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Characteristics and paleoenvironmental significance of a thin, dual-sourced loess sheet, north-central Wisconsin

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ABSTRACT

We provide the first extensive data on the characteristics, distribution, and origin(s) of a thin but extensive loess sheet in north-central Wisconsin, USA. Unlike the relatively thick loess deposits downwind of broad meltwater valleys that reflect ice sheet dynamics, thin loess sheets far from such rivers may provide unique information about local paleoenvironmental change due to their smaller, and often environmentally sensitive, source areas. Silt loam textured and thin (<35 cm thick) on its eastern margins, loess in north-central Wisconsin thickens (to >70 cm) and coarsens towards the west and northwest, such that, on its western margins, the loess mantle is dominated by very fine and fine sands. Collectively, data on loess particle size distributions, thickness, and silt mineralogy suggest that this loess sheet had sources in two distinct and disjunct landscapes: (1) the late Wisconsin terminal moraine to the northwest, and (2) the sandstone-dominated landscapes to the west and southwest. Post-glacial thawing of these permafrost-affected landscapes probably led to draining of ice-walled lake plains on and behind the moraine, as well as destabilization of slopes on the sandstone landscape; in both cases, exposing large quantities of sediment for deflation. Our study makes two significant contributions to aeolian research: (1) we determine that the north-central Wisconsin loess sheet, unlike almost all others, has two distinctly different and disjunct loess sources, and (2) neither of these two loess sources fall within the traditional mode of "glacial meltwater valley."

1. Introduction

Loess deposits occur in many parts of the world and often are associated with glacial and periglacial environments (Bettis et al., 2003; Frye et al., 1962; Pye, 1984; Ruhe and Olson, 1980; Smalley, 1966; Smith, 1942). These deposits are important both as parent materials for productive agriculture and forests and as proxies of paleoenvironmental change, because they commonly record periods of landscape instability (loess accumulation) and stability (soil development) (Bettis et al., 2003; Busacca, 1989; Follmer, 1996; Willman and Frye, 1970).

In North America, thick loess deposits typically are associated with, and thought to be derived from, valley trains and wide river valleys (i.e. the Mississippi, Missouri, and Illinois Rivers), based on our understanding of aeolian and glacial systems and observations made within modern glacial environments (Lea, 1990; Muhs et al., 2004; Smalley, 1972; Smith, 1942; Snowden and Priddy, 1968). In this model, meltwater rivers draining ice sheets would have been rich with sediment. During times of low flow, fine sands and silts are deflated from these meltwater valley trains and deposited downwind, onto stable uplands. Loess deposits of this kind record information about ice sheet dynamics and dominant wind directions (Fehrenbacher et al., 1965; Frye et al., 1962; Johnson and Follmer, 1989; Ruhe, 1954, 1969, 1983; Ruhe and Olson, 1979; Smalley, 1966; Smith, 1942).

Loess is often deposited with clear spatial patterns of thickness, particle size distribution, and mineralogy, in relation to the sediment source area (Fehrenbacher et al., 1965; Johnson and Follmer, 1989; Mason, 2001; Muhs and Bettis, 2000; Ruhe and Olson, 1979; Schaetzl and Hook, 2008; Smith, 1942). Thus, the spatial characteristics of loess can provide important information about its source area and insights into the paleoenvironmental conditions under which deposition occurred.

Although thick loess deposits have been the focus of most research, relatively thin loess deposits blanketing much of the Midwest have, until recently (Schaetzl, 2008; Schaetzl and Loope, 2008), been largely ignored. In many cases, these loess sheets do not have an obvious source because they do not lie adjacent to broad meltwater valleys. Not only do these loess sheets present an interesting question as to origin(s), but they may also provide clues about local paleoenvironmental conditions, rather than ice-sheet dynamics, during loess deposition.

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With this background in mind, the purpose of our study is to (1) document and characterize a thin loess sheet in north-central Wisconsin, especially with regard to likely source areas, and (2) discuss the implications of this loess depositional event with respect to regional paleoenvironmental change.

2. Methods

2.1. Geographic and geologic setting

In the north-central Wisconsin study area, loess overlies sandstone bedrock residuum and/or glacial sediments, derived from one of four prior glacial advances (Attig, 1993; Attig and Muldoon, 1989; Clayton, 1991; Hole, 1942, 1976; Weidman, 1907). Within the western and southwestern parts of the study area, the landscape is dominated by dissected bedrock uplands, as the landscape transitions towards the Driftless Area (Knox et al., 1982; Fig. 1). Here, soils with sandy aeolian mantles overly weakly lithified, fine grained, Cambrian sandstones (Morrison, 1968; Ostrom, 1970; Weidman, 1907). Remnant glacial deposits can be found only in protected landscape positions within these bedrock controlled uplands (Simonson and Lorenz, 2002). Toward the east, the topography becomes more subdued as the thickness of glacial deposits increases and as the bedrock transitions to crystalline rocks of the Canadian Shield. Multiple episodes of glaciation have been inferred for this area based on the character of the till sheets, as well as the geomorphic character of the landscape (Attig and Muldoon, 1989; Stewart and Mickelson, 1976; Weidman, 1907).

The most recent glacial advance, the late Wisconsin, reached the far northwestern portion of the study area (Clayton et al., 2001; Fig. 1); its terminal moraine is comprised of high relief, hummocky topography, including ice-walled lake plains, kettles, disintegration ridges, and associated outwash fans (Attig, 1993; Attig and Clayton, 1993; Ham and Attig, 1997). During and after peak glaciation, periglacial conditions presumably existed, and continuous permafrost likely extended beyond the study area by ⩾20 km, and probably ⩾90 km (Black, 1965; Clayton et al., 2001; Johnson, 1986). As the ice receded and the climate warmed, the landscape underlain by degrading permafrost probably experienced various degrees of instability and mass wasting, similar to that of the Driftless Area (see Leigh and Knox (1994) and Mason and Knox (1997)). Under these conditions, it is likely that large amounts of sediment became exposed and available for deflation. Ice-wedge casts infilled with aeolian sediment from this period, both behind the moraine and within the Driftless Area, are taken as evidence that aeolian activity was contemporaneous with the period of permafrost degradation (Clayton et al., 2001; Johnson, 1986). A relatively thin (<1.5 m thick) loess mantle has long been recognized for the study area, primarily east of the Black River, where it overlies the various members of glacial drift, as well as bedrock residuum (Attig and Muldoon, 1989; Clayton, 1991; Hole, 1942, 1976; Weidman, 1907).

2.2. Sample collection

Geographic coordinates and loess thickness at 79 sample sites were recorded using a Garmin GPS 76 unit, running in conjunction with real-time tracking software in ArcMap 9.2 GIS (ESRI software, Redlands, CA). At each location, a representative loess sample, ~500 g, was collected using a standard 7.6-cm bucket auger. We attempted to acquire the loess sample as deeply as possible (to avoid surface contamination and disturbance), but at least 20 cm above the lithologic discontinuity with underlying sediment. Samples with obvious redoximorphic features were generally avoided. Sediment samples were also collected at a depth of approximately 50 cm at ten different ice-walled lake plains within the late Wisconsin terminal moraine, as delineated by Attig (1993) and Syverson (2007). At three sites where the loess was at least as thick as, or thicker than, the mean value for the area, pits were opened to reveal soil profiles, which were described and sampled according to NRCS guidelines (Schoeneberger et al., 2002; Soil Survey Division Staff, 1993).

