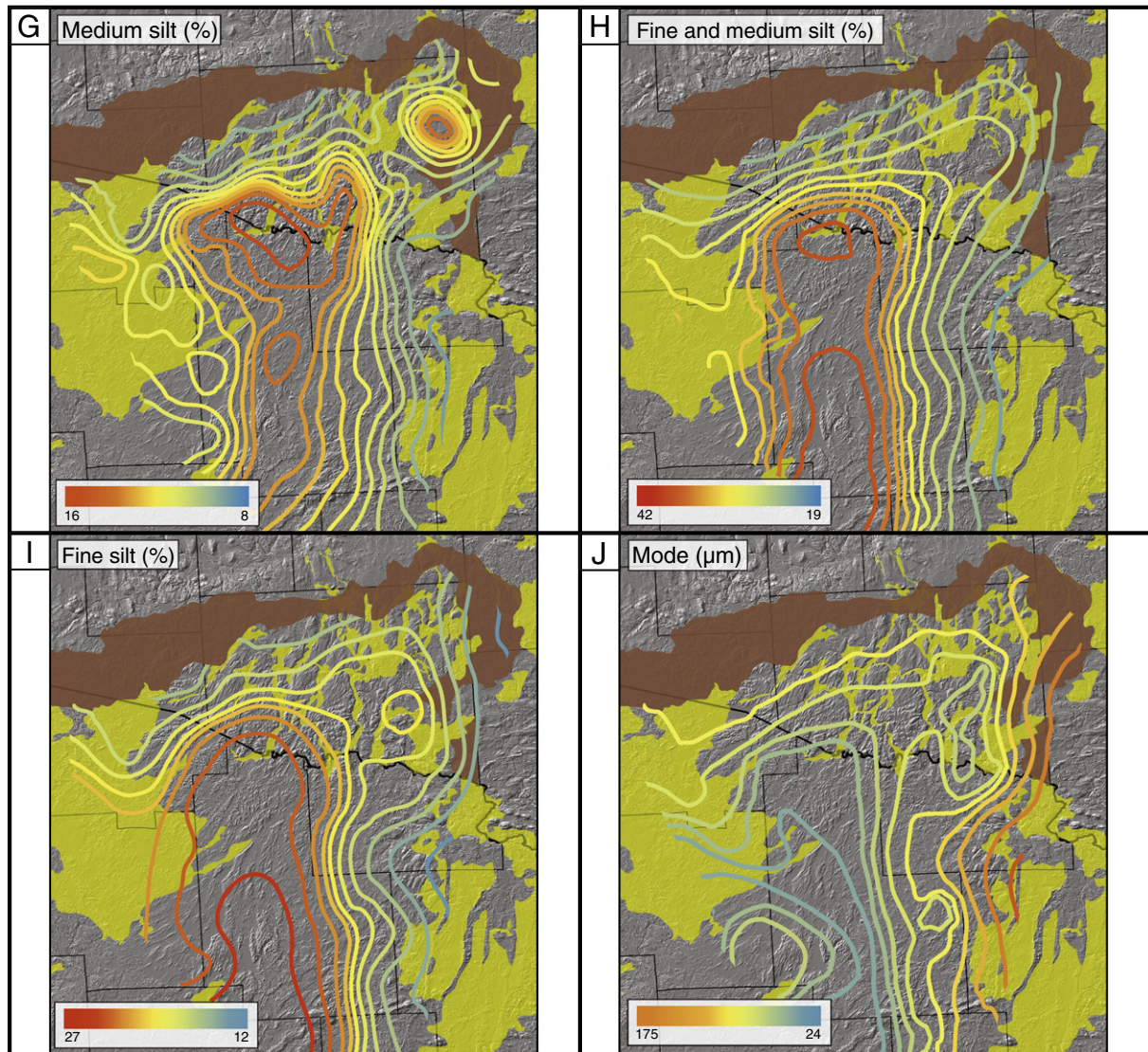


Fig. 6 (continued).

