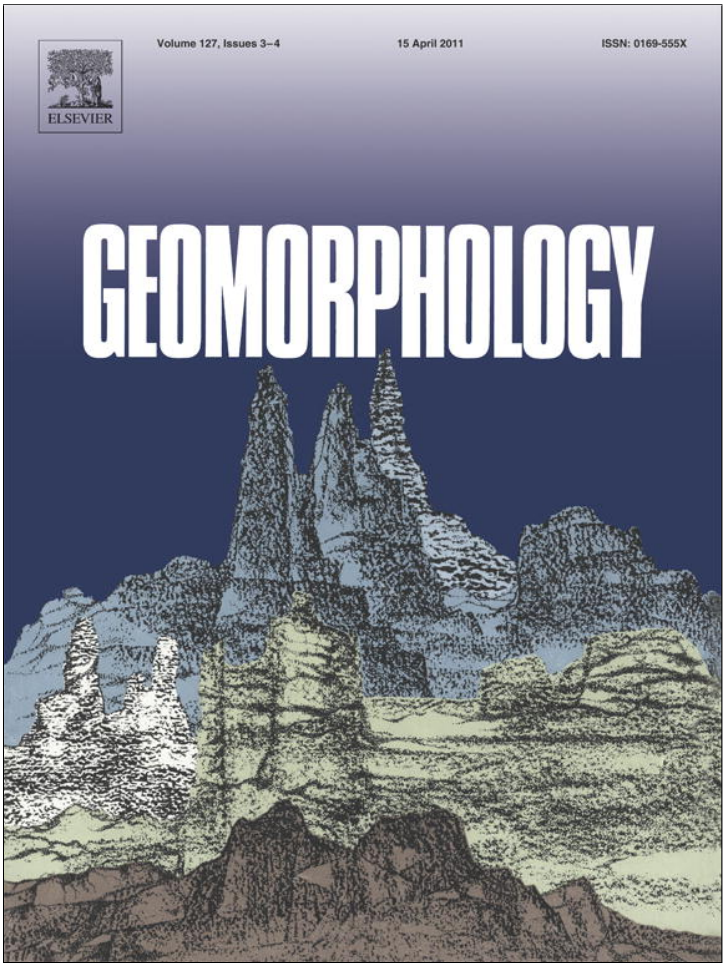
Volume 127, Issues 3–4
15 April 2011
ISSN: 0169-555X
ELSEVIER
GEOMORPHOLOGY

Geomorphology 127 (2011) 143–155

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Using PCA to characterize and differentiate loess deposits in Wisconsin and Upper Michigan, USA

Peter Scull [a], Randall J. Schaetzl [b,*]

[a] Department of Geography, Colgate University, 13 Oak Drive, Hamilton, NY 13346, USA
[b] Department of Geography, 128 Geography Building, Michigan State University, East Lansing, MI 48824-1117, USA

ARTICLE INFO

Article history:
Received 24 August 2010
Received in revised form 30 November 2010
Accepted 2 December 2010
Available online 13 December 2010

Keywords:
Loess
PCA
Wisconsin
Cover sand
Eolian

ABSTRACT

Data on loess thickness, as well as a variety of particle size fractions, were determined for 875 samples taken from several loess sheets across Wisconsin and Upper Michigan. Because the particle size characteristics of these samples varied widely within and between the loess sheets, we used principal components analysis (PCA) as a way of isolating the major textural components or signals that exist across the various loess sheets. The purpose of this research was to examine and interpret these principal components or particle size signatures, common to the different loesses, in order to better understand the loess sheets' character, formation mechanisms and likely sources. Our initial assumption — that many of these loesses varied markedly from the classical "silty loess" — was supported by the particle size data and the PCA. Although component 1 was interpreted as thick, silty loess dominated by medium silts, component 2 was mainly composed of very fine sand and coarse silt and is better viewed as "coarse loess." Components 3 and 4 were less texturally homogeneous and may reflect mixing between the loess and the underlying sediment, especially where the loess is <~40 cm thick. Alternatively, some of the loess samples in components 3 and 4 can be interpreted as poorly sorted versions of sandy eolian sediment, grading downwind to more traditional, siltier loess. Our work is the first to describe, map, and (informally) name the many small loess sheets in the upper Great Lakes region. This research demonstrates that many of the loesses here do not have silt loam textures as often described in the literature. Instead, loesses can be fine–sandy, and others, especially those that have bimodal particle size signatures, may reflect various amounts of post-depositional mixing.

1. Introduction

Silty eolian deposits, generally referred to as loess, have been the focus of over a century of geomorphic and sedimentologic study (Richthofen, 1882; Russell, 1944; Obruchev, 1945; Wascher et al., 1947; Smalley, 1966; Pye, 1984, 1987; Follmer, 1996; Bettis et al., 2003). Particularly important within this research are discussions of loess origin. Most loess deposits worldwide have originated from desert (Yaalon, 1969; Goudie et al., 1979; Ganor and Mamane, 1982; McTainsh, 1987; Tsoar and Pye, 1987; Ding et al., 1999) or periglacially/glacially active landscape systems (Smalley, 1966, 1972; Fehrenbacher, 1973; Ruhe, 1973; Smalley and Krinsley, 1978; Johnson and Follmer, 1989; Lea, 1990; Forman et al., 1992; Leigh and Knox, 1994; Muhs and Budahn, 2006). Glacial systems are particularly efficient at producing large quantities of silt-sized grains via grinding (Smalley, 1990), as are cold mountain landscapes (Smalley, 1978).

Most researchers have assumed that loess in the glaciated parts of the world, midwestern USA included, have mainly originated from large river valleys (Smalley, 1972; Pye, 1984). In theory, these river valleys fill with silt-rich glacial meltwater each summer and are largely dry in winter. Strong winds deflate the valley sediments each winter and during low-flow periods, depositing silts and finer sands downwind (Smith, 1942; Fehrenbacher et al., 1965; Putman et al., 1989), where they persist best on stable uplands. Clear and predictable patterns of loess characteristics on uplands, downwind of meltwater valley source areas, also support this theory of loess origin. Particularly well studied are the thick, extensive loess sheets in Illinois and Indiana, which have as their sources the large Mississippi, Illinois, and Wabash River valleys (Smith, 1942; Kleiss, 1973). Less well studied are the glacial loesses and other eolian sediments of the upper Midwest — the focus of this paper. Whereas some of these deposits are found near large meltwater valleys, many are distant from such potential sources. Additionally, these deposits (especially in Wisconsin and Michigan) are often small, thin, and overlapping. Finally, many of these deposits show a wide range of textures, which may be reflective of their various sources.

Our research uses (i) field work and preexisting maps to determine the extent of these smaller, little-studied loess sheets in Wisconsin and Upper Michigan, and (ii) statistical analyses of samples from these loess sheets to determine some of their key spatial

* Corresponding author. Tel.: +1 517 353 7726; fax: +1 517 432 1671.
E-mail address: soils@msu.edu (R.J. Schaetzl).

0169-555X/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2010.12.006

properties, particularly as they relate to texture. We believe that such data can be useful for the discrimination and mapping of these loess deposits and their sources, e.g., Pirkle et al. (1985). Our goal is not to present finished, detailed maps of these loess sheets, but to explore the utility of statistical analysis methods, particularly the use of principal components analysis (PCA) and spatial interpolation, in understanding the character, distributions and origins of loess in Wisconsin and Upper Michigan. Spatial interpolation of component scores from PCA is promising because loess is a wind-sorted deposit, exhibiting predictable spatial trends in particle size, thickness, and often, mineralogy (Smith, 1942; Waggoner and Bingham, 1961; Frazee et al., 1970; Kleiss, 1973; Pye, 1995; Aleinikoff et al., 1999; Muhs and Bettis, 2000; Mason, 2001; Schaetzl and Hook, 2008).

All loess deposits have at least one source area. Identification of the various loess sources has been a fruitful area of past (Waggoner and Bingham, 1961; Frazee et al., 1970; Rutledge et al., 1975; Ruhe and Olson, 1980; Johnson and Follmer, 1989) and recent paleoenvironmental research (Aleinikoff et al., 1998, 1999; Mason, 2001; Mason et al., 2003; Schaetzl, 2008; Schaetzl and Hook, 2008). Generally, source areas are identified by examining trends in loess thickness and texture, across the loess sheet. Loess deposits usually thin, away from source areas. Similarly, decreases in coarser particle size fractions, e.g., coarse silt, very fine sand, occur progressively away from loess sources, while many of the finer silt fractions concomitantly increase.

Source areas can only be determined, however, if discrete (but sometimes overlapping) loess sheets can be differentiated from each other, and their spatio-textural characteristics ascertained. Identifying such sources may provide insight into paleoenvironmental conditions at the time of deposition, particularly regarding wind direction and intensity (C.O.H.M.A.P. Members, 1988; Bartlein et al., 1998). Additionally, identifying the spatial variability in the textures of eolian deposits may assist others in identifying and mapping small, thin eolian deposits that do not fit the traditional definition of "silty loess." Our research contributes empirically (loess sheet differentiation, mapping, and description), methodologically (application of PCA to loess deposits), and theoretically (determination of most important and useful variables for discernment of loess deposits) to eolian research. Our work also highlights the textural variation in the eolian deposits of this region, and explores their interconnectivity across space.

2. Background: use of PCA in the geosciences

Principal components analysis (PCA) helps provide insight into the multivariate structure of interrelated data by reducing their dimensionality (Jolliffe, 2002). Principal components analysis transforms a large number of variables, in our case particle size data, into linearly independent sources of "information" (referred to as components) that can be interpreted to provide insight into the processes or interrelationships that underlie the data. When using georeferenced data, the routine can be extended to produce maps of each component, which can be further interpreted to shed additional light on the spatial patterns of the processes underlying the data (Morgan, 1971).

Principal components analysis is commonly used in a variety of disciplines, including pedology, where it can help with problems of multicollinearity present in soil forming factors (e.g. Antisari et al., 2010). Eolian applications include examples where researchers have used PCA to help determine source regions of particulate matter pollution (Wang et al., 2009; Contini et al., 2010). PCA has also been recently used to characterize particle size data, including studies of soil fertility (Chen and Duan, 2009) and pollution (Sielaff and Einax, 2007). Most related to our research, Pirkle et al. (1985) performed a PCA of textural and other sedimentological data to differentiate between marine and terrestrial sediments in Florida; Using grain size data, components were analyzed to help identify mode of transport and availability of source material (Pirkle et al., 1985); thus, interpretation of PCA components can help identify depositional environments. We are not aware of any applications of PCA in paleoenvironmental geomorphic research. More specifically, PCA has not been used to distinguish between different types of loess.