Eleven 500 g samples of freshly exposed, sandstone bedrock were also collected from five different outcrops immediately west and south of the study area. Preference was given to facies containing shale layers, and finer textured sandstone strata.

2.3. Lab methods

Loess samples were oven-dried at 30 °C, ground with a mortar and wooden pestle, passed through a 2 mm sieve, and sent through a sample splitter four times, to insure complete homogenization for subsequent analyses. Sandstone samples were thoroughly crushed until nearly single-grained. Particle size analysis was completed using a Mastersizer 2000E laser particle size analyzer (Malvern Instruments Ltd., Worcestershire, UK) on chemically dispersed samples. To correct for the consistent underestimation of the clay sized (<2 μm) fraction by these machines (Arriaga and Lowery, 2006; Beuselinck et al., 1998; Konert and Vandenberghe, 1997; Sperazza et al., 2004), the clay/silt boundary used to interpret standard texture classes was set to 6 μm, which most closely mimics particle size data using the sieve-pipette method, based on data from in-house studies. Laser particle size data, are output as nearly continuous curves. In order to facilitate data analysis and discussion, and to better make our data comparable to those in the published literature, we compiled the particle size data into several discrete size divisions. Initial particle size splits were based on standard USDA breaks at 50, 125, 250 μm, etc. To these, we also added several breaks at intermediate values, e.g., 12, 25, 35, and 75 μm. The finer particle size splits allowed for greater analytic rigor.

After observing that most of the silt peaks for the loess samples fall within the 20–45 μm range, silt in this size range was chosen for subsequent mineralogical analysis. Twenty loess samples were selected for this analysis, based on the descriptions recorded in field notes and by geographic location, to ensure a uniform distribution across the study area. Eight of the 15 sandstone and sandstone residuum samples were also analyzed, based on their relatively high silt contents, as were all nine ice-walled lake plain samples. Silts (20–45 μm) from these samples were micronized for 3.5 min using a Fritsch Analysette 3 Spartan Pulverisette 0 mini mill (Fritch GmbH, Idar – Oberstein, Germany). The resulting powder was then hand-packed into a sample container, in order to optimize random orientation of silt particles. X-ray diffraction (XRD) was performed on these samples, using a MiniFlex+ X-ray Diffractometer (Rigaku Corporation, The Woodlands, TX). Diffraction scans were run between the angles of 25° 2θ and 31.5° 2θ, using a step size of 0.02° 2θ, as suggested by Grimley (1996).

Mineral peaks and background values were determined using JADE computer software (Materials Data, Inc., Livermore, California), and the mineral peaks identified by JADE were manually verified. Relative feldspar contents were estimated based on F/Q peak heights and peak intensity factors (Grimley, 1996, 2000; Grimley et al., 1998).

Maps of loess thickness, particle size data, and silt mineralogy were created in ArcMap 9.2, using ordinary kriging, operating under the default smoothing factor within the geostatistical analyst extension. Particle size distributions were interpolated on a clay-free basis to mitigate pedogenic changes, i.e. clay illuviation, because loess samples were collected from variable horizons (Schaetzl, 1998).

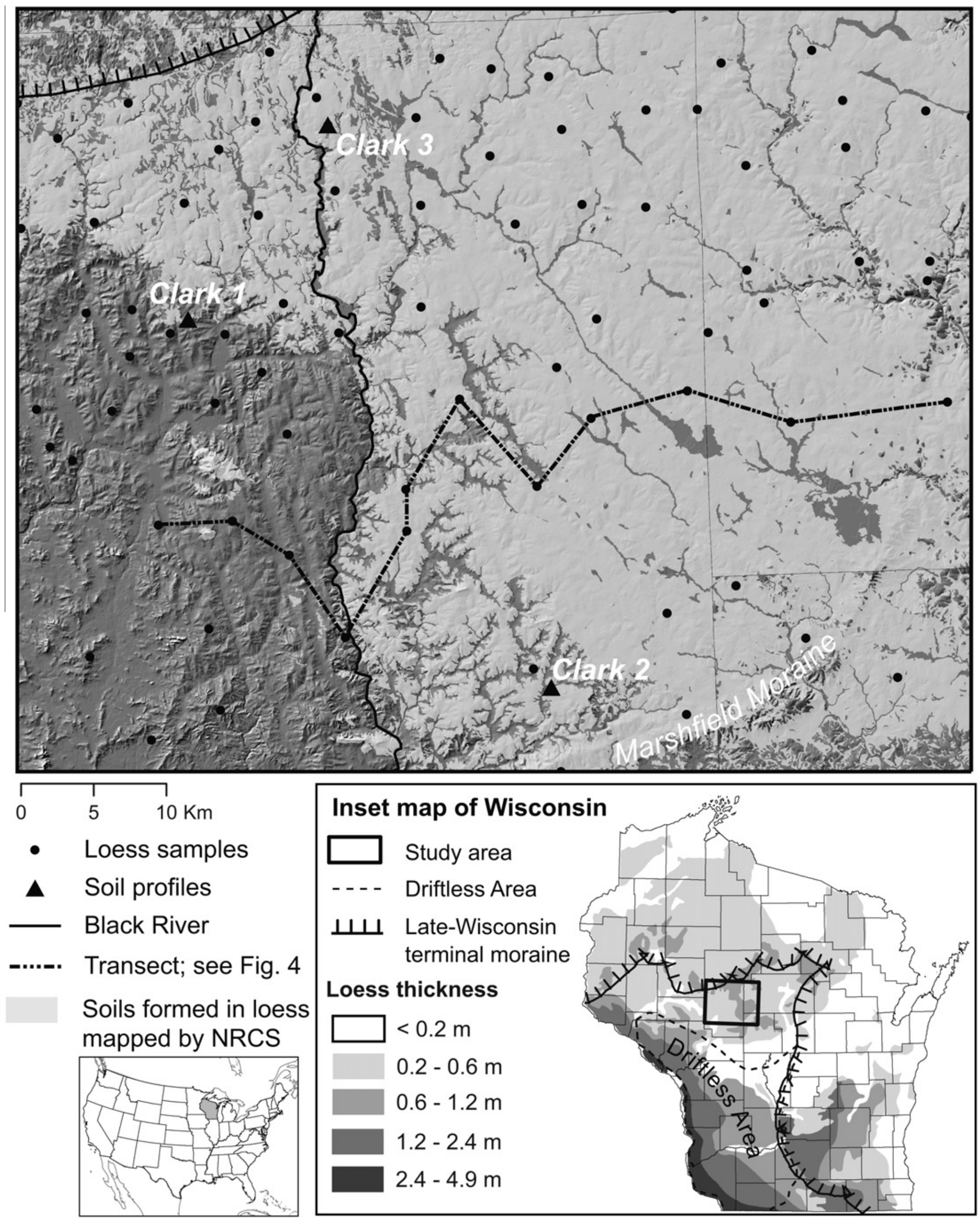

Fig. 1. Map of the study area (black rectangle) showing loess soil map units (light gray), taken from NRCS county soil surveys (Bartelme and Strelow, 1977; Boelter, 2005; Fiala, 1989; Simonson and Lorenz, 2002), overlain on a digital elevation model (DEM) (dark gray) of north-central Wisconsin. The extent of the late Wisconsin glaciation in Wisconsin is shown by a dark, hatched line. The boundary of the Driftless Area (an area lacking evidence of having been glaciated during the Quaternary) is delineated with a dashed line (after Clayton et al., 2006). Loess distribution is shown in the Wisconsin inset map with darker tones representing thicker loess accumulation (after Hole, 1968).