deposition of sediment generated from the surrounding, active outwash plains. Most of these uplands are mapped within the Patus or Pence series (Natzke and Hvizdak, 1988); Patus soils are particularly extensive across the study area (Table 1). Figure 7 shows the typical topographic expression of these uplands, as well as the particle-size curves for the coarse-textured eolian sediment found on them. This sediment is typically moderately sorted, with particle-size modal values of 33–38 μm . Considerable amounts of sand, and often a small amount of gravel, have usually been mixed into this otherwise silty, eolian material, making it appear abnormally sandy when field-textured. Pedoturbation of underlying sediment into thin loess is a common process (Rutledge et al., 1975; Schaetzl and Hook, 2008; Schaetzl and Luehmann, 2013). It is likely that vegetation began to colonize these uplands even while meltwater was flowing between them, further facilitating loess deposition, and minimizing erosion of loess that had accumulated there.

Source regions and paleoclimate implications for the loess in Wisconsin

Normally, loess thins and becomes finer-textured away from its source region (Smith, 1942; Ruhe, 1969; Fehrenbacher et al., 1986; Putman et al., 1989; Follmer, 1996; Mason et al., 1999; Bettis et al., 2003). However, the NE Wisconsin loess sheet is thickest in its central

or east-central region, and thins toward the edges (Fig. 6A). We suggest that this thickness pattern exists because the loess—at least in Wisconsin—had two distinct sources: outwash plains on its eastern and western margins. As a result, overlapping distance decay trends of loess thickness have combined to produce maximal thicknesses in the center of the deposit. The area of maximum thickness is then skewed toward (1) the source area that was contributing relatively more sediment, and/or (2) the area from which the distance–decay curve sloped most gradually (Fig. 6A).

Deflation of loess from active outwash plains is not a markedly different scenario than is the longstanding assumption of meltwater valley trains as loess sources. Indeed, Hobbs (1943) referred to the area next to the ice front as a zone of eolian deflation. Outwash plains offer broad, flat areas for winds to sweep across, and if active, provide continued exposures of fresh sediment—diurnally and seasonally—from which silts and fine sands can be entrained. Although quite sandy, outwash in the study area also contains considerable amounts of silts and fine sands (Fig. 7). Thus, our study suggests that the loess in Wisconsin was sourced primarily from outwash plains, and that the winds responsible for loess transport were dominantly off the ice, not westerly (see below).

Textural data provide strong evidence that both the Vilas and Mountain/Athelstane outwash plains were the sources of loess for