3. Study area

Our work is centered in Wisconsin, with some overlap into western Upper Michigan. This area has long been known to have thick loess deposits on its western edge, near the Mississippi River valley, mostly dating to the Late Wisconsin advance of the Laurentide ice sheet, e.g., Hole (1976), Mickelson (1986), Dott and Attig (2004). Work on the thinner, interior loess deposits has been minimal. Early work by Hole (1968), with a soils focus, established that the distribution of loess across the state was patchy, and that most of the "interior" loess deposits were thin (<1 m; Fig. 1). Since then, most of the loess-based research in the state has been associated with the thicker deposits along the Mississippi River (Leigh and Knox, 1993, 1994). Other loess deposits in the state have usually only been briefly mentioned as parts of larger reports and publications.

The most widespread, uppermost, and youngest loess unit in Wisconsin is the Peoria silt member of the Kieler Formation (Syverson et al., 2011), and that is our focus here. Peoria loess was generally deposited between ~25,000 and 12,000 radiocarbon BP (Leigh and Knox, 1993; Grimley, 2000; Forman and Pierson, 2002; Bettis et al., 2003; Syverson et al., 2011). The loesses in the study area usually overlie Quaternary-aged deposits, but in the southwestern part of the state, i.e., the Driftless area, they may rest directly on bedrock or its residuum (Frolking et al., 1983; Leigh and Knox, 1994).

4. Methods and results

4.1. Mapping the loess deposits

Using Hole's (1968) map of aeolian silt and sand deposits (Fig. 1) as a starting point, and gleaning county-level soil survey data from the

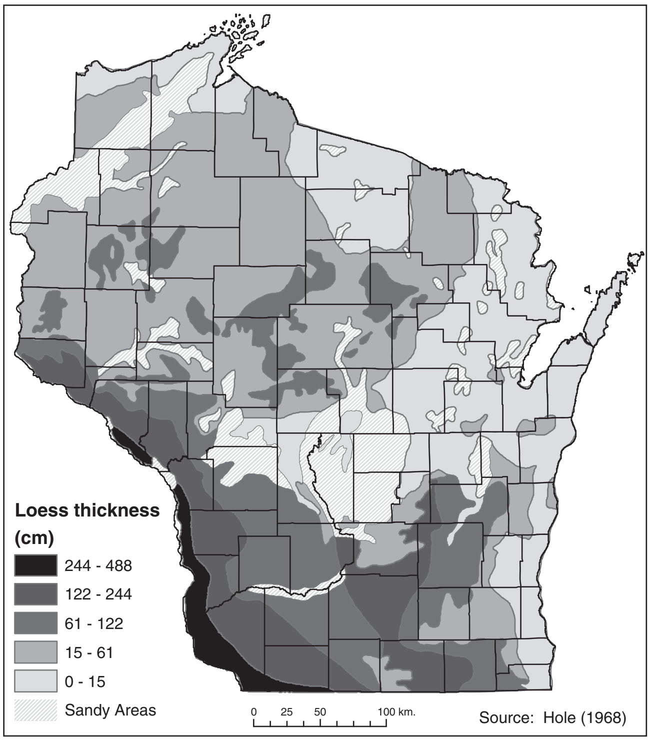

Fig. 1. A redrawn and slightly simplified version of Hole's (1968) aeolian sand and silt deposits of Wisconsin map.

Natural Resources Conservation Service (NRCS) for additional detail, we mapped the loess deposits of the region. To do this, we first downloaded the county soil maps for Wisconsin and western Upper Michigan from the NRCS's Soil Data Mart web site (http://soildatamart.nrcs.usda.gov/) and imported the data into a GIS. We determined the parent material(s) for most of the soil series in the region from the official series description on the NRCS web site (http://soils.usda.gov/technical/classification/osd/index.html). When the parent material description for a soil series was stated as loess, or loess over another sediment type, we appropriately coded the map unit symbology in the GIS coverage. Soil series with >60 in. (152 cm) of loess were coded black, whereas soils with lesser thicknesses of loess were coded as follows: 40–60 in. (102–152 cm) (dark red), 20–40 in. (51–102 cm) (red), 10–20 in. (25–51 cm) (pink), and <10 in. (<25 cm) or no loess (transparent). Although we did not sample them for this project, some areas with loamier loess deposits, especially in northern Wisconsin, were singled out and colored purple. Finally, the county-scale soil/loess maps were merged and rasterized to create a grid file of loess presence/absence and thickness (Fig. 2). To our knowledge, this is the most detailed map of loess that currently exists for the region.

To assist with communication, several of the more discrete loess sheets were given names, which should be regarded here as informal (Fig. 2). Where possible, we used established names for loess sheets derived from the literature, although again we stress that any names used for loess sheets in this paper are informal and have not, as yet, been recognized or proposed within the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983).

4.2. Sampling the loess

We used the NRCS-derived soil/loess map (Fig. 2) to guide our field sampling campaign, the goal of which was to obtain loess samples from many of the major loess sheets. Site selection for samples centered on broad uplands or areas nearby where loess was least likely to have been eroded, redistributed or disturbed. A digital elevation model (DEM), used in conjunction with the loess map (Fig. 3), helped optimize our sampling on stable uplands. Field sampling was aided by a laptop computer, running GIS software to display county-level soils and other base data. The GIS was linked to a global positioning system (GPS) unit, enabling live tracking of each sampling location. Woodlots were preferred sample sites as many have unplowed (virgin) soils; cropped fields were given low sampling preference but were, necessarily, sampled in some areas, especially where loess is thick and we were able to obtain loess samples from well below the plow layer.

We aimed for a uniform spatial distribution of loess samples, although some loess sheets were sampled more intensively and at smaller spatial intervals as precursors to more detailed, subsequent studies. Final sample density was based on (i) distance from supposed loess source area (denser sampling in areas near potential loess

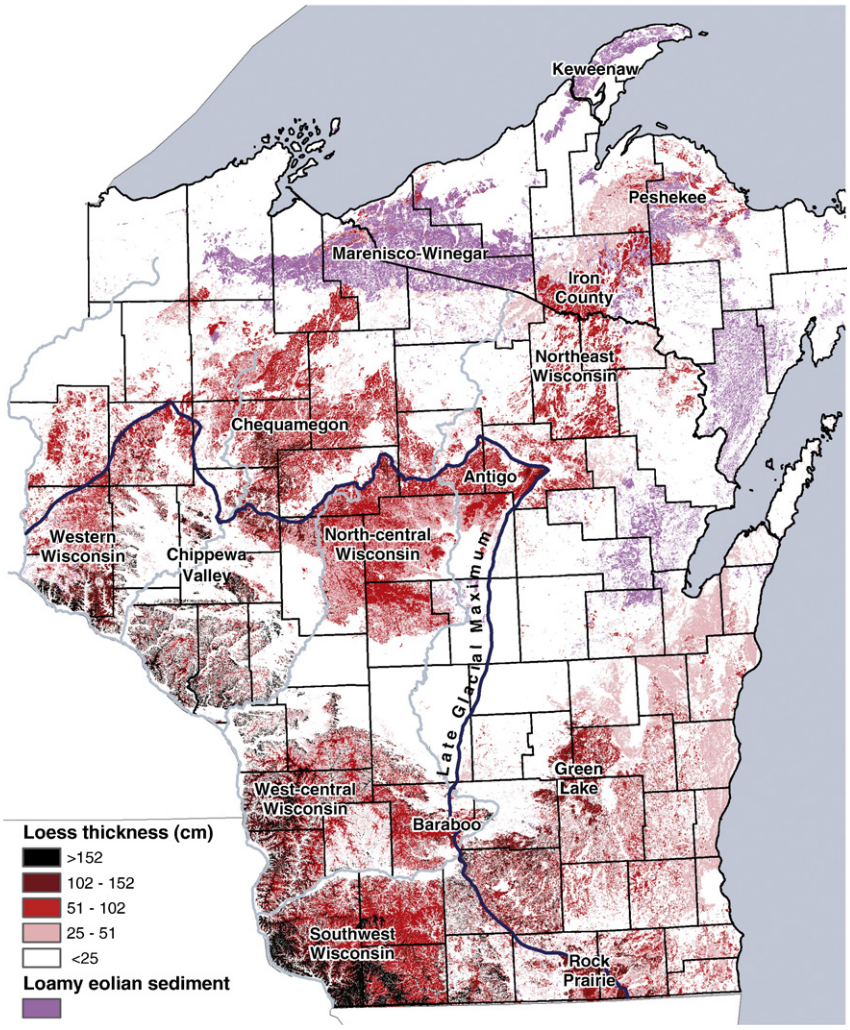

Fig. 2. Distribution of soils formed in loess parent materials of varying thickness in Wisconsin and western upper Michigan, as interpreted from NRCS, county-level, SSURGO soil data. Suggested names (informal) for some of the major loess sheets are indicated. Also shown are loess thicknesses, based on the same data source, and some late glacial ice margins. See text for map generation details.