3. Results and discussion

3.1. Loess thickness

Across the study area, loess thickness decreases gradually from thickest areas (>75 cm) in the northwest, towards the southeast, where it is commonly <45 cm thick (Fig. 2). This trend likely reflects dominant northwesterly paleowinds during loess deposition, which is consistent with paleowind directions inferred from loess deposits elsewhere within the upper Midwest (Muhs and Bettis, 2000; Ruhe, 1954). The thickness trend also points to the late Wisconsin moraine as a possible regional loess source; it lies northwest and proximal to the thickest areas of loess (Fig. 2).

In the central part of the study area, a secondary area of relatively thick loess decreases in thickness to the east and southeast, which indicates westerly winds also occurred during a time of intense aeolian activity (Leigh and Knox, 1994; Mason et al., 1994; Muhs and Bettis, 2000). This gradual thinning trend suggests a second, western loess source also existed, possibly the Cambrian sandstone landscapes that lie immediately to the west (Hole, 1942). In the southeastern corner of the study area, a relatively thick area of loess is shown on the map in Fig. 2. However, this trend is based largely on a data from a single, isolated sample. Lacking additional sample points in the vicinity, it is difficult to determine whether this measurement is an outlier, or if the increased thickness is related to its position on the lee side of the

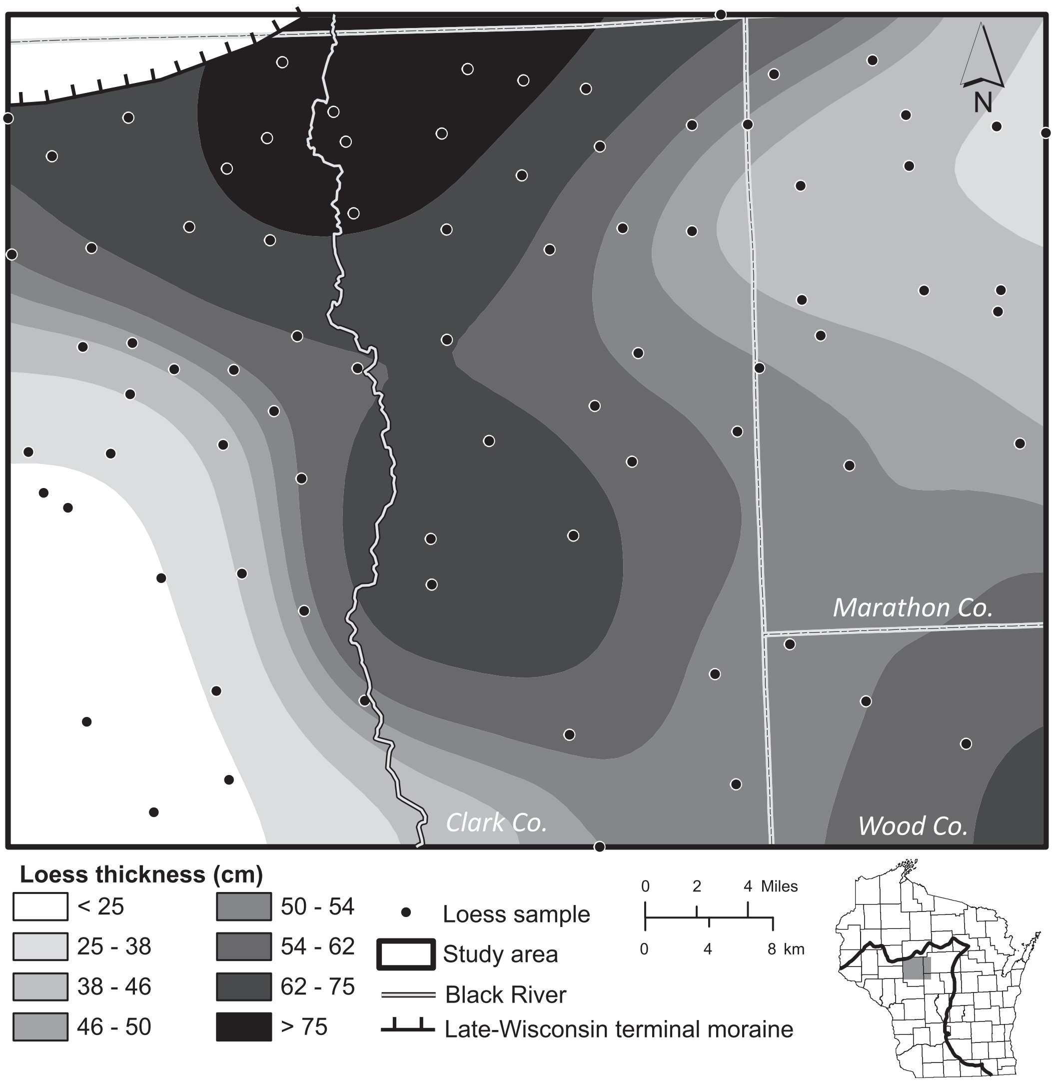

Fig. 2. Kriged map of predicted loess thickness based on 79 samples in north-central Wisconsin. Dark shades represent thickest areas of loess (>75 cm), and light/white shades represent loess thickness <25 cm.

Marshfield Moraine (Figs. 1 and 2). Unfortunately, additional samples could not be collected here, in accordance with sampling protocols, due to the low relief terrain and the nearly ubiquitous cultivation of upland sites.

3.2. Particle size data

Data from the three soil pedons sampled from pits (Clark 1, 2, and 3) unmistakably show loess above glacial drift (Table 1). Below the A horizon, contents of very fine, fine, and medium sand increase with depth in the loess at all three locations, especially at Clark 3. It is unclear whether the relative sandiness of the A horizon is a product of cultivation at these locations, or if it represents a change in source characteristics during the final pulse of aeolian activity. Increasing sand contents with depth may reflect the possibility that: (1) loess deposition rates may have been slower at first, allowing pedogenesis to keep up with aggradation, leading to mixing between the sandier substratum materials and the overlying loess, and/or (2) aeolian sediments may have contained more very fine sand initially, but may have become more silt-rich during later episodes of loess deposition. In this second scenario, the fining of loess towards the surface could have resulted from wind speed variations (stronger winds initially, decreasing in intensity over time), or from a change in sediment supply (initially sediment deflated from a sandier source, but changing over time to a more silt-rich source). Regardless, the increase in sand contents with depth suggests that paleoenvironmental conditions were not static during the period of loess deposition.