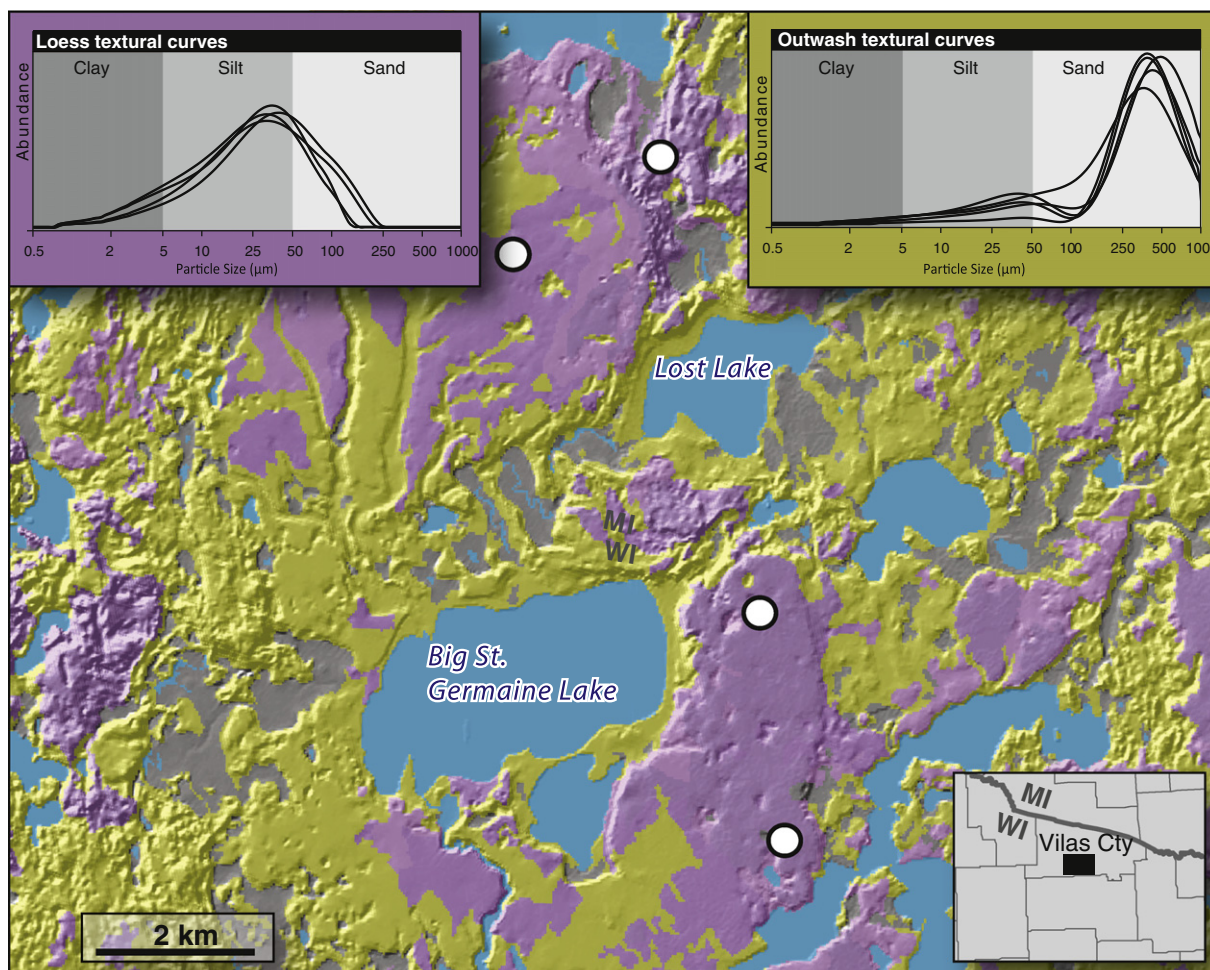


Figure 7. Shaded relief (a gray-colored hillshade DEM) map of the central section of the Vilas outwash plains, in southern Vilas County, Wisconsin. The figure illustrates the topography of the outwash plain, with its kettle lakes and ice-contact fans and uplands. In many places, these uplands are covered by coarse-textured eolian sediment, mapped within the Karlin, Keweenaw or Padus series by the NRCS county soil survey (Natzke and Hvizdak, 1988) and shown on this diagram in purple. The locations of four loess samples recovered from these areas, and their “filtered” particle-size curves, are shown. Mapping units with outwash-derived soils are colored yellow. Particle-size curves for outwash samples recovered from the Vilas outwash plains are also shown for comparison; these sample locations are not shown, for simplicity.

this loess sheet (Figs. 6, 8). Within both outwash plains, flat, stable uplands are capped with a mantle of coarse, sandy (but sorted) sediment that we interpret as loess (Fig. 7). All of the mapped textural parameters indicate that this loess sheet, unlike almost all others, is finest in the center, and coarsens toward each edge, pointing toward dual sources. Particle-size fractions coarser than 50 μm (i.e., all the sands) show similar spatial trends—decreasing regularly and predictably in abundance away from the outwash plains, with minimal values in the center of the loess sheet (Figs. 6C–F). All of the silt particle-size fractions show the opposite trend: they increase regularly away from the outwash plains, peaking within the center of the loess sheet. Lastly, particle-size modes—the size fraction found most commonly in the sample—are coarsest near and within the outwash plains, with minimum values in central Forest County (Fig. 6J).