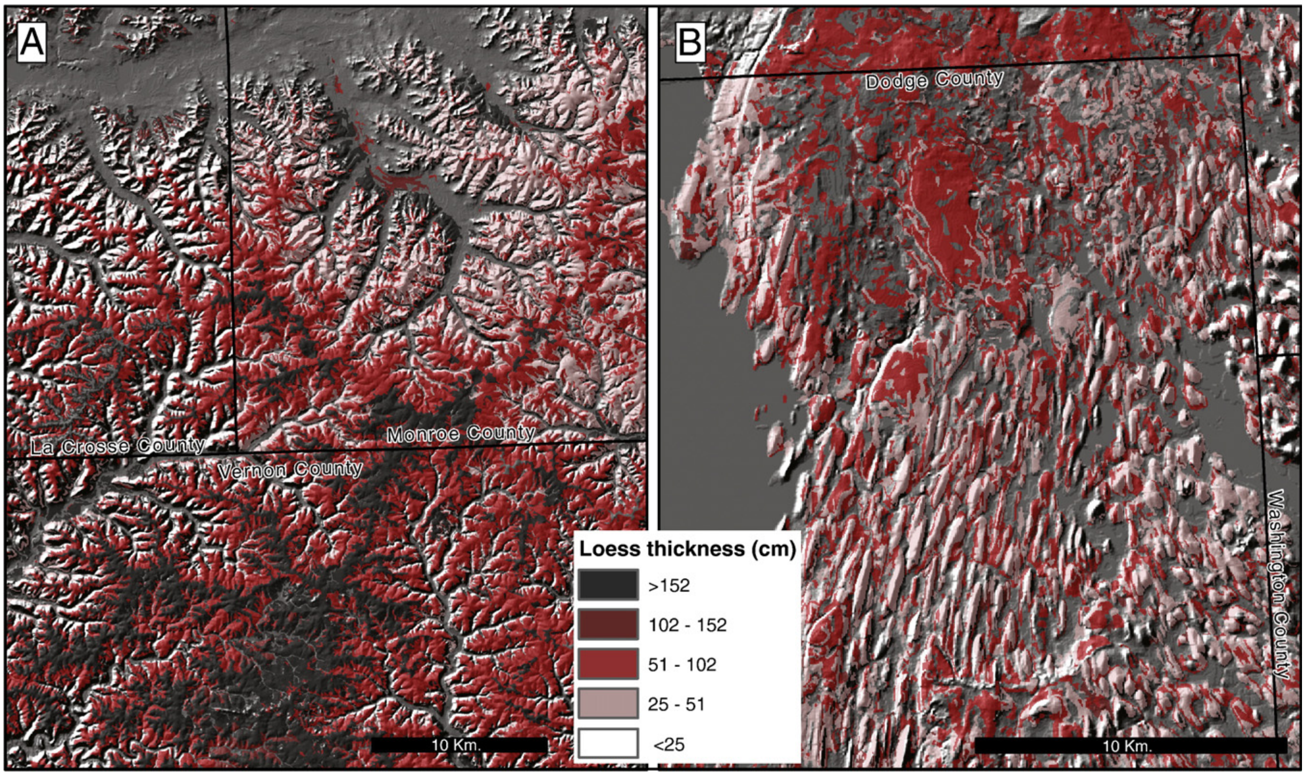

Fig. 3. Typical map of loess distribution patterns across two areas in Wisconsin, both set on a hillshade DEM base. This type of larger-scale map, showing topography and loess distribution, was used in the field to guide our sampling operations. (A) The heart of the Driftless area, near the Vernon-Monroe County line; and (B) an area just east of the Horicon Marsh, mostly in Dodge County.

sources), and (ii) distribution of loess soils across the county (few or no points were established in parts of counties that lacked significant areas of loess soils).

At each sample site, a 500–600 g loess sample was taken using a hand auger. Samples were taken at the deepest point within or below the soil profile but >~30 cm from any underlying lithologic discontinuity (Schaetzl, 1998). Loess thickness was noted at each site. At sites where the loess was as thick or thicker than the maximum depth of augering, a sample was taken from a depth no shallower than 125 cm, and the loess thickness was noted as >160 cm. Loess samples were eventually obtained from 875 sites (Fig. 4).

4.3. Lab analyses

All 875 samples were air dried and lightly ground to pass a 2-mm sieve. They were next passed through a sample splitter and recombined (four passes total) to achieve the high level of homogeneity necessary for subsequent particle size analysis on a Malvern Mastersizer 2000E laser particle size analyzer. Dispersion was accomplished on 2-g loess samples, in a water-based solution of $(NaPO_3)_{13}\cdot Na_2O$, after shaking for 2 h. When necessary, organic matter was first removed using dilute H_2O_2. Mean particle size and various (clay-free) particle size data were generated within the Malvern and Microsoft Excel software packages, respectively. The PSA data were analyzed in discrete particle size classes, e.g., 20–40 µm, 50–125 µm, etc. (Table 1).

4.4. Data analyses

We spatially interpolated the particle size data for the 875 samples, using ordinary kriging; it was selected as the most parsimonious interpolation routine for creating maps of variable data (Matheron, 1963). We used the geostatistical wizard module of ArcGIS (ESRI, 2009) to create such maps, clipping the output to the approximate spatial extent of the data. A separate surface was created for each loess variable

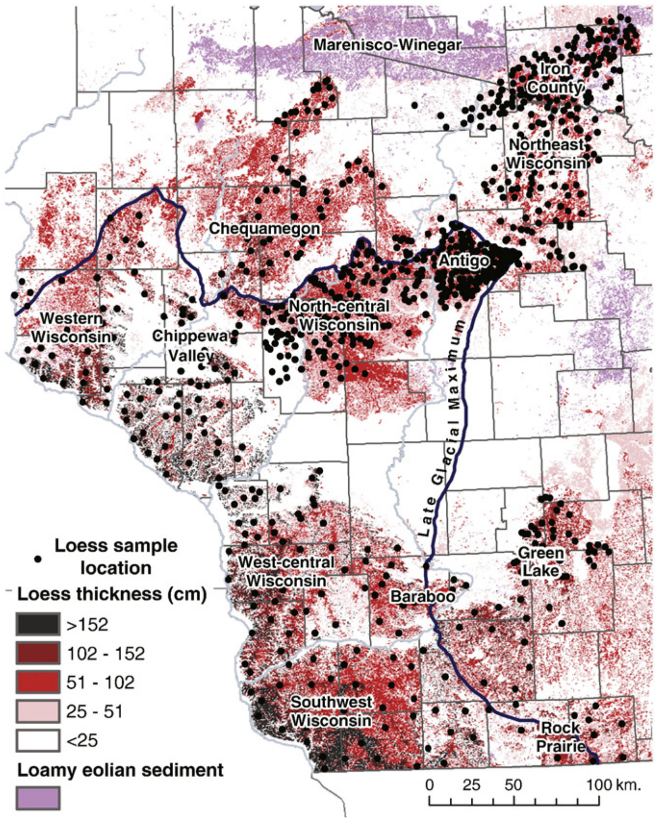

Fig. 4. The 875 locations where loess was sampled for this study, and how they compare with the general distribution of loess across the state.

Table 1
Particle size fractions used for analysis in this research.[a]

Variable	Size range (um)
Mean weighted particle size	–
Modal particle size	–
Uniformity value[b]	–
Clay	0–2
Very fine silt	2–12
Very fine and fine silt	2–25
Silt	2–50
Silt and very fine sand	2–125
Fine silt	8–20
Fine silt 2	12–25
Fine and medium silt	12–35
Fine, medium and coarse silt	12–50
Fine silt through very, very fine sand	12–75
Fine silt through very fine sand	12–125
Medium silt 2	20–40
Medium silt	25–35
Medium and coarse silt	25–50
Medium silt through fine very fine sand	25–75
Medium silt through very fine sand	25–125
Coarse silt	35–50
Coarse silt through fine very fine sand	35–75
Coarse silt through very fine sand	35–125
Coarse silt through fine sand	35–250
Very coarse silt	40–50
Very coarse silt through fine very fine sand	40–75
Very, very, very fine sand	50–60
Very, very fine sand	50–75
Very fine sand	50–125
Very fine and fine sand	50–250
Very fine, fine and medium sand	50–500
Sand[c]	50–2000
Medium very fine sand	60–75
Coarse very fine sand	75–125
Fine, fine sand	125–175
Fine sand	125–250
Fine and medium sand	125–500
Coarse fine sand	175–250
Medium sand	250–500
Medium and coarse sand	250–1000
Medium through very coarse sand[c]	250–2000
Coarse sand	500–1000
Very coarse sand[c]	1000–2000

[a] Textural variables could be, and were, determined on standard and clay-free bases.
[b] Uniformity value is a measure of the variance in the particle sizes for a given sample.
[c] Estimated, given our particular laser particle size analyzer model type.

in order to examine the spatial variation between and within the various loess sheets and to identify which of the variables was potentially most useful for loess sheet classification/discrimination. Most of the 42 particle size surfaces (and the thickness surface) exhibited interesting and unique geographic variations, suggesting that they could be used to classify and interpret loess sheets.

Finally, using the sample data, the particle size variables were entered into a PCA in order to reduce redundancy within the textural variables and to identify and accentuate the most important gradients within the data. Varimax rotation, a process by which coordinates are rotated such that only a few variables have high loadings (correlations) for each component, was utilized to maximize interpretability. Components with eigenvalues >1.0 were extracted (Kaiser, 1960), yielding four clear components, all of which were found to be reasonably interpretable (Table 2). As with the textural variables, the scores for each component were then mapped using ArcGIS.

5. Results and discussion

5.1. Loess in Wisconsin: a brief overview

Hole's map (Fig. 1) and our NRCS-derived (Fig. 2) map of loess distribution and thickness in Wisconsin are remarkably similar; the latter provides more detail because it was derived from larger scale original data, i.e., county-scale soil maps. The thickest loess in the state exists on uplands just east of the Mississippi River and was presumably at least partially sourced from the same river valley while it carried glacial meltwater during (at least) the last two major glacial advances (Leigh and Knox, 1993, 1994; Leigh, 1994).

Because most of the loess sheets in Wisconsin have not yet been studied, their sources remain unclear. In this paper, we will, by necessity, make reference to source areas for loess sheets, as the characteristics of the loess generally vary as a function of distance from a source area, and because many of the textural and thickness trends we report on point to obvious (but as yet unproven) source areas. Because the purpose of this paper is not to definitively identify source areas for any of the loess sheets, any reference to loess source areas made in this paper should, therefore, be viewed as speculative.

Wisconsin's interior loess sheets could not have been primarily sourced from the Mississippi valley because (i) the gradual thinning of the Mississippi loess is evident (see below) with the distal edge of this loess commonly only 70–100 km inland, and (ii) broad areas exist between the Mississippi-sourced loess and other interior sheets that essentially lack loess. Although preliminary, our work on these interior sheets has led us to conclude that many have been sourced from outwash plains, lake plains, and/or other recently deglaciated landscapes, e.g., moraines (Schaetzl, 2008; Schaetzl and Hook, 2008; Schaetzl and Loope, 2008; Stanley, 2008), based on the assumption that these interior loess sheets get both thicker and coarser in proximity to one of these presumed interior source areas.

5.2. Characteristics of loesses in the study area

Maps of thickness and various textural parameters illustrate the wide textural variability that exists in the loesses of the study area (Fig. 5). Loess sheets near deep, large outwash valleys or downwind from areas of Late Wisconsin loess production in Iowa (e.g., in southwestern Wisconsin) are dominated by silt, especially fine and medium silts (Fig. 5). This is archetypical loess, what Haase et al. (2007) referred to as “typical loess.” Conversely, loess adjacent to major outwash plains (e.g., the Northeastern Wisconsin loess sheet) is much sandier, with very fine and fine sands dominating. These data clearly show that loess, at least in Wisconsin and Upper Michigan, is not always silty; only 76.6% of the loess samples were silt loam in texture; many others were loam, silty clay loam, and fine sandy loam. Indeed, many of the eolian deposits near to sand-rich source areas are closer to what has typically been described as “cover sands” or “cover loams” in the European literature, e.g., Cailleux (1942), Koster (1988), Gullentops et al. (1993), Haase et al. (2007).