Spatial trends of particle size fractions in the loess mantle are consistent with loess deposits elsewhere in the Midwest, where coarse silty and fine sandy loess occurs proximal to the likely source, and medium, fine and very fine silt fractions are more abundant downwind (Muhs and Bettis, 2000; Ruhe and Olson, 1979; Schaetzl and Hook, 2008; Smith, 1942). Particle size trends in the loess sheet show a gradual, but dominant, fining pattern towards the southeast (Fig. 3), similar to the thinning pattern that also exists here (Fig. 2). The fine and medium sand fractions (125–175 μm and 175–250 μm) of the loess sheet are highest in the southwestern part of the study area, coinciding with the approximate eastern extent of the fine-grained Cambrian sandstone landscapes (Fig. 3A and B). Concentrations of these particle size fractions gradually decrease toward the northern and central parts of the study area. These fractions are also relatively high in the eastern part of the study area – likely the result of a thinner loess mantle and long-term pedoturbation with the underlying pre-Wisconsin tills (Stanley, 2008).

Table 1
Clay and clayfree particle size data for the three soil pedons sampled.

	Sample	Depth	Parent material	Fine earth[a]			Clayfree									
	ID	(cm)		S:Si:C	Texture class	MWPS[b]	S:Si	VFS[c]	FS[c]	MS[c]	CS[c]	VCS[c]	VFS [c]	FSi[c]	MSi[c]	CSi[c]
Clark 1	Ap	0–18	Loess	41:53:6	Silt loam	73.2	44:56	26.0	11.4	6.5	0.2	0.0	8.8	20.4	12.9	13.9
	E	18–40	loess	30:55:15	Silt loam	82.0	35:65	12.7	9.0	10.2	3.1	0.0	16.9	25.7	12.1	10.3
	2EB	40–51	Sandy loess ('mixed')	31:53:16	Silt loam	83.1	36:64	15.6	8.3	8.5	3.7	0.2	15.0	24.2	12.7	11.7
	2Bt/E	51–70	Sandy loess ('mixed')	48:40:12	Loam	135.3	54:46	15.9	15.6	16.4	6.2	0.2	10.8	17.2	9.1	8.6
	3Bt/Eb	70–84	Pre-Late-Wisconsin drift	26:57:17	Silt loam	87.2	31:69	10.1	6.3	8.8	5.3	0.3	20.6	28.6	11.3	8.6
	3Btb1	84–120	Pre-Late-Wisconsin drift	57:31:12	Fine sandy loam	143.1	64:36	18.0	22.2	19.4	4.7	0.1	8.2	13.0	7.2	7.2
	3Btb2	120–145	Pre-Late-Wisconsin drift	22:58:20	Silt loam	49.3	27:73	12.9	8.7	5.0	0.8	0.0	26.4	29.5	9.5	7.0
	3Cg	145–169	Pre-Late-Wisconsin drift	27:55:18	Silt loam	73.0	33:67	13.3	9.0	7.0	3.3	0.2	23.2	27.0	9.5	7.4
	4Cr/3Cg	169–179	Sandstone residuum/till													
	4Cr	179+	Sandstone residuum													
Clark 2	Ap	0–18	Loess	35:58:7	Silt loam	77.5	37:63	21.7	7.1	5.8	2.5	0.1	10.3	23.5	14.4	14.6
	E	18–27	Loess	16:68:16	Silt loam	35.7	19:81	16.9	0.2	0.8	1.0	0.1	17.9	30.4	16.8	16.0
	Bt1	27–42	Loess	21:65:14	Silt loam	31.3	24:76	23.6	0.4	0.0	0.0	0.0	15.2	26.0	16.7	18.1
	Bt2	42–50	Loess	21:64:15	Silt loam	42.5	25:75	19.9	2.0	2.6	0.7	0.0	15.1	26.6	16.4	16.7
	2Bt3	50–70	Pre-Late-Wisconsin drift	34:53:13	Silt loam	93.0	39:61	14.0	10.8	11.0	3.5	0.1	14.6	24.5	11.6	10.0
	2C	70–130	Pre-Late-Wisconsin drift	48:39:13	Loam	132.0	55:45	14.8	18.6	15.8	5.6	0.2	13.2	18.5	7.3	5.9
	3Btb	130–150	Outwash-like diamicton	52:37:11	Sandy loam	206.6	58:42	12.5	10.0	18.3	16.3	1.2	10.6	16.6	7.6	6.8
	3C	150–186	Outwash-like diamicton	54:36:10	Sandy loam	236.6	61:39	11.8	8.9	17.3	20.7	1.8	10.2	15.6	7.3	6.4
	4Cr	186 +	Saprolite													
Clark 3	Oi	0–3														
	A1	3–13	Loess	20:69:11	Silt loam	44.3	23:77	16.7	2.9	1.9	1.0	0.1	16.7	30.9	15.8	14.1
	A2	13–29	Loess	21:69:10	Silt loam	33.7	23:77	21.0	2.1	0.1	0.0	0.0	14.5	29.0	16.8	16.5
	E	29–36	Loess	13:73:14	Silt loam	26.1	15:85	14.8	0.0	0.0	0.0	0.0	17.3	33.3	18.2	16.4
	Bt/E1	36–56	Loess	16:72:12	Silt loam	35.6	18:82	15.8	0.5	1.6	0.5	0.0	14.6	32.0	18.3	16.7
	Bt/E2	56–91	Loess	19:67:14	Silt loam	36.8	22:78	17.5	2.5	2.2	0.0	0.0	16.2	28.4	16.8	16.4
	2Bt	91–114	Pre-Late-Wisconsin drift	41:46:13	Loam	123.8	47:53	18.0	9.2	11.6	7.6	0.5	12.2	18.9	10.9	11.2
	3C	114 +	Pre-Late-Wisconsin drift	55:34:11	Fine sandy loam	153.3	62:38	18.0	17.8	19.3	7.0	0.2	8.3	12.8	7.9	8.6

[a] Silt: 2–50 μm.
[b] MWPS: mean weighted particle size by volume (μm).
[c] Particle size fractions in μm. VFS: 50–125; FS: 125–250; MS: 250–500; CS: 500–1000; VCS: 1000–2000; VFSi: 2–12; FSi: 12–25; MSi: 25–35; and CSi: 35–50.

The 75–125 μm fraction in the loess exhibits the same basic spatial trend as do the 125–175 and 175–250 μm fractions; the highest concentrations are located in the southwestern corner of the study area, decreasing to the northeast (Fig. 3C). Unlike the previous particle size fractions discussed, however, the 75–125 μm fraction exhibits a parabolic protrusion of moderately high concentrations, eastwardly across the southern half of the study area. The 50–75 μm (very–very fine sand) fraction exhibits the same protrusion towards the east; however, the centers of the areas of highest and lowest concentration change dramatically (Fig. 3D). The southwestern corner of the study area contains the lowest concentrations of size fractions smaller than 75 μm (Fig. 3D–H). Taken collectively, these data suggest paleowinds from the west may have winnowed the newly exposed sediment, leaving coarser fractions (>125 μm) in the southwestern corner of the study area (Fig. 3A and B) and depositing finer particle sizes (<125 μm) downwind, to the east and northeast.