The outwash in this region contains enough fine sediment to have been a significant loess source. Six outwash samples, taken within the C horizon of soils at various locations on the late Mountain outwash plain, contained an average of $9.5 \pm 3.7\%$ silt and $5.8 \pm 5.0\%$ very fine sand. Similar data, from five samples on the Vilas outwash plains, are as follows: $10.8 \pm 4.8\%$ silt and $5.1 \pm 3.7\%$ very fine sand. Meltwater in northern and northeastern Wisconsin was silt-laden, and although

well-sorted, the outwash here retained some of that silt. Clayton (1986) mapped several areas of late Mountain-aged till in eastern Florence County, which we visited and sampled. Our field interpretation of the sediment from these areas pointed to glaciolacustrine sediment overlying silty tills. Glaciolacustrine sediment in this area formed as meltwater became ponded distal to the Mountain moraines (Thwaites, 1943). Three samples of sediment from one of these lacustrine deposits (initially mapped as till, unit *gf*, on Clayton's (1986) map) were recovered from below the soil profile; they had average values of $22.9 \pm 6.5\%$ clay, $49.7 \pm 5.5\%$ silt, and $10.9 \pm 6.3\%$ very fine sand. Collectively, these data confirm that the ice in this region carried considerable amounts of silt and fine sediments, and that this sediment was transported into outwash and proglacial lacustrine settings. These data help support our contention that the loess here was sourced from the Vilas and Mountain/Athelstane outwash plains and that loess from these two distinct sources overlaps within the center of the sheet.

Details of loess textural trends can provide additional information about the character of each of these two loess sources, as well as paleoenvironmental conditions during loess deposition. For example, loess on the eastern margins of the sheet is considerably coarser than is loess in and near the Vilas outwash plains, typically containing 10–15%