It is beyond the scope of this paper to examine and discuss the thickness and textural characteristics of each loess sheet in the study area. Instead, we used PCA (i) to examine commonalities and trends across these loess sheets, (ii) to determine if groups or “sets” of loess types exist and, if so, (iii) examine where these sediments exist on the landscape, particularly as regards proximity to, and type of, source area.

5.3. PCA analysis of loesses in the study area

The PCA procedure reduced the textural data to four independent variables that collectively accounted for 92.4% of the total variance present within the original 42 variables. The variable loadings shown in Fig. 6 are generally interpretable and appear to shed light on the mechanisms of loess formation and distribution. Fig. 6 also illustrates the textural splits for each of the four components to aid interpretation and help identify those variables most associated with each component.

Component 1, which explains 47.6% of the variation in the data, has significant loadings on various silt and very fine sand fractions and has a mean particle size value of 29.4 µm (medium silt) for the 10

Table 2
Particle size fractions of Wisconsin loesses that correlate highly with the first four principal components.

Particle size class (size range in μm)	Particle size midpoint (μm)	Correlation
PC1 — most positively correlated		
Fine and medium silt (12–35)	23.5	0.95
Total silt (2–50)	26.0	0.95
Fine silt (12–25)	18.5	0.93
Fine through coarse silt (12–50)	31.0	0.93
Very fine and fine silt (2–25)	13.5	0.90
Medium silt (20–40)	30.0	0.87
Fine silt (8–20)	14.0	0.85
Fine silt through very fine sand (12–75)	43.5	0.84
Medium silt (25–35)	30.0	0.84
Silt plus very fine sand (2–125)	63.5	0.81
Mean (st dev)	*29.4 (15.0)*	
PC 1 — most negatively correlated		
Very fine through medium sand (50–500)	275.0	−0.99
Total sand (50–2000)	1025.0	−0.95
Fine, fine sand (125–175)	150.0	−0.94
Fine sand (125–250)	187.5	−0.92
Very fine and fine sand (50–250)	150.0	−0.92
Coarse fine sand (175–250)	212.5	−0.87
Fine and medium sand (125–500)	312.5	−0.87
Coarse very fine sand (75–125)	100.0	−0.79
Mean weighted particle size	–	−0.75
Coarse silt through fine sand (35–250)	142.5	−0.73
Medium sand (250–500)	375.0	−0.73
Mean (st dev)	*293.0 (271.1)*	
PC 2 — most positively correlated		
Fine very fine sand (50–75)	62.5	0.98
Very, very fine sand (50–60)	55.0	0.97
Very coarse silt through fine, very fine sand (40–75)	57.5	0.97
Coarse silt through very fine sand (35–125)	80.0	0.97
Medium, very fine sand (60–75)	67.5	0.95
Medium silt through very fine sand (25–125)	75.0	0.95
Coarse silt through fine, very fine sand (35–75)	55.0	0.94
Very coarse silt (40–50)	45.0	0.85
Very fine sand (50–125)	87.5	0.83
Medium silt through fine, very fine sand (25–75)	50.0	0.81
Coarse silt (35–50)	42.5	0.79
Mean (st dev)	*61.6 (14.5)*	
PC 2 — most negatively correlated		
Medium sand (250–500)	375.0	−0.49
Very fine silt (2–12)	7.0	−0.48
Medium and coarse sand (250–1000)	625.0	−0.45
Medium through very coarse sand (250–2000)	1125.0	−0.45
Coarse fine sand (175–250)	212.5	−0.45
Fine and medium sand (125–500)	312.5	−0.44
Fine silt (8–20)	14.0	−0.39
Uniformity value	–	−0.35
Fine sand (125–250)	187.5	−0.34
Coarse sand (500–1000)	750.0	−0.33
Mean weighted particle size	–	−0.33
Mean (st dev)	*400.9 (369.3)*	
PC 3 — most positively correlated		
Silt through very fine sand (2–125)	63.5	0.38
Fine silt through very fine sand (12–125)	68.5	0.35
Loess thickness	–	0.30
Total silt (2–50)	26.0	0.30
Fine silt through very fine sand (12–75)	43.5	0.29
Fine and medium silt (12–35)	23.5	0.28
Fine through coarse silt (12–50)	31.0	0.28
Fine silt (12–25)	18.5	0.28
Very fine and fine silt (2–25)	13.5	0.28
Fine silt (8–20)	14.0	0.27
Very fine silt (8–20)	7.0	0.25
Medium silt (20–40)	30.0	0.25
Mean (st dev)	*30.8 (20.1)*	
PC 3 — most negatively correlated		
Very coarse sand (1000–2000)	1500.0	−0.86
Coarse sand (500–1000)	750.0	−0.83
Uniformity value	–	−0.73
Medium through very coarse sand (250–2000)	1125.0	−0.60
Medium and coarse sand (250–1000)	625.0	−0.59
Mean weighted particle size	–	−0.57
Medium sand (250–500)	375.0	−0.42
Total sand (50–2000)	1025.0	−0.29
Fine through medium sand (125–500)	312.5	−0.21
Mean (st dev)	*816.1 (427.4)*	
PC 4 — most positively correlated		
Loess thickness	–	0.55
Modal particle size	–	0.49
Medium and coarse silt (25–50)	37.5	0.24
Medium silt (25–35)	30.0	0.24
Coarse silt (35–50)	42.5	0.23
Medium silt (20–40)	30.0	0.21
Very coarse silt (40–50)	45.0	0.20
Medium silt through very fine sand (25–75)	50.0	0.18
Mean (st dev)	*39.2 (8.2)*	
PC 4 — most negatively correlated		
Uniformity value	–	−0.41
Coarse, very fine sand (75–125)	100.0	−0.30
Very fine silt (2–12)	7.0	−0.26
Very fine sand (50–125)	87.5	−0.18
Fine silt (8–20)	14.0	−0.17
Fine, fine sand (125–175)	150.0	−0.16
Very fine and fine sand (50–250)	150.0	−0.15
Very coarse sand (1000–2000)	1500.0	−0.12
Very fine and fine silt (2–25)	13.5	−0.11
Medium very fine sand (60–75)	67.5	−0.09
Mean (st dev)	*232.2 (478.6)*	

most positively correlated size fractions. Likewise, this component loads negatively on most of the finer sand fractions. The mean particle size value for the negatively correlated variables is 293.0 μm (medium sand). We interpret this component to represent "classical, medium and coarse silt-rich" loess, not unlike that defined by Smalley and Vita-Finzi (1968) and Pesci (1990). Pye (1995) referred to "typical" loess as eolian sediment that has a modal grain size of 30 μm, much like this material (see also Smalley, 1990). Particle size plots for the top eight samples, (i.e. those samples with the highest component scores) help illustrate and identify the textural characteristics of this type of loess (Fig. 7). All of these samples have modes within the medium to coarse silt fraction. Sands larger than very fine sand size are almost nonexistent.

Loess thickness does not load strongly (positively or negatively) on component 1, which we interpret as meaning that loess of this type can (and does) occur in areas of thick, thin and intermediate loess. This interpretation is further confirmed by examining the locations of the 30 samples that loaded most strongly on this component (Fig. 8). In Fig. 8, these sites are mapped onto a background of loess distribution and ice marginal positions. Most of these samples are in southwestern Wisconsin, an area of very fine-textured, thick loess (Figs. 5, 8). Although some of this loess has as its origin the meltwaters of the Mississippi River, we assume that fine-textured loess generated from various deglacial landscapes in Iowa has also been a significant contributor to the loess in this region (Mason and Nater, 1994). The Iowa-sourced loess would have been transported such a long distance that most of its sands and coarse silts would have been winnowed out. The remaining samples that represent component 1 are scattered across the thinner loess sheets of the study area, with a notable secondary area of concentration exists in the fine-textured loess of the North-Central Wisconsin loess sheet (Fig. 8), where loess thickness is typically 0.5–0.9 m. Notably, many of the component 1 samples are located significant distances from their presumed source areas, as would be expected for fine-textured, silty loess.

Because many scientists who work with soils and Quaternary sediments often report data using standard USDA-NRCS soil texture classes, we chose to do the same, for purposes of comparison. For example, of these 30 samples, 19 are silt loam in texture, 10 are silty clay loams, and one is a silty clay.

Accounting for an additional 31.9% of variance, component 2 has high positive loadings on several very fine sand and coarse silt fractions, with a mean particle size value of 61.6 μm (very, very fine sand) for the most positively correlated fractions (Table 2; Figs. 6, 7). It negatively correlates with coarser sands and some finer silt fractions. The mean particle size value for the negatively correlated variables is 400.9 μm (medium sand). This component identifies a very fine and fine "sandy" or "coarse loess" variant, somewhat like a traditional "cover sand" but not as coarse or as well sorted as typical dune sand (and with much more silt). Haase et al. (2007) referred to loess with this type of particle size distribution as "sandy loess." Nonetheless, this sediment type contains very little medium and coarser sands (Fig. 6; Table 2). The relatively high variance value for this component (31.9%) suggests that sandy loess is an important and large constituent of the larger eolian population; silty loess does not dominate the loesses of Wisconsin. In the field, many (including us) would describe this sediment as "coarse loess." Indeed, the NRCS describes several soil series in the region as having formed in "coarse loess" parent material, which agrees with our observations.