The highest concentrations of the 35–50 μm (coarse silt) fraction occur in the south-central parts of the study area, east of the Black River and near the late Wisconsin moraine (Fig. 3D and E). Coarse silt contents decrease in concentration toward the southeast and northeast. The highest concentrations of the 25–35 μm (medium silt) fraction occur in the northwest and expand across the area that is immediately distal to the late Wisconsin moraine, decreasing both to the southeast and northeast (Fig. 3F). Notably, the area of highest concentrations of the 25–75 μm fractions has a western edge nearly coincident with the western edge of soils mapped with a loess mantle, by the National Resources Conservation Service (NRCS) (Simonson and Lorenz, 2002). The western edge of the NRCS-mapped loess soils also corresponds to the Black River valley. We believe that the river acted as a topographic barrier, trapping saltating aeolian sediment moving from the west, thereby facilitating the protected deposition of finer (silt-sized) particles, traveling mainly in suspension, onto landscapes east of the river (Mason et al., 1999; Figs. 1 and 4).

The concentrations of the 2–25 μm (fine silt) fraction are relatively high in the northern and eastern parts of the study area, with the highest concentrations located near the moraine in the north-central part of the study area (Fig. 3F–H). Equally high concentrations of fine silt are located in the southeastern corner of the study area (Fig. 3G and H). Concentrations of these finer silt particle sizes decrease gradually toward the southwest as well as toward the northwest. Given that fine silt tends to concentrate far from source areas, this pattern may reflect two source regions, one to the southwest (in the direction of the Cambrian sandstone landscape) and one to the northwest (in the direction of the late Wisconsin moraine).

An area of relatively low concentrations of the 2–25 μm fraction protrudes eastward across the study area, in a pattern similar to that of relatively high 50–125 μm concentrations described above (Fig. 3C, D, G, and H). This pattern is probably due to the dilution of the 2–25 μm particle sizes from a coarser, southwestern source. Similarly, the northern region, along the late Wisconsin moraine, which contains the lowest concentrations of >75 μm particle size fraction, also exhibits the highest concentrations of 2–35 μm particle sizes. In this case, dilution via a northwestern source of finer grained loess is likely responsible for these patterns. The parabolic pattern of relatively high 75–125 μm concentrations and low 2–25 μm concentrations in the southern half of the study area is probably due, at least in part, to the greater amounts of finer grained loess from the northwest, diluting coarser-textured, western-source loess.

Taken collectively, these data strongly suggest that the loess in north-central Wisconsin was sourced from two main areas: (1) the late Wisconsin moraine, which lies to the north and northwest of the loess sheet (Fig. 1), and (2) the Cambrian sandstone-controlled

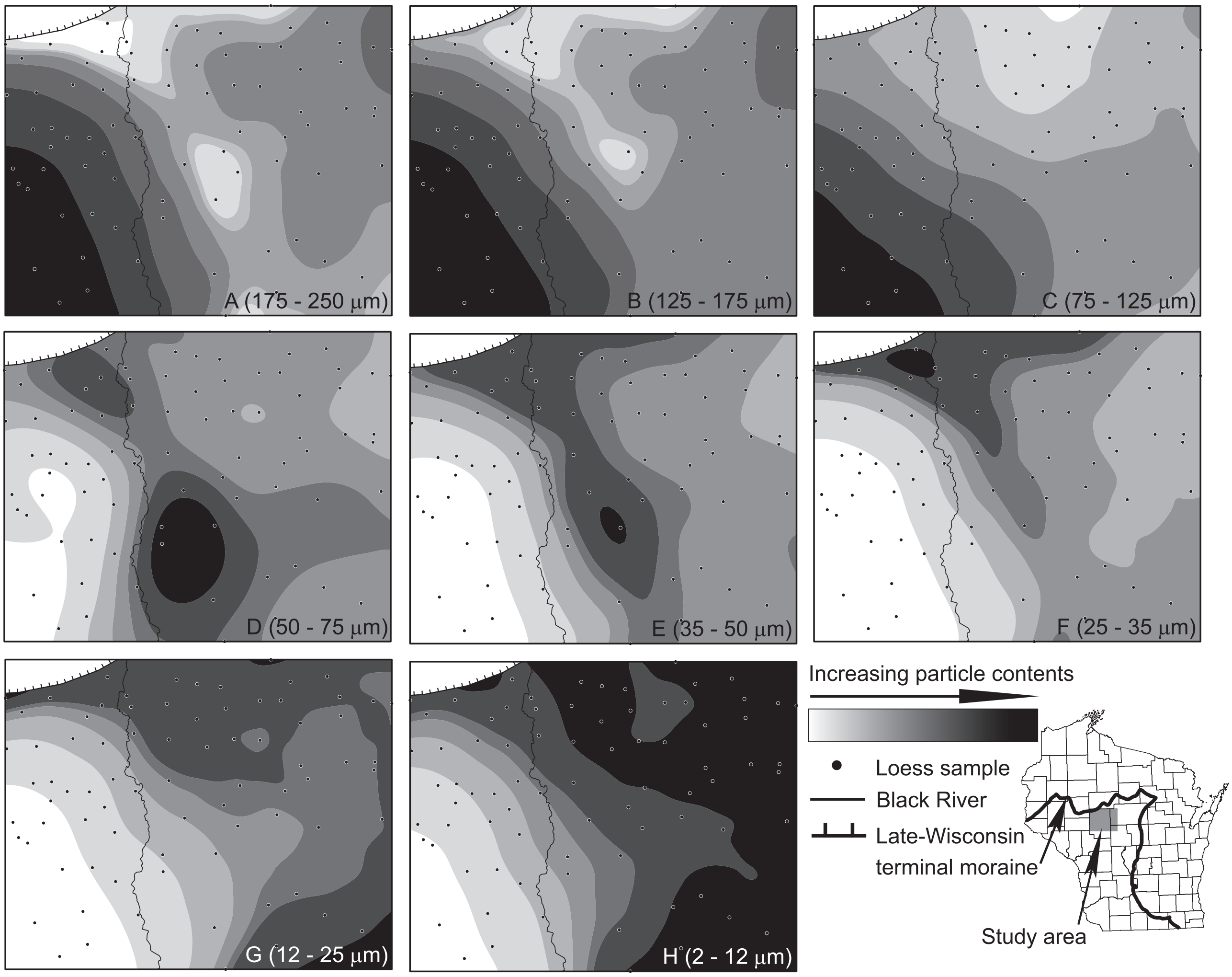

Fig. 3. Kriged maps of clayfree particle size distributions of 79 loess samples in north-central Wisconsin. Darkest shades represent highest concentrations, and light/white shades represent the lowest concentration of the following particle size fractions: (A) 175–250 µm; (B) 125–175 µm; (C) 75–125 µm; (D) 50–75 µm; (E) 35–50 µm; (F) 25–35 µm; (G) 12–25 µm; and (H) 2–12 µm.