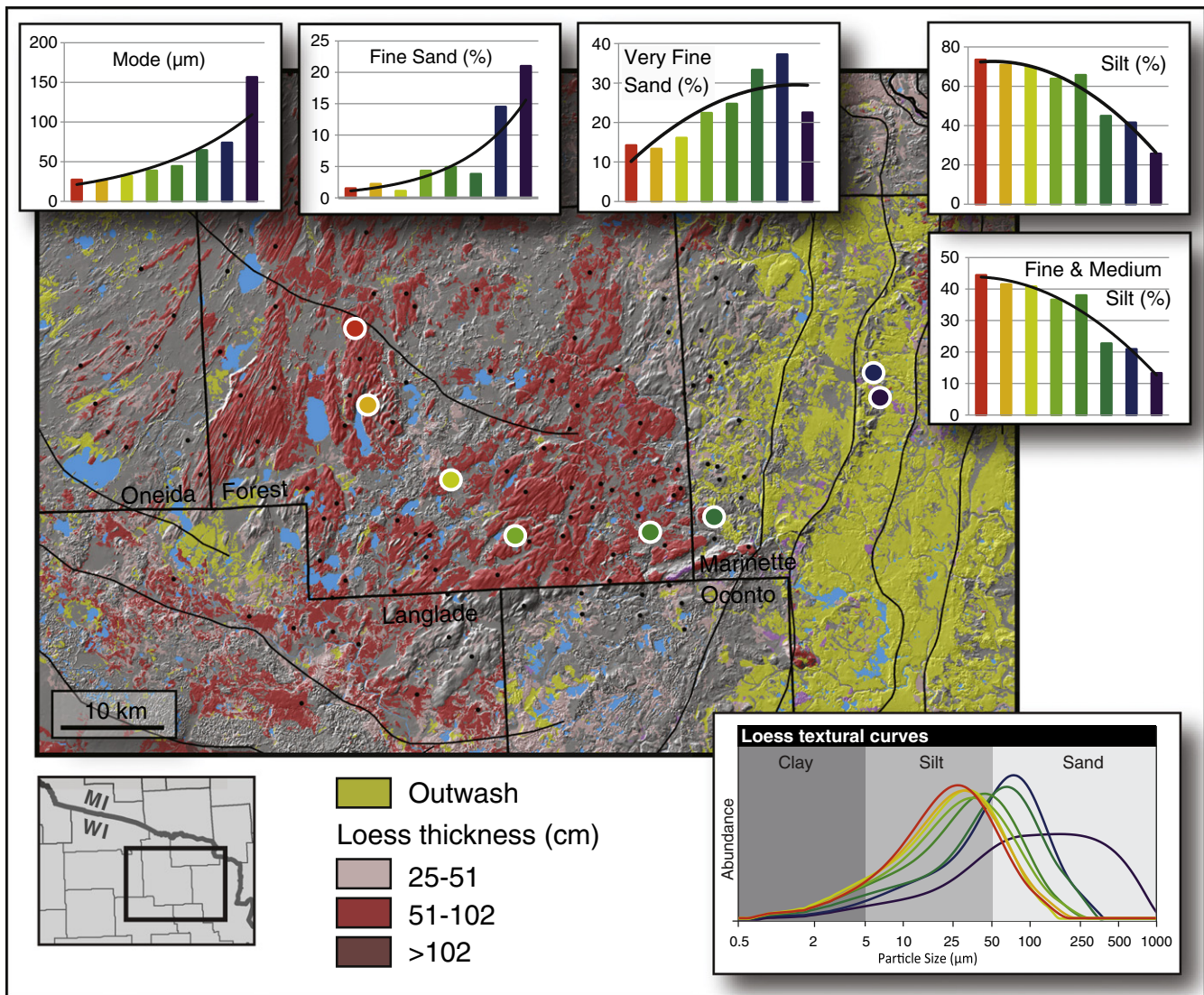


Figure 8. Data for eight sites that range in location from (east) an isolated upland within the Mountain/Athelstane outwash plains, to (west) a drumlin top within the core of the NE Wisconsin loess sheet. Shown are the particle-size distribution curves and histograms of various particle-size separates for each of the eight samples. The colored dots at the sample locations reference both the histograms for the various size fractions in the upper area and the particle-size curves below. Black dots represent other sample locations across the study area.

more very fine, fine and medium sand (Figs. 6C–J, 7). This textural-coarsening pattern is also highly regular and predictable (Fig. 8). These deposits are as coarse as many of the classic European cover sands but are not stratified (Vanmaercke-Gottigny, 1981; Kasse, 2002; Haase et al., 2007; Semmel and Terhorst, 2010). Like the European cover sands, these sandy eolian deposits transition downwind into classical, silty loess (Edelman and Maarleveld, 1958; Renssen et al., 2007). Fine sand contents in the NE Wisconsin loess sheet, likely to be most concentrated near its source area, easily attain their highest values (9–12%) at sites near the margin of the Mountain/Athelstane outwash plain (Fig. 6D). These data indicate that eolian sediment was being deflated from the Mountain/Athelstane outwash plains and transported to the west, into the NE Wisconsin loess sheet. Additionally, based on the loess textural data shown in Figure 6, we suggest that the Mountain/Athelstane outwash plain appears to have supplied more (and coarser) sediment to the eolian system than did the Vilas outwash plains. The primary evidence for this assertion is, again, spatial; for most of the coarser size fractions, the local minimum is skewed well to the eastern

side of the loess sheet (Figs. 6C–F). Much less of the fine and very fine sand fractions in the loess appears to have been derived from the Vilas County source area. Particularly notable in this regard is the map of very fine sand content (Fig. 6E). Very fine sand contents in the loess exceed 20% for 25–30 km west of the Mountain/Athelstane outwash plain, which is texturally comparable to loess only 5–15 km east of the Vilas outwash plain (Fig. 6E). The local minimum for fine sand is located at the Forest-Iron County line, almost 50 km from the Mountain/Athelstane source area, but less than 30 km from the Vilas outwash plain.

These data suggest that, in this region, easterly winds were prevalent and strong, probably coming off the Green Bay Lobe ice and traversing the Mountain/Athelstane outwash plains, deflating finer sands and silts from these active outwash surfaces. Conversely, westerly winds from the Vilas outwash plains source area, appear to have been comparatively weaker and did not transport coarser sediment as far into the loess sheet (Figs. 6C–E). Also possible is the scenario where winds traversing the Vilas outwash plains were not