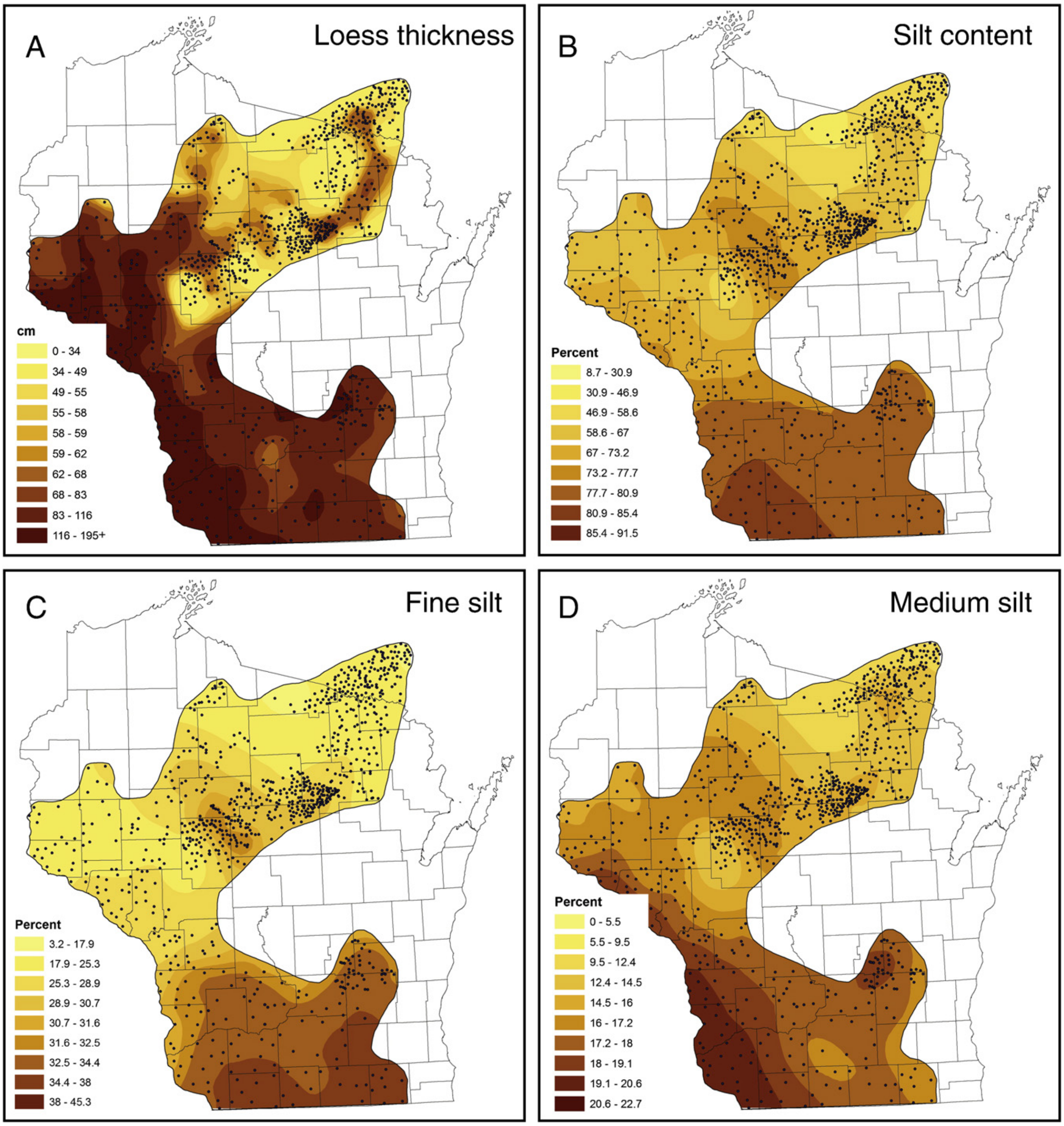

Fig. 5. Examples of kriged maps of various loess parameters across the study area, clipped to the rough extent of the data. All textural parameters have been calculated on a clay-free basis. (A) thickness (cm); (B) total silt (2–50 μm); (C) fine silt (8–20 μm); (D) medium silt (25–35 μm); (E) coarse silt (35–50 μm); (F) very, very fine sand (50–60 μm); (G) very fine through fine sand (50–250 μm); and (H) fine through medium sand (150–500 μm).

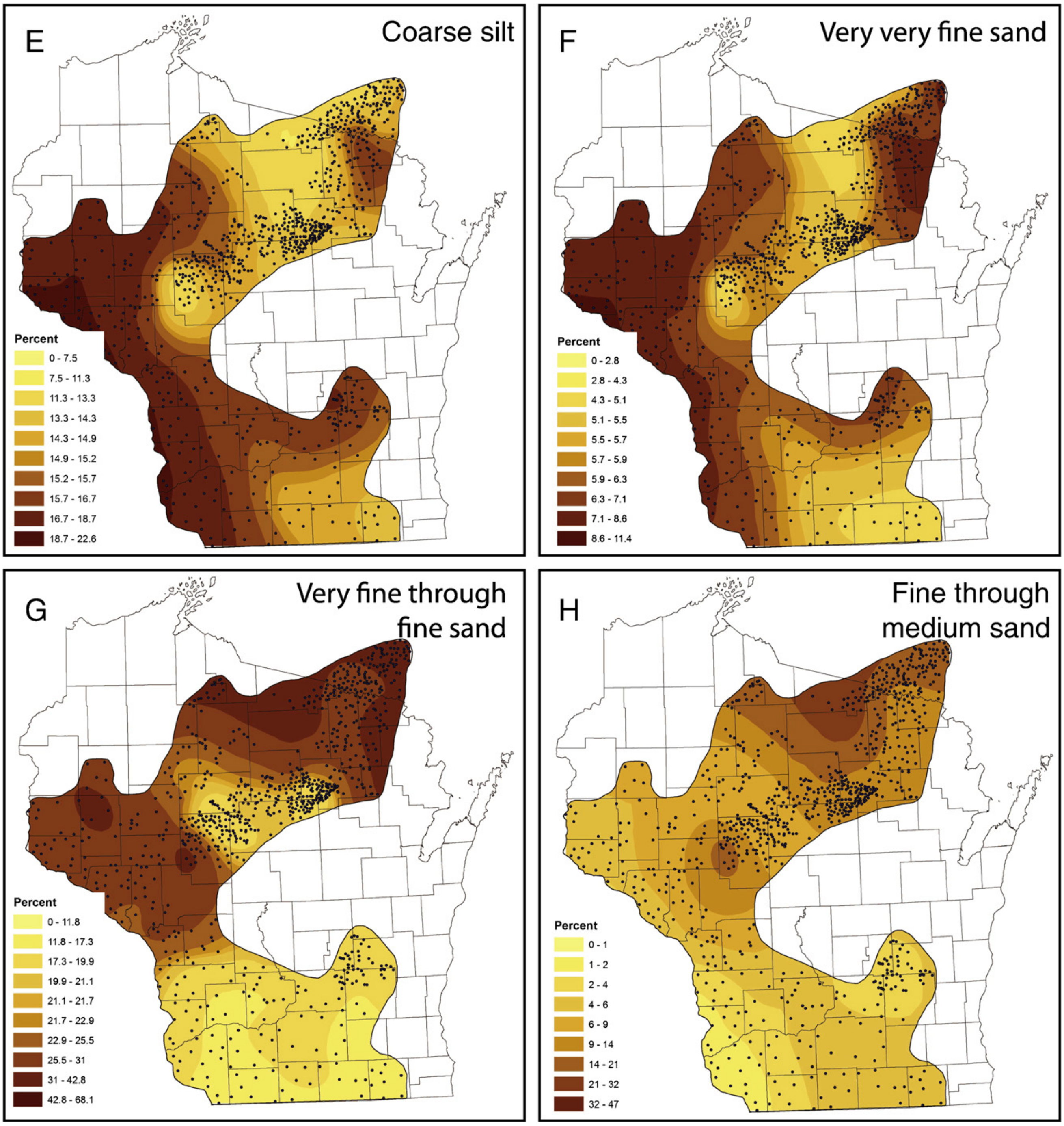

Fig. 5 (*continued*).

Of the 30 samples that loaded most strongly on component 2, 18 are silt loam in texture, nine are loams, and three are very fine sandy loams. Most of these 30 samples are located in two areas: (i) the Western Wisconsin and Chippewa Valley loess sheets, and (ii) along the eastern, proximal margins of the Northeast Wisconsin and the Iron County loess sheet (Fig. 8). The former area is shallowly underlain by poorly cemented sandstone bedrock (Syverson, 2007) and thus likely that fine sands were being deflated and transported concurrently with the more silty loess. A similar situation probably occurred on the western end of the North-Central Wisconsin loess sheet (Stanley, 2008). Interestingly, most of the other samples with high component 2 scores are in Northeastern Wisconsin and Upper Michigan on the far eastern edge of the loess sheet near the Mountain and Sagola end moraines and their outwash plains (Fig. 8; Peterson, 1985; Clayton, 1986). This area has vast expanses of fine sandy outwash and associated deposits, explaining the predominance of very fine sands in the loess immediately downwind (west). Each of these sandy loess samples is located within the loess sheet, but very close to the outwash plains to their east. In essence, this is near-source area loess with a dominant very fine sand fraction. Its presence here clearly supports the deposition of loess in this area, carried on easterly winds. As with component 1, the "loess thickness" variable does not load strongly on component 2; loess thickness varies markedly among the sites shown in Fig. 8.

Component 3 is more complex, and thus, more difficult to interpret, and the distribution of its component scores shows few

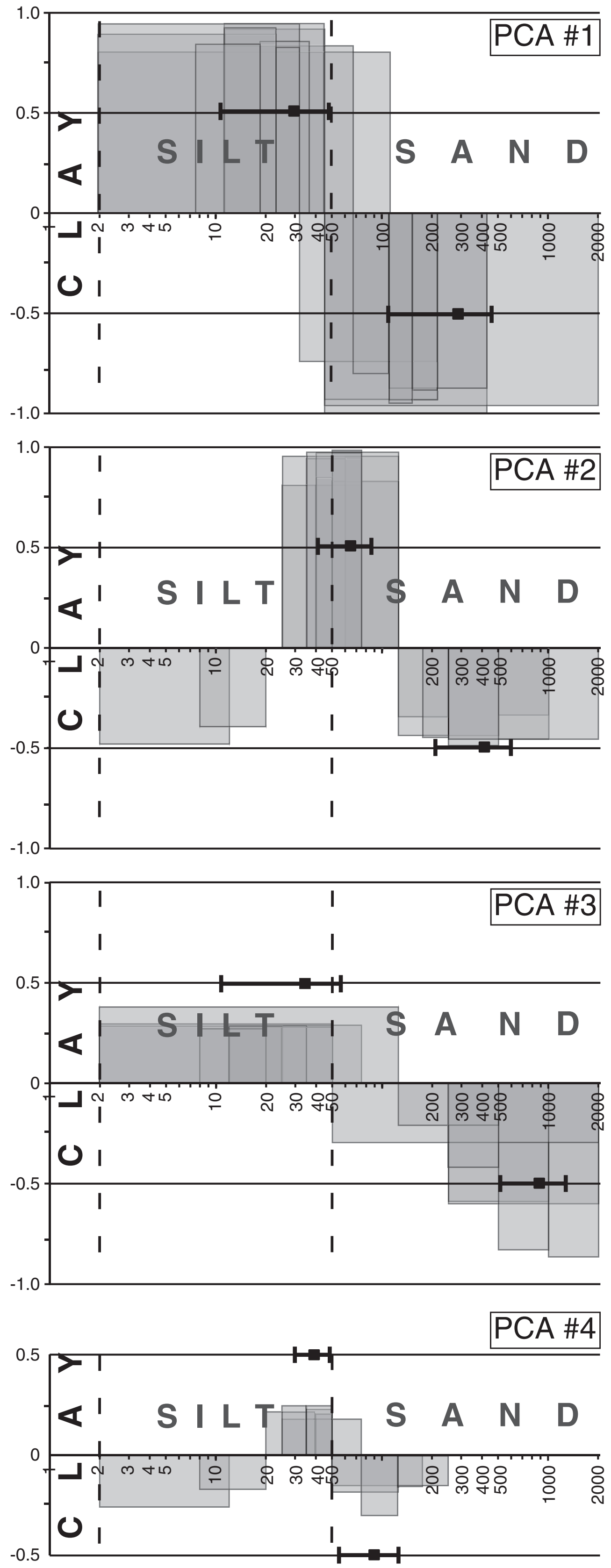

Fig. 6. Visual display of the particle size fractions that most positively and negatively correlate with each of the four principal components. Bar width represents the particle size fraction range, while bar height represents the strength of correlation for that particle size fraction on the particular component. The bar and whiskers graphic is employed to show the overall mean and standard deviations of these fractions for each component.