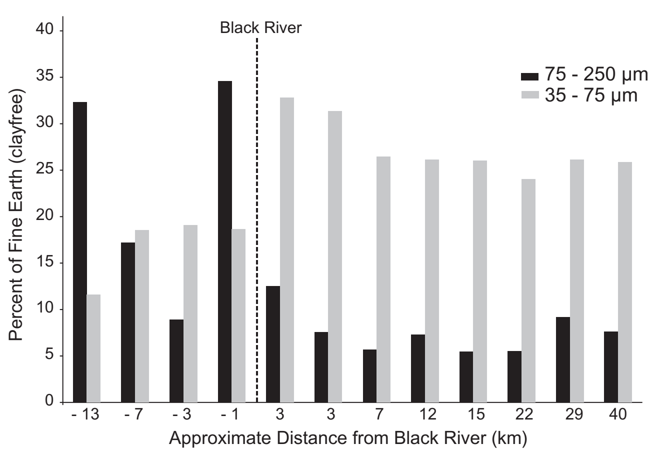

Fig. 4. Particle size comparison between the 35–75 µm and 75–250 µm fractions in a transect of eight loess samples east and west of the Black River from north-central Wisconsin. East of the Black River, very fine sand contents (black) decrease and coarse silt/very very fine sand contents (gray) increase. See Fig. 1 for location of transect and sample points.

landscapes that lie to the west and southwest. Additional data and discussion, in support of this conclusion, are presented below.

3.3. Silt mineralogy of potential sediment sources

Loess textural and thickness data (Figs. 2 and 3) suggest that the late Wisconsin moraine, located northwest of the loess sheet, likely contributed silty aeolian sediment to the north-central Wisconsin loess sheet. As the ice and permafrost within the moraine began to melt, drainage of many ice-walled lakes occurred, and landscape instability was at a maximum (Clayton et al., 2008). Ice-walled lake plains are prominent features of the moraine, and could have been relatively important source areas of fine-grained sediments (silts and clays), because they are relatively high-elevation landforms dominated by silty sediment (Fig. S1). Analysis of the feldspar mineralogy of the 20–45 µm fraction of nine ice-walled lake plain samples reveals the presence of both plagioclase and *K*-feldspar (Fig. 5; Table 2). The plagioclase peak is <14% of the quartz peak in all samples, the average being 9%. *K*-feldspar peaks are present in eight of the nine samples, with *K*/*Q* peak height ratios <5% (mean = 3%). The average plagioclase content is 23%; no individual sample exceeded 33% plagioclase. Estimated *K*-feldspar contents, in general, ranged between 8% and 12%, with a median of 10%. In comparison, estimated plagioclase contents averaged 18%, and did not exceed 25% in the loess samples analyzed, whereas the *K*-feldspar contents averaged 11% and did not exceed 15%. As the kriged plagioclase data suggest (Fig. 6), the highest plagioclase contents in the loess

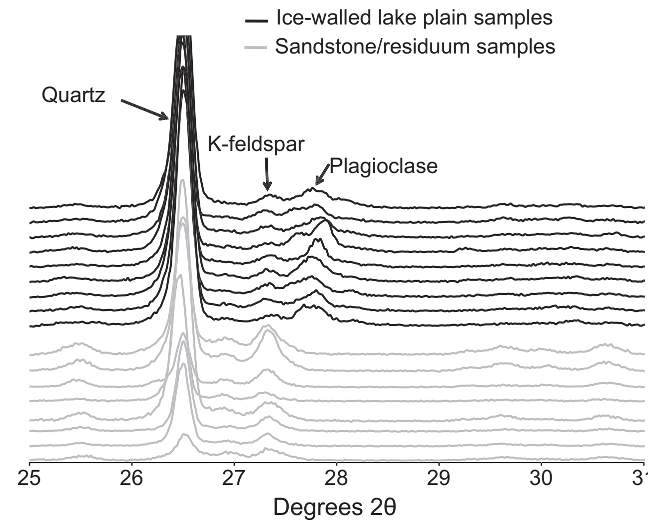

Fig. 5. X-ray diffraction data for the 20–45 μm fraction of ice walled lake plain and sandstone/residuum samples from north-central Wisconsin. Ice-walled lake plain samples (dark lines) contain quartz (26.5 2*Θ*) and plagioclase (approximately 27.8 2*Θ*), and very little *K*-feldspar (27.5 2*Θ*). Sandstone and sandstone residuum samples contain no detectable plagioclase, and higher amounts of *K*-feldspar.

sheet occur in the northwest, near the late Wisconsin moraine; thus, it is likely that much of the plagioclase in the loess may have been derived from the degrading moraine and its ice-walled lake plains. Because the *K*-feldspar contents in some loess samples exceed that of ice-walled lake plain samples, a secondary source may have contributed additional *K*-feldspar to the loess.

The 20–45 μm fraction of the Cambrian sandstone and residuum samples contains no detectable plagioclase (Fig. 5; Table 2). Estimated relative *K*-feldspar contents of these samples ranged between 18% and 60%, averaging 42%. *K*-feldspar is more concentrated in samples rich in shale, regardless of formation, which is, in general, consistent with data from Asthana (1969) and Ostrom (1970). In summary, feldspar mineralogy data for the 20–45 μm fractions indicate that the Cambrian sandstones and their residuum would have contributed mainly *K*-feldspar and quartz, and little if any plagioclase, to the loess sheet.

3.4. Loess silt (feldspar) mineralogy patterns

The lowest plagioclase contents in the loess sheet occur in the southwestern corner of the study area, near the plagioclase-poor Cambrian sandstones (Fig. 6). In general, plagioclase contents are highest in the northwestern part of the study area, and decrease to the southeast. This trend supports a model in which

Table 2
Silt mineralogy of loess and probable source samples in north-central Wisconsin.

	Sample ID	Q 3.34 Å	K 3.25 Å	P 3.20 Å	K/Q[a]	P/Q[a]	%Q	% K[§]	% P[§]
Ice walled lake plains	Delman	8146	316	677	4	8	69	11	20
	A	6738	282	523	4	8	70	12	19
	B	7868	258	673	3	9	70	9	21
	D	7267		1022	0	14	67	0	33
	E	7519	280	883	4	12	64	10	26
	F	8580	278	752	3	9	70	9	21
	G	7714	342	614	4	8	69	12	19
	H	7388	273	704	4	10	68	10	23
	I	8648	237	679	3	8	72	8	20
	Mean	7763	283	725	3	9	69	9	23
	Median	7714	279	679	4	9	69	10	21
Sandstone/Residuum	SS1C	1828	596		33	0	43	57	0
	SS2A	4220	233		6	0	82	18	0
	SS3C	8133	637		8	0	76	24	0
	SS4A	3040	502		17	0	60	40	0
	SS4B	2776	419		15	0	62	38	0
	17 Sub	4408	976		22	0	53	47	0
	50 Resid	5147	1372		27	0	48	52	0
	EC1R	912	339		37	0	40	60	0
	Mean	3808	634		20	0	58	42	0
	Median	3630	549		19	0	57	43	0
Loess	1	8132	402	732	5	9	66	13	21
	12	7804	304	616	4	8	70	11	19
	14	7358	288	540	4	7	71	11	18
	16	8804	372	844	4	10	67	11	22
	20	9141	272	316	3	4	81	10	10
	23	8925	142	551	2	6	78	5	17
	24	8140	359	511	4	6	72	13	16
	26	8268	353	517	4	6	72	12	16
	27	7578	293	441	4	6	74	11	15
	31	9444	330	468	4	5	76	11	13
	33	8913	480	744	5	8	66	14	19
	39	8597	362	585	4	7	71	12	17
	41	7776	274	631	4	8	70	10	20
	42	8485	230	555	3	7	75	8	17
	45	9272	208	594	2	6	76	7	17
	47	8206	301	598	4	7	71	11	18
	55	7140	321	431	5	6	72	13	15
	181	7099	280	767	4	11	65	10	25
	244	8471	258	457	3	5	76	9	14
	245	7305	229	599	3	8	71	9	20
	Mean	8243	303	575	4	7	72	11	18
	Median	8237	297	570	4	7	72	11	17

[a] Ratio of feldspar peak intensity height to quartz peak intensity expressed as a percentage. (E.g., 4 = 4% of quartz peak intensity; Backgrounds determined and removed by JADE.)
[§] (((Mineral peak height * peak intensity)/Σ all mineral peak heights) * 100) (Grimley, 1996).