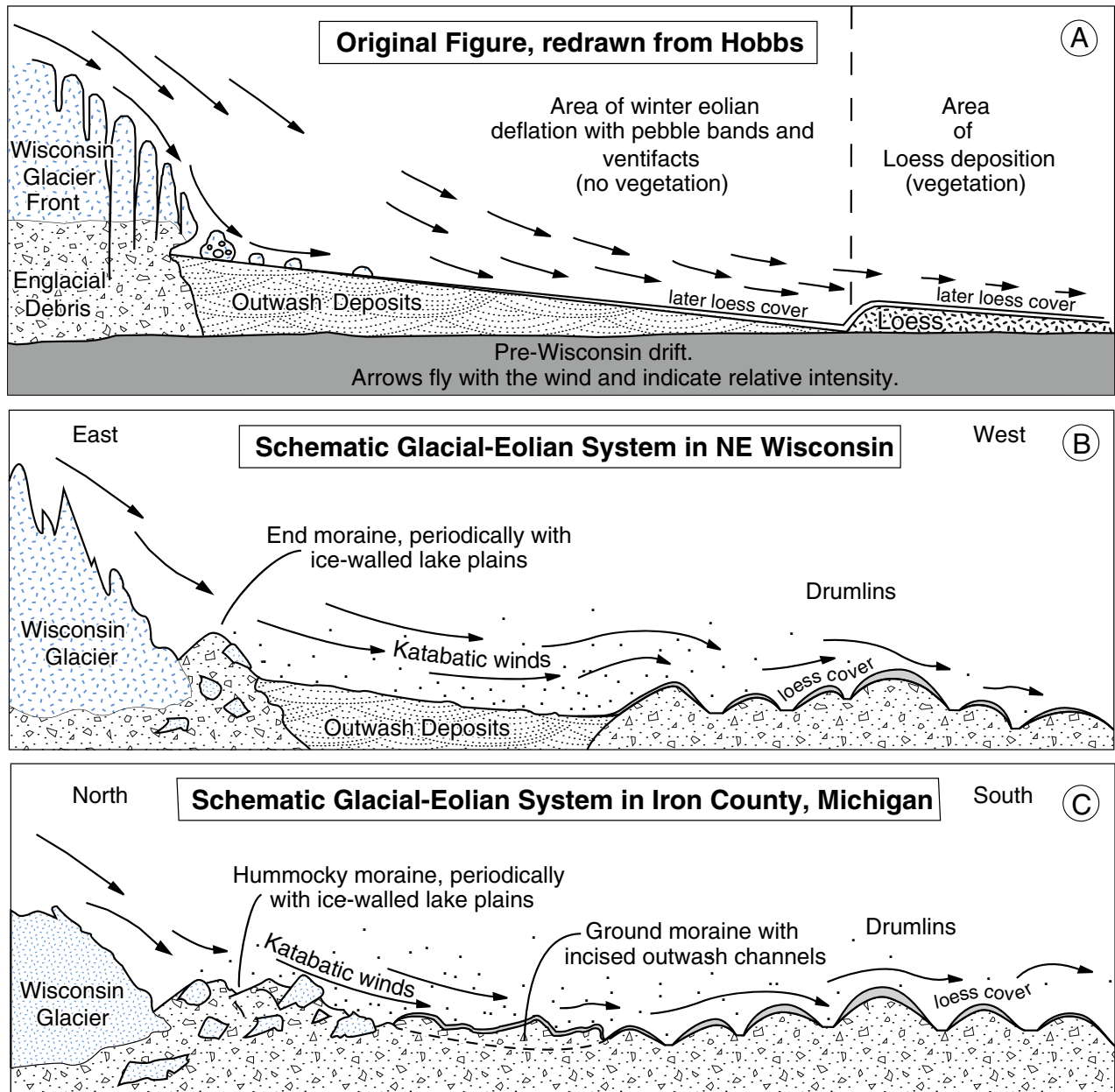


Figure 9. Diagram of loess deposition driven by katabatic winds coming off the ice front, as originally drawn by Hobbs (1943) in (A), and as modified by based on our observations, in (B) and (C). Eolian sediment is deposited on distal, stable, vegetated surfaces.

blowing dominantly to the east-southeast and onto the drumlins there, but rather, were more dominantly southward-flowing, normal to the ice front (as at the Athelstane moraine margin).