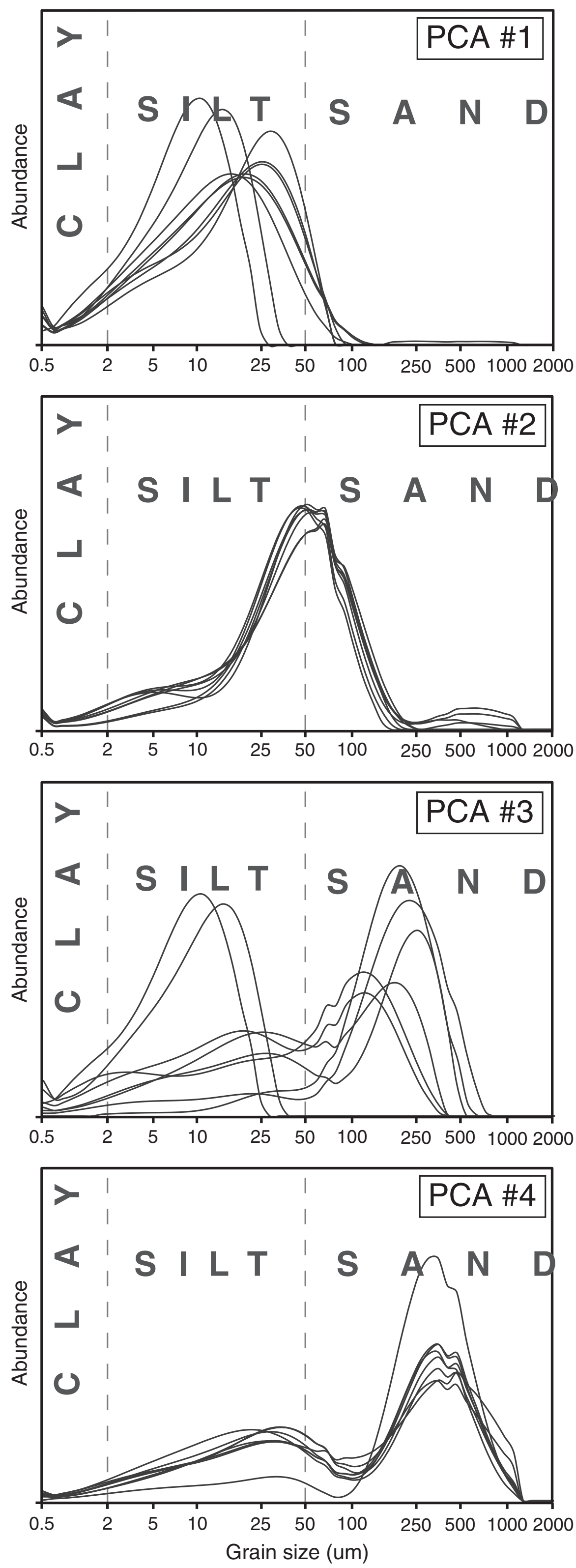

Fig. 7. Continuous particle size curves for the eight samples that most positively correlate with the first four principal components.

areas of concentrated high or low values (Fig. 8). The component explains 11.2% of the total variance and correlates positively with a wide range of silt fractions and with loess thickness. It also correlates negatively with various sand fractions, especially many of the coarser sands. Taken alone, these data might imply that component 3

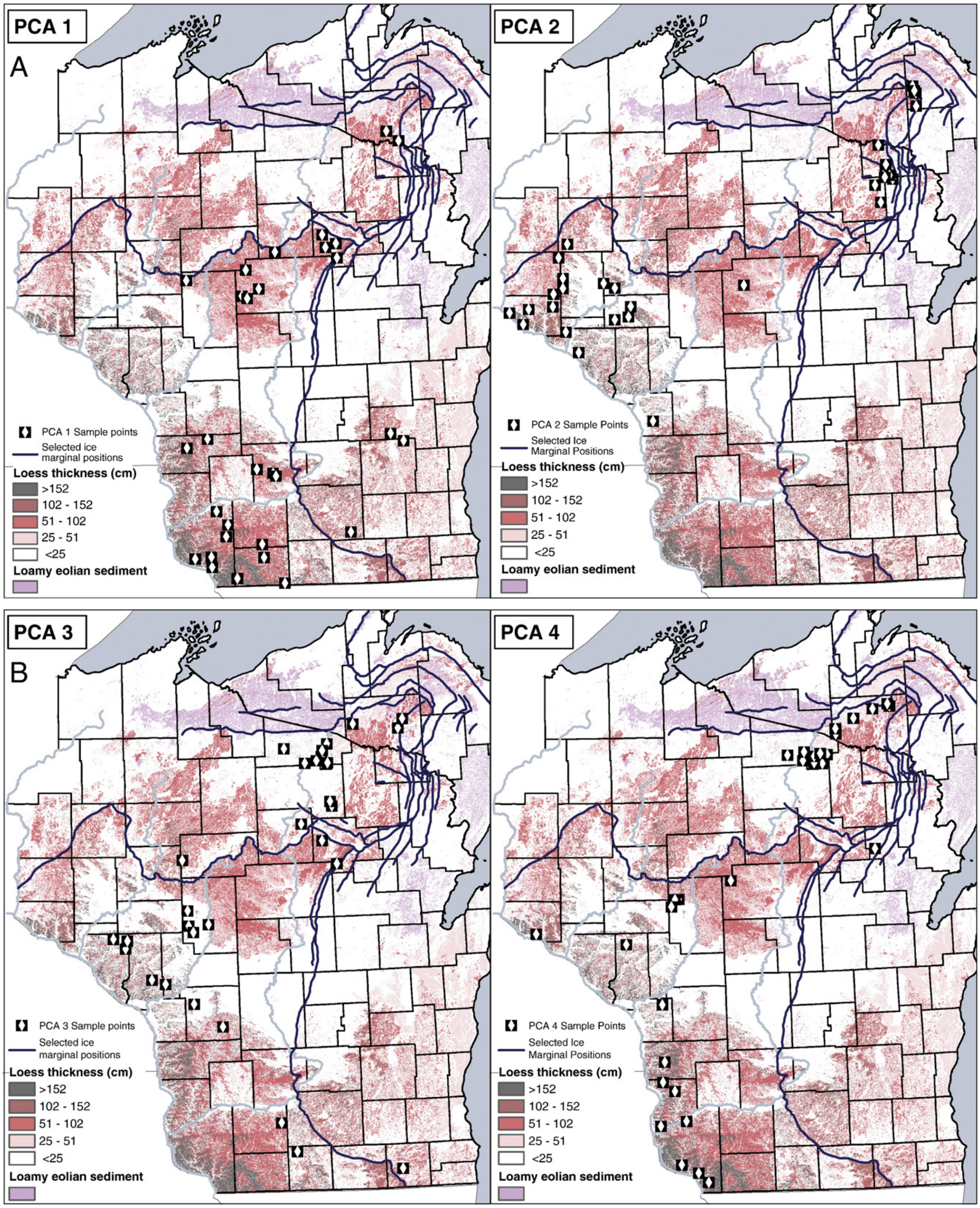

Fig. 8. Locations of the 30 samples that load most positively on each of the four principal components, overlain onto a map of the loess sheets in the study area.

represents thick, silty loess devoid of sands. However, component 3 also negatively correlates with uniformity value, implying that it is usually a rather heterogeneous mix of sediment types (Table 2). Likewise, a visual inspection of the particle size distributions of the eight samples with the highest component scores suggests that component 3 is, indeed, interpreted to represent a mix of sediment with very different textural characteristics; some samples are silt-dominated, whereas others are sandy (Fig. 7). Many samples, especially the sandy ones, have two or three particle size modes. These characteristics suggest that component 3 may include many samples of silty loess that have experienced significant amounts of inmixing from the underlying (usually more sand-rich) sediment; this process is especially common in areas of thin (<~40 cm) loess. More commonly, samples in this set appear to be sandy and coarse–silty loess (but with coarser sands than the samples in component 2).

The distribution and textures of the samples that best represent component 3 (Figs. 6–8) is perhaps more insightful as to its interpretation than is the kriged map of component 3 scores proper (Fig. 9). Several component 3 samples are found in southern, southwestern, and western Wisconsin where loess is generally fine-textured (Figs. 5, 8). Here, however, they occur in areas of thin loess far from the presumed source areas. The often "mixed" textural distributions of these samples may reflect pedoturbative mixing. Similarly, other areas of concentration for component 3 samples are on the distal edges of loess sheets, especially in the North-Central Wisconsin and Northeast Wisconsin sheets, where they merge into generally sandy landscapes that may have been source areas (Fig. 8; Stanley, 2008). Here, sandy eolian sediment was probably mixing with silty sediment during deposition, resulting in the poorly sorted, bimodal and trimodal particle size distributions shown in Fig. 7. As a result, the 30 samples with the highest component 3 scores have widely varying texture classes: 11 are loam in texture, seven are silt