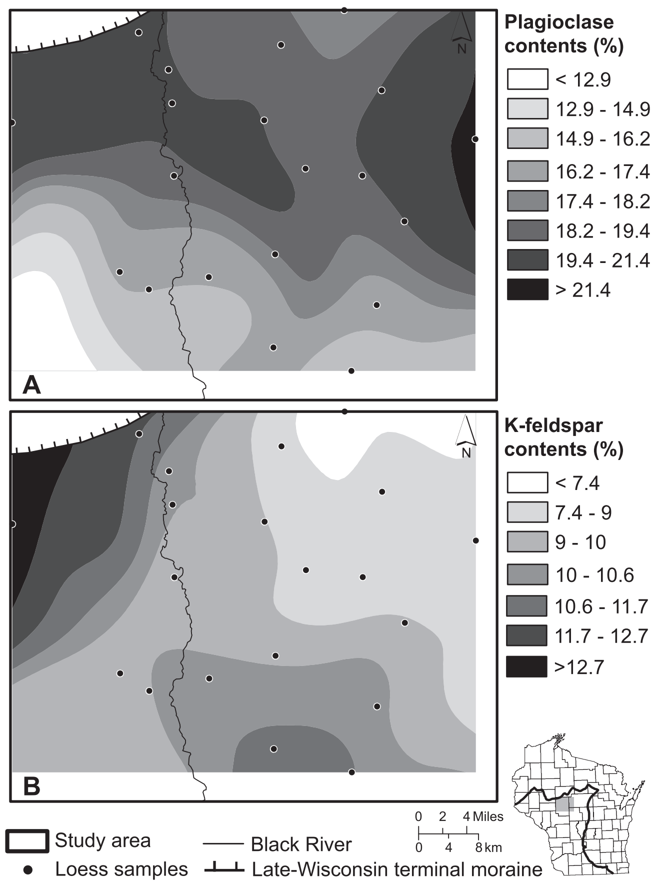

Fig. 6. Spatial distribution feldspar mineralogy of the silt fraction between 20 and 45 μm in 20 loess samples from north-central Wisconsin. Relative *K*-feldspar percentage based on *F*/*Q* peak heights determined using equation (see Grimley, 1996). (A) Spatial distribution of plagioclase contents. (B) Spatial distribution of *K*-feldspar contents.

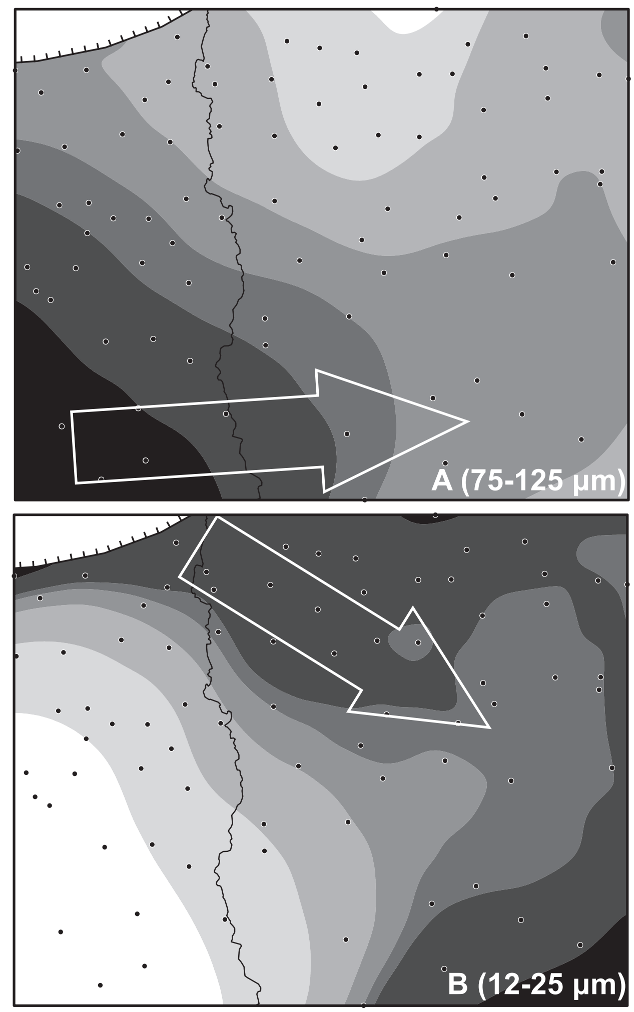

Fig. 7. Summary maps of clayfree particle size distributions of 79 loess samples in north-central Wisconsin; darker tones represent higher concentrations. (A) Kriged particle size distribution of 75–125 μm contents. Thawing permafrost likely exposed large quantities of sediment from friable, fine-grained Cambrian sandstones, rich in quartz and *K*-feldspar, to deflate and be deposited downwind. The lower contents in the north are likely due to dilution of finer grained loess derived from the northwest source. (B) Kriged particle size distribution of the 12–25 μm contents, which suggest a finer-grained source sediment to the northwest (likely ice-walled lake plains in and behind the moraine). Thawing permafrost underlying, and ice within, the late Wisconsin moraine thawed, allowing ice-walled lake plains on and behind the moraine to drain, exposing the lake beds (composed of off-shore silts and clays) to deflation. The lower contents of 12–25 μm particles in the south central region of the study area are likely due to the dilution of coarser sediment from the western/southwestern source.

northwestern paleowinds carried plagioclase-rich, silty sediment from sources on the late Wisconsin moraine. Relatively high plagioclase contents also occur in the far eastern regions of the study area (Fig. 6). This interpolated area of relatively high plagioclase contents, however, occurs in an area of relatively thin loess, and may be, at least in part, an artifact of in-mixing of the thin loess with the underlying pre-Wisconsin tills (Stanley, 2008).

Similar to the plagioclase patterns, the highest contents of *K*-feldspar occur in the northwestern part of the study area and gradually decrease to the east, southeast, and south (Fig. 6). Based on this trend, it is possible that sources in the moraine *and* on the Cambrian sandstone landscapes contributed *K*-feldspar to the loess sheet. Relatively low concentrations of *K*-feldspar occur in the southwestern corner of the study area, which is probably a result of the coarse particle size, since *K*-feldspar is concentrated in the shale layers of the Cambrian sandstones and the sand fractions are dominantly quartz. The lowest concentrations of *K*-feldspar occur in the northeastern corner of the study area, which is farthest from the Cambrian landscapes.