Data from the study area suggest that katabatic winds blowing directly off the ice sheet, often easterly but sometimes northerly, were an important mechanism of loess transport. This finding stands apart from most previous studies that document loess transport in the midcontinent region, at this time, driven mainly on westerly winds (Smith, 1942; Fehrenbacher et al., 1965; Ruhe, 1969; Mason, 2001). For example, based on loess data, Muhs and Bettis (2000) and Muhs et al. (2008) showed that late glacial paleowinds were dominantly westerly in and around the latitude of Iowa–Nebraska. In order to reconcile with these apparently conflicting data, we suggest that loess transport on katabatic winds may have only been a factor for areas within a few tens of kms from the ice margin, and

particularly in areas where the ice margin formed a reentrant. In regions farther south, regionally strong westerlies could easily have dominated the transport of loess, as the influence of the ice margin and its local katabatic winds waned.

Easterly winds have been modeled for many of the ice-marginal areas in the upper Midwest (COHMAP members, 1988; Bartlein et al., 1998; Kutzbach et al., 1998). Other evidence for easterly winds during the late Pleistocene, presumably driven by a glacial anticyclone, also exists for areas in the northern Great Lakes region. Admittedly, these areas are farther north—and much closer to the ice margin—than are many of the study areas that have found evidence for westerly winds at this time. Geomorphic evidence from spits and a delta in Glacial Lake Algonquin in northern Lower Michigan, ≈2000 years later and only 300 km to the east, provide proxy supporting data for easterly winds (Krist and Schaetzl, 2001; Vader et al., 2012). Evidence,

particularly textural data, from the loess in NE Wisconsin also points to strong easterly winds along the margin of the Green Bay Lobe in this area. Because the ice margin trends north–south in the study area, strong winds here would have been primarily katabatic in nature, or katabatically enhanced easterlies coming from a glacial anticyclone.

The notion of loess transport by katabatic winds is not new (Muhs and Budahn, 2006). Almost 70 years ago, Hobbs (1943) suggested that loess could be driven by katabatic winds blowing off the ice sheet, across proglacial outwash surfaces (Fig. 9). Modern experimental data confirm that katabatic winds can easily achieve speeds of 10–30 m s⁻¹ for sustained periods of time (Bromwich, 1989; Heinemann, 1999). Research has shown that, for most days, the maximum wind speed occurs during the early morning hours (Heinemann, 1999), when outwash surfaces would be the driest because of nighttime cooling, and that these winds routinely flow for substantial distances out, away from the ice margin, if the terrain is flat (Bromwich, 1989).

Except for situations in which they were composed of extremely well-sorted sands (i.e., lacked any silt), outwash plains and surfaces should, theoretically, have been prodigious loess sources for a variety of reasons: (1) fresh sediment was continually added to these surfaces via meltwater, (2) diurnal and seasonal fluctuations in water table/wetness conditions repeatedly refreshed and exposed outwash sediments to deflation, and kept these areas free of vegetation, (3) wind speeds could have achieved high levels due to the lack of vegetation and large expanses of flat terrain, and (4) saltation could have initiated deflation and re-suspension of any silty sediment in the depositional package (Mason et al., 1999).

In sum, our data support Hobbs' (1943) model of loess deflation and transport via katabatic winds for our study area. Hobbs' model does not appear to explain the distribution of loess along the west side of the Des Moines lobe in Iowa (cf. Ruhe, 1969), or for some of the other areas that he discusses, perhaps because these areas have different ice margin geometries or lack an area of ice-marginal outwash. However, in a glacial re-entrant area, such as NE Wisconsin, katabatic winds may have been stronger and more persistent (Millar and Nelson, 2001), facilitating deflation from the proglacial outwash plains that existed there.

Source regions and paleoclimate implications for the loess in Michigan

Although the loess in NE Wisconsin continues into Iron County, Michigan, and many of the textural trends observed on the Wisconsin side cross the border seamlessly, important differences do exist between the regions. Loess in the Michigan part of our study area is primarily located in the reentrant bordered by the Watersmeet, St. Johns and Sagola moraines (Fig. 3). The loess thins predictably and regularly toward each of the moraines, with thickness and mode isolines often paralleling the moraine fronts (Figs. 6A, J). Although thick, silty loess does occur in southern Iron County, Michigan, most of the loess here is coarser textured than the loess farther south, in Wisconsin (Fig. 6B). Contents of the various sand fractions in the loess in Michigan are high, and as with thickness, isolines of sand contents show predictable trends that parallel the moraines. Very fine to medium sand contents are highest near the moraines, and decrease away from them, toward the middle of the reentrant area (Fig. 6C). Fine sand contents show generally similar patterns (Fig. 6D). In the finer sand fractions, i.e., very fine sand, this pattern gets more complex, displaying a local maximum in the far eastern corner of the reentrant, near the Republic outwash plain (Fig. 2), and near the broad outwash channels between Iron River and the Watersmeet moraine (Fig. 6E). These data suggest that, in Iron County, loess may have been sourced from end moraines, outwash plains, and smaller, through-flowing meltwater channels (Fig. 9C).