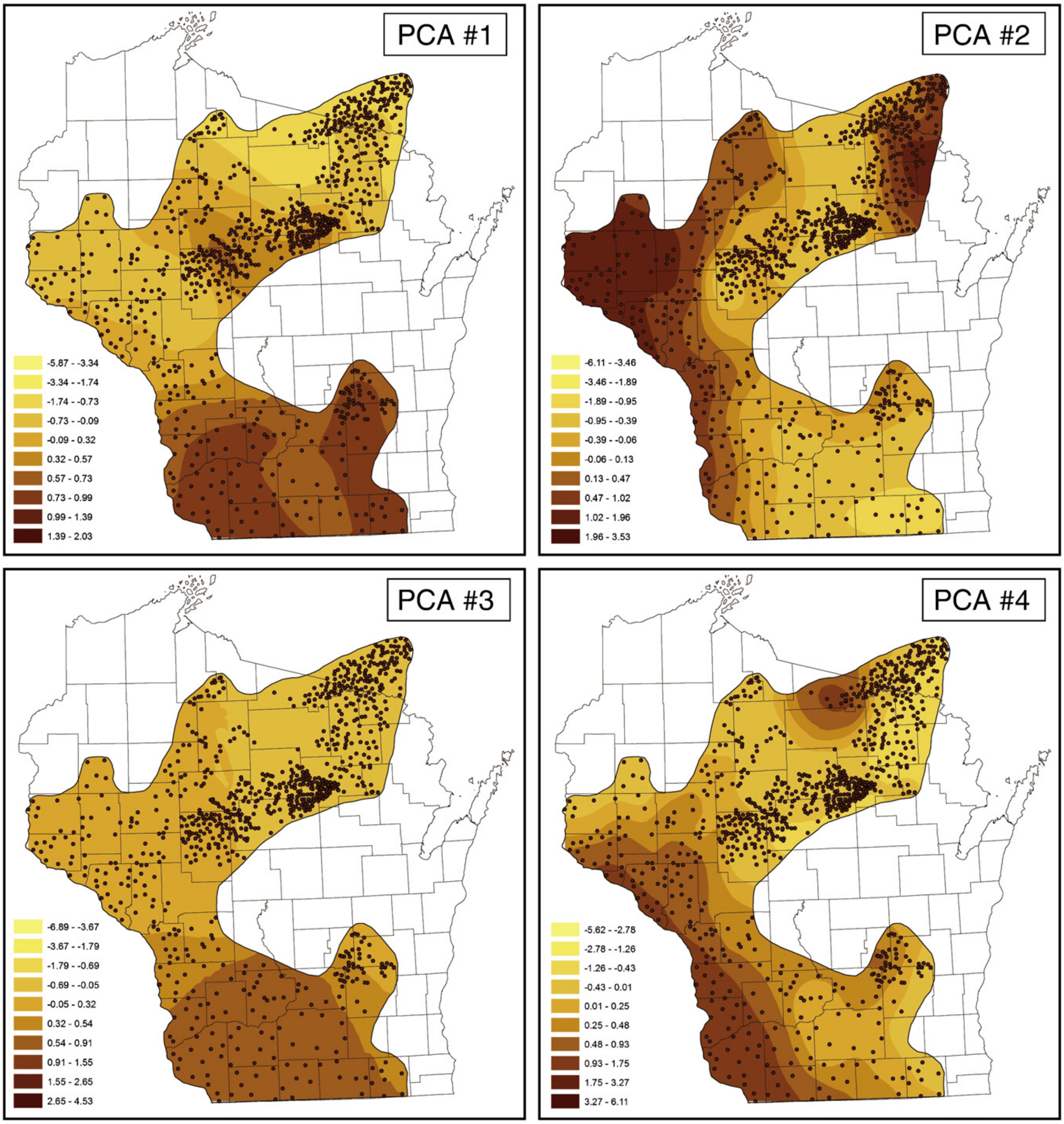

Fig. 9. Kriged maps of the four principal component scores, made in ArcGIS.

loams, four are fine sandy loams, two silty clay loams, and one each of the following textures: loamy sand, fine sand, sandy clay loam, very fine sandy loam, sandy loam and silty clay.

By far the weakest of the four components, #4 loads most positively on loess thickness and also is strongly correlated with various silt fractions (Fig. 6; Table 2). This component accounts for less than one-tenth of variance as the first component (3.5%) and is, therefore, significantly less important and more difficultly interpretable. Having a mean particle size value of 39.2 μm (coarse silt) for the positively correlated particle size fractions, it resembles component 1 in this respect. However, component 1 is negatively correlated with much coarser sand fractions. We interpret this component as coarser textured (sometimes quite sandy), generally thick, eolian sediment but with a significant admixture of silt (Fig. 7). Only 11 of the 30 samples with the highest component scores are silt loam in texture; the remainder are sandy loams (12), fine sandy loams (5), and loamy sands (1) and loams (1). As suggested by the textural uniformity value — its most negatively correlated variable — this component may be best described as poorly sorted, near-source loess, as supported by the distribution of samples that score positively on component 4 (Figs. 8, 9). Component 4 samples are often found very near potential source areas, especially sandy source areas such as outwash plains and sandy moraines. This association probably explains their high sand concentrations (Figs. 6, 7) and their strong association with thickness (Table 2). Several of these source areas are broad, sandy landscapes as with component 3.

6. Conclusions

Our research involved an extensive sampling campaign directed toward several previously unstudied and sometimes disjunct loess sheets in Wisconsin and Michigan. Unlike many of the thick, silty, and continuous loess sheets of the Midwest, we believe that the loess deposits in our study area generally were not sourced from large, deep meltwater valleys such as the Mississippi and Missouri Rivers, or from large dune fields upwind (Roberts et al., 2003). Much sand is trapped in these deep valleys or in dunefields, promoting the deposition of thick, but silt-dominated, loess on uplands that are immediately downwind, e.g., Smith (1942). Most of the 875 loess samples from this study were derived from small interior loess sheets, many of which are thin and were likely sourced from nontraditional landforms and landscapes, e.g., outwash plains, moraines, and lacustrine plains. Thus, taken together, they represent an excellent mix of the various types of loess that exist in recently deglaciated areas.

Our data illustrate the textural and thickness variability that spans such landscapes and loesses, both within and between loess sheets. Although silt loam textured loess (dominated by medium silt) is most common here, many loesses are, instead, rich in very fine sands and coarse silts. Still other loesses have a larger (and coarser) sand fraction with lesser amounts of silt, reflecting either a weakly sorted, near-source eolian deposit or a thin silty loess deposit that has been post-depositionally mixed with a sandy underlying sediment. Whereas many previous studies have defined loess largely based on a dominant particle size fraction, our work and the loesses in our study area better fit a more general definition, like that of Pye (1995, p. 654): loess (i) consists principally of wind-deposited silt, and (ii) it accumulated subaerially.

Principal components analysis identified four "groups" of loess based on a number of textural parameters and loess thickness. The first component is interpreted as classical silty loess, rich in medium silt. We refer to loess that correlates strongly on the second component as "coarse loess," with abundant very fine sands and very coarse silt. Components 3 and 4 were more difficult to interpret and may represent mixes of silty loess with the underlying sandy sediment or weakly sorted sandy end members of loess sheet continua/facies. Regardless, components 3 and 4 have notable amounts of sand — for sediment sampled in the field as loess — and are commonly found in close spatial association with sandy landscapes, particularly outwash plains, moraines, and sandy bedrock landscapes, that may have sourced some or most of this sediment.

Acknowledgements

This material was supported by the National Science Foundation under grants # BCS-0422108 and BCS-0851108 made to RJS and collaborators. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. We acknowledge the support made to K. Stanley by the MSU Graduate School. This research has had many important contributors who variously worked in the field and lab. We thank H. Aschoff, M. Bigsby, J. Hupy, M. Luehamnn, B. Maki, J. Powers, and K. Stanley for their help and dedication to this project. S. Acmoody created many of the graphics.

References

Aleinikoff, J.N., Muhs, D.R., Fanning, C.M., 1998. Isotopic evidence for the sources of Late Wisconsin (Peoria) loess, Colorado and Nebraska: implications for paleoclimate. In: Busacca, A. (Ed.), Dust Aerosols, Loess Soils and Global Change. College of Agric and Home Econ. Misc. Publication MISC0190, Wash. St. Univ, pp. 124–127.

Aleinikoff, J.N., Muhs, D.R., Sauer, R.R., Fanning, C.M., 1999. Late Quaternary loess in northeastern Colorado: part II — Pb isotopic evidence for the variability of loess sources. Geological Society of America Bulletin 111, 1876–1883.

Antisari, L.V., Dell'Abate, M.T., Buscaroli, A., Gherardi, M., Nisini, L., Vianello, G., 2010. Role of soil organic matter characteristics in a pedological survey: "Bosco Frattona" natural reserve (Site of Community Importance, Italy) case study. Geoderma 156, 302–315.

Bartlein, P.J., Anderson, K.H., Anderson, P.M., Edwards, M.E., Mock, C.J., Thompson, R.S., Webb, R.S., Webb III, T., Whitlock, C., 1998. Paleoclimate simulations for North America over the past 21,000 years: features of the simulated climate and comparisons with paleoenvironmental data. Quaternary Science Reviews 17, 494–585.

Bettis III, E.A., Muhs, D.R., Roberts, H.M., Wintle, A.G., 2003. Last glacial loess in the conterminous USA. Quaternary Science Reviews 22, 1907–1946.

Cailleux, A., 1942. Less actions eoliannes periglaciaires en Europe Paris, Memoir Soc. Geol. France 46, 1–166.

Chen, X.H., Duan, Z.H., 2009. Changes in soil physical and chemical properties during reversal of desertification in Yanchi County of Ningxia Hui autonomous region, China. Environmental Geology 57, 975–985.

Clayton, L., 1986. Pleistocene Geology of Florence County, Wisconsin. Wisconsin Geological and Natural History Survey Information Circular 51, Madison. 13 pp.

C.O.H.M.A.P. Members, 1988. Climatic changes of the last 18,000 years: observations and model simulations. Science 241, 1043–1052.

Contini, D., Genga, A., Cesari, D., Siciliano, M., Donateo, A., Bove, M.C., Guascito, M.R., 2010. Characterisation and source apportionment of PM10 in an urban background site in Lecce. Atmospheric Research 95, 40–54.

Ding, Z., Sun, J., Rutter, N.W., Rokosh, D., Liu, T., 1999. Changes in sand content of loess deposits along a north–south transect of the Chinese Loess Plateau and the implications for desert variations. Quaternary Research 52, 56–62.

Dott Jr., R.H., Attig, J.W., 2004. Roadside Geology of Wisconsin. Mountain Press, Missoula, MT. 345 pp.

ESRI (Environmental Systems Resource Institute), 2009. ArcMap 9.2. ESRI, Redlands, California.

Fehrenbacher, J.B., 1973. Loess stratigraphy, distribution and time of deposition in Illinois. Soil Science 115, 176–182.

Fehrenbacher, J.B., White, J.L., Ulrich, H.P., Odell, R.T., 1965. Loess distribution in southeastern Illinois and southwestern Indiana. Soil Science Society of America Proceedings 29, 566–572.

Follmer, L.R., 1996. Loess studies in central United States: evolution of concepts. Engineering Geology 45, 287–304.