4. Discussion

On the north-central Wisconsin loess sheet, spatial characteristics of loess particle size distributions, thickness, and feldspar mineralogy data all point to paleowind directions from both the northwest and west during loess deposition. These results are consistent with northwesterly and westerly paleowinds, as suggested elsewhere in the midcontinent (COHMAP Members, 1988; Mason et al., 1994; Muhs et al., 1999; Muhs and Bettis, 2000; Putman et al., 1988; Ruhe, 1954; Smith, 1942). These patterns also suggest that the loess was probably derived from two main source areas: (1) the late Wisconsin moraine to the northwest and (2) the Cambrian sandstone-dominated landscapes to the west. Although both probably contributed a wide range of particle sizes to the loess sheet, it appears that the late Wisconsin moraine, including the abundant ice walled lake plains both within and behind it, likely contributed proportionally more fine-grained, siltier sediment, which was relatively enriched in plagioclase feldspar. To our knowledge, our data is the first to suggest ice walled lake plains as a possible loess source. The Cambrian landscape to the west and southwest appears to have mainly contributed coarser (very fine sand-sized) aeolian sediment, with little plagioclase, to the loess sheet.

The Black River is a key component to the explanation of the loess textural and thickness patterns in the study area. The Black River heads in the late Wisconsin moraine and flows along the western extent of the north-central Wisconsin loess sheet (Fig. 1). During glacial retreat, it likely carried sediment-rich meltwater, as evidenced by the many gravel pits within the valley; thus, one might assume that the river contributed some sediment to the loess sheet. However, we believe that the river was only minimally a loess source, if at all. In the northern part of the study area, the Black River valley is <3 m deep, yet relatively thick, silt-rich loess is found both east and west of the river valley, which suggests the Black River was not a dominant source of loess in this region, but simply cross-cuts an area of thick loess. As the Black River flows southward, the valley deepens (>30 m deep in the south). This type of deep, relatively narrow, valley, often lacking a broad floodplain, is unlikely to have been a major loess source. Spatial trends in particle size data for the loess sheet further discount the Black River as a major loess source since patterns of progressive change both east and west of it are not observed. Instead, particle size trends exhibit a general coarsening westward pattern, becoming sandier west of the Black River (Figs. 3 and 4). It is difficult, if not impossible, to explain (given our knowledge of aeolian systems) how the Black River as a loess source could have contributed dominantly silty sediment east of its banks and coarser sediment west of its banks. Rather, the particle size trends of the loess sheet (Figs. 3 and 4) are better explained using the surface of transport model of Mason et al. (1999). In this scenario, the sandy landscapes west of the Black River (Figs. 1 and 3) represent areas that may have partially acted as a surface of transport (Mason et al., 1999), where particles traveling by saltation or in short-term suspension stir up finer particles, causing them to be re-entrained and carried further downwind. Using this model, the Black River valley (representing the eastern border of this transport surface) could have trapped much of the sediment traveling by saltation, allowing suspended finer, silt-sized particles to be deposited onto sites east of the river. This interpretation is supported by data shown in Fig. 4; upland loess samples from sites west of the Black River have significantly more fine sands than do sites to the east, and the pattern changes abruptly at the valley. Conversely, silt contents in the loess increase significantly (and immediately) east of the Black River valley, which would be expected in the topographic barrier model. Unlike the very fine sand fractions and coarse silt fractions, which increase abruptly at the valley edge in the southern half of the study area, coarser sand fractions decrease much more gradually east of the river. It is possible some of the coarser sands were carried by periodic storms having increased wind intensity across or out of the Black River. It is unclear why the gradual decrease in medium and fine sand contents occurs west of the Black River valley; we suspect it is partially due to the closer proximity to the northwestern, silt-rich source. Future research is needed in order to establish or rule out the Black River as a potential additional source.

Because neither dominant sources of the north-central Wisconsin loess sheet are broad, meltwater valleys, this loess sheet provides a unique opportunity to understand regional paleoenvironmental dynamics, as opposed to ice sheet (meltwater) dynamics (Schaetzl and Loope, 2008). When the late Wisconsin ice sheet was at its maximum extent, most, if not all of north-central Wisconsin was likely underlain by permafrost (Clayton et al., 2001). The inferred chronology of ice-wedge casts in Wisconsin, when combined with pollen data from regions adjacent to Wisconsin, suggest the presence of cold, permafrost-dominated conditions across north-central Wisconsin between approximately 30 and 15 ka (Baker et al., 1986; Birks, 1976; Black, 1965; Clayton and Attig, 1987; Clayton et al., 2001; Heide, 1984; Johnson, 1986). In the Driftless Area, southwest of the study area (Fig. 1), active solifluction associated with a permafrost-dominated landscape is known to have occurred between 22.3 and 13.8 ka (Mason and Knox, 1997). Pollen data from Wood Lake, approximately 30 km north of the study area, also support this interpretation (Heide, 1984). The pollen assemblage and pollen accumulation rates here suggests that paleoenvironmental conditions between 15.1 and 11.5 ka transitioned from tundra to a *Picea*-herb (open spruce) ecosystem (Heide, 1984).

In this landscape, sediment would not have been available for deflation from either of the source areas until this permafrost melted, which may have been linked to the final retreat of ice from the glacial margin. When the climate warmed, degrading permafrost in the area likely produced an unstable landscape of steeply sloping terrain – one that was likely sparsely vegetated (Cowling, 1999; Overpeck et al., 1992; Williams, 2009). Large quantities of sediment could have been, therefore, newly exposed via processes such as mass wasting and slopewash (Mason and Knox, 1997). During this period, strong winds could have entrained available sediment and deposited it downwind, where it accumulated on relatively stable uplands.

Particle size depth plots that show increasing siltiness of the loess nearer the surface (Table 1) suggest two possible scenarios: (1) wind speeds were initially greater at the onset of loess deposition, and diminished with time, or (2) that the landscape to the west/southwest may have thawed and became unstable earlier, leading to the initial deposition of sandier loess to the east and northeast. In the second scenario, ice blocks within, and permafrost underlying, the late Wisconsin moraine likely persisted longer. Once the permafrost underlying the moraine and the ice blocks within the moraine degraded, most of the ice-walled lake plains would have drained, allowing their fine-grained off-shore sediment to be entrained and deposited downwind, to the southeast. In light of the spatial distribution of particle size data, we lean towards the latter scenario; however, further research is needed to support this hypothesis. Additionally, further research is needed to examine whether the sandier A-horizons in the loess sheet may represent final stabilization of the silt rich northwest source or a final phase of increased wind speed.

5. Conclusions

This research partially substantiates an earlier hypothesis that loess in north-central Wisconsin was derived from the friable, fine-grained Cambrian sandstone landscape to the west (Hole, 1942), and adds to our understanding of this loess sheet by bringing a second loess source, the late Wisconsin moraine, into the picture. Indeed, ours may be the first research to document two such unique and disjunct source areas for a single loess sheet. The Cambrian sandstone landscape to the west and southwest likely contributed dominantly coarser grained sediment (50–125 μm) to the loess sheet, rich in quartz and *K*-feldspar but largely devoid of plagioclase (Fig. 7A). The ice-walled lake plains and moraine to the northwest probably supplied most of the finer-grained (2–50 μm) sediment, dominantly composed of quartz and plagioclase with minor amounts of *K*-feldspar, to the loess sheet (Fig. 7B). Our work illustrates that the study of thin loess sheets may provide valuable insights into the regional paleoenvironmental conditions during loess deposition.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.aeolia.2011.01.001.

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