Although spatial patterns for medium silt contents in the loess in Michigan are more complex, when fine plus medium silt contents are mapped, clear trends emerge. Again, contents of fine and medium

silt increase predictably, away from the moraines. Fine silt, particularly, shows a local minimum in the eastern corner of the Iron County loess sheet, immediately west of the Republic outwash plain (Figs. 2, 6I). Clearly, the Republic outwash was rich in sands (Figs. 6C–F) but low in silts; similarly, the morainic deposits in this area are very sandy.

Similar to the loess textural data in Wisconsin, where outwash plains functioned as loess source regions, spatial data for the loess suggest that the end moraines were source areas for the majority of the loess in Iron County, Michigan. Unlike in NE Wisconsin, where the end moraines are narrow ridges and the majority of the landscape consists of outwash surfaces, the gravel-rich moraines here are broad, generally loamy/sandy in texture, and with widespread collapse topography due to readvances over ice-rich terrain (Peterson, 1986). Subsequent meltout and slump processes would have led to continuing exposure of tills and ice-contact sediment, making them available for deflation. Small valley trains of through-flowing, proglacial outwash could also have contributed to the generally coarse-textured, near-source loess in this reentrant region (Fig. 6D). Areas in southern Iron County and eastern Vilas County may have also been receiving additions of loess from the Vilas outwash plains, from the small outwash surfaces in SE Iron County, and even from the more-distant Mountain/Athelstane outwash plains (e.g., Figs. 6H and I). Nonetheless, the coarse textures of the loess in Iron County point to the end moraines and their small outwash sluiceways as the main loess sources, similar to loess in central Wisconsin, which was partially sourced from the wide, hummocky, late Wisconsin end moraine (Stanley and Schaetzl, 2011).

As discussed above, katabatic winds in northeastern Wisconsin may have formed in association with the generally linear margin of the Green Bay Lobe. Within the reentrant area in Iron County, however, katabatic winds may have been particularly strong, because they would have converged into this relatively small geographic area from three sides. The Quaternary geology sets the area up for effective eolian transport of heavier fractions such as fine sand, despite the high-relief topography of the area. Note, for example, that fine sand contents of the loess in Iron County remain high, even 10–15 km from the ice margin, even though this sand would have to have been transported upslope and normal to the long-axis trends of the Iron County drumlins. Note that the regional low in the various sand contents (Figs. 6C–E) occurs in southwestern Iron County, at a regional topographic high. Here, topography overcame the effects of strong winds and was able to inhibit sand transport, resulting in a steep gradient in sand content away from the Watersmeet moraine.

Conclusions

This study is the first to examine a loess sheet of this extent, with a sample size this large, using textural data that have been filtered to remove particle-size data from coarse textured materials that had been mixed in to the loess from below. This type of “filtered” data better reflect the original loess particle-size distributions, and thus, can be used to more accurately identify source areas and interpret wind directions at the time of loess deposition (Luehmann et al., 2013).

The loess in NE Wisconsin and Iron County Michigan gets progressively finer along trendlines that are generally normal to the major ice margins. These patterns suggest that the loess was mainly transported via strong katabatic winds, possibly associated with, or strengthened by, a glacial anticyclone. These winds deflated sediment from hummocky end moraines and proglacial outwash plains, depositing loess on stable uplands, particularly on topographically high drumlins. Loess derived from large meltwater valleys far to the west was not a factor here. Many of the drumlinized uplands, which today are covered with up to a meter of loess, may have been deglaciated for some time and vegetated, increasing their surface roughness and facilitating loess deposition.

Acknowledgments

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