Forman, S.L., Pierson, J., 2002. Late Pleistocene luminescence chronology of loess deposition in the Missouri and Mississippi River valleys, United States. Palaeogeography, Palaeoclimatology, Palaeoecology 186, 25–46.

Forman, S.L., Bettis III, E.A., Kemmis, T.J., Miller, B.B., 1992. Chronologic evidence for multiple periods of loess deposition during the Late Pleistocene in the Missouri and Mississippi River Valley, United States: implications for the activity of the Laurentide Ice Sheet. Palaeogeography, Palaeoclimatology, Palaeoecology 93, 71–83.

Frazee, C.J., Fehrenbacher, J.B., Krumbein, W.C., 1970. Loess distribution from a source. Soil Science Society of America Proceedings 34, 296–301.

Frolking, T.A., Jackson, M.L., Knox, J.C., 1983. Origin of red clay over dolomite in the loess-covered Wisconsin Driftless uplands. Soil Science Society of America Journal 47, 817–820.

Ganor, E., Mamane, Y., 1982. Transport of Saharan dust across the Mediterranean Sea. Atmospheric Environment 16, 581–587.

Goudie, A.S., Cooke, R.U., Doornkamp, J.C., 1979. The formation of silt from quartz dune sand by salt processes in deserts. Journal of Arid Environments 2, 105–112.
Grimley, D.A., 2000. Glacial and nonglacial sediment contributions to Wisconsin Episode loess in the central United States. Geological Society of America Bulletin 112, 1475–1495.
Gullentops, F., Janssen, J., Paulissen, E., 1993. Saalian nivation activity in the Bosbeek Valley, NE Belgium. Geologie en Mijnbouw 72, 125–130.
Haase, D., Fink, J., Haase, G., Ruske, R., Pecsi, M., Richter, H., Altermann, M., Jaeger, K.-D., 2007. Loess in Europe — its spatial distribution based on a European Loess Map, scale 1:2,500,000. Quaternary Science Reviews 26, 1301–1312.
Hole, F.D., 1968. Aeolian Sand and Silt Deposits of Wisconsin. Wisconsin Geological and Natural History Survey Publication, Madison.
Hole, F.D., 1976. Soils of Wisconsin. University of Wisconsin Press, Madison. 223 pp.
Johnson, W.H., Follmer, L.R., 1989. Source and origin of Roxana silt and Middle Wisconsinan midcontinent glacial activity. Quaternary Research 31, 319–331.
Jolliffe, I.T., 2002. Principal Components Analysis. Springer and Verlag, New York. 502 pp.
Kaiser, H.F., 1960. The application of electronic computers to factor analysis. Educational and Psychological Measurement 20, 141–151.
Kleiss, H.J., 1973. Loess distribution along the Illinois soil-development sequence. Soil Science 115, 194–198.
Koster, E.A., 1988. Ancient and modern cold-climate aeolian sand deposition: a review. Journal of Quaternary Science 3, 69–83.
Lea, P.D., 1990. Pleistocene periglacial eolian deposits in southwestern Alaska: sedimentary facies and depositional processes. Journal of Sedimentary Petrology 60, 582–591.
Leigh, D.L., 1994. Roxana silt of the upper Mississippi valley: lithology, source, and paleoenvironment. Geological Society of America Bulletin 106, 430–442.
Leigh, D.L., Knox, J.C., 1993. AMS radiocarbon age of the upper Mississippi valley Roxana silt. Quaternary Research 39, 282–289.
Leigh, D.L., Knox, J.C., 1994. Loess of the upper Mississippi valley driftless area. Quaternary Research 42, 30–40.
Mason, J.A., 2001. Transport direction of Peoria loess in Nebraska and implications for loess source areas on the central Great Plains. Quaternary Research 56, 79–86.
Mason, J.A., Nater, E.A., 1994. Soil morphology–Peoria loess grain size relationships, southeastern Minnesota. Soil Science Society of America Journal 58, 432–439.
Mason, J.A., Jacobs, P.M., Hanson, P.R., Miao, X., Goble, R.J., 2003. Sources and paleoclimatic significance of Holocene Bignell loess, central Great Plains, USA. Quaternary Research 60, 330–339.
Matheron, G., 1963. Principles of geostatistics. Economic Geology 58, 1246–1266.
McTainsh, G., 1987. Desert loess in northern Nigeria. Zeitschrift fur Geomorphologie N. F. 26, 417–435.
Mickelson, D.M., 1986. Glacial and Related Deposits of Langlade County, Wisconsin. Wisconsin Geological and Natural History Survey, Information Circular 52, Madison. 30 pp.
Morgan, R.P.C., 1971. Rainfall of west Malaysia: a preliminary regionalization using principal components analysis. Area 3, 222–227.
Muhs, D.R., Bettis III, E.A., 2000. Geochemical variations in Peoria loess of western Iowa indicate paleowinds of midcontinental North America during last glaciations. Quaternary Research 53, 49–61.
Muhs, D.R., Budahn, J.R., 2006. Geochemical evidence for the origin of late Quaternary loess in central Alaska. Canadian Journal of Earth Science 43, 323–337.
North American Commission on Stratigraphic Nomenclature, 1983. North American Stratigraphic Code. American Association of Petroleum Geologists Bulletin 67, 841–875.
Obruchev, V.A., 1945. Loess types and their origin. American Journal of Science 243, 256–262.
Pesci, M., 1990. Loess is not just accumulation of airborne dust. Quaternary International 7 (8), 1–21.
Peterson, W.L., 1985. Preliminary Surficial Geologic Map of the Iron River $1^o \times 2^o$ Quadrangle, Michigan and Wisconsin. U.S. Geological Survey Open File Report 82-301, Arlington, VA.
Pirkle, F.L., Pirkle, E.C., Pirkle, W.A., Dicks, S.E., 1985. Evaluation through correlation and principal component analyses of a delta origin for the Hawthorne and Citronelle sediments of peninsular Florida. Journal of Geology 93, 493–501.
Putman, B.R., Jansen, I.J., Follmer, L.R., 1989. Loessial soils: their relationship to width of the source valley in Illinois. Soil Science 146, 241–247.
Pye, K., 1984. Loess. Progress in Physical Geography 8, 176–217.
Pye, K., 1987. Aeolian Dust and Dust Deposits. Academic Press, London. 334 pp.
Pye, K., 1995. The nature, origin and accumulation of loess. Quaternary Science Reviews 14, 653–667.
Richthofen, F., 1882. On the mode of origin of the loess. Geological Magazine 9, 293–305.
Roberts, H.M., Muhs, D.R., Wintle, A.G., Duller, G.A.T., Bettis III, E.A., 2003. Unprecedented last-glacial mass accumulation rates determined by luminescence dating of loess from western Nebraska. Quaternary Research 59, 411–419.
Ruhe, R.V., 1973. Background of model for loess-derived soils in the upper Mississippi valley. Soil Science 115, 250–253.
Ruhe, R.V., Olson, C.G., 1980. Clay-mineral indicators of glacial and nonglacial sources of Wisconsinan loesses in southern Indiana. Geoderma 24, 283–297.
Russell, R.J., 1944. Lower Mississippi valley loess. Geological Society of America Bulletin 55, 1–40.
Rutledge, E.M., Holowaychuk, N., Hall, G.F., Wilding, L.P., 1975. Loess in Ohio in relation to several possible source areas: I. Physical and chemical properties. Soil Science Society of America Proceedings 39, 1125–1132.
Schaetzl, R.J., 1998. Lithologic discontinuities in some soils on drumlins: theory, detection, and application. Soil Science 163, 570–590.
Schaetzl, R.J., 2008. The distribution of silty soils in the Grayling Fingers region of Michigan: evidence for loess deposition onto frozen ground. Geomorphology 102, 287–296.
Schaetzl, R.J., Hook, J., 2008. Evidence for loess in northwest Lower Michigan: the silty mantle on the Buckley Flats outwash plain. Physical Geography 29, 1–18.
Schaetzl, R.J., Loope, W.L., 2008. Evidence for an eolian origin for the silt-enriched soil mantles on the glaciated uplands of eastern Upper Michigan, USA. Geomorphology 100, 285–295.
Sielaff, K., Einax, J.W., 2007. The application of multivariate statistical methods for the evaluation of soil profiles. Journal of Soils and Sediments 7, 45–52.
Smalley, I.J., 1966. The properties of glacial loess and the formation of loess deposits. Journal of Sedimentary Petrology 36, 669–676.
Smalley, I.J., 1972. The interaction of great rivers and large deposits of primary loess. Transactions of the New York Academy of Science 34, 534–542.
Smalley, I.J., 1978. The New Zealand loess and the major categories of loess classification. Search 9, 281–282.
Smalley, I.J., 1990. Possible formation mechanisms for the modal coarse-silt quartz particles in loess deposits. Quaternary International 7 (8), 23–27.
Smalley, I.J., Krinsley, D.H., 1978. Loess deposits associated with deserts. Catena 5, 53–66.
Smalley, I.J., Vita-Finzi, C., 1968. The formation of fine particles in sandy deserts and the nature of “desert” loess. Journal of Sedimentary Petrology 38, 766–784.
Smith, G.D., 1942. Illinois Loess: Variations in its Properties and Distribution. University of Illinois Agricultural Experiment Station Bulletin 490, Urbana.
Stanley, K.E., 2008. Characterization and Paleoenvironmental Significance of the North Central Wisconsin Loess Sheet. M.S. Thesis, Geography, Michigan State University, East Lansing, 171 pp.
Syverson, K.M., 2007. Pleistocene Geology of Chippewa County, Wisconsin. Wisconsin Geological and Natural History Survey Bulletin 103, Madison.
Syverson, K.M., Clayton, L., Attig, J.W., Mickelson, D.M., 2011. Lexicon of Pleistocene Stratigraphic Units of Wisconsin. Wisconsin Geological and Natural History Survey Technical Report 1, Madison.
Tsoar, H., Pye, K., 1987. Dust transport and the question of desert loess formation. Sedimentology 34, 139–153.
Waggoner, P.E., Bingham, C., 1961. Depth of loess and distance from source. Soil Science 92, 396–401.
Wang, X.M., Dong, Z.B., Zhang, C.X., Qian, G.Q., Luo, W.Y., 2009. Characterization of the composition of dust fallout and identification of dust sources in arid and semiarid north China. Geomorphology 112, 144–157.
Wascher, H.L., Humbert, R.P., Cady, J.G., 1947. Loess in the southern Mississippi valley: identification and distribution of loess sheets. Soil Science Society of America Proceedings 12, 389–399.
Yaalon, D.H., 1969. Origin of desert loess. Etudes sur la Quaterna e dans le Monde., 2. 8th INQUA Congress, Paris, p. 755.